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TOPICAL REVIEW

Wireless Body Area Networks and Their Applications–A Review

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ABSTRACT In this paper, a comprehensive review of the wireless body area network is provided. A review of the WBAN architectures, standard network topologies, and WBAN communication protocols is discussed in detail. Also, the security requirements of WBAN, security threats and types of attacks, and authentications used in WBAN are discussed. The paper also includes very detailed coverage of antenna types, antenna designs, and flexible antennas used in WBAN with some design considerations and comparisons. Some new energy harvesting technologies, materials used for energy harvesting, and energy management are also discussed. Energy harvesting and power management is an ever-growing area of research. Despite the fact that there are many nanogenerator-based energy harvesting methods, the demand for more efficient energy harvesting mechanisms is ever-increasing. The paper has an extensive discussion of energy harvesting and power management methods. Subsequently, some reviews of recent developments in wearable sensors and novel materials for developing wearable sensors are discussed. Finally, the application areas of WBAN are discussed

INDEX TERMS Body area network, network security, wireless communication protocols, wearable sensors, energy harvesting, WBAN, flexible sensors, IoT.

I. INTRODUCTION

A Wireless Body Area Network (WBAN) is a network of devices comprising sensors, actuators, and transceivers placed on the surface of the body, under the skin, or inside the body as implanted or digested devices. WBANs have become an interesting topic for researchers in many fields due to the rapid developments happening in the internet of things (IoT) research. The applications of WBAN and IoT have wide usages including remote health/fitness monitoring, rehabilitation, military and sports training, active combat operations, livestock farming, interactive gaming, personal information sharing, secure authentication, assisted living, etc. [1], [2]. The number of different types of sensors that are made for IoT applications increases rapidly, making the use of WBAN more cost-effective for many fields. Further, the amount of information that the WBANs provide from people in the field could never be obtained without wireless access. Such information is widely used for monitoring and training people on specific activities. It is obvious that with the increase in WBAN usage, there will be a rise in network issues and these issues need to be addressed to get the maximum use of future WBAN. Since the WBAN generates and transmits personal biological information, the network security requirement is paramount. Other major issues are the power management of the WBAN, developing different sensors with minimum energy usage, and optimizing the network parameters for the best power management. Energy harvesting from the surrounding environment and through human movements is another crucial area of interest in WBAN where researchers have provided many different solutions [3]. Intra and inter WBAN data transmission consumes a considerable amount of

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power and choosing the correct antenna for a specific application is also critical. Antenna designs play a great role in reducing power usage, reducing the channel-loss, and increasing throughput [4]. The flexibility of sensors is another critical issue and therefore developing flexible sensors is another demanding research area [5], [6]. To provide comprehensive knowledge on all the above-mentioned areas of interest, this review paper analyses the commonly used and recently proposed WBAN architectures and communication protocols, antennas for future WBAN, energy harvesting methodologies and energy management schemes, WBAN security issues and authentication strategies, wearable sensors for WBAN, and WBAN applications in different fields.

This review is structured as follows. Section II reviews the WBAN architectures, and standard network topologies, and discusses WBAN communication protocols in detail. Section III discusses the security requirements of the WBAN, security threats and types of attacks, and authentications used in WBAN. Section IV covers the basic antenna types, antenna designs, and flexible antennas for WBAN. Section V reveals new energy harvesting technologies, materials used for energy harvesting, and energy management. Section VI reviews recent developments in wearable sensors and novel materials for developing wearable sensors. Section VII discusses the application areas of WBAN, and the conclusion section summarizes them all with future directions for research.

II. WBAN ARCHITECTURES AND COMMUNICATION PROTOCOLS

There are different WBAN architectures proposed by many different research groups for specific applications. The architecture and communication protocols are application specific for optimizing the performance. Three-tier WBAN architecture is the most common architecture while body-to-body (B2B), machine-to-machine (M2M), and *ad-hoc* type architectures are there. Figure 1. shows an example of the three-tier WBAN architecture used in healthcare systems.

Tier 1 has the sensors including electroencephalography (EEG) sensors, electrocardiography (ECG) sensors, electromyography (EMG) sensors, and peripheral oxygen saturation (SPO2) sensors attached on the body, implanted in the body, or swallowed. This tier is called the intra-WBAN tier where all the communications happen within the WBAN. Tier 2 has external communication gateways such as a mobile phone or a wi-fi router connected to the internet. There may be one WBAN communicating with another WBAN and this is called the inter-WBAN tier, but still categorized under tier 2. The communication between the gateways and end users is categorized as tier 3, commonly known as the beyond-WBAN tier. Cloud computing sits between tiers 2 and 3. There are variants and derivatives of this basic architecture which are discussed in the next section.

A. WBAN ARCHITECTURES

The architectures of WBANs are mostly situation or application dependent. Since the nature of the WBAN and the type of data vary from application to application, the transmission and processing of the sensor data are challenging and some researchers have proposed to have cloud computing integrated into WBAN [7], [8], [9], [10]. The WBAN can be directly connected to the cloud or may use multi-hop method.

Khssibi et al. present a traffic differentiation architecture for WBAN where they proposed an extension to the MAC layer of IEEE 802.15.4 by introducing a differentiation layer [11]. However, their results show a drop in received messages when the node number grows beyond three and further dropped to 40% at eight nodes. Wang et al. proposed a blockchain based eHealthcare WBAN architecture where patients, doctors, medical centers, emergency services, insurance providers, and pharmacies have access to WBAN data [12]. However, in their simulations, they have found that the latency of the transaction process is approximately 2350 ms and it theoretically limits the number of users to 51. This is a major drawback of this architecture for medical WBAN and needs to investigate ways to improve it. Shunmugapriya and Paramasivan suggested a hybrid architecture to address the signal loss within the WBAN [13]. They have made a hybrid of time division multiple access (TDMA) framing and code division multiple access (CDMA) to address the problem. Their results show that the proposed hybrid architecture produces lower packet drop, delay, overhead, and energy consumption against the standard standalone architectures.

Software defined network (SDN) architectures are alternatives for the hard-configured WBAN architectures proposed by many research groups [14], [15], [16], [17], [18]. An SDN architecture proposed by Galal et al. has an SDN enabled nano-network that acts as an interface layer between the sensor devices and the external network/internet [15]. They show the proposed SDN has interoperability, standalone interface capacity, and distributed operation capacity. Bera et al. proposed an SDN for content aware WBAN which focused on both device management and topology management [19]. They have shown that the proposed Soft-WSN has lower message overheads, lower energy consumption, and a higher packet delivery ratio in comparison to the standard WSN.

Fig 2. Illustrates a reconfigurable SDN used in a rescue team environment where the access points on each rescuer gather the medically important data from their own WBAN and sensors attached to the rescued person's body and send them to the ambulance through multi-hop configuration. The team at the ambulance or the base station can manage the entire rescue operation with more accurate resource allocation depending on the real situation. Since the network is SDN and reconfigurable, it can save power just by transmitting to the nearest neighbour closest to the final destination (ambulance) rather than all nodes communicating directly with the base station. reconfigurable SDN approach has a wide variety of usages ranging from team sports to military combat operations.

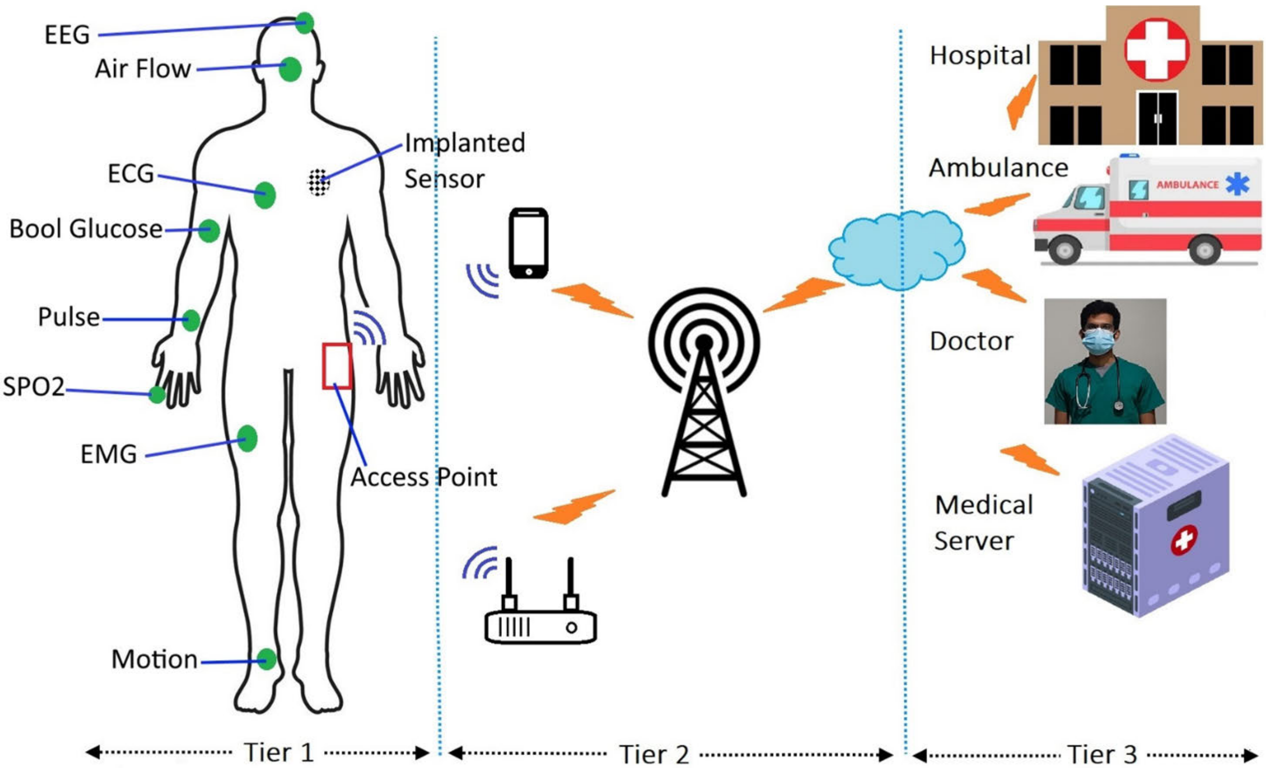

FIGURE 1. Reconfigurable SDN-WBAN architecture.

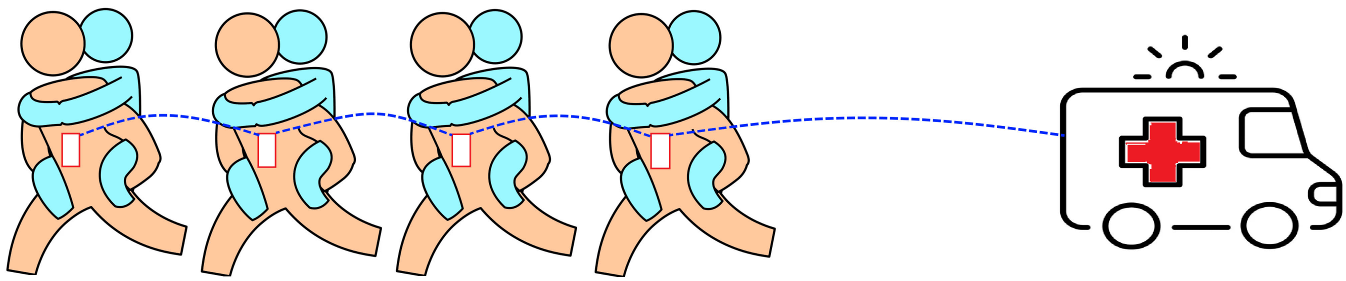

FIGURE 2. Reconfigurable SDN-WBAN architecture *'Rescue Team.'*

B. WBAN TOPOLOGIES

WBANs have four common network topologies as shown in Fig.3, where the star topology has equal access levels for all peripheral sensor nodes to the access point or the central node. This is preferred when the sensor nodes do not need to communicate with each other. In case one sensor node needs to talk to another node, it must go through the central node. In contrast, the mesh topology provides all sensor nodes the same level of access rights as in star topology and each sensor node can talk to the other sensor nodes individually. However, this comes with the cost of high signal collision probability and therefore may cause delays in successful data transmission. Therefore, the fully meshed network topology is not used unless it is essential for a particular application. The tree network topology has different priority levels for different sensors and the number of hops needed to access the central node is also dependent on how they are configured. Sensor-to-sensor communication in a tree network always needs more than one hop unless it is between parent and child nodes. The hybrid topology has all the above-mentioned configurations within it dependent on the configuration and this is the most common WBAN configuration used in the field when the sensor node number grows.

C. WBAN COMMUNICATION PROTOCOLS

IEEE has derived several network standards related to WBANs. The first one was IEEE 802.15.1 developed in 2002 for Wireless Personal Area Network (WPAN) which was based on Bluetooth. It defined the physical layer (PHY) and the media. IEEE 802.15.4 low rate WPAN was also introduced in 2003 for longer battery access control (MAC) layer specifications for fixed and mobile WPAN [20]. Later IEEE 802.15.2 was developed as a coexisting network and IEEE 802.15.3 was developed as the high rate WPAN in 2003 life

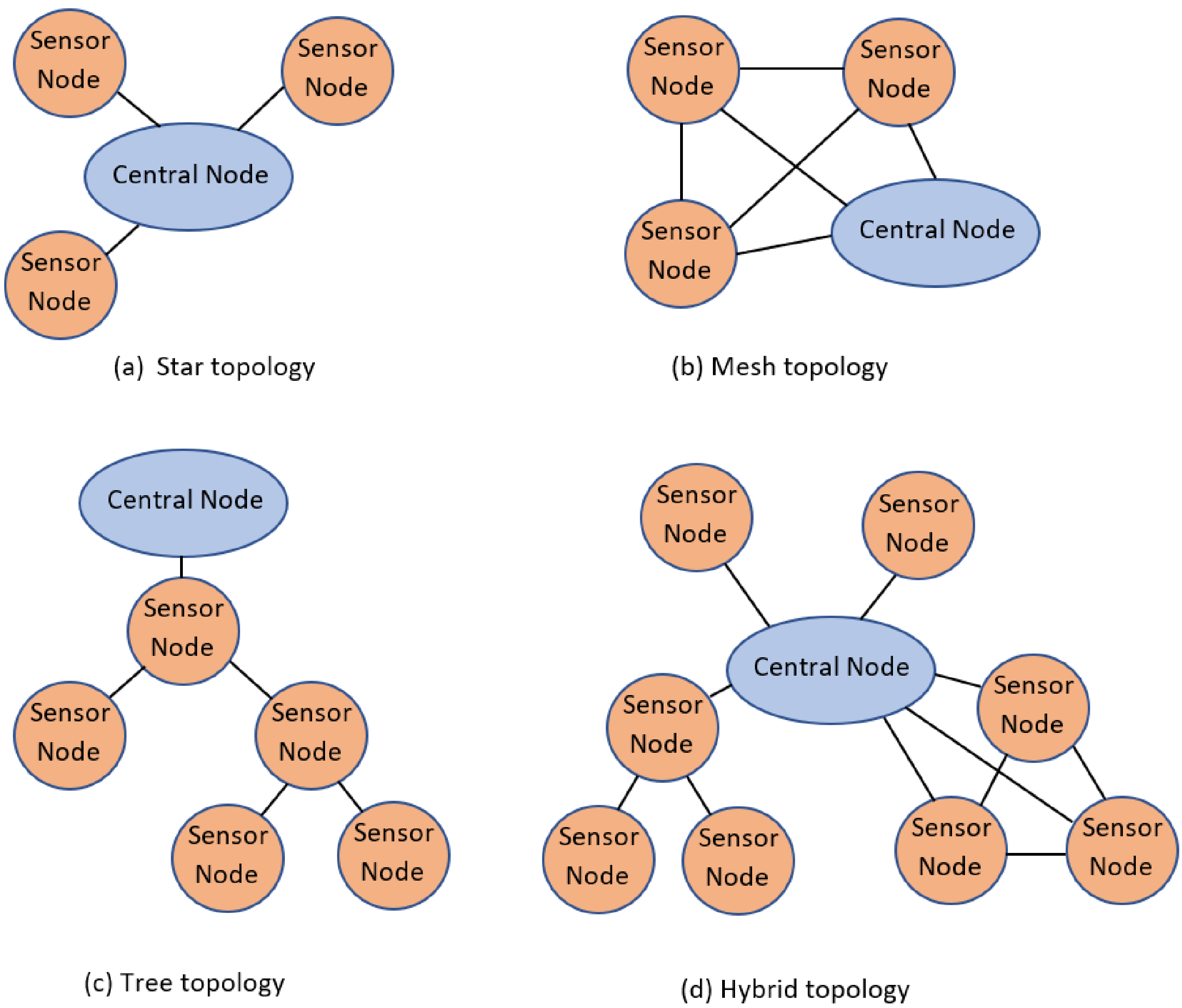

FIGURE 3. **Reconfigurable SDN-WBAN architecture *'Rescue Team.'***

networks and had a couple of amendments thereafter to accommodate different country-specific regulatory changes. IEEE 802.15.5 is the standard provided for interoperable, scalable, and stable WPANs. The IEEE 802.15.6 standard was specifically developed for WBAN. The body area network node locations have three major zones namely, implant, on the surface, and external where the external devices can operate from a maximum of 5 m away from the body. Dependent on the scenario of transmission, the channel models (CMs) and frequency bands have been allocated as follows [21].

There are different design and implementation challenges associated with WBAN. Pramanic et al. have summarized them as shown in Table 2 [22].

The MAC layer has the most challenges associated with it, while the network layer and physical layer follow in terms of challenges. Olatinwo et al. have reviewed recent research to achieve efficient MAC protocols for WBAN [23]. There they have discussed the WBAN MAC layer requirements and improvements suggested by various research groups.

Different research groups have tried to address the issues listed in Table 2 at different layers in different ways. Channel bonding and dynamic channel allocation are two techniques adopted by various research groups to improve the network performance [24], [25], [26], [27], [28]. Channel bonding has been utilized in wireless sensor networks for a long time, which was first introduced in IEEE 802.11n protocol combining 20 MHz from the main channel with 20 MHz from an adjacent channel. IEEE 802.11ac can combine the main channel with additional four or eight adjacent channels of 20 MHz each. Kim et al. has developed a non-structured Markov chain model for testing IEEE 802.11ac networks and shown that the process of channel bonding can be divided into static channel bonding and dynamic channel bonding [28]. Sun et al. proposed an on-demand channel bonding scheme based on outage probability [25]. They have tested their

TABLE 1. Channel model and frequency band allocation for different situations [21].

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

TABLE 2. Designing and implementation challenges in different layers of WBAN protocols [22].

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

proposed algorithm in IEEE 802.11 ac/ah networks but state that it can be tried in IEEE 802.15.6 frequency band as well. Kim et al. have proposed an analytical model for throughput estimation of IEEE 802.11ac networks [28]. However, there are not many reported works on channel bonding for WBAN and the opportunity for further investigation exists. Niaz et al. presented a traffic load aware bonded channel algorithm (TLA-BCA) and they have shown that their model produces an end-to-end delay of 2.151 s for a 12 node network against a delay of 2.585 s for traffic priority based channel assignment Technique (TP-CAT) network and a delay of 2.796 s for static channel assignment (SCA) network with the same number of nodes [24].

III. SECURITY AND AUTHENTICATION

Network security is the utmost important thing when it comes to WBAN as all data from individuals have a lot of confidential personal information. Unlawful or unauthorized access should not be allowed and therefore network security plays a key role in network design. Some networks use end to end encryption while others use different authentication mechanisms to reach the level of security required. Al-Janabi et al. have summarized security threats and measures taken in the WBANs used in healthcare networks [29]. Data confidentiality, data integrity, and data availability are three major requirements in WBANs used in healthcare applications [30], [31]. Data authentication, data freshness, secure management, accountability, flexibility, privacy rules and compliance requirements, anonymity, and revocability are some of the other key requirements commonly appear in WBAN security schemes [29], [32].

A. SECURITY REQUIREMENTS

The key data security requirements of WBAN can be categorized into four levels as data acquisition level requirements, data transmission level requirements, data storage level requirements, and access level requirements. Implementing all requirements at all four levels makes the network throughput lower as it needs so many additional frames to be transmitted or encryption/decryption operations take place at every level. To optimize data security and network performance, one must balance the security requirement implementation at each level. Data confidentiality, data integrity, and revocability requirements need to be implemented at all four levels while other requirements can be implemented at different levels as shown in table 3.

B. SECURITY THREATS AND ATTACKS

Security breaches in WBAN can happen at the physical level, communication level, or data storage and processing

TABLE 3. Security requirements at different levels of a WBAN.

Security requirement	Description	Data gathering level	Data transmission level	Data storage level	Data access level
Data confidentiality	The data should not be available to any unauthorized parties at any level.	✓	✓	✓	✓
Data integrity	The data should not be altered or artificially generated by intruders.	✓	✓	✓	✓
Data availability	The data should be readily available for authorised end user with efficient access.			✓	✓
Data authentication	Authentication of nodes is needed to establish data authentication during the transmission and receive operations.		✓	✓	✓
User authentication	Authentication of users is needed to ensure the data authenticity at storage and access levels.			✓	✓
Forward security	Already transmitted data until a security breach should still be secured even if a nodes long-term key is compromised.		✓	✓	✓
Data freshness	Data capture and retransmission as new data by unauthorised parties can be prevented by data freshness techniques.		✓	✓	
Data accountability	Those who access data in storage are accountable for secure and ethical use of data.			✓	✓
Flexibility	The ability to grant emergency crew access to the WBAN as necessary.		✓	✓	✓
Secured data management	Manage the stored data securely and limit the access to the database only for authorized users.			✓	✓
Privacy rules and compliance	Comply with the privacy and compliance regulations of state or government where the WBAN operates.			✓	✓
Anonymity	Separate user identification from data and save them under high level of encryption.		✓	✓	✓
Revocability	The ability to revoke the accessibility permission of a user or a sensor node as soon as they are found to be compromised.	✓	✓	✓	✓

level [33]. Physical level security breaches are rare and easy to detect as they happen between the sensor and the transponder/transmitter to access the raw data. Therefore, physical level access is needed for the intruders and this type of security threat can easily be avoided through properly developed physical access control protocols within the operation cycle of the WBAN. One of the common security threats is *jamming* or radio frequency interfering where the attacker can disturb the spectrum that the WBAN uses by continuously transmitting powerful signals [29]. This may either retard or completely block the WBAN from accessing tier 1 and 2 devices. It also can send intermittent jamming signals to interrupt the network intermittently where partial data may be lost depending on the way the data validation has been set up. Denial of service (DoS) is another type of attack where the attacker can block a particular sensor or a group of sensors by jamming or *flooding* interference signals [30]. Frequency hopping (FH) is the traditional solution for jamming attacks. However, with the requirement to prior-share the channel codes in order to hop the channels, there is a risk of an attacker acquiring the information and easily hopping the channels accordingly. Gopalakrishnan and Bhagyaveni proposed a chaotic frequency hopping (CFH) to solve this problem and have demonstrated the percentage error reduction of 55.03% and 84.24% for FH and CFH respectively for the same reactive jamming period [34]. DoS can take place in Tier 1, 2, or 3 but there are different strategies the attacker uses in each tier. A sinkhole attack is a special form of DoS attack where the attacker invites all traffic to go through a specific node pretending that it is the shortest route to the sink node which is the legitimate node for external connection [35]. This provides an opportunity for other types of attacks such as grey hole or black hole attacks. Another type of common attack is *data sniffing* or *eavesdropping* where the attacker receives a copy of transmitted data between a sensor and a node or between nodes [32]. This is a passive attack where the WBAN users or administrators may not notice that the transmitted data is being sniffed by an attacker and is therefore hard to rectify unless a key security management scheme was implemented [31]. Data tampering is another common type of security threat that occurs in WBAN and this can happen in any of the three tiers. Data tampering can be done by transmitting pseudo data or retransmitting old data. This can lead to DoS if that happened at a high data rate as the node device memory overflows [29]. Node replication is a kind of security threat if the credentials of a node are compromised [32]. Data tampering can also happen at the tier 3 network level where the end-user level security is compromised [31]. All these security threats may come from external parties however, data tampering may come from internal parties who have legitimate access as well, which may take time to detect.

C. AUTHENTICATION SYSTEMS

Authentication is the common way to prevent unauthorized access to the WBAN at any level, where it can be based on passwords, physical identification or biometrics, cryptography, channel, or proximity [32], [33]. Biometrics may deal with facial recognition, fingerprint, retinal pattern recognition, and voice recognition etc. The cryptographic authentications that use secret keys are categorized as symmetric cryptography while the authentication systems that use public keys are categorized as asymmetric key cryptography and hash functions [36]. Malviya et al. showed that symmetric cryptosystems provide perfect security when the probability distribution of the ciphertext space is uniform for any probability distribution of plaintext space under the assumption that key-space is uniform [37]. There are symmetric/asymmetric systems suggested by some other researchers for some other usages of WANs, but not commonly used in WBANs [38]. RSA cryptography is a widely used public-key cryptography method for data transmission where it was named after the inventors' names. RSA uses extremely large unknown prime numbers and therefore it is extremely difficult to guess and consumes a very long time [39]. Xiong et al. proposed a heterogeneous signcryption scheme for WBANs to work from identity-based-cryptosystems(IBC) to public key infrastructures(PKI) and equality test [40]. The proposed system allows sensitive biological data captured by body area sensors to signcrypt with public key and upload to a cloud server. Then the uploaded data can be subjected to equality test at the cloud server to check whether they contain identical plain text data.

Fotouhi et al. propose a two-factor authentication scheme where a single time password is issued to a registered user device to confirm that the intended user is the same as who holds the secondary device such as mobile phones of the registered users [41]. They designed an authentication system where the user selects an identity and a password as the first factor and save them on a mobile device as the second factor. In addition, they use Real-or-Random (ROR) model for security. This combination makes it slower than direct authentication despite the higher degree of security proposed. Rangwani and Om have done a cryptanalysis and found that the Fotouhi et al.'s method suffers from numerous attacks including privileged insider attacks, denial of service attacks, sensor node capture attacks, replay attacks, stolen verifier attacks etc. [42]. In contrast, they have proposed a four-factor authentication scheme suitable for real-life WBANs.

Blockchain based authentication is another way of establishing network security but, this time without pre agreed authentication keys. There are many different approaches by various research groups to establish blockchain based security systems for WBANS [12], [43], [44], [45], [46], [47]. Kumari et al. proposed a blockchain for the connection between the wireless master device of the WBAN and the gateway of the health database, but they need to have another authentication method for tier 1 devices [46]. Hassan et al. proposed a secure data sharing framework for SDN based WBANs where the blockchain is implemented on the data storage and user access level [45] while row data transmission between the tier 1 devices and the off chain data storage need to be protected using different security mechanisms. Wang et al. have proposed a blockchain based secured architecture for eHealth applications to work in collaboration with the body area network, however, their network can have a user number limitation which makes it unsuitable for large medical center applications [12]. Sharmila and Jaisankar proposed an edge intelligent agent-assisted hierarchical blockchain system for 5G based WBAN IoT [44]. They have used a combination of private and public key generation in their scheme and the success rate of packet transfer has increased to 92% in comparison to 88% in a private blockchain. The network throughput has increased by 50% compared to prioritized MAC scheduling. They also claim that the proposed edge intelligent agent-assisted system can protect the network against flooding, impersonation, DoS, and on-off attacks where most of the other types of security schemes cannot. Son et al. presented a design of a secure authentication protocol for cloud-based telecare system [47]. They claim that their protocol could tackle most of the common security threats. Mwitende et al. have used a certificateless authenticated key agreement method for the body area network and claimed that it does not suffer from key escrows commonly found in identity-based systems [43]. In general, these blockchain based security systems are computation intensive and therefore cannot be implemented in tier 1 of the WBAN where most of these networks use IEEE 802.15.6 protocol.

IV. ANTENNAS FOR WBAN

RF antenna is an essential and critically important part of the WBANs where the antenna design plays a major role in transmission range, energy efficiency, cross band interference, antenna directivity, radiation pattern etc. There are many different types of antennas developed for WBAN in the past, but they are still being improved, redesigned, and newly designed to address demands from the industry. Ultra-wideband (UWB) antennas have gained attraction in WBANs due to the varying frequency requirements employed by the sensor nodes associated in them [48]. Most of the antennas used are linearly polarized and they may be polarized vertically, horizontally, or inclined. Some others are circularly polarized. Designing of antenna for WBAN transmissions is extremely challenging as its characteristics are modified when an ordinary antenna touches the human body due to the permittivity and permeability changes w.r.t free air. Therefore, these parameters need to be taken into consideration in the WBAN antenna design. We can see most of the designed antennas demonstrate a significant drop in radiation efficiency in the presence of the human body or a phantom.

A. LINEARLY POLARIZED ANTENNA

Linear polarization is the most common type of polarization used in conventional antenna design and is still widely used. The standard monopole antenna is a typical example of this, and it can be oriented to have vertical, horizontal, or inclined polarization. However, the conventional type monopole antenna is not convenient for the user to wear in a WBAN node and therefore many researchers have developed planar linearly polarized antennas to address this issue [48], [49], [50], [51], [52], [53], [54], [55], [56]. However, single-sided planar monopole antennas for WBAN suffer from the drawback of not providing conductive shielding on its backplane and hence the characteristics change when it touched the human body [57]. In response to this, some designers have introduced back-plane shielding or a ground plane on the back of the substrate.

Gupta et al. have designed a planar antenna to operate on the industrial, scientific and medical (ISM) bands which can transmit at 5.0 GHz and receive at 2.45 GHz [52]. They have measured the radiation efficiency of the antenna in free-air and on a tissue phantom and shown that it has dropped from 90% for free-air to 24% for an on-tissue phantom with a gap of 3 mm. When the antenna was directly on the tissue phantom it dropped further 15% and 35% at lower and upper resonance frequencies, respectively. However, this antenna is a good choice for close-proximity applications in WBAN. Chaturvedi and Raghavan have designed a substrate integrated waveguide (SIW) antenna for the same ISM band where they used the half-mode design strategy for their design [49]. Their free-air resonance frequency is 5.89 GHz with an on-body gain of 5.25 dBi. The simulated free-air radiation efficiency of 83% dropped to 69% when tested on a pork tissue sample, which is still a promising value for WBAN applications. The pork tissue has caused only a minor frequency change of 0.5% compared to a free-air resonance frequency in the range of 5.71 – 5.93 GHz, which covers the entire 5 GHz ISM range of 5.725 - 5.825 GHz. Gupta et al., in another work of theirs, developed an L-shaped radiator and ground on one side of the antenna substrate and added a conducting reflector to the other side of the substrate. This antenna has a dual-band capacity where the resonance frequencies are 2.45 GHz and 5.8 GHz [51]. The radiation efficiencies are 50% and 32% at 2.45 GHz and 5.8 GHz respectively. The size of the antenna is 30 × 31 mm^2 with a substrate thickness of 6.48 mm. This design illustrates unidirectional radiation, and it is suitable for WBAN applications. Farahat and Hussein have developed a dual-band dual-mode monopole spiral antenna transmitting at 5.8 GHz and receiving at 2.45 GHz [53]. The size of the antenna is 12 × 12 mm^2 and a height of 8.5 mm where the gains at lower and upper frequencies are 4.9 dBi and 7.1 dBi respectively. The antenna efficiencies at lower and upper resonant frequencies are 83% and 88% respectively. This antenna has shown that it can work as an on-body antenna to communicate with biosensors and communicate with the base-station as an off-body antenna. Rano and Hashimi have proposed an interesting planar antenna design using modified interdigitate electrodes (IDEs) [54]. The modified IDE structure has the ends of the parallel segments connected to form a cascaded structure and the two ends were connected to the long side-conductors. They have used two of these structures as patch and a strip of copper in the middle on the other side as ground. In another design, they used a copper plane as a planar monopole separated by the substrate on top of the previous design. They have shown through their experiments that one can vary the geometric parameters such as the gap between IDE lines or the number of IDE lines to obtain the resonating frequency of the device around 2.5 GHz. Mallat and Iqbal have proposed a waveguide-fed full-duplex antenna that can work at 4.9 GHz and 5.8 GHz compatible with both WBAN and SIW [56]. The designed antenna is 52 × 63 × 17 mm^3 in size and provided gains of 4.93 dBi and 5.97 dBi at lower and upper resonating frequencies. Since this is a full-duplex antenna, it can be used as a transmitting and receiving antenna for WBAN applications. S. Mirhadi presented a design of a single-layer circular, dual-mode, dual-port antenna for WBAN communications [55]. This antenna has a resonance frequency of 5.8 GHz and radiation efficiencies of 92% and 94% for port 1 and port 2, respectively. The gains reported are 0.5 dBi and 3.9 dBi for port 1 and port 2 while the port isolation is 26.5 dB. The antenna dimensions are $0.96\lambda_0 \times 0.96\lambda_0 \times 0.03\lambda_0$, where λ_0 is the design frequency of 5.8 GHz.

Koohestani et al. proposed a vertically polarized ultra-wideband (UWB) low-profile conical antenna suitable for WBAN [48]. The overall height of the conical antenna was 8.5 mm and therefore it can be used for on and off-body communication purposes in WBAN. The measured bandwidth of the antenna is nearly 9 GHz (3.06 – 12 GHz) however, they have not tested it on a human body or a suitable phantom. The radiation efficiency for the whole frequency range is more than 95%. Another UWB antenna has been developed by Das and Rawat for Terra hertz range [50]. This antenna can operate in the range of 299 GHz to 19.602 THz with a maximum gain of 21.62 dB at 12.08 THz. This is a very compact antenna with outside dimensions of 600 ×600 μm.

B. CIRCULARLY POLARIZED ANTENNA

Circularly polarized (CP) antennas have certain advantages over linearly polarized antennas for different applications. Especially, they are very effective in reducing multi-path interferences or fading effects [58]. The reflected RF signals from the ground for left-hand circularly polarized (LHCP) signals become right-hand circularly polarized (RHCP) signals, thus minimizing the effect of odd-numbered reflected signals. Another advantage of them is that they do not require a particular orientation of the transmitting and receiving antennas, which becomes very useful in WBANs. There are further advantages such as their inherent ability to reduce the *Faraday Rotation* effect, but this does not apply to WBAN. Meher et al. have done a very good review on circularly polarized dielectric resonator antenna design and development over last the three decades where they covered CP antenna for a variety of applications [59]. In this review, we focused on the CP antenna designs for WBAN applications within the last few years to give a more focused and contemporary review to the reader. Anirban Karmakar has another review on fractal antennas where they have summarized many different designs with their advantages and disadvantages [60].

Liu et al. have developed an Archimedean spiral antenna with circular polarization for a wideband range of 1.7 GHz to 5GHz with the measured antenna efficiency greater than 60% for the entire frequency range [61]. Though they have not tested it for body area transmission using phantoms, the principle of the design can easily be adapted for developing WBAN antennas. The size of the antenna is $65 \times 65 \times 50$ mm^3 and that need to be modified to suit the application if used for WBAN. Tiwari et al. have presented a multi-input multi-output printed antenna for wideband applications [62]. They have introduced a stub loaded ground plane to achieve impedance matching and introduced ring slots to the ground plane reducing the cross-polarization. Their antenna has a size of $0.24\lambda \times 0.24\lambda$ where λ is the lower edge frequency wavelength and the displayed axial ratio bandwidth of the antenna is 3.04 GHz to 8.11 GHz (90.94%). This antenna is truly a wide band antenna and capable of working in the WBAN band if the antenna parameters were adjusted accordingly. However, it needs to be tested for placing on the human body to determine the actual suitability. Sing and Verma proposed a CP antenna with a bowtie slot on a planar structure for 4.1 GHz to 6.7 GHz band and it displayed a 3-dB axial ratio bandwidth of 48.14% in that band [63]. When tested on the human chest and on a human arm, it reduced the upper cutoff frequency to 6.4 GHz and 6.3 GHz respectively. Similarly, the lower-end cutoff frequency shifted from 4.1 GHz to 4.3 GHz. Meher et al. have developed a compact and circularly polarized monopole antenna with a slightly bent perpendicular ground plane and a dielectric resonator parallel to the monopole in their recent work [64]. This antenna showed an axial ratio bandwidth of 6.22 GHz to 7.33 GHz for free air, 6.21 GHz to 7.22 GHz on the body, and 6.20 GHz to 7.28 GHz on the phantom. The phantom they used had an 80 mm $\times$ 80 mm cross section and three layers of skin, fat, and muscle at depths of 1 mm, 2 mm, and 10 mm with relative permittivity (ϵ_r) of 34.34, 4.87, and 47.2. These layers were replaced by a single layer of the same cross section area and 19.9 mm depth with relative permittivity (ϵ_r) of 19.9 for the measurements. It has shown an LHCP process and the measured axial bandwidth of 6.22 GHz to 7.23 GHz with an efficiency of 85% and a gain of 7.5 dBi.

Another class of CP antenna specifically designed for wearable devices have been presented by different research groups [65], [66], [67], [68], [69]. Pathan and Karn have designed a flexible antenna printed on fabric with dimensions of $22 \times 22 \times 1.6$ mm^3 using a fabric of (ϵ_r) of 1.6 for 2.45 GHz frequency applications in WBAN [65]. The antenna has a total bandwidth of 140 MHz with an axial bandwidth of 80 MHz around the designed frequency of 2.45 GHz. Vaezi et al. have developed a $20 \times 2.7 \times 0.1$ mm^3 antenna with more than 75% measured bandwidth around the design frequency of 2.4 GHz for medical body area networks (MBANs) [66]. This bowtie antenna on a phantom has produced an operating range of 1.5 to 3.5 GHz and it has shown

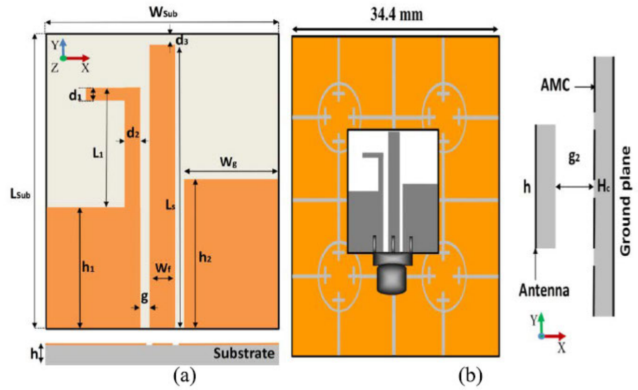

FIGURE 4. **(a) 2-D diagrams of the planar antenna designed (b) integrated design layout with artificial magnetic conductors (AMC) [67].** ***(Reproduced under creative commons license CC BY 4.0).***

measured efficiencies of 87% and 79% making it suitable for free air and on phantom respectively proving that it is suitable for MBAN applications. Chaouche et al. have developed a wearable CP antenna with a design frequency of 5.8 GHz for WBAN applications [67]. They have used a 0.58 mm thick semi-flexible substrate with (ϵ_r) of 2.2 for the fabrication of their antenna and the design is shown in figure 4 (a) and (b). The designed antenna has demonstrated an efficiency of 94.7% and a peak gain of 7.6 dBi on the human body, which are promising performances for a wearable antenna. Though they claimed it as a wearable antenna, the actual dimensions of 34.4×34.4 mm^2 may restrict its applications in WBANs. Illahi et al. have proposed a wearable CP antenna that has a dielectric reflector to make it circularly polarized [68]. Their dielectric reflector has the dimensions of $15 \times 12 \times 8$ mm^3 and larger flexible ground planes (50×50 mm^2 to 80×80 mm^2) and they have placed the antenna 10 mm away from the phantom in their measurements to simulate the feeding network. They have obtained $|S_{11}| \leq -10dB$ bandwidth of 6.96 GHz to 8.68 GHz and an axial bandwidth of 7.47 GHz to 8.25 GHz. Saleh et al. have presented a switchable frequency wearable antenna for WBAN applications [69]. It can be set to one of the frequencies in the range of 1.57 GHz to 2.55 GHz (1.57, 1.67, 1.68, 2.43, 2.50, or 2.55 GHz) depending on the application requirement. The switches employed here are RF PIN diodes which will provide different slot lengths on the backplane to change the antenna design frequency. This antenna has the ability to reconfigure its polarization as well to make it an LP or LHCP antenna.

C. FRACTAL ANTENNA

Fractal geometry was formally presented to the world in graphical form using computer graphics by Benoit Mandelbrot based on Mandelbrot set in the early 1980s [70]. However, his mathematical set is based on Julia set and other multiple mathematical sets presented by a number of mathematicians in the past including Waclaw Sierpinski (1882–1969), Niels Fabian Helge von Koch (1870–1924), David Hilbert (1862–1943), Georg Ferdinand Ludwig Philipp Cantor (1845–1918), Hermann Minkowski

(1864–1909), and Giuseppe Peano (1858–1932) [71]. Researchers have used fractal geometrical shapes as building blocks to develop planar antennas for various applications [72], [73], [74], [75], [76], [77], [78], [79]. Figure 5 shows some of the common building blocks of fractal antenna designs.

Tripathi et al. have proposed a Koch fractal geometry-based antenna for WBAN applications where they have used a skin, fat, muscle, and bone model with of (ϵ_r) 33.6, 4.8, 46.2, and 8.9 with thickness parameters of 1.7 mm, 8 mm, 10 mm, and 3.3 mm respectively for their simulations and actual measurements [73]. They have used Koch fractal geometry in the ground plane as well and reported that it helped to achieve an operational bandwidth (where $S_{11} < 10$ dB) of 122% with a stable radiation pattern. Goswami and Goswami have developed a truncated T-parasite staircase-shaped fractal antenna for IoT use [79]. The antenna has three design frequencies of 2.4, 5, and 9.55 GHz and depicts an ultra-wideband operation. The size of the antenna is $12 \times 18 \times 1.6$ mm^3 and can be used for WBAN applications. In another work by the same authors, they have presented a corner truncated fractal slot antenna that covers the frequency range of 0.75 – 12 GHz [72]. The antenna comprises of a fractal slot patch and an electromagnetic bandgap ground (EBG) with the same dimensions as of the previously mentioned work of their own. The average gain reported for this antenna is 2.51 dBi. Karimbu Vallappil et al. have proposed a Minkowski-Sierpinski fractal antenna for WBAN and displayed resonance frequencies of 4.17 GHz and 5.97 GHz with bandwidths of 120 MHz and 160 MHz respectively [76]. The gains at these frequencies were reported as 0.4 dBi and 6.2 dBi respectively. However, this has not been tested on the human body or a phantom for real-world applications. Oaraizi and Hedayati have developed a miniaturized antenna by combining Giusepe Peano and Sierpinski Carpet Fractals where they have reported a bandwidth of 1 to 15 GHz which essentially covers part of the WBAN range [77].

D. FLEXIBLE AND WEARABLE ANTENNA

The WBAN applications become more common in healthcare, sports, military, space, and industrial applications, and therefore it becomes essential to develop flexible antennas facilitating the undisturbed use of these networks by the end users. Researchers have addressed this requirement from many different angles and have come up with different solutions [80], [81], [82], [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93].

Cui et al. have presented a flexible antenna fabricated on textiles with Rogers 4350 based substrate mounted thin copper sheet of 8.5 mm $\times$ 30 mm and two hairpin resonators [80]. This unique design has revealed that it operates between 5.08 GHz and 5.96 GHz with a minimum gain of 5 dBi. They have tested the developed antenna on the human body under different situations and reported that it is very stable against the curvature of the body. Another antenna fabricated on a flexible Roger substrate is reported by Wang et al. where they have developed a double-layer Alford loop antenna on a circular substrate. The developed antenna has shown dual operating frequencies of 2.45 GHz and 5.8 GHz where the measured peak gains were 6.1 dBi and 2.2 dBi and measured impedance bandwidths were 14.1% and 6.7% at 2.45 GHz and 5.8 GHz respectively. They have presented the performance of the antenna under bent conditions and showed very good resonance characteristics from a flat surface to a curvature of 25 mm radius surface. They also tested it on different places on the human body to verify the characteristics. Tong et al. have presented a reconfigurable wearable repeater antenna for WBAN applications [82]. The measured resonance frequency of the repeater antenna was 2.45 GHz for on/off body modes where the gains were 1.2 dBi and 5.4 dBi for on-body and off-body modes respectively. The repeater mode resonance frequency was 403 MHz, which is compatible with the implantable medical devices as most of the implantable devices operate in the medical implantable communication service (IMCS) band of 402 - 405 MHz. Therefore, this is a good candidate for most of the WBAN applications. Mashagba et al. proposed a hybrid mutual coupling reduction technique using a flexible antenna fabricated on textile for WBAN and 5G applications [83]. This proposed multiple input multiple output (MIMO) antenna has dual frequencies 2.45 GHz and 3.5 GHz with measured radiation efficiencies of 30.5% and 49.5% where the realized gains were 1.5 dBi and 5.9 dBi respectively. This antenna also showed that the resonance frequencies were slightly lowered when bent along either x-axis or y-axis, but still within the WBAN bandwidth for transmitting and receiving. Ramanujam and Perumalsamy reported a quasi Yagi-Uda antenna developed on flexible polyimide substrate operates at 2.45 GHz [85]. The designed antenna has dimensions of 42 $\times$ 36 mm and the thickness is 50 μm. The minimum apparent diversity gain reported is 7.2 dB and the bandwidth is 2.38 – 2.52 GHz with a peak gain of 4 dBi. They have tested the antenna prototype on the human body and shown that the proposed antenna exhibits frequency responses under bending and severe crumpling. Le and Yun have presented a dual band antenna fabricated on a semi-flexible substrate with resonance frequencies of 2.45 GHz and 5.85 GHz with a maximum gain of 2.1 dBi and 3.5 dBi respectively [90]. They tested their antenna on curved surfaces with radii of 20 mm, 40 mm, and 60 mm in both x and y directions and reported that the higher resonating frequency was more sensitive to the curvature of the antenna. Yin et al. have proposed a wearable button antenna for WBAN applications with an omnidirectional radiation pattern at 2.45 GHZ and a gain of 2.2 dBi [93]. More interestingly the same antenna displays a cross polarized pattern and operates in the range of 5.72 to 7.85 GHz with a maximum gain of 9.4 dBiC. The antenna dimensions were 18 mm $\times$ 10 mm and a could easily be placed on the human body as it has a cloth-based ground. All the above-listed antennas can work as wearable antennas for WBAN applications and have their own advantages and disadvantages.

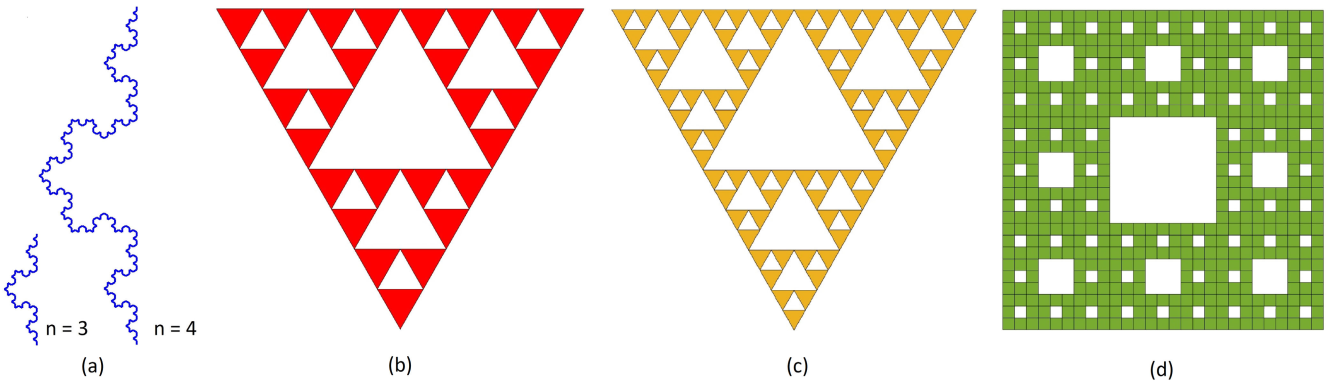

FIGURE 5. Figure 5. Common fractal antenna designs (a) Koch curves for n = 3 and n = 4 (b) Sierpinski Gasket for n = 3 (c) Sierpinski Gasket for n = 4 and (d) Sierpinski Carpet for n = 3.

V. ENERGY HARVESTING AND ENERGY MANAGEMENT

One of the critical problems in WBAN is the energy for the network nodes and sensors to work in the field. Especially, when the people wearing the sensors are engaged in intense activities such as sports, military, or rescue operations, having a battery with a large form factor may decrease their performance and changing the batteries frequently may disrupt their activities. Therefore, a sustainable solution to this problem is essential. Researchers have proposed multiple options, but they can be categorized into two main streams namely, energy harvesting and energy management. Centralized energy harvesting at the network level or nanoscale energy harvesting at the sensor level can be seen in literature, where the main methods used for energy harvesting are photovoltaic, thermoelectric, piezoelectric, radio frequency, and triboelectric [94], [95], [96], [97], [98], [99], [100].

A. ENERGY HARVESTING METHODS

Photovoltaic energy harvesters are the simplest type of energy generators that can be implemented with current efficient silicon solar cells for outdoor usage whereas the flexible conducting polymer based solar cells are much suited for indoor or low light environments. Normally, maximum power point tracking (MPPT) is employed in solar power generation, but at the scale of WBAN implementation it is difficult and, in most cases, inefficient to employ such a technique in WBAN applications as the energy harvesters are placed on the human body in motion. Thermoelectric nano generators (TENG) are another type of energy generating device that works on the Peltier-Seebeck effect. However, the difference between the body temperature and the environmental temperature may not be sufficient to generate a high voltage, and therefore we need to use suitable material and configure multiple TENGs carefully. There are conducting polymer-based TENGs developed by different research groups. Xu et al. have proposed a poly(3,4-ethylenedioxithiophene):poly(styrenesulfonate) (PEDOT:PSS) based TENG [101]. They have treated PEDOT:PSS with formamide (CH_3NO), concentrated sulfuric acid (H_2SO_4), and sodium borohydride ($NaBH_4$) to obtain a flexible PEDOT:PSS thermoelectric films, which resulted in a power density of 141 $\mu Wm^{-1}K^{-2}$ at 25 °C.The TENG they have developed has produced $\sim$ 1 μWcm^{-2} on human arm. Pan et al. have presented another PEDOT:PSS based TENG [102]. They have optimized the performance of PEDOT:PSS strings by solvent treatment with different solvents and obtained an optimum power density of 9.42 $\mu Wm^{-1}K^{-2}$. Kang et al. have analyzed a range of conjugated polymer materials for their suitability as the base material for TENGs and have come up with the conclusion that the conjugated polymers such as poly(3-hexyl- thiophene) (P3HT), doped by solid-state diffusion of 2,3,5,6-tetrafluoro-7,7,8,8-tetracyanoquinodimethane (F4-TCNQ) yield a superior power density [103]. They have attributed it to the controlled solid-state doping of conducting polymers which produced higher intrinsic mobility and higher free career concentration. Nozariasbmarz et al. have used inorganic nano compound $(Bi_xSb_{1-x})_2Te_3$ where the alloys have direct bandgap changes from 0.28 eV to 0.24 eV as x varying from 0 to 1 [104]. Compared to the conducting polymer based TENGs this one has a high output power density of 44 μWcm^{-2} on the human body, but the flexibility is in question.

Triboelectric nanogenerators (TrENG) are commonly used in wearable applications. TrENGs work on the principle of the electric potential generated when two dissimilar surfaces with different electron affinity rub each other. The materials used for TrENG range from natural materials such as cotton, silk, wool etc. to metals such as iron, copper, zinc etc., lead zirconate titanate (PZT), or synthetic materials such as polyamide, polyester, and peptide etc. [105].

Piezoelectric nanogenerators (PENG) are another class of energy harvesters commonly used for wearable devices. He et al. presented a PN junction based piezoelectric [106]. They have made the TENG by spin coating a seed layer of ZnO on the conducting Cu/Ni coated fabric and subsequently chemically growing ZnO nanorods, followed by drop-casting CuSCN layer and finally, coating a layer of PEDOT:PSS on ZnO nanorods. The developed wearable fabric TENG has displayed very good flexibility with a power density of 0.83 μWcm^{-2} at 26 Hz shaking.

B. ENERGY MANAGEMENT

Efficient energy management is the other key point for running WBAN for an extended period with available energy. Behura and Kabat have proposed an optimization-based energy efficient scheme for WBAN [107]. They have made many assumptions and the optimization algorithm either fails or may result in sub-optimized solution if one or more assumptions are not valid for any WBAN. Therefore, the algorithm may need further improvements if adopted for a generic case. There are routing protocol-based energy management approaches as well. Abidi et al. developed an energy efficient cluster-based routing protocol to use in hospital environments where some biosensor data need to be transmitted directly as they come in while some other data may transmit in cluster mode [108]. They have used local data aggregation at the sensor node level to minimize the transmission energy cost for non-time critical data. They have shown through simulation work that their proposed network consumes minimum energy till 60% of the simulation time. Ciciolu and Çalhan proposed an SDN-enabled algorithm to optimize the energy management in WBAN [109]. Their proposed routing protocol used a fuzzy-based Dijkstra technique and the algorithm ensured that the packets reach the gateway using the most suitable paths as per the defined priority levels while maintaining the expected service quality requirements. They have compared their algorithm with Ad hoc On-Demand Distance Vector Routing [110] and SDN Routing [18] and shown that the successful transmission rate of their proposed algorithm is 97%, while the other two were 90% and 94% respectively. Subramanian et al. have proposed a priority based energy efficient MAC protocol for WBAN [111]. They have modified the existing IEEE 802.15.4 header bits to distinguish the level of importance for transmission by predefining the priority levels of nodes. Compared to the baseline and ZigBee MAC protocols the proposed MAC protocol consumes significantly less energy. They have shown that it is less than 90% of the baseline MAC energy consumption.

There are hardware-based energy management schemes proposed by some research groups. Sarma and Biswas proposed a VLSI based adaptive power management scheme for WBAN [112]. Their proposed hardware monitors the battery level and automatically switches between low-power and high-power transmission modes. They have predicted through simulations that at least 98% of transmission power can be saved in the low-power transmission mode over the high-power transmission. This specific method is validated only for ECG signals and therefore the VLSI hardware may need modifications for different WBAN applications.

VI. WEARABLE SENSORS FOR WBAN

The standard industrial sensors may provide accurate information, but the bulky and rigid nature of most of them constrain the movements of the user if integrated into the bodywear for sensing purposes. Therefore, the development of flexible, lightweight, low-power consuming, and small-in-size new sensors is essential for WBAN applications. Selecting or developing suitable material for wearable sensors is a key research area when developing WBAN-focused sensors. Main materials used in wearable sensors include conventional polymers such as polyimide (PI), polyurethane (PU), polyethylene naphthalene (PEN), polyethylene terephthalate (PET), etc., and various conducting polymers including polypyrrole (PPY), polyaniline (PANI), PEDOT, and PEDOT:PSS [113]. Wearable sensors generally fall into four categories based on their principle of operation as electrical, electrochemical, microelectromechanical systems (MEMS), and optical. There is an increase in the tendency of using nanomaterial and nanocomposites for the manufacture of flexible wearable sensors in the recent past.

Human activity monitoring (HAM) sensors have become an essential part in WBAN applications and their flexibility is an inherent property as explained earlier. There is a human activity monitoring WBAN sensors summarized in the literature and they include many different types of sensors [114], [115], [116], [117]. Mukhopadhyay has focused on WBAN sensors in healthcare applications where the WBAN provides temporal information including both the intended movements and unintended movements such as sudden falls etc. of elderly people living in care facilities [114]. The HAM sensors commonly used include oximetry sensors, magnetometers, gyroscopes, accelerometers, electromyography, electrocardiography, bending curvature sensors, GPS sensors, and body temperature sensors [116], [117], [118], [119]. Huang et al. have developed a stretchable adhesive substrate material using a conductive nanogel and a cellulose nanofiber-reinforced conductive nanocomposite [120]. The substrate material showed 2795% of stretchability and a tensile stress of 128.6 kPa while displaying a linear relationship between the percentage resistance change ((ΔR/R)%) and the percentage strain in the range of 0 to 400%. Maddirala et al. have developed a capacitive pressure sensor for detecting human motion and physiological signals [121]. The percentage change in capacitance ((ΔC/C)%) is linear for the applied pressure range of 0 to 100 Pa, and the maximum value of ΔC/C is approximately 8% for roughly 45 μm displacement. However, at lower pressures, it needs to interface with a suitable front-end circuit to measure the very small changes in capacitance [122]. Zhou et al. have presented a nanocomposite based piezoelectro-triboelectric sensor to detect human physiological activities [123]. The main materials they used were copper nanoparticles, multi-wall carbon nanotubes, polyvinylidene Fluoride (PVDF), and an epoxy resin where the fabrication process is lengthy and need to be carried out in the way presented on their paper. They tested the sensor for acceleration from 1 g (gravity) to 1.5 g on a cantilever and showed that the sensitivities are 1.4 V/g and 0.73 V/mm. They have shown that the sensor can accurately measure the moving velocity of humans. Li et al. have used a PVDF substrate to make a piezoelectric motion sensor for WBAN applications [124]. The β phase PVDF/Pt sensor they made has shown a sensitivity of 4.96 V/N for forces less than 0.3 N and 0.94 V/N for 0.3 – 3.8 N with an average response time of 87 ms. All these HAM sensors discussed here are suitable for WBAN applications and more novel sensors are being developed by different research groups.

Wearable humidity sensors are another type of sensor commonly used in WBAN. Park et al. have proposed a poly(ionic liquid) based humidity sensor [125]. This is a semitransparent flexible sensor that can work between 10% – 80% relative humidity (RH) levels with a sensitivity of 1.8 nF/%RH. They have tested the sensor in the temperature range of 20 – 60 °C and frequencies up to 1 MHz showing that the sensor works fine for these conditions. Zhou et al. have summarized wearable sweat sensors from 2010 to 2021 and it provides a wealth of information on research and development during that period. The sensors are mostly electrochemical type of sensors and they measure the variation of resistance or capacitance of a sweat sensitive substrate. Some of these electrochemical sensors use electrochemical impedance spectroscopy (EIS) to determine various parameter changes in sweat during an activity. Wang et al. have presented a human sweat glucose detection sensor using Raman spectroscopy [126]. The same sensor has been demonstrated as a lab-on-glove device for pesticide monitoring. However, its usage in WBAN applications may be expensive or limited to specific applications due to the use of Raman spectroscopy in measurements. Another WBAN wearable sensor application is therapeutic drug monitoring. Raymundo-Pereira et al. have summarized wearable glove-embedded sweat sensors for therapeutic drug monitoring [127]. They have developed a sensor for monitoring uric acid, paracetamol, paroxetine, and ethinylestradiol with the limit of detection (LOD) of 1.37, 0.247, 0.493, and 0.935 μmolL^{-1} respectively.

Graphene is another material used for developing biosensors due to its atomic structure. Recently, the three categories namely graphene (G), graphene oxide (GO), and reduced graphene oxide (rGO) have become equally popular in sensor development. GO can directly be obtained by mechanical or ultrasonic stripping of graphite, while G or rGO can be obtained by controlled reduction of GO [6]. The reason behind the popularity of graphene as a base material for developing sensors is the ability of graphene to respond to many different parameters. For example, graphene has piezoelectric properties, which inherently relate to its mechanical and electrical properties where the capacitance and resistance change with mechanical deformation. Graphene also responds to light signals in the ranges of visible, near-infrared, and infrared, enabling the development of G based photo detectors. Due to the super-high thermal conductivity of graphene (single layer G has a thermal conductivity of 3000 - 5000 Wm^{-1}K^{-1}), G and rGO are ideal candidates for temperature sensor developments. Graphene can easily be made in different geometries, for example, 1D (fibers), 2D (films), or 3D (nanocomposites, nanogels, nanoforms). The above properties of graphene have made significant contributions to flexible wearable sensors for WBAN.

In recent years, (MXene)-based sensors have attracted significant attention as wearable sensors. The term MXene is designed as $M_{n+1}X_nT_n$ (where $_n$ is 1 to 3), where M is transition metals such as V, Ti, Zr, Nb, Cr, Mo, etc., X is Carbon and/or Nitrogen, and T is oxygen, fluorine, or hydroxyl [128]. J. Wang et al. have proposed a ($Ti_3C_2T_x$)-based organohydrogel sensor having self-adhesion property enabling the sensor to be directly applied on human skin for strain sensing [129]. The results demonstrate that the sensor can withstand a 600% strain and provides stable resistance change in response to the strain. They have created a range of sensors with MXenes and one has been used as a heartbeat sensor on a mice and worked at different temperatures ranging from -20 °C to 60 °C. Shu et al. have reported another ($Ti_3C_2T_x$)-based sensor for monitoring pressure and have successfully used it to monitor thermotherapy [130]. All these flexible and wearable sensors discussed in this section are still in the research and development stage. They need to be further optimized for production on a mass scale to be successful in the developing sensor market.

VII. WBAN APPLICATIONS

WBAN has applications in many different areas including health monitoring, assisted living, sports, military activities, rescue operations, occupational health and safety, and security. Karunanithy and Velusamy have proposed an edge device based smart WBAN health monitoring system with efficient data collection for healthcare applications [131]. They have employed minimum edge-shared vertex path selection (MEVPS) to mitigate the network congestion and the ant colony algorithm has been used with the global information of the network to find the possible paths. The EEG data acquired was processed locally to decide whether it is normal data or needs to be transmitted to the base station for further processing. This way it can significantly reduce the amount of data transmitted to the base station and thus the network traffic. Aghababaei et al. have presented a WBAN application to detect epileptic seizures from compressively sensed EEG signals [132]. Compressed sensing is a near-lossless data compression technique, and it has been implemented here to reduce the network traffic and reconstructed original signal at the server is compared with EEG databases to detect epileptic seizures. This kind of WBAN is an effective mechanism to detect and attend to epileptic patients when they have a seizure while in normal activities.

Correct human body motion and posture are critical in some occupations, particularly when dealing with heavy weights to avoid workplace injuries. Valero et al. proposed a WBAN system to track the musculoskeletal disorders commonly happening in the construction industry [133]. They have used multiple inertia measure units (IMUs) on specific locations of the human body connected to a WBAN. They measured the acceleration, velocity, and orientation, and send them with the node information to the base station. The server at the base station then fuses these sensor data to reconstruct the human body posture to access the safety of these postures. This system can be further developed by integrating muscle strain sensors into the same WBAN to understand the stresses the muscles undergo while at work. Moin et al. proposed an adaptive WBAN for using bio-signals and kinematics to address the problem of unexpected channel loss due to sudden changes in body postures [134]. They have tried to optimize the channel allocation algorithm and packet delivery using EMG and heartrate signals minimizing the transmission power. They have reported a 41% increase in the packet delivery ratio of IMU data through the proposed method and this is a significant saving of power for the WBAN.

Li and Gao proposed a physiological state monitoring WBAN based on multisensory data-fusion to assess and predict the physiological state of the human body [135]. This kind of WBAN is useful for monitoring the well being of elders living alone. They used pulse oximeter signals, breath signals, and body temperature signals to estimate the state of the physiological system. Sen et al. used WBAN and IoT based GPS sensors to monitor human subjects geographically to assist them to survive in a pandemic situation [136]. They also had other sensors on each human subject and prioritized the signal categories from highest to lowest as respiration rate, body temperature, blood pressure, oxygen saturation, and heart rate, respectively. The medical experts at the base station can identify the infected subjects and take necessary actions accordingly.

A WBAN application for monitoring the dynamics of skiing equipment and how individuals react while skiing has been presented by Crandall et al. [137]. They have a Raspberry-pi based central node with a GPS sensor and the central node collects all peripheral node data and the nodes have IMUs. They used a three axes accelerometer and gyroscope data from the IMUs, three access magnetometer data, and air pressure, temperature, and humidity data from the digital barometer. They have tested this WBAN device in the field and verified that the developed system provides accurate information on the equipment such as tip and tail velocity and direction information of skies and they can be used for training purposes.

VIII. CONCLUSION

This paper presented a comprehensive review of WBAN networks covering the areas of WBAN architecture, security and authentication, antennas, energy harvesting and management, wearable sensors for WBAN, and WBAN applications. There are many new developments in these areas, but the following opportunities are identified for future research. Each WBAN application is different and therefore the sensor requirements, network requirements, power requirements, and other WBAN requirements are different. Network security is a critical issue and addressing it with high-end computing hardware node cost and power demand increases is highly challenging. Therefore, applying the standard network security schemes is not possible and WBAN-specific network security protocols and network architectures focused on specific applications need to be developed. The antenna designs discussed in this review provide a vast knowledge of how designers have addressed different application areas and will guide future researchers to design customized antennas for their specific WBAN applications. This review discussed a broad range of flexible materials including organic, inorganic, and conducting polymer-based materials as suitable substrate materials for sensor development in WBAN applications. There are many opportunities in developing new substrate materials for flexible sensors using flexible nanomaterials. The antenna design is another research area that has huge potential due to the high demand from different applications. For example, the antenna for WBAN used in healthcare applications may not be suitable for a sports WBAN application. FR4-based small antenna, flexible PCB based antenna, and fabric-based antenna are popular types of antennas for WBAN, but printable antennas have a high demand due to ease of fabrication and the low production cost.

Energy harvesting and power management is an ever-growing area of research. Despite the fact that there are many nanogenerator-based energy harvesting methods, the demand for more efficient energy harvesting mechanisms is ever increasing. Standard materials such as PVDF, PZT, and microfiber composites have been used widely in triboelectric nanogenerators, but more efficient piezoelectric materials are being developed. A lot of opportunities are there in this area for future developments, not only to develop nanogenerators, but also the same material may work as a substrate material for some other sensors. In other words, it will be interesting to develop a device to gather information while it works as a sensor, and generates energy for the network when idling.

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