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Technological aspects of WBANs for health monitoring: a comprehensive review

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Abstract

According to the World Health Organization, most of the world population is affected by chronic diseases, obesity, cardiovascular diseases and diabetes while another dominant problem is of aging population. Thus, it is desirable to have cost effective solutions for health monitoring, especially for countries that have minimum conventionally trained healthcare staff and infrastructure. Healthcare has shifted from hospital dominant services to patient dominant services which has thrived WBANs to provide ubiquitous health monitoring by virtue of wearable or implantable sensor nodes that commonly monitor biological signals. As the society becomes more health conscious, WBANs have the potential to revolutionize the way people integrate their health and information technology. Hence, WBANs are desired to strengthen conventional healthcare systems. Notwithstanding the current achievements, technological advances, proposed solutions and commercialized products; WBANs still experience many obstacles in their foolproof adoption. This paper surveys the plethora of WBAN applications and network architecture in detail used for data collection, data transmission and data analysis that form sensor analyst system in the realm of Internet of Things. Wireless communicational technologies are also discussed in this paper. Also, we have categorized the routing protocols and have provided with their critical qualitative analysis. Towards the end we discuss several projects in the field of WBANs and some open research areas. These findings on how the sensor nodes, newest routing protocols and data analysis techniques influence ubiquitous health monitoring sets this survey apart from the already existing surveys on WBANs.

Keywords Data aggregation · Data analysis · Network architecture · Routing protocols · Sensors · Ubiquitous healthcare · Wireless body area networks

1 Introduction

An alarming increase in the world population is forcing speedy increase in healthcare costs as the conventional healthcare systems are challenged by economic and demographic factors all over the world. The world economies are spending a lot in healthcare like the United States spent an estimated 17.2%[1] of its Gross Domestic Product (GDP) on healthcare whereas India spent 2.5%[2] of its GDP in 2017. If the global GDP grows by 4.5% per year (US $) over the next decade, global health spending would be expected to increase by 7.5% per year [1]. Also, the conventional healthcare systems fail in early diagnosis of the diseases whereas research has shown that the early diagnosis can reduce the overall treatment costs and improve the quality of life. Moreover, if the symptoms are visible at early phases, the diseases can be prevented. Furthermore, conventional healthcare systems purely focus on the medical perspective and barely on the non-medical applications. To overcome these short-comings, we need to focus on the transformation of existing reactive healthcare

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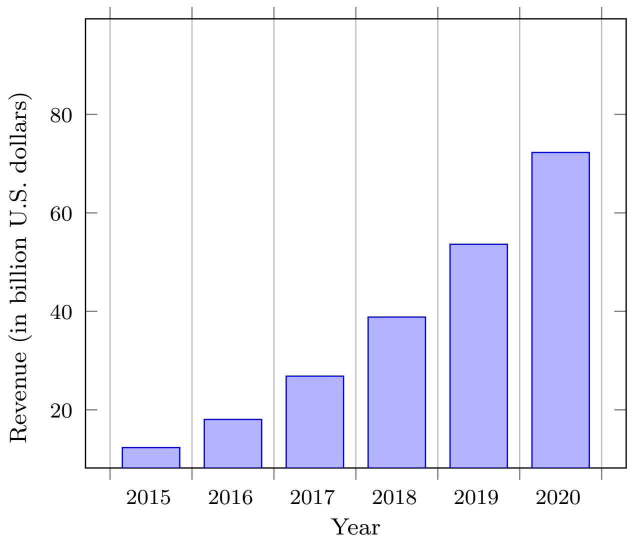


Fig. 1 Revenue of sensor based wearable devices globally

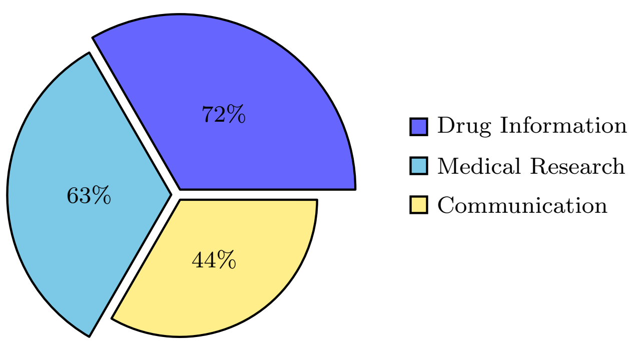


Fig. 2 Usage of smartphones and social media by physicians

systems to proactive healthcare systems that provide ubiquitous monitoring and affordable healthcare.

The rising costs of healthcare have prompted novel technological boosts to enhance current healthcare systems. The technological advancements of low power electronic devices, sensing devices, wearable systems and wireless communication technologies have made it possible to develop smart wearable health monitoring systems. These systems consist of many small and intelligent (bio-) medical sensors used for measuring physiological parameters such as body temperature [2–4], heart rate [5, 6], body movements [7–9], ECG (Electro-Cardio Gram) [10, 11] and so on. Conventional health care systems tend to prevent, diagnose, monitor and treat diseases. However, in lieu of technological advancements health care systems demand innovation for improving care and quality of life. According to a survey [12], Next-generation sequencing (NGS), 3D-printed devices, Immunotherapy, Artfcial intelligence (AI), Virtual reality (VR), Point-of-care (POC) diagnostics, Leveraging social media to improve patient experience, Biosensors and trackers, Convenient care and Telehealth are some of the innovations to achieve the desired healthcare. The demand of technology-prone devices has increased by both medical practioners as well as end users as Fig. 1 shows the estimated global revenue of sensor based wearable devices from year 2015 to 2020 and Fig. 2 shows the distribution of various activities performed by medical professionals through smartphones and social media.

Also, the WBANs can measure contextual information such as location, social activity, mental state, physical activity, environment, movement patterns, body posture and interruptibility which is useful for correlating sensed signals and the current context [13]. These systems are capable of early diagnosis of various physiological symptoms, early diagnosis of diseases, quick response in case of emergencies and provide real-time feedback to avoid any dire consequences. The Healthcare is moving from eHealth to mHealth where eHealth is healthcare supported by electronic processes and mHe-alth is defined as mobile Healthcare which integrates cloud computing and smartphone devices [14]. For this purpose, wired interface involves a high cost of deployment and maintenance whereas wireless interface is easier to deploy and cost effective solution [15]. Thus, the personal wireless health care systems are cost-effective and reliable.

The recent availability of various emerging technologies have enabled physical, physiological, psychological and behavioral data collection about humans in both rural and urban areas. This has led to the emergence of Wireless Sensor Networks (WSNs) in healthcare focusing on various application domains exploring wireless technologies in telemedicine and mHealth. Wireless Body Area Network (WBAN); the term first coined in 2001 by Van Dam et al. [14], is defined by *IEEE 802.15 (Task group 6) as a real-time, wireless, short-range communication standard consisting of low power devices for communicating in and around human body for various medical and non-medical applications* [15–17].

A Wireless Body Area Network constitute of low power, minute and intelligent sensor nodes based on Radio Frequency (RF) technology. Sensor nodes interconnect each other in, on or around a human body. They are either implanted on human body or are wearable on accessories like shirts, belts, wrist watches, rings, shoes, socks etc. Sensor nodes continuously monitor patients everywhere, anytime and provide ubiquitous distant health monitoring; thus reducing the number of visits to the doctor. Sensor nodes aim to increase speed, accuracy and reliability of patient data which is being collected by the sensor nodes. WBANs continuously perform sampling, monitoring, processing and communication of vital physical parameters

Table 1 Comparison of surveys on WBANs

Survey	Background	Data collection	Data transmission	Data analysis
This article	WBANs	✔	✔	✔
Effatparvar et al. [62]	Routing Protocols in WBANs	×	✔	×
Xu et al. [19]	WBANs	✔	✔	✔
Mukhopadhyay [48]	Wearable Sensors	✔	✔	×
Cavallari et al. [51]	WBANs	×	✔	×
Zhang et al. [20]	Ubiquitous Healthcare	✔	✔	✔
Touati and Tabish [21]	U-Healthcare Systems	✔	✔	✔
Movassaghi et al. [61]	WBANs	×	✔	×
Ullah et al. [24]	PHY, MAC, Network Layers	✔	✔	×
Latre et al. [15]	WBANs	✔	✔	×
Li et al. [25]	Security in WBANs	×	×	×
Cao et al. [18]	Technologies in WBANs	✔	✔	×

such as body temperature, blood pressure, ECG, Electro-Encephalon Gram (EEG), respiration rate, pulse rate etc. and provide real-time feedback [18].

WBANs have recently given unprecedented rise to proactive ubiquitous e-HealthCare systems for distant health monitoring as WBANs focus on wellness rather than treating illness. WBANs have changed the way people integrate their health and information technology thereby promoting healthy lifestyle, enriched healthcare and independent living. WBANs provide flexible, reliable and cost-effective e-HealthCare systems allowing patients to move freely irrespective of their geographical locations and daily activities. The patients can be monitored continuously and data collection in natural habitat allows unambiguous diagnosis. This reduces the of number of visits to the doctor and lowers hospital costs simultaneously. e-HealthCare systems also provide real-time feedback from doctors avoiding any future complications. The patient data is stored on the medical databases for long term trend analysis, predicting outcomes, detecting anomalies, non-occurring behavior and to study the effect of treatment. This redefines a doctor-patient relationship.

In this article, we have surveyed the state-of-the-art of WBANs, recent applications based on IoT, network architecture for cloud-based WBANs, communicational technologies, routing protocols, challenges and projects in WBANs. Our intent in this paper is for detailed investigation of the three phases of the network architecture, viz., data collection, data transmission and data analysis that form sensor analyst systems integrating health based sensors, cloud computing and smartphone dvices in the realm of Internet of Things. Unlike previous works, this paper is not a general study of WBANs instead it focuses on the three layers of network architecture of cloud-based WBANs as shown in Table 1. The articles [19–21] have similar contributions, however, the authors emphasize more on energy harvesting and green sources of power supply to sensor nodes, Ubiquitous Sensing for Healthcare (USH) systems with pro-activeness, transparency, awareness, trustworthiness and hardware, communication, computing requirements for uHealth systems respectively. The main contributions of this paper are as follows

- An overview of need and research conducted in the field of WBANs.
- A classification of WBAN applications in various medical and non-medical domains.
- A detailed analysis of the three layers of network architecture for cloud-based WBANs.
- A comparison of various communicational technologies for WBANs.
- A classification and critical qualitative analysis of routing protocols in WBANs.
- An investigation of data analytics in WBANs for ubiquitous and pervasive health monitoring.
- Examining challenges in WBANs which are still open for research.
- A compilation of WBAN projects.

The remaining sections of this article are as follows. Section 2 describes WBAN applications in both medical and non-medical domains. Section 3 discusses Network Architecture for cloud-based WBANs in detail. Section 4 explains data collection in detail, the first layer of network architecture. Data transmission, second layer of network architecture is explained in Sect. 5 along with data communication, protocol stack, energy model, routing protocols and data aggregation. Data analytics, third layer of network architecture is surveyed in Sect. 6. Section 7 broadly indicates inferences drawn from extensive

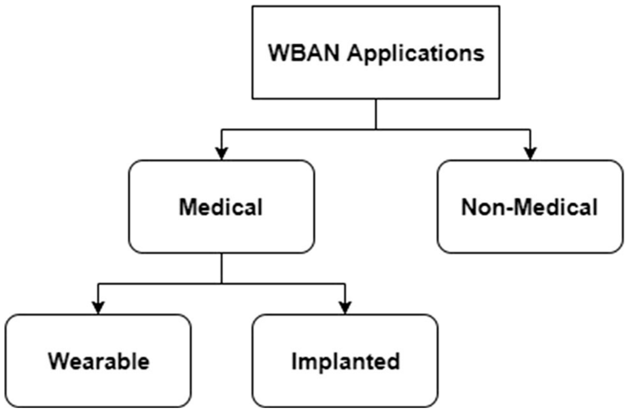


Fig. 3 Classification of WBAN applications

literature review. Section 8 discusses some of the open research issues in WBANs. Section 9 concludes the paper.

2 Applications

WBANs, being a subset of WSNs, have plethora of applications in various medical and non-medical domains as classified in Fig. 3 [22, 23]. WBANs offer many innovative applications to improve patient's health care and quality of life. However, technological requirements are application specific as described in Table 2. In context of medical realm, WBAN applications can be further classified as either wearable or implanted with different use cases. These applications focus on continuous monitoring of various physiological signals for quick dissemination of information to caregivers. In frame of reference of non medical applications, WBANs have found their indispensable usage in Entertainment, Consumer Electronics and Interactive Learning. The following subsection includes various WBAN services offered in both medical and non-medical spheres.

2.1 Medical applications

Medical applications allow continuous patient monitoring with the help of sensor nodes which can be either wearable or implant nodes. Wearable nodes are worn by the patient on clothes or accessories such as shirt, vest, watches, socks, belts, sunglasses whereas implant nodes are put either in the blood stream or beneath the skin as shown in Fig. 4. Healthcare applications of WBANs also include monitoring animal healthcare.

2.1.1 Wearable WBANs

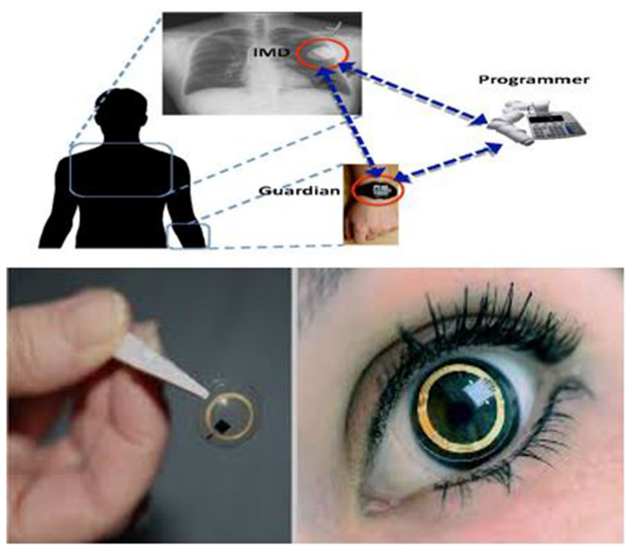
Wearable devices allow patient to monitor health status without actually being hospitalized and irrespective of geographical location. This provides unobtrusive solutions for continuous patient monitoring. Wearable applications embrace personal healthcare solutions for athletes, old age patients, pregnant women and chronic patients. Also, useful for accessing soldiers in battlefields [24], amateur sports training, measuring muscle fatigue, glucose monitoring and many more. This reduces number of visits to the doctor and lowers hospital costs simultaneously. It is advantageous as the patient can move freely, perform routine activities and all the functions can be monitored easily. This significantly improves the quality of life [25]. Some of the wearable applications of WBANs are discussed below.

(a) *Patient monitoring* The patients can be monitored in hospital and at home both allowing unobtrusive and ubiquitous health monitoring without visiting the doctor personally. The wearable sensors sense the physiological parameters and send the sensed data to the remote terminal from where the data is easily accessible to the medical fraternity. The doctors can take necessary actions in case of abnormal conditions and also provide real-time feedback. Many parameters such as ECG, Blood Sugar Level, Blood Oxygen Level, Pulse Rate, Body Temperature etc. can be measured using the wearable sensors. Most of the vital signals can be measured using the wearable sensors while few can be measured using implantable sensors. Thus the usage of WBANs is

Table 2 Technological requirements of WBAN applications

Application	Context awareness	QoS	Privacy
Remote patient monitoring	Event specific	Yes	High
Rehabilitation	Event specific	Yes	High
Biofeedback	Environment specific	Yes	High
Assisted living	Environment and event specific	Yes	High
Wellness monitoring	Event specific	Yes	High
Biometrics	Stress level	Yes	High
Gaming	Stress level	Yes	High

(a) Wearable Sensor Nodes



(b) Implanted Sensor Nodes

Fig. 4 Sensor nodes used in WBANs

expected to augment the conventional health care systems by providing technological solutions.

(b) *Ambient assisted living* Ambient Assisted Living (AAL) provides elderly a smart home for independent living by connecting wireless devices that communicate with remote server. AAL not only analyses the elderly but also assist them in living. AAL devices are context aware and can measure environmental conditions of the elderly. This is useful for fall detection, gait detection and movement etc. Also, AAL is useful for persons with disabilities as it provides an environment to live in a convenient manner.

(c) *Adverse drug reaction* It is the effect of medication either of single or combination of two or more drugs. It is administered either for a prolonged time period or in a quick succession. The consequences of medication can be adverse and are not related to a particular disease, individual or community. Thus, Adverse Drug Reactions are referred to as generic. Therefore, there is a need to list technical details of every drug which is used in medication purposes so that the drug can be matched with the allergic profile and electronic health record of the patients at the time of giving prescriptions.

(d) *Community healthcare* Community Healthcare is the concept of covering a larger geographical area by having a larger WBAN on top of few smaller WBANs. By smaller WBANs, we refer to a community, a residential area, a dispensary or hospital, a building etc. which forms a LAN. The nexus of such smaller WBANs form a Community Healthcare. Many authors have proposed community healthcare network which is also viewed as a virtual hospital.

(e) *Emergency services* Wearable sensors can also be used in emergency services like fire outbreak, gas leak, disasters etc. It is used by firemen, police personnel in emergency situations. The real time data can be shared with remote servers for combating the situation. Safety of personnels can be checked during emergency services. Also during disaster situation, sensors can be deployed on affected people to know their health status and all the privileges can be provided to them.

(f) *Rehabilitation centres* Wearable sensors have also found their usage in rehabilitation centres where they are able to provide independent and assisted living to the patients. Patients can be monitored continuously which provides a healthy feedback.

(g) *Wheelchair management* Many authors have proposed WBANs based wheelchairs, smart and automatic, providing healthcare monitoring for wheelchair users. These wheelchairs are useful for disabled people and are provided with chair vibrations to detect the status of users. Another researcher proposed a wheelchair to monitor vital signs of patients and their surroundings.

(h) *Behavioral studies* WBANs are used to conduct large scale behavioral studies which is useful in relating ailment to human behavior and living conditions. The traditional methods suffer from complexities, time consumption, errors and researcher's bias. Behavioral studies using WBANs permit prolonged data collection form human subjects in their natural environment. The collected data is sent to the remote server for analysis, visualization and data sharing. These systems are useful for diagnosing psychological stress, addiction, depression and their relationship. A major challenge with these systems is ensuring privacy of the information thus shared.

(i) *Defense and battlefield* Wearable sensors are used for accessing soldier fatigue, body movement and motion of the soldiers. Thus, allowing to continuously monitor soldiers in battlefield. Also, it can be used in the training process of soldiers. With use of sensors in training soldiers, we can decide the level of training, health issues and diet on the basis of fatigue. The location of soldiers can also be detected.

(j) *Sports training* Wearable sensors can be used in sports training to access muscle fatigue, glucose level, blood sugar level, heart rate, respiration rate, pulse rate which enhance the performance of the athletes. The data can be shared with the coaches to improve the training of the athletes on the basis of their data.

(k) *Tele-medicine systems* Telemedicine systems if integrated with WBANs can provide unobtrusive health monitoring for a long period of time. The real time information is transferred to the remote servers using wireless communication technologies. Power consumption and interference are major challenges in transmitting information.

2.1.2 Implant WBANs

The implanted WBANs provide Ambient Assisted Living (AAL) to chronic patients for cardiovascular diseases, diabetes and cancer detection etc. [14, 24, 26]. These systems are useful for remote control of medical devices and patient rehabilitation via capturing the movements and posture of patients [13, 26]. Some of the implanted applications of WBANs are discussed below.

(a) *Cardiovascular diseases* Cardiovascular diseases, one of the major reasons for deaths in the world, can be prevented by monitoring the patients using sensors implanted in the blood stream of the patient. Using WBANs, abnormalities in the cardiac events can be detected beforehand which can help greatly in reducing the number of deaths.

(b) *Cancer detection* Implanted sensors integrated with WBANs are able to monitor cancer cells in human body and can diagnose tumours and other abnormal symptoms. The sensed information can be then shared with the medical staff for further analysis and treatment.

(c) *Diabetes* A large number of people suffer from diabetes. Sensor nodes in WBANs can monitor the diabetic patient and can reduce the risk of fainting, blindness and over dose. Diabetes can be detected and treated at early stages with the help of WBANs. Actuators, devices that act upon receiving data from sensors, can be used to inject the correct dosage of insulin in the human body on recommendation of the medical staff.

(d) *Artificial retina* Retina sensors can be implanted in the human eye to help people with limited or no vision.

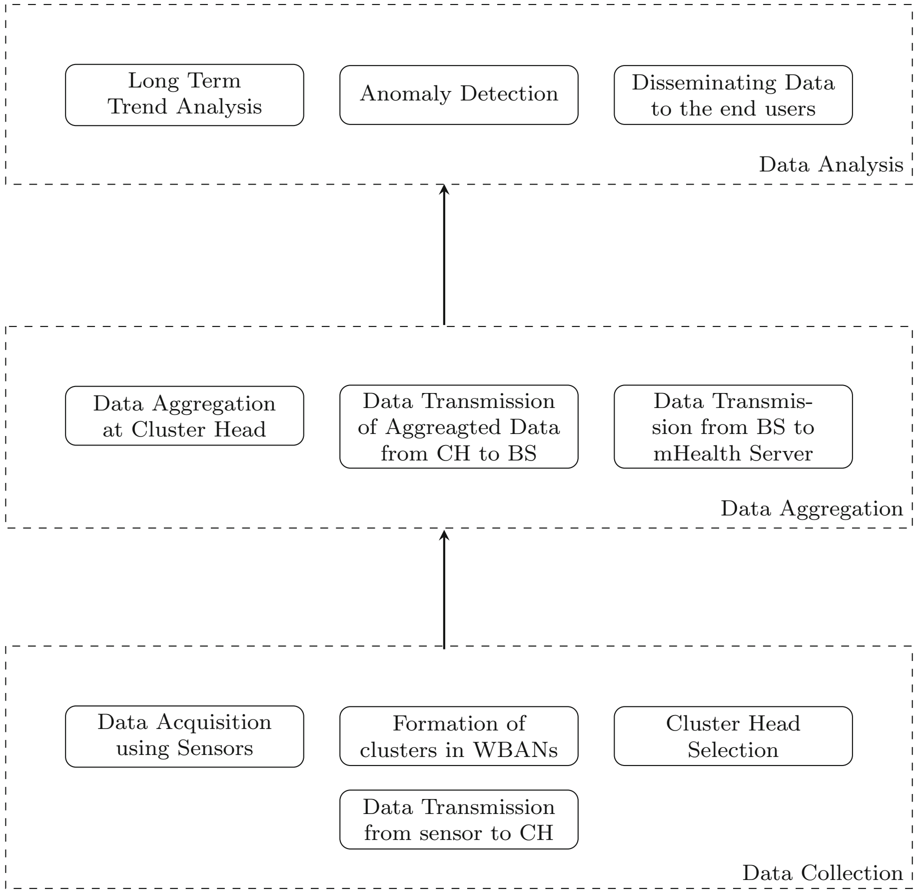


Fig. 5 Network architecture of cloud based WBAN [30]

2.2 Non-medical applications

The non-medical applications of WBANs are found in entertainment and consumer electronics in which advance computer devices like MP3-players, microphones and cameras can be integrated in WBANs useful for virtual reality and item tracking. WBANs are used in gaming for skill, educational and technological enhancements using neuro-feedback and emotional signals [13]. Also, WBANs can be used to create smart homes and have found their usage in emergency services like dealing with fire, leakage of poisonous gas etc. This can be used at homes, by fire-fighters and police personnel for peace making services [27].

(a) *Real time data streaming* Real time data streaming allows data capturing of a video or audio clip from camera or headsets for instant data sharing. This is also useful for stream transfer of data which is used for entertainment devices and motion capture. WBANs can also be used to send reminder/alert to the users thus help to remember things.

(b) *Entertainment* WBANs can be used with various entertainment devices such as microphones, cameras, MP3 players and advanced computing appliances that can form a wireless network. These applications continuously monitor players' neuro-feedback to control the volume and brightness settings of the interactive screens while watching movies or listening to music. Also, WBANs can be used in social networking.

(c) *Interactive learning* WBANs can provide interactive learning via serious gaming and education. WBANs are used in gaming and education for skill enhancement purposes. Technological enhancements allow WBANs to use neuro-feedback and emotional signals for promoting behavioral changes. These applications continuously monitor EEG signals of players to control the game settings. Also, WBANs can improve the educational skills of the children by providing them the exam like scenarios via virtual reality. WBANs can also monitor the stress while performing a particular task and can measure its effect on human nature.

Table 3 Some of the cloud-based WBAN approaches

Authors	Applications	Approach	Cloud services
Joshi et al. [40]	Ambulatory health monitoring	CoAP protocol	Storage and processing
Ghanavati et al. [41]	Real-time health monitoring	Software-as-a-Service	Storage and processing
Rachkidi et al. [42]	eHealth service placement	Cooperative dynamic strategy	IaaS, storage and processing
Rachkidi et al. [43]	eHealth service provider	Location aware auto scaling mechanism for scalability	QoS
Roopali et al. [44]	Health record management service	Data aggragtion	Storage-as-a-Service
Quwaider et al. [45]	Health awareness	Local cloud model and MapReduce infrastructure	Data processing
Diallo et al. [31]	Real-time diagnosis	Statistical modeling techniques	Storage and processing
Rolim et al. [32]	Real-time data collection	On demand resource provisioning	Utility computing
Pandey et al. [33]	Real-time data collection	Autonomic middleware for ECG analysis	Cloud-based information repository
Rashid et al. [34]	Health information and management system	Service oriented architecture	Storage-as-a-Service
Almashaqbeh et al. [36, 37]	Cloud-based real-time remote health monitoring system	Data classification and aggregation	Storage and processing

(d) *Emotion detection* Emotions of human beings can be measured by monitoring the emotion related physiological signals such as ECG, EEG, EMG (Electromyography), EDA (Electrodermal Activity) etc. As WBANs can monitor these signals, they can also detect the emotional signal with the induction of these signals.

In [14, 26, 28, 29], the authors have also mentioned data rate, duty cycle, power consumption, Quality of Service (QoS), bandwidth, context awareness and privacy concerns of various WBAN applications. The usage and properties of different types of sensor devices (hardware) which may be used in various WBAN applications are described in [18].

3 Network architecture for WBAN applications

Recently WBANs have witnessed computing, storage, wireless networking and communication for sharing patient-oriented data in the form of text, image, voice, etc. in various applications. WBANs are resource intensive. However, cloud-assisted WBANs have become popular as they can provide extensive computing and storage in an on-demand fashion for various WBAN applications. A general network architecture for cloud based WBANs is shown in Fig. 5 illustrating the three layers, namely, Data Collection, Data Aggregation and Data Analysis.

Firstly, data collection layer acquires health related data using various types of sensors depending upon the parameter to be collected, viz., ECG, EEG, EMG, Body Temperature, Blood Pressure, Pulse rate etc. The sensor nodes are either implanted or wearable and promote real-time data collection. Also, sensor nodes can have local processing for formation of clusters and routing forming networks (WBANs), and communicate using wireless communicational technologies. Secondly, data transmission layer transmits the data from sensor nodes to the mHealth server via base station or access points. Data aggregation plays a crucial role at this stage for enhancing network lifetime, minimizing energy consumption, end-to-end delay, latency by reducing the number of hops from the sensor node to the base station. This also improves scalability and flexibility for the network. Thirdly, data analysis layer disseminates data to the mHealth server for storage, processing and analysis. These layers store and manage data on cloud for various healthcare applications and reduce processing delay. This also provides end-users with real-time feedback, monitoring, analysis, disease prediction and anomaly detection etc. Thus, the network architecture generally consists of WBAN, coordinator node and mHealth server. The various layers of the architecture are explained in detail in the following sections. However, issues related to guaranteed QoS, high mobility, packet delivery ratio and end-to-end delay still prevail.

Table 4 Generally used sensors in WBAN applications

Sensors	Type	Power consumption	Data rate	Topology	Working
Intertial Measurement Sensors					
Accelerometer	Wearable	Low	High	Star	It measures body posture, falling, vibration and shock with respect to acceleration in three dimensions
Gyroscope	Wearable	Low	High	Star	It measures body movement and orientation based on angular momentum
Blood pressure	Wearable	Low	Low	Star	It measures blood pressure (Systolic and Diastolic)
Electrical measurement sensors					
ECG	Wearable	High	High	Star	It measures electrical activity of the heart using potential difference during contraction and relaxation
EEG	Wearable	High	High	Star	It measures electrical activity of the brain using potential difference
EMG	Wearable	High	Very high	Star	It measures electrical activity of the muscles using potential difference
Brain pacemaker	Implanted	Low	Low	Star	It measures electrical signals of the brain in the form of low frequency and high frequency waves
Chemical sensors					
Blood sugar	Implanted	Extremely low	High	Star	It measures blood sugar level without pricking the finger
Pulse oximetry (SpO_2)	Wearable	High	Low	Star	It measures amount of oxygen absorbed in the human blood in terms of oxyhemoglobin saturation
Body temperature	Wearable	Low	Very low	Star	It measures changes in temperature of human body
Optical motion sensors					
Image/video sensor	Implanted	High	Very high	P2P	It records the images or video of the internal human organs like capsule endoscopy

3.1 Cloud and WBANs

The traditional patient data collection and analysis is a manual, exhaustive and error prone task. The process can be automated by integrating two promising techniques of WBANs and Cloud Computing. Various sensors can be employed to collect patient data and also be used to exchange vital physiological information regarding patient to and from the cloud. Thus, information on the cloud can be analyzed by the medical fraternity. The potential advantages are the real-time data collection and deployment of the process as WBANs do not require physical installation. It dynamically diagnoses the diseases and other related biological information. Cloud computing allows the data to be offloaded from sensor nodes to the cloud. This allows the resource-intensive WBANs to be resource-extensive by using resources of the cloud in terms of storage and processing. Thus, maintaining QoS which the user demands. Some cloud based WBAN approaches are proposed to optimize performance of the conventional health monitoring systems as summarized in Table 3. This makes the health monitoring systems more reliable and realistic.

A cloud-enabled WBAN architecture can provide pervasive healthcare by transmission of vital parameters to the cloud server using energy-efficient routing, cloud resource allocation, semantic interactions, and data security mechanisms. Cloud-based WBANs can optimize query processing time in terms of energy consumption and latency for real time data processing at cloud. Also, it can provide utility computing in which sensors connect to medical equipment useful for transmitting information of the patient to cloud for further processing and analysis. This increases QoS as there is minimum delay in delivering data to and from the cloud. This network architecture projects WBANs as Software-as-a-Service that collects the data of the patients and disseminate it to the cloud based repositories for further analysis and diagnosis. This is a good example of the coordination of IT sector and Health industry. With the help of cloud computing, many health assessment systems are designed for data communication over the Internet with geographically distributed locations and heterogeneous client systems. The health assessment systems can acquire, retrieve, analyze and monitor the health status of patients and can deliver health-promoting messages in a non-interruptive fashion in real-time. The

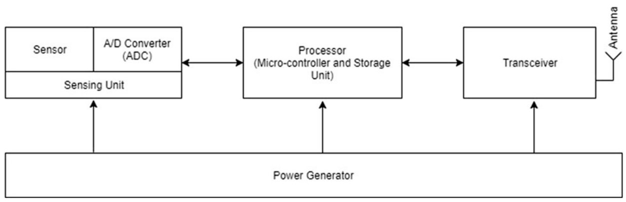


Fig. 6 Basic architecture of a sensor node [47, 48]

health status and the test results of the subjects are stored in the central database on the cloud. The integration of cloud computing and WBANs make healthcare system less expensive, more powerful, realistic and feasible in terms of providing expert-based medical care [31–39].

4 Data collection

WBANs are heterogeneous in nature consisting of several sensors capable of sensing, processing and communicating independently. The sensor nodes being in direct contact with the human body, either wearable or implanted, can bridge the gap between the human body and the electronic systems. Nodes in WBANs can act either as sensor node or actuator. Sensor nodes can monitor certain biological parameters in the human body either internally or externally whereas actuator node interacts upon receiving data from the sensors. Many sensor nodes are available commercially like EMG, ECG, EEG, body temperature, blood pressure, blood glucose, SpO_2, DNA, pulse oximetry, sweat rate, retina, motion sensor etc. Similarly, actuators are available that provide feedback, for example insulin actuator that actually injects the correct dosage of insulin into the human body. With the advances in Micro-Electro-Mechanical Systems (MEMS), modern medical sensors are smart, miniature, low power, multi-parameter and non-invasive. Table 4 summarizes various sensor nodes used in WBANs.

The basic architecture of wearable sensor node for activity monitoring is explained in Fig. 6. Depending upon the application in hand, different types of sensors are used like physiological sensors, MEMS, bio-kinetic sensors and ambient sensors. Sensing unit consists of a sensor node and an Analog-to-Digital Converter (ADC), sensor gathers the information and ADC is used to convert analog signal to digital signal which is then fed into the processing unit where the signals are processed and stored. Transceiver is used to communicate between two sensor nodes as it is capable of transmitting and receiving signals. Power generator provides power to the sensor node and the limited capacity of the power generator demands energy-efficient operations by each unit. Antennas are used as required by the transceiver to couple its electrical connection to the electromagnetic field [46].

4.1 Sensors for health monitoring

Sensors for health monitoring can be categorized into two types based upon the parameters they measure, i.e., electrical signals and non-electrical signals. Electrical sensors can derive electrical signals such as ECG, EEG, EMG etc. whereas non-electrical sensors can derive all other physical and chemical signals. The basic sensing technologies that are used in sensors are piezoelectric effect, photoelectric effect, spectrophotometry, conductivity and hall effect. Some of the sensors are discussed below [49].

(a) *Pulse oximetry sensor* Pulse oximeters measure oxygen saturation in blood and pulse rate. It makes use of spectral analysis or spectrometry for measuring ratio of oxy-haemoglobin and haemoglobin. Spectrometry depends on the distance that the light travels through a substance. The light will be emitted at different wavelength due to different absorption levels of substance. Nowadays, piezo ultrasonic transducers are designed into imaging probes for customization.

(b) *Sweat sensor* Sweat sensors use humidity sensors on a textile substance. The difference in humidity level can be used to calculate the diffusion flow. Another type of sweat sensors are proposed that use conductivity value for measuring the sweat rate in human body.

(c) *ECG electrode* ECG signals reflect electrical activity of heart and regularity of heart beats. It shows myocardial activity through de-polarization and re-polarization of the cardiac muscles. Nowadays, there are wearable and flexible electrodes for measuring ECG. Textile electrodes are also available which are washable.

(d) *Temperature sensor* Temperature sensor is used to measure body temperature at different situations such as routine body temperature, before or after surgery, after extraneous exertion etc. Micro-thermistors or thermocouples are used to measure temperature.

(e) *Glucose sensor* The earliest developed bio-sensor is the glucose sensor which is required to measure metabolism of human body. The electro-chemical glucose sensor is used to measure glucose concentration in human body through colorimetry, fluorescence with high selectivity and sensitivity. The most recent glucose sensors are based on the enzymatic glucose reactions in human body.

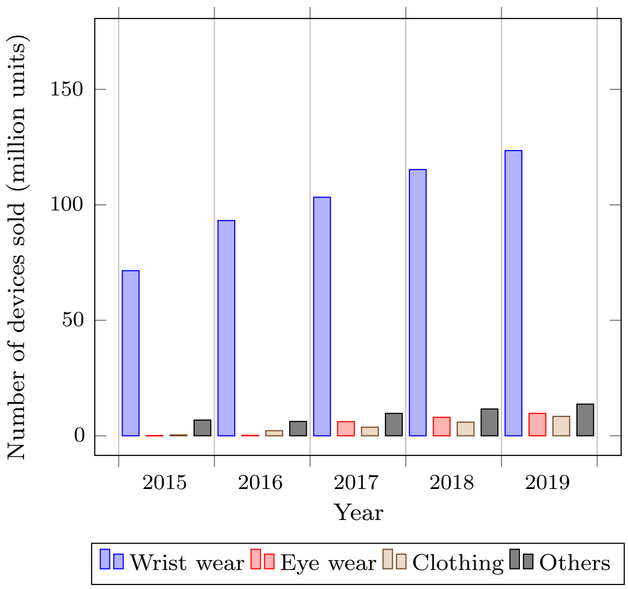


Fig. 7 Sale of wearable devices

(f) *Accelerometer* Accelerometer sensor is used to detect motion, velocity, tilt, position and fall based on angular velocity and piezoelectric effect. The recent tri-axial accelerometer sensor measures the position of human body in three dimensions. Rotatory transducers are also used to measure the multi-position of human body.

Many wearable monitoring devices have been developed for utilization in health monitoring systems as they support intelligent features such as real-time monitoring, easy detection of abnormalities, lower cost, minimum power consumption, context awareness etc. The increasing demand of these devices can be seen in Fig. 7 as it shows (estimated) sale of wearable devices from the year 2015 to 2020 worldwide. Some of the wearable devices are Georgia Tech, a vest for monitoring vital parameters; smart shirt, measures ECG; electronic patch and photodiode as pulse oximetry sensors; AMON and BIOTEX, measures sweat rate, ECG and heart rate; Healthwear, a wearable garment to measure pulse rate and heart rate; posture monitoirng, a vest for measuring multi-postures.

4.2 Design challenges

Digital revolution in healthcare is speeding up as lot of wearable devices such as wrist worn devices, textile-based systems, cyber glasses have been fully utilized by the end users. However, there are several challenges in designing wearable systems for day to day health monitoring such as fabrication, implementation, hardware and software constraints, light weight, energy scavenging, efficiency, accuracy, reliability, interoperability, comfort, security, safety requirements to avoid physical and thermal injury, standardization and commercialization. These challenges pose a serious limitation in designing cost effective and user friendly wearable systems in spite of technological advances.

5 Data transmission

Data sensed by sensor nodes is thus transmitted to the remote server for analysis and sense making by the medical fraternity. Energy consumed during process of data acquisition depends on the parameter which is being sensed by the sensor nodes whereas the energy consumed during data processing depends upon the hardware and the instruction set [50]. Also, energy consumed during the process of data communication is sum of energy consumed during data transmission and reception. Hence, it makes use of low power short range wireless communication technologies for communicating data from the sensor nodes to the remote server. In accordance with the IEEE standards, the number of nodes may vary from 6 to 2^8 that a WBAN can support. The number of nodes is limited due to the network constraints like communicational protocols and network resources. The number of nodes in a WBAN can change depending upon their interaction with other WBANs and networks in the surrounding environment. The topology as considered by the IEEE standards can either be one-hop, i.e., all the sensor nodes in the network are directly connected to the sink or multi-hop, i.e., all the sensor nodes are connected to a central hub which is further connected to the sink. Multi-hop topology is supported at the cost of increased complexity. The following subsections explain the communicational architecture of WBANs along with a detailed comparison of the varied communicational technologies that can be used in WBANs and the layers of protocol stack.

5.1 Data communication

For seamless connectivity of sensor nodes to the remote server, communication in WBANs can be divided into three categories, viz., intra-BAN communication, inter-BAN communication, and beyond-BAN communication as explained in Fig. 8 [17, 19].

Intra-BAN communication, i.e., Tier-1 in Fig. 8 is defined as communication of sensor nodes around the human body for monitoring various biological parameters. Inter-BAN communication, i.e., Tier-2 in Fig. 8 is defined as communication between the coordinating node and an access point. Beyond-BAN communication, i.e., Tier-3 in Fig. 8 is defined as communication between an access

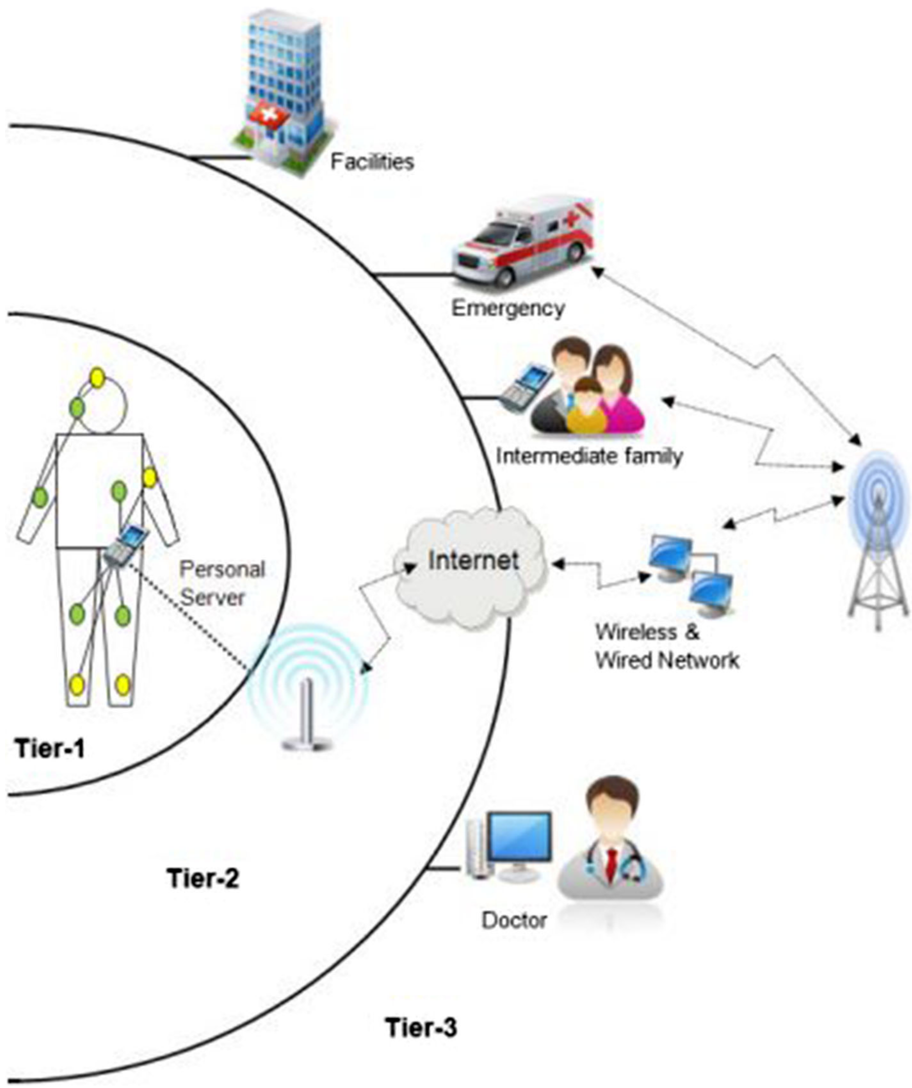


Fig. 8 Communication in wireless body area networks [26]

point and the medical server from where the data is easily accessible to the doctors who can provide the patients with real-time feedback. The various wireless communication technologies such as ZigBee, Ultra-Wideband (UWB), Radio Frequency Identification (RFID), Near Field Communication (NFC), Sensium, Zarlink, RuBee, Z-Wave and Bluetooth etc. [26] can be used in WBAN communication. Table 5 describes the communicational technologies used in WBAN.

5.2 Protocol stack

There are generally two layers in WBAN protocol stack as proposed by 802.15.x, namely, Physical (PHY) and Medium Access Control (MAC) layers for communication purposes in and around human body in WBANs. All other layers are application specific. The Physical layer is responsible for data transmission and reception, activation and deactivation of radio transceiver, RF communication (in/along the body). It is of three types, namely, Human Body Communication (HBC), Narrow Band (NB) and Ultra Wide Band (UWB) as specified by IEEE 802.15.6 [15, 26, 51, 52]. The NB PHY layer is responsible for activities such as data transmission and reception, activation and deactivation of radio transceiver. The HBC PHY layer is responsible for modulation/ demodulation, preamble, Start Frame Delimiter (SFD) and packet structure. The UWB PHY layer is responsible for communication between devices. Channel Modelling is done at PHY layer which is important for signaling techniques in various frequency bands to help the development of antennas with lower Specific Absorption Rate (SAR). Also, the body

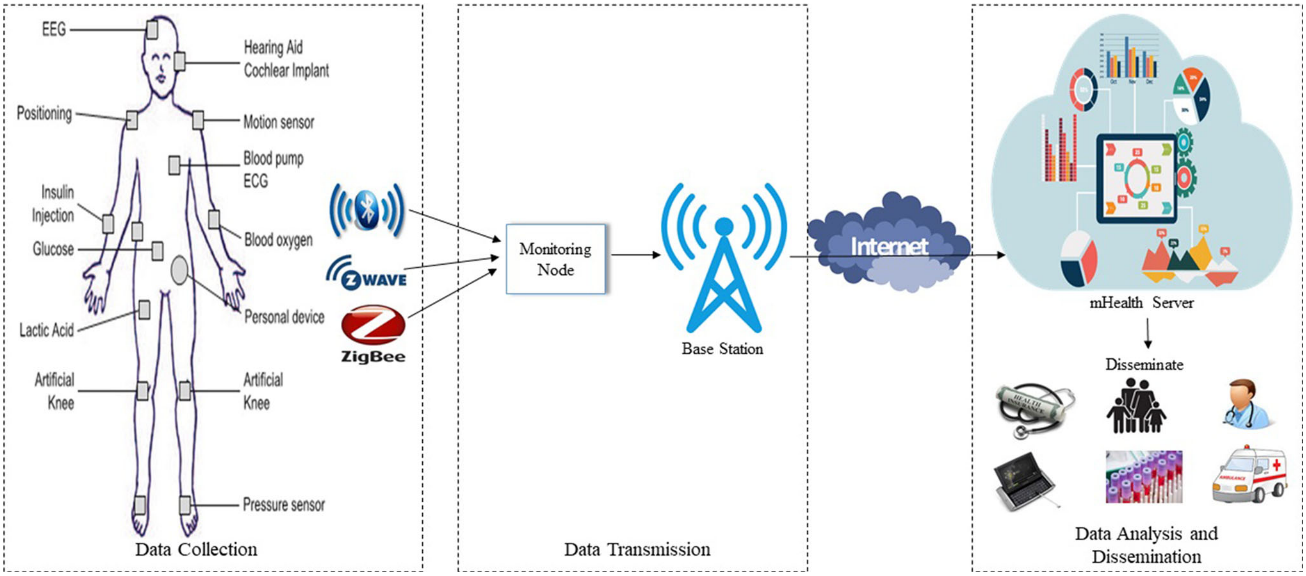


Fig. 9 General framework for sensor analyst systems

Table 5 Communicational technologies for WBANs

Technology	Radio frequency	Data rate	Current consumption	Network topology	Range	Access method	Security
Bluetooth	2.4 GHz ISM	1–3 Mbps	30 mA	Scatternet	10–100 m	CSMA	128-bit Encryption
Bluetooth low energy	2.4 GHz ISM	1 Mbps	15 mA	Star	10 m	Fh + TDMA	AES-128 Encryption
Bluetooth high speed	2.4 GHz ISM	3–24 Mbps	more than 30 mA	Star	10 m	FH + TDMA/ CSMA	AES-128 Encryption
Zigbee	868 MHz, 915 MHz, 2.4 GHz ISM	250 Kbps	15 mA	Star, Mesh	10–200 m	CSMA	128 bit Symmetric Encryption
Ultra WideBand (UWB)	3.1–10.6 GHz	480 Mbps	1 mA	Star	< 10 m	CSMA/ TDMA	Yes
RFID	850–960 MHz	10–100 Kbps	Unknown	Star	30 m	Slotted Aloha	Yes
NFC	13.56 MHz	106 Kbits/s, 212 Kbits/s, 424 Kbits/s	Unknown	P2P	3.9 inches	Unknown	Yes
Sensium	900 MHz	160 Kbps	Low	Star	5 m	TDMA, FDMA	Public Key Encryption
Zarlink	402,405 and 433,434 MHz	800 Kbps	1 mA	P2P	2 m	Unknown	Unknown
RuBee	131 KHz	9.6 Kbps	Low	P2P	30 m	Unknown	AES Encryption, Private Key, Public Key
z-wzve	1 GHz	9.6 and 40 Kbps	Unknown	P2P	100 m	CSMA/ CA	128-bit AES Encryption
ANT	2.4 GHz	1 Mbps	Ultra Low	P2P	30 m	TDMA	AES-128 Data Encryption
MICS	402–405 MHz	500 Kbps	25 µA	P2P	2 m	NA	CRC
Insteon	915, 921 MHz	13.1 Kbps	Ultra Low	P2P, Mesh	45 m	TDMA	Public Key Encryption

posture, limb movement and body weight affect the antenna design which demands more flexible and textile antennas. There are two types of antenna used in WBANs, electrical antenna and magnetic antenna. The designing of antenna is further limited by the location where it is to be placed on human body. The material which is used to design antennas are also specific to human body.

The IEEE 802.15.6 working group also defines MAC layer on top of the PHY layer for controlling channel access. The important features for MAC layer designing

Table 6 Classification of WBAN routing protocols

WBAN routing protocols							
Thermal aware	Cross layer	QoS	Relay	Cost effective	Cluster	Opportunistic	Link aware
– M-Attempt [52]	– Opportunistic [50]	– QPRR [116]	– REEC [120]	– PSR [90]	– Anybody [64]	– Opportunistic [50]	– Co-LEEBA [129]
– ETPA [53]	– EPR [84]	– FPSS [112]	– Co-Communication [121]	– PRPLC [98]	– HIT [65, 66]	– Opportunistic Routing [125]	– MEPF [130]
– TARA [54]	– QoS Based [85]	– LOCALMOR [114]	– PEA [122]	– OBSFR [100]	– AMR [69]	– SOR [126]	– AMR [69]
– LTR [55]	– Simple [86]	– DMQoS [115]	– Incremental relay [123]	– EAWD [101]	– Uniform Clustering [70]	– COMR [127]	– RVCR [131]
– ALTR [55]	– WASP [87]	– RL-QRP [117]	– Hybrid AFDF [124]	– AODV [102]	– EERS [71]	– OMAR [128]	– RRT [132]
– HPR [56]	– CICADA [88]	– GAbR [118]		– Priority AODV [103]	– Forwarding Scheme [72]		
– MTR [57]	– TICOSS [82]	– OFSR [119]		– OCER [104]	– Fuzzy Based [73]		
– DCR [58]	– BIOCOM [83]			– E-OCER [104]	– SEA-BAN [74]		
– TSHR [59]	– PCLMAC [89]			– ESR [105]	– CMOGA [75]		
– RPL [60]	– Cross Layer Opportunistic [89]			– New-Attempt [106]	– Intelligent Agent [76]		
– RAIN [61]	– COMR [91]			– RMRG [107]	– SFDR [77]		
– TaPSCM [62]	– ARBA [92]			– EETR [108]			
– LR Routing [61]	– APMAC [93]			– HEAT [109]			
	– Cooperative [94]			– BAPR [110]			
	– QoS Aware [95]						
	– BANMAC [96]						

Table 7 Temperature based routing protocols for WBANs

Protocol	Hotspot detection	Energy consumption	Packet loss	Packet transmission	Network lifetime	End-to-end delay
M-Attempt [65]	Yes	Low	Low	Multi-Hop	High	NA
ETPA [66]	Yes	Low	Low	Multi-Hop	High	High
TARA [67]	Yes	NA	High	Single-Hop	NA	High
LTR, ALTR [68]	Yes	High	High	Single-Hop	NA	Low
HPR [69]	Yes	NA	Very low	Shortest Hop	NA	Very low
RAIN [70]	Yes	Low	Low	Single-Hop	High	Low
MTR [71]	Yes	NA	Low	Single-Hop	NA	Low
DCR [72]	NA	Low	Low	Multi-Hop	NA	Low
TSHR [73]	Yes	Low	Low	–	High	Low
RPL [74]	NA	Low	Low	NA	NA	Low
TaPSCM [75]	–	Low	Low	–	NA	Low
LRR [76]	Yes	Low	Low	Multi-Hop	NA	Low

are access fairness, reduced latency, high throughput and bandwidth utilization that can provide energy efficiency, increased network lifetime by playing significant role in controlling duty cycle [47]. The coordinator divides the entire channel into superframes as the coordinator is responsible for controlling channel access. The coordinator provides channel access in three access modes, namely, Beacon mode with beacon period superframe boundaries, Non-beacon mode with superframe boundaries and Non-beacon mode without superframe boundaries. There is a tradeoff between energy consumption, latency, QoS and reliability that affect the overall complexity of the protocol. To enhance the battery lifetime of the sensor nodes, energy-efficient MAC protocols are required and the schematic overview of MAC protocols for WBANs is provided in [14, 24].

5.3 Energy model

It is observed from the related literature that energy consumption of sensor nodes is negligible during data acquisition, minimum in data processing but maximum in data communication. Thus, more focus is given by the researchers on energy consumption during communication. Most of the energy is consumed in data transmission and reception. This is represented as First Order Radio model [53, 54]. Energy consumption is calculated with the help of the following equations, energy consumed by transmitter and amplifier is shown in Eq. 1 at the transmitter end whereas energy consumed by the receiver is shown in Eq. 2 at the receiving end.

$$\begin{aligned} E_{Tx}(p,r) &= E_{Telec}(r) + E_{Amp}(p,r) \\ E_{Tx}(p,r) &= E_{elec} \times r + \varepsilon_{Amp} \times r \times p^2 \end{aligned} \tag{1}$$

where E_{Tx} is total energy consumption at the transmitter end, E_{Telec} is energy consumed by the transmitter, E_{Amp} is energy consumed by the amplifier for transmitting r-bit long message at p distance.

$$\begin{aligned} E_{Rx}(r) &= E_{Relec}(r) \\ E_{Rx}(r) &= E_{elec} \times r \end{aligned} \tag{2}$$

where E_{Rx} is total energy consumption at the receiver end, E_{Relec} is energy consumed by the receiver, for receiving r-bit long message at p distance.

The IEEE 802.15.6 working group also defines MAC layer on top of the PHY layer for controlling channel access that enhances energy conservation [47]. Many mechanisms such as Low Power Listening (LPL), Contention and scheduled-contention, and TDMA are proposed for energy efficiency. Also, they enhance bandwidth utilization, access fairness, reduce latency, high throughput and can provide increased network lifetime by playing significant role in controlling duty cycle. MAC protocols for WBANs are discussed in [14, 24].

In recent times many energy harvesting techniques for regular supply of power to sensor nodes in WBANs are proposed to improve the energy efficiency of WBANs. They are classified as Mechanical Energy Harvesting Technique (MEHT) that converts mechanical energy into power by mechanical pressure, stress, vibrations, high-pressure motors, strain from the surface of the sensor, waste rotational movements, fluid, and force. Photovoltaic Energy Harvesting Technique (PEHT) converts received photons (solar light) into power. Thermal Energy

Table 8 Cluster based routing protocols for WBANs

Protocol	Energy saving	Cluster head selection	Network lifetime	End-to-end delay	Challenges
Anybody [77]	Low	Random	Medium	High	Cluster building either periodically or event driven
HIT [78, 79]	High	Random	High	Low	More energy consumption in dense networks and is not reliable
AMR [81]	High	Tree structure	High	Low	Not reliable
Uniform clustering [82]	High	Tree structure	High	Low	Works only for homogeneous sensor nodes
EERS [83]	High	Tree structure	High	Low	Transmission overhead
Cluster based forwarding scheme [84]	High	On the basis of residual energy	High	Low	Does not consider channel capacity
Fuzzy based adaptive routing [85]	High	Proximity to BNC	High	Low	Transmission overhead
SEA-BAN [86]	High	Tree structure	High	Low	Transmission overhead
CMOGA [87]	High	Random	High	Moderate	Tradeoff between energy consumption and end-to-end delay
Intelligent agent based routing [88]	NA	Static	NA	NA	Agent Co-ordination
SFDR [89]	High	Static	NA	Low	Static nodes

Harvesting Technique (TEHT) obtains electric energy from thermal gradient. Wireless Energy Harvesting Technique (WEHT) converts electromagnetic waves into electricity by a rectifying antenna. Biochemical Energy Harvesting Technique (BEHT) converts endogenous substances into electricity by electrochemical reactions. Acoustic Energy Harvesting Technique (AEHT) converts continuous and high acoustic waves from environment into electrical energy by a resonator or acoustic transducer.

It is another promising technology to reallocate the harvested energy amongst sensors. It supplies sufficient energy to sensors. Optimal resource allocation is required to fully utilize the harvested energy as it can improve the communication performance of WBANs in terms of higher throughput, longer network lifetime, and less wastage of harvested energy [55, 56]. Energy gained while transmission and reception of radio signals can also be harvested for powering the devices. However, this process interferes with data transmission. Hence, there is a tradeoff between rate of information transmission and harvested energy. Thus, it is suggested to have balance between energy harvesting and information transmission for reliable information transmission with continuous energy supply [57, 58].

5.4 Routing protocols

The routing protocols designed for WSNs [59] and Ad-hoc Networks [60] are not appropriate for WBANs as the latter have extra constraints such as energy, delay, temperature, network lifetime, higher moving speed and frequent topology changes [24, 26]. Therefore, there is a need for designing routing protocols specifically for WBANs that deal with WBAN specific issues and challenges. The routing protocols for WBANs are classified as shown in Table 6. The routing protocols for WBANs face various challenges like postural body movements, temperature rise, interference, local energy awareness, global network lifetime, efficient transmission range, heterogeneous environment and scarcity of resources [24, 61–63].

(a) *Temperature based* Human tissues on being exposed to radio signal communication, generate electric and magnetic fields. These radiations are absorbed by human tissues and lead to temperature rise followed by reduced blood flow in human body which results in the damage of the tissues. The amount of radiation energy absorbed by body tissue is referred to as Specific Absorption Rate (SAR) [64]. Temperature based protocols are used to route data differently so that the body temperature is not increased and hot spots are not created as the increased temperature can damage human tissue to a great extent. Various thermal aware routing protocols for WBANs are discussed below in Table 7.

(b) *Cluster based and tree based* Cluster-based protocols divide the network into clusters, each cluster having a cluster head with the aim of reducing number of direct transmissions from source to sink. The sensor nodes transmit their data to the cluster head which in turn transmits data to the base station. The selection of CH is based on the factors like size of cluster, residual energy, number of hops and

Table 9 Cross layer routing protocols for WBANs

Protocol	Energy consumption	Throughput	Mobility	Challenges
Opportunistic [63]	Low	High	Considered	Relay node placement
EPR [96]	Low	High	NA	Security
QoS Based [97]	Low	High	NA	Communication overhead
SIMPLE [98]	Low	High	NA	More transmissions
WASP [99]	Low	High	NA	Link quality
CICADA [100]	Low	High	Considered	Packet loss
TICOSS [94]	Low	High	Considered	Application specific protocol and not suitable for delay tolerant networks
BIOCOMM [95]	Low	NA	NA	Packet loss
PCLMAC [101]	Low	High	NA	Mobility
Cross layer Optimization [102]	Low	NA	Considered	Single hop communication
COMR [103]	Low	High	Considered	Network load
ARBA [104]	Low	High	NA	High delay
APMAC [105]	Low	High	NA	Residual energy
Cooperative [106]	High	High	NA	High energy consumption
QoS Aware [107]	Low	High	NA	Network traffic
BANMAC [108]	Low	High	NA	Non-Periodic movements

Table 10 Cost effective routing protocols for WBANs

Protocol	Network lifetime	Energy consumption	End to end delay	Mobility	Challenges
PSR [111]	Low	High	High	Considered	Not scalable
PRPLC [110]	High	Low	High	Considered	One hop communication
OBSFR [112]	Low	High	Low	Considered	Not scalable
EAWD [113]	High	Low	Low	NA	Number of installed relays
AODV [114]	High	Low	Low	Considered	Single channel communication
Priority AODV [115]	High	Low	Low	Considered	Residual energy
OCER [116]	High	Low	Low	Considered	Cross layer interactions
ESR, EERS [117]	High	Low	Low	Considered	Energy management
NEW-ATTEMPT [118]	High	Low	NA	NA	High data transmission
RMRG [119]	High	Low	NA	NA	Delay
EETR [120]	High	Low	Low	NA	Static posture
HEAT [121]	High	Low	Medium	Considered	Packet drop
BAPR [122]	High	Low	Medium	Considered	End to end delay

distance to the sink [53, 66, 77–80]. These protocols encounter major challenges like communicational overhead, cluster head selection, energy consumption and network lifetime (Table 8).

(c) *Cross layer* Cross-layer protocols combine the network layer with other layers in the protocol stack. This can improve efficiency and interaction between various protocols [90, 91]. Cross layer protocols for WBANs [81, 92–95] provides high throughput, low energy consumption and fixed delay but does not take body motion into consideration (Table 9).

(d) *Cost-effective* Cost-effective protocols, also known as probabilistic algorithms, update their cost function periodically. They use the link information for updating the cost function and finds the route with

Table 11 QoS based routing protocols for WBANs

Protocol	Reliability	Energy consumption	Delay	Mobility	Challenges
QPRR [128]	High	Low	Low	Yes	Higher network traffic
FPSS [124]	High	Low	Low	NA	Relay node processes data of each node separately
LOCALMOR [126]	High	Low	Low	NA	Not scalable
DMQoS [127]	High	Low	Low	NA	CH uses more energy
RL-QRP [129]	High	Low	Low	NA	Not scalable
GAbR [130]	High	Low	Low	NA	Prime population is selected accidentally
OFSR [131]	High	Low	Low	NA	Residual energy

Table 12 Relay based routing protocols for WBANs

Protocol	Stability	Energy consumption	Packet loss	Network lifetime	Challenges
REEC [132]	High	Low	Low	High	Works only for critical data
Cooperative Communication [133]	High	Low	Low	High	MAC is not considered for energy efficiency
PEA [134]	NA	Low	Low	High	Possibility of collisions
Incremental Relay [135]	Yes	Low	Low	High	Low data transmission rate in case of emergency packets
Hybrid AF DF [136]	Yes	Low	Low	High	Amplification of noise at relay node
BSECC [137]	Yes	Low	Low	High	Signal decoding at relay node

minimum cost [63, 66, 109–111]. The major drawback with these protocols is that they use large number of transmissions for updating cost function based on the link state information (Table 10).

(e) *QoS-based* QoS-based protocols are based on performance measurement with a set of parameters that define QoS of the application. These protocols define modular approach by providing separate modules for QoS metrics. QoS is defined in terms of power efficiency, reliability, utilization of wireless channel, effectiveness of each node in terms of transmission and reception of data, network traffic, priority of data, delay-sensitive, neighbor manager and many more [123, 124]. The modules were provided with data storage capability in the form of buffers which can store intermediate data for further processing. The metrics considered for measuring the effectiveness of a routing protocol are end-to-end delay, packet conveyance proportion and overall power consumed for routing process [97, 125]. These protocols suffer from high complexity due to processing of different modules that satisfy the specific requirements of WBANs [126, 127] (Table 11).

(f) *Relay based* Relay based routing protocols make use of additional devices called relay nodes to maximize network lifetime. These nodes are more powerful as they have more residual energy, battery and larger communication range [132, 133]. Relay nodes are used for receiving or transmitting data to the sink node. Relay nodes reduce packet drop and thus less number of packets are re-transmitted [134] (Table 12).

(g) *Opportunistic* Opportunistic protocols constitute another category of routing protocols that focus on communication channel between the nodes. In such protocols, a source node transmits its data towards the neighbouring node which serves the function of relay node and in turn, the neighbouring nodes send data to the sink node in a multi-hop fashion. Depending upon the position of relay node; communication between the sensor nodes and relay node can be non line of sight (NLOS) and line of sight (LOS) [26, 61]. Every node selects a node closer for forwarding data to have better link quality. Thus these protocols have average energy consumption and increased traffic due to increased number of nodes, high packet drop and less reliability [138, 139] (Table 13).

Table 13 Opportunistic routing protocols for WBANs

Protocol	Energy saving	Mobility	Network lifetime	Reliability	Challenges
Opportunistic [63]	High	Yes	High	NA	Does not consider residual energy of nodes and is not scalable
Opportunistic routing [138]	High	NA	High	Yes	Not scalable
SOR [139]	High	Yes	High	Low	Some metrics to be defined for reliability
COMR [140]	High	Yes	High	High	Coordination of multi-WBANs
OMAR [141]	High	Yes	High	High	Residual energy of nodes is not considered

Table 14 Link aware routing protocols for WBANs

Protocol	Energy consumption	Packet loss	Network lifetime	Challenges
Co-LEEBA [142]	Low	Low	High	High end-to-end delay
MEPF [143]	Low	Low	High	Trade-off between transmission power and packet loss
AMR [81]	Low	Low	High	Mobility of nodes is not considered
RVCR [144]	Low	Low	Low	Single hop communication
RRT [145]	Low	Low	High	Reconfiguration time will go to infinity if speed increases

(h) *Link aware* Link aware routing protocols focus on the link connections in WBANs as they are intended to work for longer duration. The nodes can not be easily recharged or replaced so it is essential to maintain the link quality. Link aware protocols provide longer network lifetime and minimum energy consumption [62, 142]. Another parameter is stability of the link that defines the path on which data is to be forwarded with minimum packet loss. A cost function is used to define the cost of each link. A link with minimum packet loss, reduced energy consumption and maximum network lifetime is chosen for data transmission [81, 143] (Table 14).

5.5 Data aggregation

Aggregation, i.e., to combine, mainly focus on aggregating data at cluster heads to reduce the number of packets for transmission. Data collected by sensor nodes either relates to the sensor's specific location or data collected at multiple sensors over time. The aggregator node combines data from multiple sensors and is more powerful than the sensor nodes. Aggregator node can also act as an interface between the nodes by its sensing capabilities. As data communication is more expensive than data processing, aggregator node can affirm rich information about the patient from data using data mining systems. In hierarchial networks, aggregator node at each level must support more data and inferences resulting in extraction of more useful information. This can provide greater insights into information collected at each level, feature extraction, classification, sensor node coordination and energy consumption at sensor nodes. Aggregation of data from multiple, heterogeneous, sensor nodes is a fundamental non-trivial task that directly impacts the performance of application.

Many authors have proposed data aggregation schemes for WBANs that consider packet delivery ratio, delay and communication overhead. In [146], the authors have proposed a priority based data aggregation scheme that sets different priorities for data forwarding and privacy preserving aggregation scheme to authenticate and validate the user data. The performance evaluation shows that the proposed algorithm satisfies delay, delivery ratio, data privacy and communication overhead however could not detect the attack from malicious users (outside and inside). In [147, 148], the authors have proposed a home monitoring system for learning the Activities of Daily Living (ADLs). The authors described a fuzzy logic based system for recognizing the activities of elderly people consisting of three subsystems; first to monitor acoustical or sound environment, second to measure physiological data and third subsystem to detect the presence of person in any part of the surroundings. It is advantageous as fuzzy logic has low computational expenses and this enforces easy multimodal data fusion. A major disadvantage is that this system

Table 15 Qualitative comparison of data analytic approaches in WBANs

Authors	System	Technique	Parameters
Anooj et al. [151]	Clinical decision support system	Risk prediction using automated fuzzy rules	Specificity, sensitivity and accuracy
Amaral et al. [152]	Automatic identification system	Machine learning and forced oscillations	Sensitivity, specificity, area under ROC curve
Shi et al. [157]	Multiple fusion sensor system for disease tendency and prediction	Machine learning	Accuracy
Baytas et al. [158]	Reporting, generating, evaluation, visualization and interpretation tool	Sparse Principal Component Analysis (SPCA)	Visualization of records
Miah et al. [159]	On-cloud healthcare clinic	Decision support system	Delivery of services
Black et al. [154]	eHealth-as-a-Service	sustainable quality healthcare delivery	Delivery of services
Gong et al. [160]	Patient centered mHealth systems	Logistic regression	Privacy-preserving
Davis et al. [161]	Ambient assisted living	SVM, HMM, SVM-HMM, ANNs	Accuracy, sensitivity
Kumarage et al. [156]	Cloud-based data analytics systems	Homomorphic encryption	Security
Cao et al. [155]	Decision support systems	Non-Occuring behavior	Accuracy, classification
Ahmadi et al. [162]	Motion analysis systems	Discrete wavelet transform, Random forest classifier	Accuracy, reliability
Tapp et al. [163]	Shared decision making systems	Traditional and participatory dissemination	Dissemination of data
Mourao et al. [164]	Pattern recognition systems	OC-SVM	Accuracy of outlier detection
Li et al. [165]	Clinical data analysis Systems	PSO, BAT	Efficiency, accuracy
Jiang et al. [166]	Wearable sensor system	Hidden markov model	Locality sensitive, context awareness
Walker and Bhatia [167]	Prototype for automated ingestion detection	Nave Bayes, discriminant analysis, support vector machine, k-nearest neighbor, regression tree, and Bayes net	Accuracy
Nguyen et al. [168]	Decision support systems	Fuzzy standard additive model (SAM) with genetic algorithm (GA)	Accuracy, F-measure, mutual information and area under the ROC curve
Alaa et al. [169]	Clinical decision support systems	Clustering	Efficiency, accuracy, false positive rates

Table 16 Projects in the field of WBANs

Project	Sensors	Parameters	Data communication	Data aggregation	Data analysis	Advantages	Applications
MobiHealth [184]	Implanted	ECG, heart rate, blood pressure	ZigBee/ Bluetooth	NA	NA	The platform is scalable for large scale mobile remote health monitoring and treatment	Patient monitoring
AID-N [185]	Implanted	Pulse rate, ECG, body temperature	ZigBee	NA	NA	This system supports data collection and dissemination from the incident site to distributed emergency response community	Mass casualty monitoring
MAHS [186]	Implanted	Pulse rate, motion, EKG	Zigbee	NA	Yes	This system can handle urgent situations from farther geographical locations	Healthcare
CodeBlue [187]	Wearable	Pulse rate, blood pressure, body temperature	Zigbee	NA	NA	This system considers the location of the patients	Medical care
LifeMinder [188]	Wearable	Galvanic skin reflex (GSR) electrodes, pulse meter, thermometer, accelerometer	Bluetooth	NA	Yes	This system considers health conditions, movements and behaviors of patients to guide the user in daily self-care	Self-Care
SMART [189]	Implanted	(SpO_2), ECG	Wired	NA	Yes	It provides a viable method for monitoring patients at risk in the waiting areas of an emergency room	Health monitoring in waiting room and at disaster site
CareNet [190]	Implanted	Motion	Zigbee	Yes	NA	This system is a two-tier wireless network architecture with built-in secure communication	Remote healthcare
ASNET [191]	Wearable	Body temperature, blood pressure	WiFi	NA	NA	Flexible in terms of number of mobile patients that can be supported for a given delay threshold for critical messages	Telemedicine system
MITHril [192]	Wearable	EKG, ECG	WiFi	Yes	Yes	It is a prototype of human–computer interaction for body-worn applications	Healthcare
BASUMA [193]	Implanted	ECG, (SpO_2)	UWB	NA	Yes	The system alerts patient in a timely manner before a critical condition arises	Health monitoring of chronically ill patients
WHMS [194]	Implanted	EKG, ECG	IEEE 802.11a/ b/g	NA	Yes	This system detects abnormal conditions through data mining	Healthcare
HUMAN++ [195]	Implanted	ECG, EEG, EMG	UWB	Yes	Yes	Integration of technologies such as sensors, energy saving low power devices	Consumer electronics, Assisted living
WiMoCA [196]	Implanted	Motion	Bluetooth	NA	NA	It is flexible as is able to handle diverse application requirements	Sports, Gesture and Gait detection

Table 16 (continued)

Project	Sensors	Parameters	Data communication	Data aggregation	Data analysis	Advantages	Applications
MIMOSA [197]	Implanted	Any sensors	RFID/ BLuetooth	Yes	NA	It provides an open architecture platform for implementing mobile-phone-centric ambient intelligence applications	Ambient intelligence
HealthService [197]	Wireless	ECG, EMG, pulse rate, temperature, motion	UMTS/ GPRS	NA	Yes	It considers mobility of patients and reduced time to provide assistance	Mobile healthcare

is offline and does not consider the challenges associated with communication between sensors like residual energy, sense radius and communication radius.

In [149], the authors have proposed a framework for healthcare in post-disaster scenario where health data of patients is transmitted from Local Data Processing Units (LDPUs) to health cloud via a set of mobile monitoring nodes. The authors focused on aggregation and channelization where data transferred by LDPUs is aggregated and the aggregated data is channelized by dynamically selecting cloud gateway. The proposed architecture worked in accordance with the Theory of Social Choice. The proposed algorithm Body Area Network Data Aggregation Algorithm (BANAG) dealt with the pseudo cluster formation. Optimal Channelization Algorithm (OCA) channelize aggregated data to the cloud. Patients are prioritized on criticality of patient data. The simulation results show the better performance of proposed algorithms BANAG and OCA than structure tree, cluster based and tree based aggregation techniques. As a future work, the authors suggested to aggregate data from heterogeneous body sensors and implanted sensors. However the issues regarding selection of aggregator node, aggregation route, data fusion, packet length and overhead signals still prevail. Most data fusion techniques for WBANs are offline [147, 148] and do not consider communication between the sensor nodes. So, there is a need of data fusion techniques for WBANs that consider data communication.

6 Data analytics

Biomedical sensing allows various biomedical sensors to collect variety of biomedical signals such as ECG, EEG, EMG, Heart Rate etc. which can be transmitted to a remote server for further analysis and feedback forming Sensor Analyst Systems. On the remote server, also referred to as mHealth server, data is stored and is easily accessible to the medical fraternity, caretaker, family members, pathology laboratories, emergency services, health insurance companies, patient etc. The doctor can then access the data and give the real-time feedback to the subject. Also, the remote server can analyse the data stored on it before disseminating to the end users. This helps in transmitting data through various communication infrastructures across networks.

6.1 Sensor analyst systems

Machine Learning and Artificial Intelligence are foreseen to transform health care by completing tasks with greater speed and accuracy using fewer resources. Machine Learning techniques such as genetic algorithm, clustering, bayesian classification, fuzzy logic, neural network, k-nearest neighbour, SVM (Support Vector Machine), regression, decision tree, nature inspired meta-heuristic techniques etc. are used for feature extraction and building decision models for prediction. Thus, provides end users with insights to improve quality and reduce costs in combination. Hence, sensor analyst systems contribute technology driven health care solutions that impart virtual care in terms of telemedicine, eHealth, mHealth in virtue of wearable and implantable health monitoring devices to allow patients to connect with doctors in real-time as shown in Fig. 9. Firstly with the usage of WBANs, remote server will have data of both the healthy subjects as well as the patients in contradiction to the conventional health care systems which have data only of the patients as data is collected only when the patients visit the doctor. Secondly, WBANs can monitor patients continuously so the volume of data collection is large as compared to the conventional health care systems. Sensor Analyst Systems enforce data analysis to make data driven decisions, predict outcomes and detect anomalies. These decisions and outcomes are useful to the end users. These can detect the abnormalities in the health status of the patients. WBANs also require multi-sensor data fusion which is focused on physical activity recognition and identifies distinctive properties and parameters at different levels (data, feature, and decision)

[150]. Table 15 gives comparative analysis of data analytic approaches in WBANs and the description is as follows.

In [151], the authors proposed a clinical decision support system for predicting risk level of heart disease using automated weighted fuzzy rules. The automated decision support systems were efficient, low cost and useful for accurate diagnosis of diseases at pre-mature stage with minimum inconvenience. Also, the author had discussed in detail the factors required for computer-aided diagnosis of heart diseases. The proposed algorithm was compared with neural network based system on specificity, sensitivity and accuracy and the experimentation results had shown that the proposed system is more accurate in diagnosing heart diseases. In [152], the authors proposed an automatic identification of pulmonary disease identification based on machine learning and forced oscillations. Various classifiers such as Linear Bayes, k-Nearest Neighbor (KN-N), ANN and SVM are compared to choose the best classifier. The performance was evaluated on sensitivity, specificity and area under Receiver Operating Characteristic (ROC) curve. The parameters were selected using Forced Oscillation Technique (FOT) which had an associated bias, thus lacks usage. The proposed algorithm had identified the disease with high accuracy and minimum specificity and sensitivity.

In [153], the authors surveyed data mining in healthcare as it had been playing an efficient role in information and communication technologies for disseminating health data to the end users. The authors had discussed various data mining approaches for diagnosing various diseases like cancer, diabetes, neurological disorders, detecting frauds in insurance claims, predicting health outcomes, medical image classification and detecting anomalies in health data. Also, the various data mining techniques useful for extracting relevant information, clinical and administrative decision making, evidence based medicine, predict outcomes like health insurance fraud, under-diagnosed patients, identify at-risk people, to calculate length of stay in a hospital and to find association amongst health conditions, disease and drugs were explained in detail. In [154], the authors surveyed the necessity of integrating healthcare and cloud computing for scalable and cost-effective eHealth solutions. They had suggested to aggregate and disseminate health information to end users for better usage. Also, this lead to the development of novel process models for analysis and recommendations for patients. The system must had maintained the data collection sources over time and share those data with multiple users when required. But, there were issues like QoS to be delivered to the end users as well as the patients by cloud service providers, security and privacy concerns and communicational challenges for transmitting digital information over the Internet.

In [155], the authors surveyed a new area in data analytics, i.e., Non-occurring behaviour. It identifies the behaviour that should occur but had not occurred or not easily identifiable due to some reason. The authors suggest that Non-occurring behaviour was informative as they were associated with some phenomenon and useful for many application domains like healthcare, government reporting systems, tax-related claims, social welfare, security management and climate change. But computing Non-occurring behaviour was complex because of their hidden nature and large candidate space and no system was found in the literature for detecting Non-occurring behaviour. In [156], the authors focused on integration of Internet of Things (IoT) and cloud computing to deliver applications like smart cities, healthcare, power systems and environmental monitoring to the end users with high computational and storage requirements. The authors had focused on secure cloud based billing systems, data anomaly detection and patient classification and diagnosis for eHealth systems. Also, the authors had discussed in detail the homomorphic encryption scheme for improving security and machine learning algorithms which could detect anomalies in data and perform classification of data. The authors also presented the future research areas in analytics task and encryption for effective services to the end users.

In [157], the authors proposed a disease tendency and prediction algorithm based on multiple sensor fusion system. The proposed algorithm had two components, i.e., wearable bio-sensor system for health monitoring which transmitted data to analyzing system for feature extraction and disease prediction system using machine learning algorithm for predictive outcomes. The proposed algorithm was accurate in classification and prediction. However, the proposed algorithm could not classify using single attribute and could be extended to predict many other diseases. In [158], the authors proposed a novel tool, PHENOTREE, for visual analytics from large-scale electronic health records. The proposed tool interactively explore the records for reporting, generating, evaluation, visualization and interpretation. The authors had compared the proposed tool with Sparse Principal Component Analysis (SPCA) based analysis. The experimental results had shown that proposed tool outperforms the analysis using SPCA on different datasets. It was useful for clinical decision support systems that performed diagnosis of various diseases and helped to present the results in visualized manner. The authors had not taken into account the temporal information of the data.

From the literature review, it is seen that bio-medical sensing is an important feature before disseminating data to various end users. Bio-medical sensing conducts analysis on health data and provides timely feedback from the medical fraternity. The data sensed form the wearable sensors is transmitted to mHealth server which performs analysis for predicting long-term outcomes, detecting anomalies, decision making, identifying frauds in health insurance claims, patient classification, disease mapping and identifying non-occurring behavior. Most of the literature is focused on data mining and machine learning approaches for analyzing data and a few on detecting anomalies using temporal information and non-occurring behavior.

6.2 Challenges in data analytics

Few of the major challenges with Health Data Analytics are discussed in this section. Data integrity is one of the major issue as it is important for maintaining a consistent and integrated database by hospital management. This data is used by the physicians for giving feedback, for analysing the effects of drugs, medicines, clinical procedures, calculating effective cost, improving facilities and hospital management. Another issue is of data security and privacy of sensitive health data as once the data is on Internet it is prone to malicious users and attacks. Therefore, access and privileges for providing security, authentication and accessibility to the data stored should be taken care of. Data cleaning, de-noising, re-sampling, synchronizing and extracting features from multiple and heterogeneous data streams are also some of the challenging tasks.

7 Inferences from literature review

The following lessons are learnt from extensive literature review which broadly indicate the gaps for further research in the field of ubiquitous health monitoring in cloud-based WBANs.

- The various challenges faced by WBANs are antenna design, energy consumption, network lifetime, fault tolerance, scalability, privacy and security [26, 47, 170].
- Already existing protocols for Ad-hoc Networks [60] and WSNs [59] are not suitable for WBANs as the latter have some specific properties such as longer network lifetime, frequent topology changes and higher mobility [24, 26].
- It is found that lot of interference occurs when two WBANs are present in close proximity which affects signal strength. This requires further exploration [26].
- The number of studies present regarding communication in WBANs focus on different routing protocols but consider only few aspects like body movements, temperature rise and data transmission range which provide limited scope.
- The present cluster-based routing protocols focus on energy consumption, cluster head selection and network delay of the sensor nodes but do not consider random distribution and residual energy of the sensor nodes [53, 66, 77–79, 171].
- Limited usage of computationally intelligent optimization techniques for clustering in WBANs is observed in the literature.
- This review has found that data transmission is expensive as data fusion is possible only for the same size data. Also, the data transmission does not consider packet length and overhead signals [149].
- This literature suggested that data aggregation techniques in WBANs reduce the number of packets in data transmission. An offline data fusion technique is present that uses fuzzy logic but it does not consider communication between the sensor nodes [147, 148].
- It is observed that social information and vital signs may not be collected easily for WBAN applications, hence the applications lack QoS [171].
- In most of the literature, a WBAN consists of multiple sensor nodes on a single body. The network of a single sensor node on multiple bodies is not considered.
- It is observed that health data is monitored before disseminating data to end users. Most of the work is focused on predicting outcomes based on clinical decision support systems but a few authors had considered temporal analysis of data and detecting anomalies based on non-occurring behavior which requires further research [155, 157].

Health monitoring is long term and continuous using bio-medical sensors that connect with a wireless connection forming WBANs. Bio-medical sensors can collect many vital biological parameters such as blood pressure, body temperature, pulse rate, heartbeat, ECG, EEG, EMG, respiration rate etc. providing reliable and cost-effective e-HealthCare systems. The sensed data is transmitted to mHealth server which analyzes the data and disseminates it to the end users for timely feedback. Hence improving the quality of life and healthcare status.

It is significant from the literature that energy consumption of sensors is negligible during data acquisition, minimum during data processing and maximum during communication. To reduce the communicational cost and energy dissipation while enhancing network lifetime, many cluster-based routing protocols [77–79, 171] had been proposed that reduce the number of direct transmissions from source to sink but do not take residual energy, sense radius and network lifetime into account. Also, many data aggregation schemes [147–149] had been proposed for reducing number of packets to be transmitted from source to sink and multi-modal data fusion offline system which had not taken into account the sense radius of the sensor nodes. For disseminating data to the end users, many clinical decision support schemes [151, 152, 157] for predicting outcomes had been proposed for data analysis by the mHealth server but do not detect anomalies with minimal feature set and non-occurring behavior. Thus, it is proposed to develop an approach for efficient and ubiquitous health monitoring in cloud based WBANs (Table 15).

8 Open research issues in WBANs

In the prospect of WBANs, the recent advances are focused firstly on sensor design which includes design and structure of sensor nodes, energy consumption and harvesting for regular supply of power and deployment of sensors on the human body. Secondly, efficient communication of data to the server which includes channel access control, topology design, routing protocols, privacy and security of data. Thirdly, data fusion which concerns data classification, data denoising, feature extraction, anomaly detection and data compression. However, a number of challenges and constraints must be overcome for WBANs to be developed as truly ubiquitous, few of the major challenges and open research issues are discussed below [26, 47, 170, 172, 173].

(a) *Physical characteristics of the sensors* Considering the fact that the sensors are worn on the human body, factors such as size, shape, material etc. are essential to humans which prompts design and development of new materials for sensors. The material should be non-corrosive and non-reactive so that the sensors are easily adaptable by the human body. Sensor nodes should be small in size so that they are comfortable to wear, should not require any training to use and should be placed at accurate position [15, 17, 26]. Another research issue is of the antenna design of the senors due to electromagnetic interaction between the human body and the antenna of sensor nodes. Existing antennas are magnetic and electric in nature that create strong electric field emitting radiations which are absorbed by human tissues. The amount of radiation energy absorbed by the body tissue is referred to as Specific Absorption Rate (SAR) [64]. Thus the designers of antennas are forced to design antennas with lower SAR values.

(b) *Physical layer challenges* One of the major research issue is of interference that occurs when many people with WBAN devices are in close proximity to each other which results in packet loss, increased energy consumption and decreased battery lifetime. As the sensor nodes are resource intensive, signal propagation should have minimum energy consumption [24, 26] so that more and more WBANs can be connected in a single network with seamless communication.

(c) *MAC layer challenges* The sensor nodes have positive correlation between energy consumption and power source. Due to energy consumption at every process, sensor nodes may shed their energy soon forcing either replacement or recharging of the sensor nodes which may not be possible. Power consumption in sensor nodes may be contributed to domains: acquisition, communication and processing where it is negligible for acquisition and maximum for communication. Thus, there is still a need for efficient MAC that must comply with the energy efficiency requirements of WBANs, network capacity, channel models, sensor node heterogeneity and trade-off between energy consumption and efficient performance [14, 24]. They must have flexible channel modeling that provides reliability and robustness. Hence can prolong the network lifetime. Also, specific QoS requirements of varied WBAN applications which must be met by MAC protocols require energy consumption. Thus, the data transmission must be optimal to allow maximizing energy efficiency and minimizing delay. MAC protocols can increase channel usage and emphasize efficient usage of resources by usage of sleep mode and awake mode. This decreases end-to-end delay [174]. Data can be ranked on the basis of priority and network traffic for channel usage [175].

(d) *Network challenges* Sensor nodes in WBANs must be capable of fault tolerance as the nodes may run out of energy or might be damaged. This may lead to partitioning of the network and the communication between the nodes may also be interrupted. Network Lifetime is application specific but generally is considered as the time before 100% sensor nodes die. Network lifetime is directly proportional to energy consumption of the sensor nodes. To improve network lifetime, energy-efficient operations must be performed. Also, network lifetime has trade-off with QoS i.e., investing more energy can increase QoS but can decrease network lifetime [61, 176]. The MAC protocols proposed must ensure longer network lifetime for robust working of the network. The WBANs have different node densities depending upon the nature of application. All the employed architectures and protocols must be able to scale dynamically. Node density fluctuates over time and space because nodes fail or move in a single application. The network should be able to adapt such variations. Interference in WBANs is due to the coexistence of WBANs in proximity to each other, i.e., WBANs have inter-WBAN interference during communication. However, according to [177], upto 10 co-located WBANs can function properly. Also, other wireless technologies present in the proximity of WBANs can lead to interference. Interference leads to collisions from external sensors which makes coordination infeasible and faded signal strength which affects the overall performance.

(e) *QoS* Quality of service is defined as its strength to satisfy the implicit and explicit needs of the user. It is a major aspect of the healthcare systems. The QoS metrics such as earliest deadlines, minimum delay in transmission, data loss sensitive, data quality, energy consumption, energy efficiency, delay, bandwidth must be realized without performance degradation [178]. QoS is defined either to be application based or network based. In WBANs, MAC layer provides QoS in terms of network parameters such as traffic differentiation mechanisms, priority mechanisms, and scheduling schemes, latency, reliability, throughput, and energy consumption parameters. QoS is also defined on the basis of traffic which may be critical and non-critical and, data may also be assigned on priority. A detailed survey is also presented in [107]. However, the issues regarding latency, throughput and energy consumption still require further research.

(f) *Privacy and security* As health related sensitive information is collected using WBANs, security and privacy of data is a concern. The collected data is exposed to malicious intrusions and attacks as the data is stored distributively. One of the major issue is of data security which means to securely store and transfer data while another issue is of data privacy which means that data is accessible to authorized users only. Security requirements also include confidentiality, dependability, access control, accountability, non-repudiation, authentication etc. [179]. As WBANs operate in open wireless communication channel, there are threats like sink hole, replay attack, sybil attack, flooding attack, link spoofing, eavesdropping, modification, injection, tampering of device on which the data is stored, masquerade, data could be lost due to network dynamics [25, 180]. For distributed data storage in WBANs, data must have confidentiality, integrity and freshness. To ensure that only an authorized user is having an access to the data, data access control, accountability, non-repudiation must be observed. However, some of the constraints that are dominant challenges to provide data privacy and security in WBANs, is to obtain equity between security and efficiency, security and usability and device interoperability. Some of the authors have proposed solutions for distributed data storage and privacy using Redundant Residue Number System (RRNS), SKC and algebraic signatures, elliptic-curve cryptography and PKC but incur significant communication, computational and storage overhead [181, 182].

(g) *IoT and healthcare* IoT has become the most influential paradigm of technology. IoT allows seamless integration of devices such as sensors, cameras, home appliances etc. making them capable of computing and communicating. IoT connects anything anytime anywhere improving quality of life and healthcare irrespective of geographical location. Healthcare is one of the major application of IoT which has the potential to transform healthcare by providing network architectures that supports medical data transmission and reception [179]. IoT is also expected to reduce healthcare costs. Also, IoT provides efficient utilization of limited resources for connecting more and more people and providing healthcare services to them. Many issues such as development of cost effective IoT based healthcare platforms, scalability, connecting new devices, monitoring rare diseases, QoS, security and privacy, and ecological issues persist and require further research. However, the research in IoT and healthcare is still in its infancy stage and requires more effort for seamless integration of individuals and healthcare organizations [183].

Existing wearable devices and projects in the field of WBANs are compared in Table 16. Important aspects considered in these projects are type of sensors, parameters, data communication, data aggregation, data analysis and applications.

9 Conclusion and future scope

WBANs provide ubiquitous healthcare and have huge potential market in consumer electronics as WBANs can continuously monitor patients and results in early detection of abnormal conditions ultimately improving the quality of life. In this survey, we have provided a state-of-the-art of WBANs focusing on the three layers of network architecture, viz., data collection, data transmission and data analysis. We have discussed in detail various application domains in which WBANs have found their promising usage. Various sensor nodes used in WBANs for data collection have been highlighted. Also, we have highlighted wireless short range communicational technologies used in WBANs for transmission and reception of data. After analysing the routing protocols, it is seen that changing the physical structure of sensors could result in energy efficient data transmission and reception. Data analysed by sensor analyst systems can predict the future outcomes. Towards the end, we have also reviewed pioneer projects in the field of WBANs and areas which are still open to research. Thus, this paper provides in depth investigation of WBANs which may be useful for future researchers for analysing various domains of WBANs. With added research and enhancement in the field of antenna design, routing protocols, energy efficient data communication, sensor analyst systems and security and privacy; WBANs can deliver seamless integration of healthcare and information technology.

After observing the development trends in WBANs and increasing user demand of wearable devices, it is encouraged for future to integrate smartphones, cloud computing, IoT and WBANs for realizing dynamic changes in ubiquitous healthcare monitoring systems. We emphasize that standardization at all levels is essential for open solutions to prevail.

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