Review Paper

Performance issues in wireless body area networks for the healthcare application: a survey and future prospects

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Abstract

This study presents a survey of the current issues, application areas, findings, and performance challenges in wireless body area networks (WBAN). The survey discusses selected areas in WBAN signal processing, network reliability, spectrum management, security, and WBAN integration with other technologies for highly efficient future healthcare applications. The foundation of the study bases on the recent growing advances in microelectronic technology and commercialization, which ease device availability, miniaturization, and communication. The survey considers a systemic review conducted using reports, standard documents, and peer-reviewed articles. Based on the comprehensive review, we find WBANs faces several operational, standardization, and security issues, affecting performance and maintenance of user safety and privacy. We envision the increasing dependency of future healthcare on WBAN for medical and non-medical applications due to internet connectivity advances. In this view, despite the WBAN advantages in remote health monitoring, further studies need to be conducted for performance optimization. Therefore we finalize our study by proposing various current and future research directions and open issues in WBAN's performance enhancement.

Keywords Cognitive radio (CR) · Energy efficiency · Network reliability · Routing · Security · Signal processing · Wireless body area networks (WBAN)

1 Introduction

Technology advances in the areas, including miniaturized electronic devices, application software, human–machine interaction, wireless communication, and other smart technologies, support not only social-economic development but also ease access to social services, such as health monitoring in normal and critical conditions.

The invention of the internet and the increasing number of internet users and smart devices across the globe materialized the deployment of remote access to various mobile services through the internet of things (IoT) [1]. The growing connectivity between integrated remote devices spurred the continued development of various application services in the health sector, including electronic health information management, telemedicine, vital signs monitoring, and analytics.

Sophistication in monitoring the vital health signs using integrated biological sensors poises for improved service delivery through early detection of the underlying deterioration of the vital health condition, prediction and prevention of critical ailment. Health monitoring leverages for early disease detection, reduces mortality rate, and consequently extends people's lifespan.

Besides, remote health monitoring carters for various medical and non-medical applications, such as athletes' health monitoring during physical training, reduced patients' prolonged bed rest on the costly rehabilitation

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process and avoidance of the unnecessary frequent movement to the health care facility through swift remote data access [1]. However, in the future, the aged population may face several unforeseen health challenges due to the changing lifestyles and higher susceptibility to age-related diseases (NIH/WHO, 2011). Some of the common age-related diseases at the moment include; dementia, diabetes, blood pressure, and cardiovascular disorders. On this basis, addressing prospective future health threats and mitigation measures requires continued exploration of the challenging health issues and technical sophistication.

Focusing on the aging population with the rising life expectancy across the globe due to advanced medicine and healthcare technology, measures to monitor and respond to future unanticipated health challenges necessitate the use of smart interactive technologies, such as the use of wireless biological sensors and actuators fixed within, on or off the body of a remote subject [2]. In this view, as a result of advances in technology, Moore's law signifies the on-going miniaturization and mass production of sensor devices with improved operational performance for different application areas. Therefore, affordability, flexibility, and device usage versatility are on the rise. Correspondingly, due to sophisticated sensor technology, in recent days we find ubiquitous deployment of the automated systems in healthcare applications, including ambient assisted living. For example, commercialized wireless controlled robots in developed countries taking care of various security, social, and healthcare services delivery [3].

To date, wireless body area network (WBAN) is a technology that is widely deployed in the health care sector for remote health monitoring within or outside hospital premises. WBAN uses coordinated biological sensors to collect health information of the monitored body condition. The coordination of the sensors with the actuators, provide conditional responses to health ailment. For example, the use of miniaturized actuators for insulin injection in high blood sugar regulation.

Wireless body sensors consist of the transducers for signal detection, a power source, and the transceiver circuitry for wireless linkages. WBAN uses battery-powered wireless biological sensors to measure and transmit vital information over the wireless media to remote health units. Due to the reduced size of the biological sensors, WBAN devices cannot be replaced easily. Similarly, the durability of the WBAN battery depends on its size. Therefore, a miniaturized battery size threaten WBAN operational lifetime. Apart from power constraints, WBANs face hindrance and other media impediments due to the harshness of the working environment or interfering frequencies in the transmission channel when operated near other devices within the same radio frequency spectrum such as ZigBee and WiFi coexistence in the ISM band (2.4 GHz).

In the ISM band, the support bandwidth is limited, raising the possibility of excessive packet collision, signal interference, complex channel access mechanisms during transmission, increased routing overheads, and packet queuing delays when the number of active devices increases [4]. Similarly, miniaturization of sensors limits memory capacity and hence the information processing capabilities, which further affect energy efficiency, link reliability and packet transmission due to network resource competition.

For body implants, a set of WBAN receivers' and transmitters' radiating elements work over the curved body surfaces exposed to nearly 70% of body fluids (tissue). The body tissues' absorption characteristics increase radio frequency (RF) thermal effects and WBAN signal attenuation. Besides, tissues' absorption characteristics affect signal transmission and other biosensor circuit transients. Alterations in the circuit transients may change the data acquisition devices' operational characteristics resulting in data anomalies, devices, and network faults. Also, the signal attenuation due to tissue absorption characteristics weakens the signal strength; hence it can easily be disrupted by noises [5].

In addition, body movement affects RF signal propagation due to the varying dynamics and the WBAN topology resulting in changing packet transmission distance and link outages that disrupt reliability [6].

Based on the constraints faced by WBANs and its necessity for future healthcare, the emphasis for performance enhancement and improved quality of service for efficient operation under the resource-constrained and challenging environment is required. In this essence, future modern healthcare services depend on the quality of service delivered by the technology enablers embodying; affordability, flexibility, and operational efficiency.

On the other hand, the fast-growing WBAN commercialization may raise security and user privacy issues besides other performance concerns. Jeopardized health information may raise legal and loyalty issues. On this basis, health information requires higher confidentiality and adequately maintained user privacy. However, WBAN pervasiveness and the increasing number of users increases its security vulnerability, leading to a possible information breach and performance degradation due to adversarial constraints. Adversaries may mislead medical diagnosis, jam the communication network, and use medical information for illegal practices. Therefore, measures against security breach need to be well implemented [7].

Due to limited memory and computational capacity, most of the conventional security features in WBAN enabled protocols use authentication keys which are not sufficient in securing user data. Since attackers use advanced techniques, WBAN commercialization for universal health monitoring requires advanced countermeasures to maintain user privacy and avoid falsified diagnosis. Therefore, despite its advantage and an increasing dependency for future healthcare, WBANs have several flaws in need of continued research to address current and future security challenges.

Generally, the growing WBAN commercialization addresses many areas that require further research for compelling future applications. Universal deployment of the WBAN for health monitoring needs low cost devices, comfortability, improved accuracy, integrity, extended memory systems, information security, user safety, proper spectrum management, link reliability, mobility convenience, and energy efficiency.

This survey aims to discuss some of the driving and open performance issues to the current and future WBAN application technologies in improving efficiency through signal processing with concerns for packet processing and queuing delays, information security, and reliability with their contribution to WBAN operational performance.

The design of the study in this article bases on systemic literature review approach. We identified areas of importance today and of the future by reviewing articles, standard documents, and reports with influence in WBAN topics of interest. Selection of the reports and articles', based on the key topics' relevance, year of publication, article influence, or citations number between 2011 and 2020. In the review process, we identified application areas, current achievements, and technological gaps now and in the future. Hence, projections for current and future WBAN research bases on the foundation of the literature.

The survey is organized into the following sections; Sect. 2 discusses IEEE 802.15.6 (WBAN) standard overview, Sect. 3 covers the WBAN architecture, channel model, and security vulnerability, Sect. 4 gives a review of the literature, Sect. 5 discusses selected application areas, Sect. 6 covers prospects for open research fields, and Sect. 7 concludes the survey.

2 IEEE 802.15.6 (WBAN) standard overview

WBAN standard falls under the IEEE 802.15 task group 6, specified for short-range communication, extremely low power, applications requiring high quality of service (QoS), and data rate up to 10Mbps [8]. It supports both physical and data link (MAC) mechanisms and conforms to the standard frequencies used worldwide for medical purposes.

In the physical layer (PHY), the WBAN standard is responsible for; activation and deactivation of the radio transceivers, clear channel assessment (CCA), data transmission and reception. The PHY supports signal propagation through Ultra-wideband (UWB), non –radio human body communication (usually referred to as HBC), and an optional narrow-band (NB) communication. IEEE 802.15.6 is not limited to support radio frequency bands, such as ISM, medical implant communication services (MICS), and wireless medical telemetry services (WMTS) [9]. Detailed frequency range supported by the IEEE 802.15.6 standard is given in [8].

In the data link layer (mainly referred to as MAC), IEEE 802.15.6 standard is responsible for control channel access mechanisms, supporting carrier sense multiple access with collision avoidance (CSMA-CA), time division multiple access (TDMA), or a combination of both CSMA-CA and TDMA. The standard supports three different channel access scheduling modes, categorized based on the time referencing of the superframe and allocation slots. Time referencing determines the device synchronization and network association during medium access scheduling. The IEEE 802.15.6 standard access modes are; beacon mode with superframe boundaries whose time reference allocation depends on the beacon arrival. Non-beacon mode with superframe boundaries with which devices need not wait for a beacon signal. However, the superframe time referencing is predefined. Also, there is a non-beacon mode without superframe boundaries, which does not need time referencing to set up superframe and allocation slots [8, 9]. For a beacon mode, the MAC layer channel is divided into superframes of equal length. The superframe is subdivided into different fields assigned to different types of traffic. The superframe fields include Exclusive Access Phase (EAP), Random Access Phase (RAP), Managed Access Phase (MAP), and the Contention Access Phase (CAP), as described in [8, 10].

Further, the standard gives provision for three security levels; 0, 1, and 2. In security level 0, there is no data authentication nor encryption, the application is completely insecure, security level 1 has medium level security allowing data transmission in secured authentication without encryption, and security level 2 involves data transmission in a secured authentication with encryption frames.

3 WBAN architecture, channel model, and security vulnerability

This section discusses the architectural flow of the information in WBANs involving individual body area networks beyond the WBAN communication range. We also discuss essential features to be included for the transmission channel model and WBAN security-related issues.

3.1 WBAN architecture

WBAN is composed of sensors and actuators linked by a computing unit. Sensors measure biological parameters such as blood pressure, temperature, sugar, echo-cardiograph (ECG), electroencephalograph (EEG) and other body vital signs while actuators respond to the instruction based on the sensor measurement after computation [11]. For example, in diabetic illness, the actuator regulates blood sugar by controlling the insulin level. WBAN sensors can be deployed in or on the body using invasive and non-invasive techniques as body implants, surface contacts, or as wearable devices. The coverage distance of the WBAN devices in transmitting and detecting signals is limited to within the body. However, with the assistance of other technologies like WiFi, WAN, ZigBee, and other wireless communication technologies, WBAN can forward information to the remote health care units for further decision support.

Figure 1 illustrates a WBAN and beyond WBAN architecture comprising of three functional sections, namely; intra-BAN, inter-BAN, and the health care unit. The intra-BAN segment composes wireless biological sensors which can measure and share information between themselves and also interact with the coordinator (master node) [12]. An intra-BAN's master node can manage and aggregate measured physiological parameters from source devices [13]. Further, an intra-BAN's master node has abilities to forward information to the computing unit, or coupling of the intra-BAN to other networks, such as neighboring WBAN, gateways, access points, or telecommunications base stations [12]. Inter-BAN section, which is represented by the wireless interface, links the intra-BANs' coordinator with the access points, neighboring WBANs, or body to body communication (B2B). Also, the inter-BAN links data from the individual WBAN with the health caretakers, and the data processing centre through the long haul telecommunication networks. Similarly, the inter-BAN section may also have Personal Digital Assistant (PDA) and smart digital displays linked to the intra-BAN coordinator providing interactive user interfaces when accessing information for personal awareness. The data processing centre systems compute and analyze received information for health-related prognosis and decision support for medical professionals.

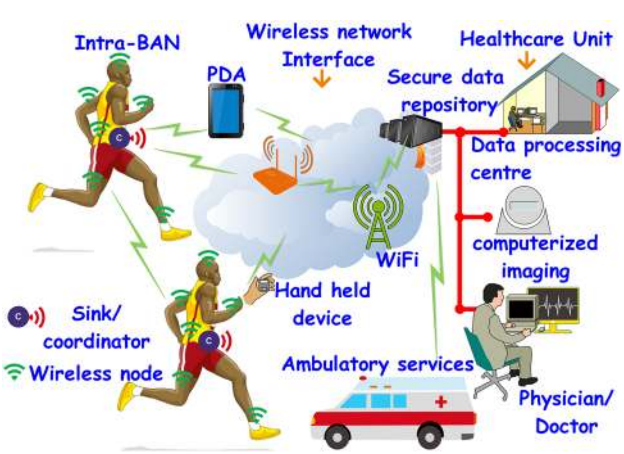

Fig. 1 WBAN and beyond WBAN architecture

In the data processing centre, health care applications use vital physiological signs collected through WBAN to assess the health status of individuals. After the assessment of the health information, results are used in decision support for the provision of treatment or preventive measures to the monitored individuals before symptoms severity.

Based on the sensitivity of remote health monitoring and prognosis, WBAN has captured the researchers' attention and interest as one of the exciting research fields [14].

Apart from the current research dominance in designing wireless body area networks' devices and routing mechanisms, the growing user demands and curiosity remain as the major challenge for the limited network resources and the underlying technology [15]. Increasing user demand calls for researchers to unfold prospective future challenges due to a projected increase in data rates, data volume, inter-BAN communication in the wireless interface (colocation), as well as the requirement for network security, reliability, and standardization [16]. Moreover, in sports and assisted living, consideration for posture and mobility of the monitored individuals are some of the areas which need attention when instilling patient-centric management.

3.2 WBAN channel model

WBAN networking is challenging due to the complex signal propagation mechanism in the vicinity of the human body. Signal propagation may depend on several factors, including distance between devices in the line or non-line of sight, path loss, and other media characteristics. WBAN movement may result in topology changes, shadowing of biosensors, signal reflection, diffraction, and scattering. Hence, it is not easy to guarantee each sensor a direct link from the coordinator [17]. Based on nature and WBAN environment, such constraints may result to deep fading effects and performance degradation. Therefore, reliable communication in a dynamic channel conditions need a greater understanding of the communication channel [18].

WBAN communication model should be appropriate to the propagation model and communication scenario considering point to point link and environmental viability. WBAN propagation methods include:

(i) **Narrowband (NB) communications** it uses low carrier frequency and suffers less from the signal attenuation by the human body. However, NB suffers more from signal interference in dense networks.
(ii) **Ultra-wideband (UWB) communication** supports higher data rates and is suitable for low power consumption.
(iii) **Human body communication (HBC)** In this method, signal communication is performed through electric field coupling, where transmission is over a medium of human skin by electrodes using capacitive or galvanic coupling without antennas.

Besides propagation methods, the WBAN channel model may fall under three communication scenarios; on-body, in-body, and off-body communication setups. On-body communication involves the sink node and its linked sensors on the body surface. In-body communication involves linking body implants within the body and off-body communication whose sensors and coordinators may communicate within 3 m around the human body. The signal propagation from different communication scenarios varies from one another due to the varying propagation medium [19].

WBAN users may be mobile or fixed, and sometimes with varying node distribution or changing body posture. Therefore, defining a proper channel model is complicated [20]. Similarly, the communication model may be affected due to the variations of the user body sizes, shape, skin texture, and flexibility. Features associated with the subject determines the quality of the signal communication [17, 21]. In a very dynamic environment of a signal carrier, such as WBAN application, network designers must consider several normalized features when proposing a transmission model. Different models are commonly used in wireless communication based on statistical distributions, including Rayleigh, Weibull, Normal, Lognormal, Gamma, and Nakagami. However, the authors in [17] declares that Rayleigh fading, line/non-line of sight models are both poor models for WBAN radio channel since WBANs can experience deep fade that lasts long in few seconds. Similarly, the channel model using distance-based path loss is inaccurate since the values of the path loss exponent for both NB and UWB varies, even in similar environments. Hence, the models may not be energy efficient for a WBAN standard.

However, selection of the best WBAN channel model must take into consideration of other channel conditions, including factors, such as scattering, reflection, or diffraction, which changes based on the subject activity besides the distance-based path loss models for reliability enhancement.

3.3 WBAN security vulnerability

WBANs use a license-free spectrum under ISM, which raises more security and performance concerns. In this essence, the growing number of users shortly may eventually attract more adversaries breaching user information and jeopardize its operational efficiency. Attacks can be located in different layers of the architecture, such as at the intra-BAN (layer 1), inter-BAN (layer 2), transmission medium (layer 2), and at the data repository centers (layer 3) as illustrated in Fig. 2. Besides threatening user privacy, attacks in WBAN may also focus on degrading network performance by introducing malicious information and affect the quality of service by overwhelming transmission bandwidth capacity, energy inefficiencies, increase packet loss, and link instability.

Attacks may be launched through security loopholes of the WBAN protocols at different architectural levels. The types of attack include the use of shared authentication keys in multi-hop communication schemes, the use of counterfeit acknowledgment packets, signal jamming, and distributed denial of service (DDoS) due to limited WBAN device memory operating in the big data [22].

4 Literature survey

Prospects for health care services show an increasing demand for healthy living in line with advances in technology and innovation. As the world fertility rate is decreasing, studies in [23] have shown that adults with small families have a longer lifespan compared to larger ones,

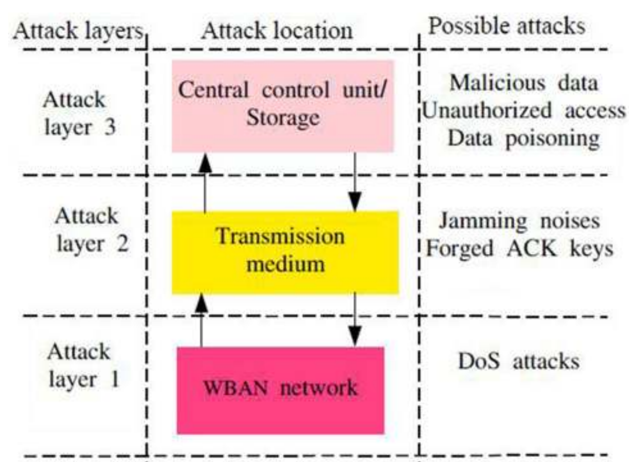

Fig. 2 Layers of attacks in WBANs

so in the future, the elderly population is expected to be higher than that of the youth. In this view, where there is limited attention to elders, alternative health care support applications must meet user expectations in terms of portability, sensitivity, accuracy, durability, integrity, security, and interoperability [2, 23]. Further to that, technology advances in health care services anticipate fully deployment of the wireless body area networks to do more than it can do today for remote health and mobility monitoring and communication over the wireless interface.

In the following subsections of the survey, we discuss WBAN performance improvement issues, which recapitulates key challenging areas on the basis signalled through signal processing, security, network routing and reliability. In the discussion, we also include essential considerations on the path loss, anomalies, and network faults since shortly the healthcare system avails to the big data processing.

4.1 Signal processing

The commercialization of miniaturized WBAN devices anticipates for an increase in the number of WBAN users, which signals for the enormous demand in network resources management and utilization due to higher data traffic. The considerable data volume from users raises new WBAN requirements to support higher data rates with limited network resources in the transmission channel. Apart from the increasing network devices causing the rise in data volume, other sources such as abnormal changes in data configuration and frame structure due to insertion and forging of data by adversaries may also contribute to excessive network resource requirements due to noises and anomalies [7].

For real time health monitoring, communication of the streaming video (e.g., endoscopic capsule) and ECG trace demands higher bandwidth and transmission power due to complications which may be associated with data acquisition noises, data volume, and transmission channel errors. Such requirements may rise performance degradation issues requiring costly mitigation measures. For example, for error reduction and enhancement of the quality of the time series ECG amplitude patterns, i.e., P, Q, R, S and T, in [24] authors use adaptive mapping process of the channel quality indicator (CQI) to enhance the quality of the ECG signal by reducing possible channel coding errors using conservative modulation and coding. However, the reduction of channel errors affects the throughput performance of the network due to bandwidth limitations. So, application of the signal processing algorithms such as wavelets analysis, K-means classification, Markov or Bayesian network models (MM/BNM), are used for data dimension reduction (feature extraction), classification and anomaly detection, respectively. Although, application of these methods must consider trade-offs between signal quality due to channel coding and network performance parameters such as energy efficiency and throughput [25].

Besides, as the data volume increases in parallel with WBAN commercialization, processing of the medical information at the node level reduces the excessive requirement of the network resources in the transmission channel [26]. In this essence, simplification of data size at the node level may include the implementation of various data compression and coding technique, sampling, feature extraction, segmentation, and classification. Performing node level signal processing lowers traffic in the transmission channel, reduce latency, data collisions, and link drop rate due to reduced network resource competition [26, 27]. However, node level signal processing faces several challenges including its complexity on timing and synchronization between operations, need for specific application language developers, computing power constraint and limited memory size with adverse effects on data processing overheads [28].

Proactive measures using feedback systems in WBAN builds another necessity for signal processing within body area network coverage. In intensive care units, patients' physiological data require accurate monitoring in every single unit of time. Therefore, unregulated variation of any parameter may endanger patients' life. So, the feedback system, which only based on the analysis of the sensed vital signs such as respiration rate, Myocardial infarction and oxygen concentration in the blood need immediate reactive emergency measures from the actuation system on such discrepancies. The feedback system may include local alarms to alert physicians and carers or actuators using electromechanical principles for the immediate reaction [29].

Moreover, spectrum sensing and management are among the critical issues in WBAN communication since studies have shown [30]; most of the licensed spectrum are unused. Although network designers are keen about network resource utilization, they have not given enough balance on reliable data routing, node parameters management, configurable networking, and other cognitive functions. Also, the heterogeneity and growing demand for network resources, the WBAN operation under the unlicensed industrial, Scientific and Medical (ISM) band may not be enough. Due to scarce resources, WBAN may require to use unlicensed frequency band outside the ISM spectrum. On this basis Cognitive Radio (CR) enabled base stations can be used for spectrum sensing and allow WBAN to access and transmit packets to the related medical units [12]. So, incorporating WBAN and CR technology

(CRT) will enhance efficient use of the radio spectrum through spectrum aware routing and resource allocation in reducing interference while improving other communication features and the quality of service [31].

4.2 Energy efficient routing and network reliability

Energy is a fundamental driving force of any network. However, apart from energy efficiency, effective monitoring of the remote health critical situation depends on network timeliness, routing and link reliability. Reliability of the wireless network infrastructure counts on the composition of the features, including; reduced discordant in data, minimum link and packet drop rates, lower end to end packet delay, network lifetime longevity, interference-free communication, and channel utilization which ensures network survival and efficient delivery of the WBAN assignments [26]. Usually, networks which can communicate information through a range of devices without hindrance or errors are regarded to be of higher transmission reliability. On the basis of energy efficiency as a fundamental resource of network operations, an unconstrained network with a longer life has a higher probability for better performance, such as a significant packet delivery success before nodes start dying (usually) particularly in cooperative routing [32].

On the other hand, since metrics determining the system's reliability depend on the configuration of the logical medium, reliability issues are also dependent on the network routing techniques. In WBAN, routing techniques are categorized based on application purposes while taking into account protocol usability in different network applications with minimum modifications. Some of the conventional routing techniques include energy-aware, temperature-aware, and QoS-aware routing of which, energy efficient routing has mostly contributed to the network lifetime maximization and, hence, enhancement of the other performance indicators.

Under other conditions, routing protocols are application specific and the efficiency of each routing protocol depend on the node distribution, topology, energy difference between nodes and the environment of deployment. So, selection of the routing protocols must consider the nature of application since each application face different performance challenges. Routing decision in some of the routing protocols considers the node's location, methods for data aggregation, node or subject mobility and quality of service. Although such algorithms face challenges, WBAN designers must consider optimization criteria tradeoffs based on the node power requirement, delay, lifetime, and packet drop rate without affecting the performance of one metric to the other [33].

For example, Since WBAN devices are battery powered, miniaturization of the sensors limits its battery size, and hence its capacity so, appropriate power budget consideration during network design and operation is essential. Node remaining energy has been used as a baseline when designing energy-efficient protocols. Similarly, ability of the node to participate in packet forwarding takes into consideration the instantaneous remaining power before a node involves in packet routing. Node compliance to participate in network activities depend on many factors, including the minimum energy threshold allowed by the routing policy, received signal strength (RSSI), and its distance from the master node [34].

Yet, for energy efficiency, routing protocols considers the number of hops taken by a data packet to the destination. In doing so, while avoiding communication delays; reactive routing (AODV) takes the shortest path, which bases on the low hop count between the source and the destination node [35]. However, incorporating hop count and the distance between peer nodes as an additional requirement gives assurance for better energy conservation. For energy consideration, while maintaining consistent links, multi-hop routing techniques are preferred since the transmission distance between peer nodes is reduced, and so do the transmission power requirement [35]. Although the shortest route gives assurance for the minimal energy consumption, authors in [36] recommends consideration of sufficient criteria when designing efficient and authentic path for reliable network links.

In health monitoring, forwarding of the critical emergency information demands better network reliability. However, different body organs have varying data generation rates [37], with different channel assignment priority. So, in WBAN, heterogeneity of data from various sources demand a complex system which can handle variations in packet traffic [38]. Some of the routing protocols allow channel access through data prioritization schemes and other multiple access mechanisms such as TDMA using dynamic transmission scheduling based on sleeping slots or buffers. However, TDMA without adaptations based on the network conditions suffers from deep fading affecting system reliability through degraded energy efficiency and packet delivery success rate in contention access period [6].

Depending on the nature of the application, data packets are categorized into different categories, including: emergency traffic, delay-sensitive, and general monitoring with varying priorities of transmission when handling various situations during monitoring of physiological signs [39]. The priority of the data packets decides the type of the channel access mechanism; some mechanisms set preferences and allowable threshold based on the generation rate or sensitivity of the particular data on normal, emergencies, or retransmission schemes. For example, based on the traffic generation scheme, data packets with higher data rate are prioritized for transmission compared to others. In this view, in some specific applications, routing of the data packets gives higher priority to emergency data other than common data. However, commercialization of WBAN may have a different data communication approach in a more advanced system.

The available low data rate, low energy protocols support for WBAN applications help to mitigate the energy efficiency challenges. Wireless standards, such as Bluetooth (IEEE 802.15.1), ZigBee (IEEE 802.15.4), and the IEEE 802.15.6, are characterized by low energy consumption during network operation and short distance communication giving higher network reliability. The medium access control (MAC) mechanisms of the standards mentioned above, such as, the IEEE 802.15.4 MAC's duty cycle flexibility allow the variations of the node active and sleep duration when there is no data to transmit. IEEE 802.15.6 frame structure allows transmission prioritization for the emergency and normal data traffic in specific transmission slots that lower the collision possibilities and energy demand for packet retransmission [40]. However, since both IEEE 802.11, IEEE 802.15.4, and IEEE 802.15.6 use CSMA-CA, packet collision remains a big challenge due to the CSMA-CA mechanism during contention period. Similarly, standards' support for transmission frequency and channel hopping reduces risks of interference. For example, IEEE 802.15.4e can operate based on a deterministic and synchronous multichannel extension (DSME) model, which uses enhanced beacons (EB) to generate multisuperframes giving allowance for accommodating many transmission channels. Deploying DSME boosts throughput performance and lowers energy loss through resource competition. Also, IEEE 802.15.4e may operate under a time-slotted channel hopping (TSCH) model for interference mitigation. Even though, the standard MAC mechanisms still suffer from several performance issues that need to be addressed, such as mobility, device coexistence, queuing delays, latency, and device socialization when the number of devices per network increases.

4.3 Data anomalies and network faults

The gradual increase in the number of WBAN users will shortly generate WBAN big data through streaming video, voice, images, and other coded information [33]. WBAN Big data has characteristics, including high velocity, data variation, and volume. In a limited network resource, big data may overwhelm network capacity and effective WBAN performance. Hence increasing susceptibility to data anomalies and collision possibilities [41]. Anomalies are atypical characteristics observed in data or device operation showing discrepancy from the actual attributes. In a big data scenario, sources of anomalies can be associated with ageing or malfunctioning devices, energy scarcity, adversarial intrusion, noises, erroneous calibration, electromagnetic interference, moisture on sensor contacts, and insertion of forged data.

Since WBAN devices have limited power, memory, and computational capacity, they are prone to failure. Due to limited computational capacity WBANs are susceptible to generation of anomalous data, which increases intricacy in network operation, and yet may have fatal effects to the patients [42, 43]. Besides, scarce network resources increase channel utilization competition and collision probabilities leading to persistent link drop out, which raise network faults and affect WBAN reliability. Persisting network faults increases power requirement and therefore provide network power imbalance and performance degradation [24].

Mitigation of the defects in a data or network may involve deploying big data analytic techniques which ease data categorization, selection, and processing within the intra-BAN or at the destination devices. Correspondingly, data processing may involve discriminating unwanted from clean data, identification of the faulty devices based on the collected data, data and traffic classification using supervised or unsupervised machine learning techniques, and secure storage [44].

Moreover, faults in WBAN may originate from the device or network operation, such as sensor working conditions (environment), or poor device placement [44]. On this basis, during medical diagnosis, efficient WBAN operation needs a precise distinction between the device and network-based faults.

Apart from device faults, defects in the communication networks are mainly due to discrepancies in the frame structure of the shared data. The data frame disparity results in incomplete or erroneous data leading to difficulties in the analysis and medical diagnosis. Therefore, supervised machine learning techniques such as support vector machines (SVM), nearest neighbor (NN), and decision trees can be deployed to classify anomalous data. In contrast, methods including linear regression and exponentially weighted moving average (EWMA) can be used to find deviation between measured and expected data values. However, classification methods, such as NN have higher computational complexity and most of the machine learning techniques for anomaly detection face challenges as the availability of the training data for anomaly detection is nearly infeasible [45, 46].

Even though WBAN systems may deploy methods including EWMA, Bayesian probability techniques, and linear regression for prediction of the damaged data and use predicted results to distinguish between anomalous data from faulty device based on the characteristics of the devices in the neighborhood and data sequence relationships [44, 46]. For regular network errors, WBANs can be associated with error correction coding schemes to restore incorrect data based on the automatic repeat request (ARQ) or forward error correction (FEC) techniques, such as cyclic redundancy check (CRC) and use of parity bits along with data traffic, respectively [34]. During transmission, data packets embody redundancy bits or error-detection codes at the source; these are additional data bits along with the transmitted data for correctness verification of the delivered data at the receiver. Any variation in the sequence or composition of the data bits between the sender and receiver implies a transmission error, which requires retransmission of the packet as a corrective measure or application of error correction coding techniques. Error detection may use checksum calculation, where any variation in data sequence requires retransmission or using corrective measures such as convolutional or block codes estimation. However, some network faults are device based. So, network devices may change data generation sequence either due to power failures, misconfiguration, ageing, or overheating circuits [47].

In avoiding sensor faulty measurements, fault detection algorithms consider a comparative analysis of the statistical data sequence of the hardware over a duration of time. Even so, consideration of the trade-offs when distinguishing faults from real anomalies must not interfere with the network performance [46].

Besides, efficiency of the detection algorithms need validation testing. Therefore, validation of the anomaly or fault detection algorithms may use some predefined intrusive data (e.g., ECG patterns) inserted in different training data locations for testing purposes. The deviation of the test data from the labeled data is evaluated during classification and determine classification accuracy. Accuracy of the detection algorithm will depend on the magnitude of the false positives of the detection results and trust management model between network devices for different data sets and algorithms. In most cases, devices with the average working condition have uniform characteristics when operated under the same situation while faulty devices have deviations, which indicate an abnormal condition.

On the other hand, anomalies arising from faulty devices due to scarce residue energy can be mitigated by using fault tolerant algorithms. Fault-tolerant algorithms in WBAN helps in improving reliability by reducing energy waste and emergence of discordant in data. Algorithms implementing methods, such as node clustering, largely reduces network faults. Clustering algorithms allow dynamic changes in the cluster head among cluster members during network operation by considering several criteria, for example, at a given time, a node with higher residue energy within the cluster automatically becomes the cluster head. The approach supports the extension of the network lifetime, improve energy efficiency, and the precision of data in the transmission channel due to network self-healing characteristics [48, 49].

Generally, data anomalies and network faults have significant side effects on regular network operation due to the increasing demand for resources, delay and the need for data integrity. In a license-free spectrum, WBANs share a limited bandwidth, with which in the presence of errors and anomalies the support bandwidth is very minimal due to overheads and the support for data flow is degraded. Similarly, implementation of the complex algorithms for anomalies and fault detection is limited by the computational capacity of the devices. Despite the availability of several methods for anomaly and fault detection, yet it is a complex challenge in need of continuing research.

4.4 Path loss

Signal communication between sensors depends on several factors, including transmission distance, media characteristics, and mode of data communication. Biological sensors are integrated with micro radios which are embedded with microstrip patch antennas as signal radiators. Microstrip patch antennas are the commonly used radiators in WBAN applications due to their flexibility and miniaturized sizes. Microstrip patch antennas can be categorized based on the nature of the application or the shape of the radiating plane surface. Based on the application, microstrip patches are categorized based on the support bandwidth, which consists of the narrow and ultra-wideband (NB/UWB) antennas. Based on the shape, notches are implemented on the planar patch for efficiency enhancement. A planar patch can exist in different shapes, including E, H, U, F, and PIFA antennas.

Along the transmission media radio signals may face hampering issues which lowers signal strength and hence affect data communication. Communication between wireless devices depends on the structure containing the communication device, environmental conditions, and operating frequency [48]. WBAN devices can be positioned in, on or off-body, whereas in regard of the environment and tissue absorption characteristics, on and off-body devices may have lower path loss compared to in and into-on body devices [49]. Also, radiating antennas transmit data based on the point to point communication through the line of sight or in a multipath route. Along the transmission channel (e.g., implant to on-body communication), signal strength may be hindered by attenuation due to absorption properties of the media [50]. Apart from signal attenuation on free space, the absorption characteristics of the body tissues (SAR) may cause extreme health hazards. The impact of excessive SAR into the body causes rising body temperature, various biological system disorders, and cancer development susceptibility [51].

Body implants are positioned several centimeters deep below the skin near vital organs. For example, during intestinal wall diagnosis, endoscopic capsule locates itself between thick abdominal walls. Hence, propagation of the radio signals is profoundly affected by the different dielectric properties of the body tissues. Since different body tissues have different dielectric properties, during in-to-on body (I2O) communication, the transmission of the radio signal through various body tissue layers face extreme attenuation.

Moreover, the structure of the infrastructure within which the WBAN operates can also contribute to radio link loss due to prospective partition losses [52]. To overcome excessive signal power losses, WBAN designers must choose a suitable modulation scheme and propagation paths [53, 54]. Even so, furthest nodes may not qualify for direct transmission to the master node since distant links are more susceptible to excessive path loss due to fading or transmission distance compared to relay-based routing according to the node distribution. Friis path loss formula in Eq. (1) verdicts that, transmission distance has an impact to the overall path loss whereas distant nodes have higher chances for huge path loss compared to nodes close to each other [55, 56]. Therefore, multipath routing can be an alternative for low transmission power [55].

$$PL = PLo + 10nLog\left(\frac{D}{d_0}\right) + S \tag{1}$$

where 'PL' = path loss, 'PLo' = path loss at a reference distance, 'n' = is the coefficient of path loss, 'D' = distance between the source and destination nodes, 'd_0' = reference distance and 'S' = is the scattering loss. As $D \gg d_0$, PL increases.

In the transmission channel, signal propagation may face losses due to scattering, shadowing, reflection, and refraction. Radio signals can be redirected to other location through reflection or refraction depending on the characteristics of the medium and therefore detune receivers due to transmission impairment in the communication network, which results in massive data loss [57]. Since, signal interference contributes to WBAN path loss, interference mitigation may sometimes consider forwarding of the data packets by configuring nodes to transmit at some distinct time intervals which automatically creates free contention window before transmission channel access [58].

Besides, the design of the RF radiators may result in adverse effects to WBAN performance. Therefore, selection of the design material and fabrication style may reduce radiation losses; for example, recent patch antennas have crumples to fit in curved body surfaces however studies show excessive crumpling increases SAR. Similarly, fabrication of the radiating elements using flexible materials such as textiles or a mixture of textile and conformal materials increases comfortability of the users and lowers the surface wave losses due to their low dielectric constant [59]. For low losses through absorption, radiating antennas may be fixed at a distance of several millimeters from the body surface, use lower dielectric constant materials and reduce crumpled antenna structures.

According to the WBAN working environment, antenna parameters of interest include higher gain, low return loss, wider support bandwidth, and directivity, which suits both in-to-out, on, and for off-body communication. These parameters can be adjusted by implementing different modifications on the patch and the backplane, such as introducing slots, cutting the patch into different shapes, or changing the substrate materials. In the future, it is envisioned that radiating materials must take some additional fabrication consideration for low losses, low energy, and compliance for high frequency operation in the 5G era. So, antenna topologies may use meta-materials, comfortable antenna design accommodating mechanical robustness to mobility, and deformation.

4.5 Security

Personal health information must be handled with high confidentiality to avoid any data breach. Any leakage of the patients' health information may cause loss of integrity and lead to legal and loyalty issues. Therefore, the WBAN applications' deployment must observe legal privacy rights. However, the recent growing number of WBAN users, may face adverse security issues from adversaries. In this view, WBAN must conform to a proper assessment of the security threats and mitigation measures.

To the moment, different technologies are used to couple information between end-users (monitored individuals) and the health care facility. Those technologies include Bluetooth, ZigBee, WLAN, and WiMAX, among others. However, the strength of the data security in these platforms varies from one another. Some of the protocol-based security models are implemented based on; encryption or authentication keys, which in a multihop scheme may be shared between devices. Shared authentication keys increase security breach loopholes [22]. Insecure WBAN may lead to degraded network performance, inaccurate data, prognosis, and erroneous health-care decision support services apart from the loss of customer loyalty when patient privacy is compromised [60].

With reference to Fig. 2, security issues in WBAN take different phases; in the WBAN section, transmission medium, and at the information processing repository center. In the WBAN interconnection layers, a data security breach is mainly due to signal jamming and tampering in the physical layer or through the master node (sink). Attackers may send flawed data, jamming signal, or may tamper with the overall network operation [61]. The attack can happen through the wireless link (transmission channel-physical layer) and affect the smooth operation of other network layers; in the data link layer, WBAN may face excessive collision and interference of data packets, in the network layer the network gets complicated by creating routing loops [62]. Both of these attacks causes network failure to handle a large volume of information in the transmission channel as well as distortion of the information data bits due to insufficient resources.

Constraints in data bit format may cause incorrect diagnosis and therefore endanger the patient's life. Also, data collected from various patients can be stored securely in the health-care facility cloud server. In the cloud server, patients' information is categorized based on the physiological data using unique identity or any other secure cryptographic access. The possibility of data encroachment in the cloud alerts for a secure and reliable database system requirement. Big data analytic techniques such as map-reduce can be used to categorize random data sets for authorized access by users [7, 62].

The security vulnerability of the WBANs may be contributed by the factors including; multihop communication scheme as devices in the network may share authentication keys for secure communication; acknowledgment packets (ACK) implemented by some protocols such as IEEE 802.15.4 MAC whose attacks can be derived through fictitious ACK sequence generation by adversaries; energy efficiency strategy, through which the ON–OFF switching may create attack loophole if the transmission synchronization is non-uniform over the system; and weak security suite, which attackers can use counterfeit keys to infringe the network [63].

Attacked WBAN may show several indications, such as increased network congestion, higher energy consumption, and higher delay besides erroneous data communication. The flooding of the malicious information may overwhelm the limited network resources, increase packet collision, raising demands for frequent packet retransmission, and delayed communication due to the lower computational capacity of the network devices with over flooded information. All these impediments subject the WBAN into DDoS attacks.

Besides conventional security mechanisms, the up to date intrusion detection methods make use of machine learning techniques, different statistical models, and information theories [64]. Machine learning algorithms, such as clustering, decision trees, artificial neural networks (ANN), and SVM, can learn and adapt to real-time scenarios by providing countermeasures before further harm by adversaries with or without human intervention [65, 66]. However, the limited memory and computational capacity of the WBAN devices limits its performance. Therefore, attack detection schemes require lightweight machine learning algorithms. Also, the machine learning algorithms are prone to attack through its training data set, where forged data sets can be used to train the machine learning algorithms and give wrong results, which may mislead the WBAN diagnostic results [65].

5 WBAN application areas

WBAN, as an extension of the wireless sensor networks (WSN), find broad application areas today and in the future. The current increment of the internet speed, number of internet users across the globe, affordability of the wearable devices, and advances in artificial intelligence and big data analytics paves the way for pervasive WBAN deployment in the daily life of the humankind. WBAN complies, interconnected devices (wireless sensors) over a short communication distance within or outside the body. Bodies can be anything including a self-driving vehicle, spacecraft or humans. The definition of the body area networks widens its application areas from security, sports, and entertainment to monitoring events and health. Despite its primary objective in health monitoring, WBAN finds numerous medical and non-medical application areas, as illustrated in Fig. 3.

5.1 Sports training and military

From several sudden death incidences reported in sports'; medical findings showed that most casualties happened due to the failure of the various vital organs in the body as a result of fatigue. In recent days, wearable WBAN devices

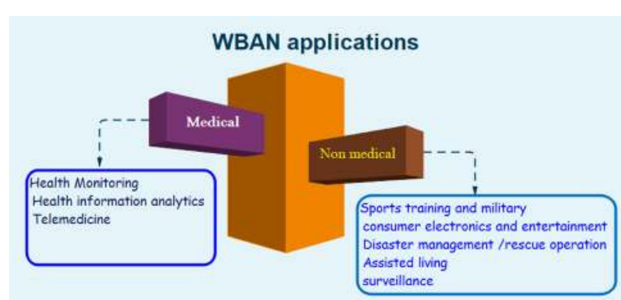

Fig. 3 WBAN applications

are deployed to monitor the health status of the athletes during physical training and military men in various military operations [6, 67].

WBAN sensors embedded in wearable devices, such as wristbands, fabrics in the clothing, etc., measure and aggregates engaged subjects' physiological parameters for health condition prognosis. Wearable devices reports in real-time, information, such as the rate of heartbeat and oxygen level in the blood of an athlete, or the communication between military men when reporting individual health condition such as hydration and stress level.

Sensors and wearable devices are linked to the access point or personal servers, such as a mobile phone or PDA. The linkage between wearables and other PDAs ease users' and physicians' access to the health information and estimate health condition or environment's status. The information may include body fitness, emotions, and temperature. For healthcare application, whenever the values of the monitored physiological condition go beyond or below standard health limits (set threshold), the biofeedback provides decision support on the immediate countermeasures through alarms. Based on the biofeedback or prognostic results, decisive measures are taken before the emergence of any casualty.

5.2 Health monitoring and telemedicine

WBAN plays a significant role in health monitoring. To date, WBAN sensors deployed in the human body as implants, surface contacts or wearables, aggregates, and forward patients' vital health information to the remote health care units. Attached biosensors measure several parameters, including body temperature, heart rate, and blood sugar. The acquired health information is used for disease prognosis or the provision of corrective measures using artificial intelligence techniques [5]. Besides, WBAN finds broad application in early detection of cancer cells, diabetes control, monitoring the rehabilitation progress, and decision support in intensive care units [4–6].

Apart from astronauts' health monitoring in space exploration, WBAN provides network infrastructure for telemedicine services where patient's access to virtual health care is agile [67]. The coordination between the biological sensors, data processing units, and the miniaturized actuators, provide an assessment of the health status and makes a decision that is implemented as feedback through the actuators. For example, on high blood sugar, the processor will use the detected sugar status to command actuator's regulation by pumping the insulin into the blood vessels.

5.3 Disaster management and rescue operations

On the occasion of the disasters, in most cases the communication and other infrastructure fails to support intended functions. Rescue teams may fail a rescue operation if the reliable communication network is not functional. Apart from the use of WBAN for information monitoring (health etc.,), the coverage distance by the WBAN is short. Hence in [12] authors propose the use of WBAN alongside with CR. Where the CR will support data communication based on opportunistic channel access to link the information in the WBAN network to the intended health units using the unlicensed frequency spectrum outside the ISM band. Therefore despite the weakened telecommunication infrastructure, WBANs can still serve the purpose.

5.4 Assisted living

The increasing elderly population draws attention to elderly care through motion and gesture recognition [3]. WBAN sensors (accelerometer and gyroscope) are used to monitor movements, and changing posture of the elders under assisted living in smart homes [23, 67]. Alternatively, individuals can easily interact with WBAN health care systems and reduce dependency by using remote controllers. For severe incidences, monitored activities alert other family members and caretakers for response, e.g., an emergence of a slump in need of attention. Similarly, the increasing elderly population alerts for scarce future employees and employment plan turnaround. It is expected that WBAN gadgets will assist the elderly to work beyond retirement age by monitoring physical and emotional fitness on extended tenures.

5.5 Consumer electronics and entertainment

The invention of the millimetre-wave devices boosts the use of short-range communication between different wireless-enabled accessories. Usage of wearable devices for interconnection and interaction between smart wristwatch or handheld devices and smart TV, games, or playing MP3 on Bluetooth devices illustrates the interaction between WBAN applications with the recent people's lifestyles and entertainment [6]. The growing customization justifies the sophistication in technology and the growing integration between wearables and smart devices. Also, the higher internet speed in 5G promotes the usability of the wearable devices as a fashion besides the healthcare application.

5.6 Surveillance, device monitoring and emergency healthcare services

Surveillance devices, such as integrated satellites and unmanned aerial vehicles, use high definition cameras and other sensors to monitor various social activities that involve gait movement, change in position, interaction, and collection of health information into data servers using UWB transceivers. Apart from surveillance, Visual health information can also be collected from multiple sources using unmanned aerial vehicles (UAV) linked to WBANs. Acquired information in the data servers is required by the controllers, physicians, and engineers to respond to the prevailing situation based on the health status of the individuals or of the device depending on the nature of the data [68, 69]. For remote or isolated areas WBAN combined with satellites can be used to provide health emergency services with minimum delayed biosignals.

The coordination and communication of information within a remote device use embedded sensors (WBAN) to measure different parameters. Depending on the embedded intelligence, remote devices can independently control its functions, store data in the logger (or servers) and communicate to the control station [70].

5.7 Security

WBAN security is vital since any security breach leads to serious privacy matters. Conventional systems use different security measures such as passwords, fingerprints, iris, and face recognition, which are too bulky for a limited WBAN device memory. Recently, the echocardiography (ECG) tress becomes one of the emerging biometric patterns which can suit security purposes for WBAN and other applications [9, 71].

ECG trace is said to be unique from one person to another [72, 73]. So, an embedded lightweight wireless sensor which generates ECG signal can be coupled to a neighboring PDA to access services around its vicinity. Nevertheless, a set of WBAN sensors apart from generating biometric signals may continually provide information about devices in the same network to avoid data breach from intruders [61, 73].

6 Open research areas

The growing number of WBAN users and the continued research interests open other application areas which may use WBAN devices. With the increasing dependency and affordability for WBAN devices, addressed WBAN issues requires immediate attendance for further performance improvement. In this work, we have proposed, in summary, some of the compelling future research directions as described in the following sections.

6.1 WBAN spectrum management

Commercialization of the wireless body area networks increases the number of users contributing to massive data traffic in the transmission channel and the increased network resource competition [47]. Excessive network resource competition may end up in packet collision, inter-BAN interference, end to end delays and data loss [26, 27]. Since the network resource is limited, the current use of the available spectrum may not suit future demand to provide a better quality of service [6, 35].

Several approaches used to improve network performance by using low-frequency devices in reducing; collisions, delay, interference and power requirement have not provided satisfactory solutions for the dynamics in WBAN emergency cases with tremendous data heterogeneity [30, 49, 50, 58]. Therefore, proper utilization of the communication spectrum will further reduce the current challenges on network resource requirement. However, at a time the ISM band may not suffice the use of the WBAN in a network resource scarce environment. WBAN may require to use unlicensed band outside ISM. In this case, CR enabled base stations, may help to link WBAN with the healthcare units [12].

On the other hand, miniaturization of the high efficiency electronic devices provides a room for embedding cognitive radios (CR) in WBAN. CR will bring about a dynamic spectrum assignment by avoiding transmission channel from being fully utilized [31]. Similarly, embedded CR will reduce WBAN resource competition and hence improve network performance. Therefore, further studies to sandwich CR into WBAN applications will give alternative solutions for the current and future network related WBAN challenges.

6.2 Body to body network connectivity

The increasing speed and efficiency of internet services will change future WBAN user requirements, which will bring new challenges. Most of the recent research efforts only focus on enhancing network performance by designing efficient routing policies, energy conservation, improved data delivery success, and security [15, 25, 32, 33]. The increasing deployment may require a paradigm shift in solving problems related to WBAN scalability, channel accessibility, and integrity in distributed networks.

Besides network connectivity, the determination of the most reliable routes ensures network performance enhancement. Usually, using the traditional routing algorithms (Dijkstra's), optimum, and energy efficient pathfinding depends on the shortest route. However, the overuse of the selected paths is not attended in detail. The increasing pervasiveness of the WBAN technology calls on using more efficient methods for efficient network connectivity. Despite memory scarcity, the use of the software-defined networks (SDN) in WBAN will enhance WBAN performance by finding the best route instead of only the shortest route, encountering data heterogeneity, network scalability, and handling of the complex topologies [74, 75].

Moreover, future demands for packet routing, energy efficiency, and quality of service call for robust solutions to address challenges related to mobility, coexistence and inter-BAN interference [16], in this view, problems related to data frame variation, incomplete data, data flow rate, packet collisions, faults, malicious attacks, and resource utilization for distributed BAN need to be revisited at the intersection of big data for B2B connectivity.

6.3 Network security

With expanding WBAN usage, data security is becoming one of the primary requirements in maintaining patients' privacy and legal rights to personal health information. From the literature, we have seen most of the recent research activities focus on securing data at the far end in the repository, and less has been done for the WBAN in particular due to its low memory and computation complexity [7].

In WBAN, data damage may happen at the node level when we have malicious nodes, or in the transmission media by an adversary [61]. Developing a data security strategy may involve the use of authentication messages and deciphering keys [73–76]. Regarding the WBAN environment (users), complex authentication algorithms are undesirable. Therefore, the use of distinctive biometrics, e.g., ECG/EKG trace for secure end to end connection is a promising future research area [7]. Similarly, machine learning algorithms based on artificial neural networks will provide the best security features through the detection and mitigation of malicious activities before happening. However, embedding security firmware in a resource-scarce environment may result in insufficient resource availability for intended data communication. It is necessary to enhance WBAN memory and computational capacities, or desire alternative security measures considering such trade-offs without affecting regular network performance in the body to body and personal area networks [71].

6.4 Network delay

Path loss reduction strategy for energy efficiency in WBAN recommends the use of multihop routing. The multihop systems usually face an end to end delay since the routing of the data packets takes several network devices to reach the destination [28]. For coexisting WBAN communication, issues of network delay need attention, especially when handling emergency data. Coexisting WBANs, which transmit data at the same time in a densely populated area with high mobility subjects the network into extreme interference ending up with delays due to transmission or association waiting time. Apart from DDoS attacks, additional causes of network delay, include excessive packet collision, complex packet processing and routing mechanism, which raises retransmission requirement, network overheads, and limited bandwidth, respectively. A delay constrained network faces increased difficulties in channel accessibility when the number of WBAN devices is large.

On the other hand, independent WBANs may or may not have an emergency at the same time; in such cases, channel contention becomes unpredictable [35, 38]. Therefore, the projected increase in commercialization of the WBAN and the number of users alert researchers to take into account the configuration of the transmission channel and channel management as an exciting research challenge to handle emergencies, interference issues, latency and network delays in such scenarios [76, 77].

Since the channel access mechanism faces a lot of challenges through contention-based access, alternative channel access mechanisms need to be implemented. Excessive competition in accessing the transmission channel may cause congestion, especially for CSMA-CA mechanisms during the contention period, which consequently increases network queuing delay and packet loss. Alternative methods of sharing the transmission channel through other techniques such as TDMA, DSME and TSCH may be applied for congestion reduction. Nodes may be assigned dedicated transmission slots in TDMA, coordinators may increase the number of transmission slots based on the enhanced beacon, and appropriate scheduling of the packet transmission in IEEE 802.15.4 MAC, respectively. Also, further findings on the use of SDN-WBAN may contribute in solving future network challenges [74].

Similarly, queuing delay may originate from handshaking mechanisms, which requires source nodes to stay in a listening mode due to control signal interaction. Using a fixed duty cycle in a dynamic environment may further bar nodes from accessing the transmission channel hence increasing queue in the buffer depending on the packet arrival model, increased retransmission requirement due to higher collision rates, and unreliable links. In such schemes, controlling data queues may require the use of dynamic duty cycle adaptation mechanisms, which will reduce collision possibilities and adjust packet sending and receiving duration according to the data packets' size. Although, by using the methods mentioned above, WBAN performance enhancement requires trade-offs consideration when solving challenges associated with these methods. So, as the commercialization increases, further studies on the most efficient methods is required.

6.5 Wban device standardization

Commercialization of the body to body communicating devices need an explicit integration of devices from different vendors and between OSI layers. Manufacturing of the devices which can easily link to one another without any network limitations will ease forwarding of the data packets through relay BANs [78]. Standardization of the WBAN devices must also consider; network scalability when defining a maximum number of localized BANs which can communicate at a time, and packet communication between different layers in every device. Device standardization implies that devices from different vendors can easily communicate with each other using embedded applications or service providers without any network limitations, and so should the body to body networks. Standardized devices give users confidence and assurance of the cost reduction in smart homes and other IoT technologies, including health monitoring [67]. WBAN users being one of the stakeholders will have a variety of options to choose devices from different manufacturers, which can easily interlink with other systems and reduce unnecessary inconveniences and network faults [47, 67, 78].

6.6 Radio frequency radiation safety

Recent advances in 5G cellular mobile communication support high data rate and internet connectivity far beyond 4G. Commercialization of 5G systems will automatically increase services via the internet of things due to the supporting data rates. The technology commercialization poises for increased use of radio frequency (RF) devices shortly, and so increased radiation exposure among users [79]. The increased RF exposure will subject the majority of the community in the vicinity of the electromagnetic radiation health hazards. WBAN devices fixed in, on or around the human body emits electromagnetic radiations through its radiators as it operates. These radiations may cause electromagnetic interference (EMI) affecting neighbouring devices operation and consequently may result in malfunction, damage or reduced device lifespan and endangering patient safety. Standardization on radiation safety depends on the device acceptable measures for susceptibility based on the standard limits by different authorities, such as food and drug authority (FDA).

Despite the existing approaches for standardization, the radiation exposure limits set by Federal Communication Commission (FCC) and International Commission for non-ionizing radiations (INCR), need to be revisited considering multiple RF radiating elements per unit area. Further studies on the RF safety measures must be taken to ensure that there will be no or minimum radiation effect to human health as a result of an increased number of signal radiators and connectivity which evolves RF exposure among service users [51].

Besides, measures, including EMI shielding or filtering, can be applied for radiation risks mitigation. However, WBAN devices operate under an open system, so implementation of the EMI shield is likely impossible. Similarly, the implementation of the EMI filtering using active or passive devices needs extra consideration on the power requirement, user comfort and flexibility. Even though some methods, including the use of the routing mechanisms whose routing decision considers the radiation effects based on the node involvement to WBAN activity can help to reduce radiation effects and SAR. So, continuing research on securing patient safety against radiation hazards in miniaturized medical devices is necessary.

7 Conclusion

In this survey, we have given a summary of the prospects for age-related health challenges and the increasing dependency of the future healthcare on WBAN, current WBAN performance issues, application areas, and some open research directions for performance enhancement. The survey shows changing lifestyles and advances in technology poise for a considerable dependency on automated health technologies despite the general unawareness of future health challenges and aging-related diseases, which require further studies.

Apart from the increasing commercialization of the WBAN devices in health monitoring and sports, WBAN faces performance challenges due to the limited shared frequency band for ISM applications, device associations in dense networks, congestion, and fading. Yet, WBAN suffers from channel accessibility in a dense environment, since the channel access mechanism faces huge competition with the increasing data volume and devices. In this essence, adaptive channel access mechanisms for future WBANs need advancement, such as the integration of WBAN with cognitive radios and software defined networks with mobility considerations. WBAN transceiver needs to be able to dynamically adjust its transmission parameters to adapt accordingly with different situations on its existence. In doing so, the issues of interference and packet collision will be highly reduced despite multiple collocation existence.

The implementation of the authentication key in different protocols show operational flaws against adversaries and forged access keys. Implementation of the spread spectrum techniques can primarily fit for data protection and synchronization. However, WBAN has memory constraints and bandwidth limitations. So, it is recommended to use advanced lightweight security measures, such as the artificial intelligence-based applications for WBAN security enhancement.

Similarly, when health monitoring becomes fully online, susceptibility to attacks that breach user privacy alarms for the future healthcare systems' integrity. Despite the machine learning algorithms for enhancing security measures through data classification, there are still other limitations due to the finite memory and computational capacity of the WBAN devices. Besides, the existing machine learning algorithms are not completely secure because of the emerging adversarial attacks. Therefore, further consideration to avoid possibilities of a security breach in adversarial detection algorithms at a device or data repository level, and enhancing devices' computational capacity is insisted. So, WBAN devices' memory computational power need to be enhanced, and the implementation of the lightweight machine learning algorithms would significantly help to minimize issues of anomalies, intrusion and trust in medical data for efficient healthcare undertakings.

Even so, WBAN is expected to solve most of the future technical health challenges, so continued research and innovation on the healthcare solutions are necessary. In line with that, the projected increase of the WBAN dependency for medical and non-medical applications calls for efficient but also standardized, scalable, secure, and interoperable WBAN devices. With the growing number of users, WBAN biosensors can easily be embedded in different materials, such as safety boots for security and firefighters, in textiles, etc., so, WBANs becomes ubiquitous. Hence the health care systems must be capable of integrating devices from different vendors, associate, and dissociate devices in the network without interrupting its performance, keeping user privacy a priority.

Moreover, the commercialization of the WBAN in the high-speed internet connectivity under 5G, poises other concerns, such as user safety against electromagnetic radiation for distributed and coexisting networks, since the number of radio frequency devices is poised to increase per unit area. Similarly, future WBAN demand advances in energy efficiency and management, channel utilization, flexible radiators and more robust design materials complying with high frequency spectrum, low SAR devices, and spectrum management besides network security and anomalies in big medical data sets for efficient medical diagnosis and user comfortability.

We further envision that research in WBAN will solve many future health-related challenges since the continuing findings and achievements show better prospects for the future.

Authors' contributions Qingling Liu conceptualized the article, designed organization structure, and reviewed the article, Kefa G. Mkongwa conducted revisions, organized article flow, conceptualization, presentation, and preparation of the article, whereas Chaozhu Zhang proofread the article and revised the organization structure.

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References

1. Chatterjee S et al (2018) Internet of things and body area network-an integrated future. In: 2017 IEEE 8th annual ubiquitous computing, electronics and mobile communication conference, UEMCON 2017 pp 396–400, 2017. https://doi.org/10.1109/UEMCON.2017.8249094
2. Letwin O, Harper S, Walport M (2016) Future of an ageing population. Oxford Inst Popul Ageing, p. 1–124, 2016. Retrieved from https://www.ageing.ox.ac.uk/files/Future_of_Ageing_Report.pdf
3. Cangelosi A, Schlesinger M (2018) Social robots. In: Developmental robotics. https://doi.org/10.7551/mitpress/9320.003.0009
4. Movassaghi S, Majidi A, Jamalipour A, Smith D, Abolhasan M (2016) Enabling interference-aware and energy-efficient coexistence of multiple wireless body area networks with

unknown dynamics. IEEE Access. https://doi.org/10.1109/ACCESS.2016.2577681

5. El Houssaini D, Khriji S, Besbes K, Kanoun O (2018) Performance analysis of received signal strength and link quality in wireless sensor networks. In: 2018 15th International multi-conference on systems, signals and devices, SSD 2018. https://doi.org/10.1109/SSD.2018.8570634
6. Salayma M, Al-Dubai A, Romdhani I, Nasser Y (2018) Reliability and energy efficiency enhancement for emergency-aware wireless body area networks (WBANs). IEEE Trans Green Commun Netw 2(3):804–816
7. Aslam F, Ali A, Abbas H, Al N, Haldar H (2014) A cloud-based healthcare framework for security and patients' data privacy using wireless body area networks. Procedia Procedia Comput Sci 34:511–517. https://doi.org/10.1016/j.procs.2014.07.058
8. IEEE Standard for local and metropolitan area networks - Part 15.6: Wireless body area networks. In IEEE std 802.15.6-2012, pp 1–271, (2012). https://doi.org/10.1109/ieeestd.2012.6161600
9. Salehi SA, Razzaque MA, Tomeo-Reyes I, Hussain N (2016) IEEE 802.15.6 standard in wireless body area networks from a healthcare point of view. In: Proceedings—Asia-Pacific conference on communications, APCC 2016. https://doi.org/10.1109/APCC.2016.7581523
10. Frigo G, Giorgi G (2017) IEEE 802.15.6 compliant WBSN: A case study. In: 2017 IEEE international workshop on measurement and networking, M and N 2017—Proceedings. https://doi.org/10.1109/IWMN.2017.8078369
11. Salam HA, Khan BM (2016) Use of wireless system in healthcare for developing countries. Digit Commun Netw. https://doi.org/10.1016/j.dcan.2015.11.001
12. Cicioğlu M, Çalhan A (2020) Channel aware wireless body area network with cognitive radio technology in disaster cases. Int J Commun Syst. https://doi.org/10.1002/dac.4565
13. Negra R, Jemili I, Belghith A (2016) Wireless body area networks: applications and technologies. In: Procedia computer science. https://doi.org/10.1016/j.procs.2016.04.266
14. Khan RA, Pathan ASK (2018) The state-of-the-art wireless body area sensor networks: a survey. Int J Distrib Sens Netw. 14 (1204). https://doi.org/10.1177/1550147718768994
15. Kaur N, Singh S (2017) Ad Hoc Networks Optimized cost effective and energy efficient routing protocol for wireless body area networks. Ad Hoc Netw 61:65–84
16. Arbia D, Alam M, Moullec Y, Hamida E (2017) Communication challenges in on-body and body-to-body wearable wireless networks—a connectivity perspective. Technologies. pp 1–18. https://doi.org/10.3390/technologies5030043
17. Smith DB, Miniutti D, Lamahewa TA, Hanlen LW (2013) Propagation models for body-area networks: a survey and new outlook. IEEE Antennas Propag Mag. https://doi.org/10.1109/MAP.2013.6735479
18. Mohamed M, Cheffena M, Fontán FP, Moldsvor A (2018) A dynamic channel model for indoor wireless signals: working around interference caused by moving human bodies. IEEE Antennas Propag Mag. https://doi.org/10.1109/MAP.2018.2796022
19. Nahali A, Hamdi A, Gautier M, Courtay A, Braham R (2019) Energy modeling of wireless body area networks with on-body communication channel characterization. In: 2019 15th International wireless communications and mobile computing conference, IWCMC 2019. https://doi.org/10.1109/IWCMC.2019.8766608
20. Kadel R, Islam N (2019) Comparison of channel models for wireless body area networks (WBANs). In: 2018 IEEE conference on wireless sensors, ICWiSe 2018. https://doi.org/10.1109/ICWISE.2018.8633288
21. Haddad O, Khalighi M-A, Zvanovec S, Adel M (2020) Channel characterization and modeling for optical wireless body-area networks. IEEE Open J Commun Soc. https://doi.org/10.1109/ojcoms.2020.2999104
22. Khernane N, Potop-Butucaru M, Chaudet C (2017). BANZKP: a secure authentication scheme using zero knowledge proof for WBANs. In: Proceedings—2016 IEEE 13th international conference on mobile ad hoc and sensor systems, MASS 2016. https://doi.org/10.1109/mass.2016.046
23. Jagger C (2015) Trends in life expectancy and healthy life expectancy. Foresight, Gov Off Sci. pp 1–29, Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/464275/gs-15-13-future-ageing-trends-life-expectancy-er12.pdf
24. Cho Y, Shin H, Kang K (2018) Scalable coding and prioritized transmission of ECG for low-latency cardiac monitoring over cellular M2M networks. IEEE Access. https://doi.org/10.1109/ACCESS.2018.2795028
25. Arefin MT, Ali MH, Haque AKMF (2017) Wireless body area network: an overview and various applications. J Comput Commun. https://doi.org/10.4236/jcc.2017.57006
26. Wang Y, Liu R, Shu M, Chen C (2017) Advances in robotics & automation stochastic geometry analysis of throughput for wireless body area networks. 6(3):3–8
27. Barsocchi P, Potortì F (2014) Wireless body area networks.Wearable Sensors: Fundamentals, Implementation and Applications. New York: Pan Stanford, (**Chapter 5**). https://doi.org/10.1016/B978-0-12-418662-0.00012-X
28. Kim BS, Kim KH, Il Kim K (2017) A survey on mobility support in wireless body area networks. Sensors (Switzerland). https://doi.org/10.3390/s17040797
29. Al-Saud KA, Mahmuddin M, Mohamed A (2012) Wireless body area sensor networks signal processing and communication framework: survey on sensing, communication technologies, delivery, and feedback. J Comput Sci. https://doi.org/10.3844/jcssp.2012.121.132
30. Bhandari S, Moh S (2015) A survey of MAC protocols for cognitive radio body area networks. Sensors (Switzerland). https://doi.org/10.3390/s150409189
31. Rathee D, Rangi S, Singh VR, Engineers E (2014) Recent trends in wireless body area network (WBAN) research and cognition based adaptive WBAN architecture for healthcare. Health Technol 4(3):239–244. https://doi.org/10.1007/s12553-014-0083-x
32. Bangash JI, Abdullah AH, Anisi MH, Khan AW (2014) A survey of routing protocols in wireless body sensor networks. Sensors (Switzerland) 14(1):1322–1357
33. Karthiga I, Sankar S, Dhivahar P (2015) A study on routing protocols in wireless body area networks and its suitability for m-health applications. In: 2015 International conference on communication signal processing, pp 1064–1069
34. Negi S (2016) Modified new-attempt routing protocol for wireless body area network. In: 2016 2nd Int Conf Adv Comput Commun Autom, pp 1–5
35. Chen X, Xu Y, Liu A (2017) Cross-layer design for optimizing transmission reliability, energy efficiency, and lifetime in body sensor networks. Sensors (Switzerland) 17(4):11–15
36. Esmaeili H, Minaei Bidgoli B (2018) EMRP: Evolutionary-based multi-hop routing protocol for wireless body area networks. Int J Electron Commun, AEU 93(February):63–74. https://doi.org/10.1016/j.aeue.2018.06.003
37. Shu M, Yuan D, Zhang C, Wang Y, Chen C (2015) A MAC protocol for medical monitoring applications of wireless body area networks. Sensors (Switzerland) 15(6):12906–12931
38. Ambigavathi M, Sridharan D (2015) Priority-based AODV routing protocol for critical data in Wireless Body Area Network. In: 2015

3rd Int Conf Signal Process Commun Networking, ICSCN, pp 1–5, 2015, March 2015. https://doi.org/10.1109/ICSCN.2015.7219885
39. Ben Elhadj H, Elias J, Chaari L, and Kamoun L (2016) A Priority based Cross-Layer Routing Protocol for healthcare applications. Ad Hoc Netw. https://doi.org/10.1016/j.adhoc.2015.10.007
40. Yuan D, Zheng G, Ma H, Shang J, Li J (2019) An adaptive MAC protocol based on IEEE802.15.6 for wireless body area networks. Wirel Commun Mob Comput. https://doi.org/10.1155/2019/3681631.s
41. Chandra SR, Goswami RT (2017) Big data security in healthcare: survey on frameworks and algorithms. 2017 IEEE 7th Int Adv Comput Conf. https://doi.org/10.1109/IACC.2017.25
42. Salem O, Guerassimov A, Mehaoua A, Marcus A, Furht B (2015) Anomaly detection in medical wireless sensor networks using SVM and linear regression models. In: E-health and telemedicine: concepts, methodologies, tools, and applications. https://doi.org/10.4018/978-1-4666-8756-1.ch024
43. Kadel R, Islam N, Ahmed K, Halder SJ (2018) Opportunities and challenges for error correction scheme for wireless body area network—a survey. J Sens Actuator Netw. https://doi.org/10.3390/jsan8010001
44. Jeong YS, Kim HW, Park JH (2014) Visual scheme monitoring of sensors for fault tolerance on wireless body area networks with cloud service infrastructure. Int J Distrib Sens Netw. https://doi.org/10.1155/2014/154180
45. Salem O, Guerassimov A, Mehaoua A, Marcus A, Furht B (2013) Sensor fault and patient anomaly detection and classification in medical wireless sensor networks. In: IEEE international conference on communications, (ICC), pp 4373–4378, 2013. https://doi.org/10.1109/ICC.2013.6655254
46. Arfaoui A, Kribeche A, Senouci SM, Hamdi M (2019) Game-based adaptive anomaly detection in wireless body area networks. Comput Netw. https://doi.org/10.1016/j.comnet.2019.106870
47. Du Y, Hu F, Wang L, Wang F (2015) Framework and challenges for Wireless body area networks based on big data. In: International conference on digital signal processing, DSP, pp 497–501, 2015. https://doi.org/10.1109/ICDSP.2015.7251922
48. Khodabandeh H, Ayatollahitafti V, Taghizadeh MS (2018) Link aware and energy efficient routing algorithm in wireless body area networks. Netw Protoc Algorithms. https://doi.org/10.5296/npa.v9i1-2.11547
49. Galzarano S, Fortino G, Liotta A (2012) Embedded self-healing layer for detecting and recovering sensor faults in body sensor networks. In: Conference proceedings—IEEE international conference on systems, man and cybernetics, (SMC), pp 2377–2382. https://doi.org/10.1109/ICSMC.2012.6378098
50. Sarma KC, Mahanta A, Goswami D (2016) Path loss variation of on-body UWB channel in the frequency bands of IEEE 802.15.6 standard. Healthc Technol Lett 3(2):129–135. https://doi.org/10.1049/htl.2016.0005
51. Smith DB, Hanlen LW (2015) Channel Modeling for Wireless Body Area Networks. In: Ultra-Low–Power Short-Range Radios 2015. Springer, Cham, pp 25–55. https://doi.org/10.1007/978-3-319-14714-7_2
52. Chowdhury HR, Hassan S, Ahmed A (2017) Analysis of path loss characteristics in body area network for different physical structures. In: Proceedings of 9th international conference on electrical and computer engineering, ICECE 2016, 2017 pp 299–302 (2016). https://doi.org/10.1109/ICECE.2016.7853915
53. Gil I, Fernández-García R (2017) Wearable PIFA antenna implemented on the jean substrate for wireless body area network. J Electromagn Waves Appl. https://doi.org/10.1080/09205071.2017.1341854
54. Hausman S (2014) Impact of the indoor environment on path loss in body area networks. Sensors (Switzerland). https://doi.org/10.3390/s141019551
55. Liao Y, Leeson M, Higgins M, Bai C (2016) Analysis of in-to-out wireless body area network systems: towards QoS-aware health internet of things applications. Electronics 5(4):38
56. Chavva SR, Sangam RS (2019) An energy-efficient multi-hop routing protocol for health monitoring in wireless body area networks. Netw Model Anal Heal Inform Bioinform. https://doi.org/10.1007/s13721-019-0201-9
57. Kumpuniemi T, Tuovinen T, Hämäläinen M, Yazdandoost KY, Vuohtoniemi R, Iinatti J (2013) Measurement-based on-body path loss modeling for UWB WBAN communications. In: International symposium on medical information and communication technology, (ISMICT) 2013 Mar 6 (pp. 233–237). IEEE. https://doi.org/10.1109/ISMICT.2013.6521735
58. Zafar H, Ali Khan R, Mazhar Soomro A (2017) minimizing path loss in medical wireless sensors in wireless body area sensor networks. Indian J Sci Technol. https://doi.org/10.17485/ijst/2017/v10i32/117001
59. Aun NFM, Soh PJ, Al-Hadi AA, Jamlos MF, Vandenbosch GAE, Schreurs DS (2017) Revolutionizing Wearables for 5G: 5G technologies: recent developments and future perspectives for wearable devices and antennas. IEEE Microw Mag. https://doi.org/10.1109/MMM.2017.2664019
60. Ahmed T, Le Moullec Y (2017) A QoS optimization approach in cognitive body area networks for healthcare applications. Sensors (Switzerland). https://doi.org/10.3390/s17040780
61. Al-janabi S, Al-shourbaji I, Shojafar M, Shamshirband S (2017) Survey of main challenges (security and privacy) in wireless body area networks for healthcare applications. Egypt Inform J 18(2):113–122
62. Awais M, Abdullah T, Ahmed M, Malik MSA, Nigar M, Kousar N (2018) Wireless body area network security and privacy issue in E-healthcare. Int J Adv Comput Sci Appl 9(4):209–215
63. Zou S, Xu Y, Wang H, Li Z, Chen S, Hu B (2017) A survey on secure wireless body area networks. Secur Commun Netw. https://doi.org/10.3390/s17040780
64. Patil NV, Rama Krishna C, Kumar K, Behal S (2019) E-Had: a distributed and collaborative detection framework for early detection of DDoS attacks. J King Saud Univ Comput Inf Sci. https://doi.org/10.1016/j.jksuci.2019.06.016
65. Singh R, Kumar H, Singla RK (2015) An intrusion detection system using network traffic profiling and online sequential extreme learning machine. Expert Syst Appl. https://doi.org/10.1016/j.eswa.2015.07.015
66. De Lima Filho FS, Silveira FAF, De Medeiros Brito Junior A, Vargas-Solar G, Silveira LF (2019) Smart detection: an online approach for DoS/DDoS attack detection using machine learning. Secur Commun Netw. https://doi.org/10.1155/2019/1574749
67. Latah M, Toker L (2018) A novel intelligent approach for detecting DoS flooding attacks in software-defined networks. Int J Adv Intell Inform. https://doi.org/10.26555/ijain.v4i1.138
68. Majumder S et al (2017) Smart homes for elderly healthcare—Recent advances and research challenges. Sensors (Switzerland). https://doi.org/10.3390/s17040780
69. Ha L, Cho Y-Z (2016) Unmanned aerial vehicles-based health monitoring system for prevention of disaster in activities of the mountain. Int J Control Autom. https://doi.org/10.14257/ijca.2016.9.9.34
70. Kobayashi T et al (2018) Wireless technologies to assist search and localization of victims of wide-scale natural disasters by unmanned aerial vehicles. In: International symposium on wireless personal multimedia communications (WPMC). https://doi.org/10.1109/WPMC.2017.8301846
71. Rahman AFA, Ahmad R, Ramli SN (2014) Forensics readiness for Wireless Body Area Network (WBAN) system. In: International conference on advanced communication technology, ICACT, 2014

72. Fratini A, Sansone M, Bifulco P, Cesarelli M (2015) Individual identification via electrocardiogram analysis. BioMed Eng Online 14:78. https://doi.org/10.1186/s12938-015-0072-y
73. Zebboudj S, Cherifi F, Mohammedi M, Omar M (2017) Secure and efficient ECG-based authentication scheme for medical body area sensor networks. Smart Heal. https://doi.org/10.1016/j.smhl.2017.07.001
74. Cicioğlu M, Çalhan A (2019) SDN-based wireless body area network routing algorithm for healthcare architecture. ETRI J. https://doi.org/10.4218/etrij.2018-0630
75. Cicioğlu M, Çalhan A (2020) Energy-efficient and SDN-enabled routing algorithm for wireless body area network. Comput Commun. https://doi.org/10.1016/j.comcom.2020.06.003
76. Peter S, Reddy BP, Momtaz F, Givargis T (2016) Design of secure ECG-based biometric authentication in body area sensor networks. Sensors (Switzerland). https://doi.org/10.3390/s16040570
77. Yuan X et al (2018a) Dynamic interference analysis of coexisting mobile WBANs for health monitoring. In: IEEE international conference on communications (ICC). https://doi.org/10.1109/ICC.2018.8422791
78. Aragues et al (2011) Trends and challenges of the emerging technologies towards interoperability and standardization in e-health communications. IEEE Commun Mag. https://doi.org/10.1109/MCOM.2011.6069727
79. McClelland S, Jaboin JJ (2018) The radiation safety of 5G Wi-Fi: reassuring or Russian Roullete? Int J Radiat Oncol. https://doi.org/10.1016/j.ijrobp.2018.04.051