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Review Article

Routing Protocols in Wireless Body Area Networks: Architecture, Challenges, and Classification

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The wireless body area network (WBAN) is a branch of the wireless sensor network (WSN) intended for tracking essential patients' physiological signals and transferring this knowledge to the coordinator. During the routing of data, WBANs encounter critical routing problems like WSNs. Moreover, the particular constraints of WBANs make it more challenging that they need to be addressed. This survey article categorizes and briefly analyzes a range of current routing methods utilized in WBANs. The routing protocol is essential to the creation of any efficient and reliable wireless body area network due to a limited size of battery in the body sensor nodes. A comparison study of numerous routing protocols has been made in this paper, which is helpful in selecting the optimal routing protocol for the application being targeted. The article describes the WBAN architecture and addresses numerous challenges in the context of successful WBAN routing. In this paper, several existing WBAN routing methods are presented which are influenced by network structure, energy, quality of service (QoS), node temperature, human position, node transmission range, and other factors. The protocols, including cross-layered, cluster-based, QoS-aware, postural movement-based, temperature-aware, postural movement-based, and routing protocols, are given in an expressive taxonomy. Different routing protocols that have already been developed for WBANs are compared with more advanced protocols. The pros and cons of each protocol are looked at based on factors like delay, packet delivery ratio, and energy use. The researchers can utilize this survey paper as a reference for studying various routing protocols particularly in the medical and healthcare systems.

1. Introduction

As per review in 2017 from the world population scenario, the elderly people count—those 60 and older—is predicted to more than twofold by 2050 and more than threefold by 2100, going from 962 million in 2017 to 2.1 billion in 2050 and 3.1 billion worldwide in 2100 [1]. Older people who belong to this age category may need more frequent medical care because they run the risk of developing various health issues. Nevertheless, the elderly or patients with chronic illnesses should be helped by providing continuous healthcare services while they remain at home and carry out their regular activities. The advances in microelectronics and micro-electro-mechanical systems (MEMS) and compact and intelligent technologies in the 21st century made it possible to create a wireless body area network (WBAN) that connects all of these types of sensors. The WBAN is a category of wireless sensor network that can be employed to identify various diseases at an early level. The different types of body sensors [2] (such as electroencephalogram (EEG), electrocardiogram (ECG), body temperature, and blood pressure) are structured on the human body, which can capture and interpret the essential physiological signals, thereby minimizing the healthcare cost. The body node may be mounted on or within the human body. All nodes provide their detected information to the coordinator that is situated within the vicinity of the human body [3]. The coordinator takes charge of forwarding the assembled knowledge to the sink node, from where the concerned healthcare centre can receive the patient's information and accordingly give him a prescription. The new international WBAN standard, IEEE 802.15.6 [4], enables a diverse range of data speeds for a variety of applications which require low-power, limited-range, and extremely erudite wireless communication. The goal of WBAN protocols is to improve network life by avoiding energy waste caused by overhearing, idle listening, and packet collisions while meeting QoS criteria such as least latency, maximum throughput, and minimal packet loss rate (PLR) [5].

The sensor nodes' deployment, the nodes' mobility (due to installation of nodes on patients and their movement), data storage, battery life or energy efficiency, and security are the primary problems and challenges to the WBAN. The two crucial factors—energy usage over the system's lifespan and network throughput—define the success of WBAN. Due to the power-hungry nature of WBAN routing algorithms, the data transmission phase uses up the majority of the battery's power. So far, a number of routing protocols have been suggested for WBAN applications. In order to successfully implement WBAN, a thorough analysis of routing protocols must be conducted in order to classify them according to their intended uses. The reason of this analysis is to use the specific WBAN routing protocol in accordance with the requirement of the application which may address energy efficiency, throughput of the network, latency, security, packet delivery ratio (PDR), etc.; like in case of emergency data, accuracy is the primary concern with the compromise of little delay in medical data.

This survey paper provides collective information or review on routing protocols in WBAN. The paper describes the challenges encountered when developing routing protocols. The most recent different routing protocol types for each category of WBAN are presented and compared in a table with their key traits or parameters. In addition, various categories of routing protocols are contrasted with one another based on the most important WBAN parameters. This article covers and reveals all of the features, applications, pros, and cons of various WBAN routing protocols in addition to their possibilities for future research. This form of collective information about WBAN routing protocols was missing in the existing survey papers. Section 2 outlines the WBAN's basic architecture, while Section 3 describes the numerous routing problems and difficulties confronting WBANs. The various routing protocols established in the last decade are explored in Section 4, and a comparison study of various categories of routing protocols along with pros and cons and future scope is given in Section 5. Section 6 presents the open research challenges with their proposed directions, and conclusions are described in Section 7.

2. WBAN Architecture

The WBAN is the incorporation of intelligent, extremely low-power, tiny sensor nodes that are put inside or adjacent to the human body and can link to other electronic devices autonomously. The WBAN is based on radio frequency (RF) wireless networking technology. The WBAN architecture can be segmented into three distinct levels as shown in Figure 1 [6].

2.1. Tier 1-Intra-WBAN. Tier 1 is the WBAN portion where several body sensor nodes are entrenched inside the human body, or on clothing, or strategically mounted on the skin. The body nodes are responsible for continuously monitoring crucial physiological signals such as blood pressure, temperature, pulse rate, ECG, and the environment around them and processing the detected data at their end. These sensor nodes are legally connected to the coordinator and submit their processed records to it. The coordinator further takes the mission of gathering sensed data from all the nodes, processing it, and then sending all the compiled data to the following layer in the hierarchy. The WBAN can be a remarkably effective arrangement, especially in healthcare environments where a patient may be continuously examined and require portability.

2.2. Tier 2-Inter-WBAN. A wireless networking setup that serves as a gateway is present at Tier 2. Wireless local area network (WLAN), Bluetooth, ZigBee, Wi-Fi, GSM, 3G, 4G, and other wireless networking standards are potential WBAN networking technologies. Apart from this, a laptop or cellular network can be utilized as a gateway. With the exception of cellular networks, all technologies are frequently usable for narrow-band communication.

2.3. Tier 3-Extra-WBAN. Tier 3 contains the decision control unit (DCU), which carries out all the major operations and takes the final decision regarding a patient's health on the basis of the results obtained. This tier also maintains the database of the patients; therefore, the patient's history can be extracted at any time by the physician or healthcare taker. The patient also has online access to the practitioner's prescription regarding his health status. In an emergency, an ambulance service is also offered.

3. Routing Challenges in WBANs

The limited bandwidth, low transmission range, and limited battery backup are the various characteristics of WBAN. Because of these special characteristics of WBANs [6], the designing of effective routing protocols is a critical job. Network topology, postural body motions, resource limitations, service quality metrics, interference and radiation, network lifespan, diverse environments, etc. are some of the routing concerns and obstacles [7]. The resource limitations including power consumption, limited computing capabilities, transmission range, and available bandwidth are due to the restricted size of body sensor nodes. Therefore, the routing protocols for WBAN are designed by keeping in mind the above-mentioned resources. From this analysis, we can draw a conclusion and make a list of the most important performance criteria to keep in mind when putting the whole WBAN into action. These criteria are discussed in the next sections.

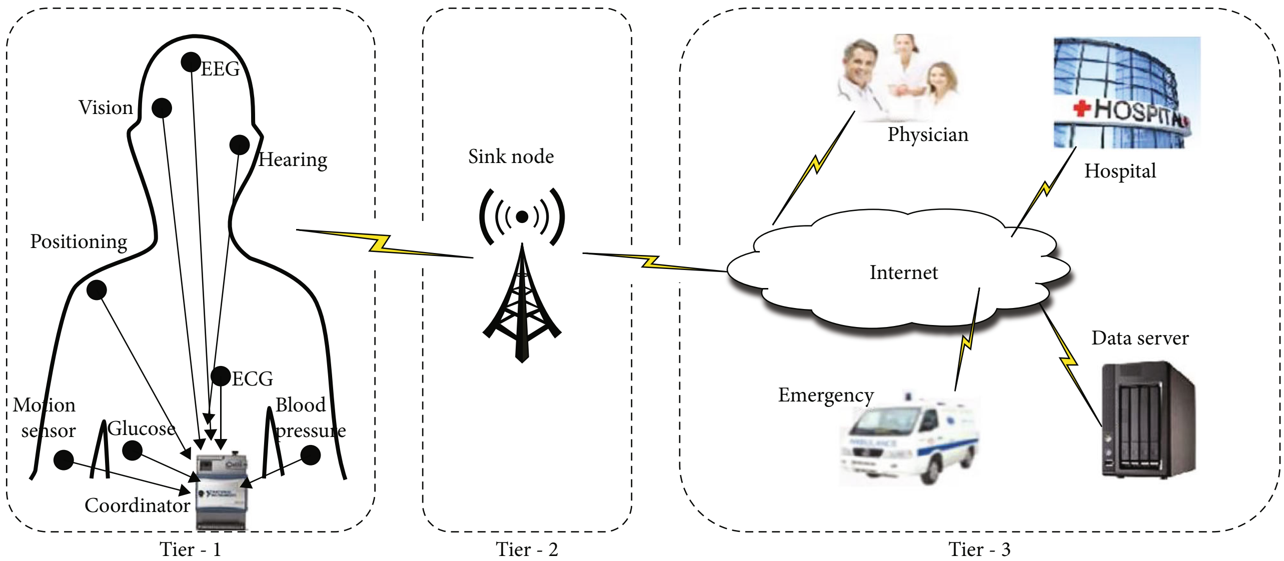

Figure 1: WBAN architecture.

3.1. Network Partitioning. Due to short transmission range and postural changes, WBAN often experiences network partitioning, which further causes problems in routing the data to the coordinator. Many authors addressed the problem of network partitioning and developed many protocols to resolve this problem [4, 5]. For example, in [8], each sensor node contains two pathways, a main path and a backup path, to address this issue. The backup path employs a body-coupled communication (BCC) connection. The BCC link is used to forward the data to PDA through the human body as a medium. It is utilized in case of emergency data or in the event when the primary path fails as it may affect human tissues. BCC connection can be established by using two-electrode transmitter/receiver devices capacitive coupled to the human body. The transmitter creates a variable electric field, and the receiver detects the body's fluctuating potential with respect to its surroundings. This link is always available once the setup has been established and uses human body as a medium. The prime path sends the usual data over an RF link. The sensor node flips to the backup connection to alert the coordinator about the link breakdown and reconfigure the network. The authors in [9–11] use store-and-forward routing, and the writers in [12] are discussing this issue by utilizing the correspondence on line-of-sight and non-line-of-sight.

3.2. Energy Efficiency. Energy efficiency is the main issue for WBAN because replacing the battery of body nodes is not simple, especially if the nodes are entrenched inside the body. As a consequence, energy usage and network survival in WBANs are serious hurdles. The primary source of energy usage is due to coordination among the body nodes as compared to analyzing and evaluating [13]. There should be a dynamic path to route the data instead of a static path so that the total energy of a specific node may not be consumed so early as compared to the other nodes. To boost the energy efficiency of the WBAN, a framework that takes care of both the constraints of QoS measures and the dynamic link features is devised in [4]. In [10], the researchers describe the lifespan of the network as the moment the network begins till the first node dies.

3.3. Quality of Service (QoS). In WBANs, meeting QoS such as packet delivery ratio, throughput, packet drop ratio, and latency is the main challenge. The medical data of the patient is categorized into normal data (such as heartbeat and temperature), emergency data (such as ECG and EEG), delay-responsive data (e.g., video streaming), and reliability-sensitive data (such as pH observing and respiration monitoring) [14, 15]. In [5], a system is devised where the energy efficiency of the WBAN is maximized while factoring both dynamic link features and the restrictions of QoS measures. Each BN's transmission rates are tuned with GABAT-TRAP to guarantee QoS performance in terms of PLR, latency, and throughput [5]. Furthermore, in this system, emergency packets are delivered without delay and with a higher priority than regular packets in order to ensure stricter limits and to increase performance.

3.4. Privacy and Security. The WBAN's fundamental criterion is patient data security and privacy, but the conventional privacy and security strategies cannot be applied to the WBAN because of limited energy and other resources [16]. In developing the routing protocols, researchers should be aware of the patient's data privacy and security. In data security, the database is protected from destructive influences by retaining secrecy. As a result, an illegal or unauthorized person is unable to access or change data. Data transmission security is ensured by the use of encryption technology. Only a legitimate and authorized person has the approval of using the data and information in a data privacy. When data is released to unauthorized entities (persons), this poses a number of risks. Medical information of a person is particularly a sensitive matter and should only be accessible by authorized people. A mechanism known as phantom routing can enhance the source location's secrecy,

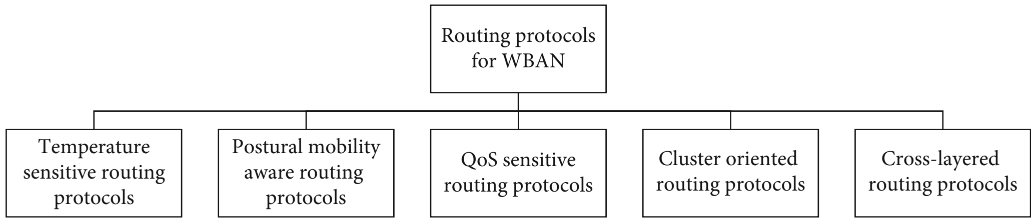

Figure 2: Categories of WBAN routing protocols.

which is crucial in WBAN. By creating a phantom source and flooding it with data, this approach significantly increases the anonymity of the source location [17]. All systems must provide suitable mechanisms to ensure network data privacy, including the privacy of medical data.

3.5. Limited Resources. WBANs have restricted resources like short RF transmission range, low bandwidth, limited computing power, and inadequate storage capability, and moreover, they tend to change in accordance with noise and various other intrusions [18]. When designing WBANs' routing protocols, scientists should be mindful of the restricted resources.

Taking into account all the above issues at the hardware and software levels, our objective is to develop a trustworthy wireless body area network system by developing optimized routing protocols at the network layer. A group of protocols known as routing protocols must be created in order for data to be efficiently transferred between nodes. These protocols must be appropriate for a particular application and able to identify and maintain the paths in a network while preserving different QoS metrics. Consequently, the routing protocol is essential in WBAN for ensuring secure communication between sensor nodes. To achieve this target, numerous existing routing protocols are briefly examined and discussed in this paper, along with their benefits, drawbacks, and applications.

4. Routing Protocols for WBANs

The latest routing protocols over the past decade are categorized as temperature-sensitive routing protocols, postural-mobility-aware routing protocols, QoS-sensitive routing protocols, cluster-oriented routing protocols, and cross-layered routing protocols. They are discussed in this portion, outlined in Figure 2.

4.1. Temperature-Sensitive Routing Protocols. The use of radio signals in wireless communications generates magnetic and electrical fields because of the radio antenna use and the node power use, which trigger temperatures to increase, especially in implanted nodes [19]. This might harm the growth of underlying tissues and other important organs if placed over long periods [20]. The specific absorption rate (SAR) [19] is the radioactive intensity volume that the tissue absorbs per unit weight and is given in

$$\mathrm{SAR} = \frac{\sigma |E|^2}{\rho}\left(\frac{W}{Kg}\right), \tag{1}$$

where "σ" denotes tissue's electrical conductivity, "E" refers to an induced electric field through radiation, and "ρ" is tissue's density. Finally, each temperature-sensitive routing protocol is aimed at minimizing the rise in temperature of embedded body nodes. Table 1 provides a contrast with other state-of-art techniques on the basis of rise in temperature, discarding of packet mechanism, address scheme, latency, packet distribution ratio, and usage of energy.

4.2. QoS-Sensitive Routing Protocols. The QoS-sensitive protocols for routing are structured protocols that utilize various components for various kinds of QoS statistics. The expansion of these protocols is a tough task because of the intricacy of including separate components for separate QoS parameters and interaction between such modules. The QoS-sensitive routing protocols developed for wireless sensor networks (WSNs) [21–24] cannot be explicitly implemented on WBANs due to their specific restrictions. The comparison chart of various recently developed QoS-sensitive routing protocols with regard to network throughput, network size, mobility, latency, packet delivery ratio (PDR), and energy usage is given in Table 2.

4.3. Cluster-Oriented Routing Protocols. In the category of cluster-oriented routing protocols, the body nodes are segmented into various clusters on the basis of particular criteria, and one specific node within each cluster is designated as a cluster head. All the chosen cluster heads take the charge of collecting all the data sensed by each node corresponding to its cluster and providing all the accumulated information to the coordinator. No interaction between body nodes is possible, and they can communicate only through their cluster head. The comparison of two cluster-based protocols is given in Table 3.

4.4. Postural-Mobility-Aware Routing Protocols. The WBAN topology may be partitioned due to movements in the body posture and/or short RF transmission ranges. Network partitioning may cause link disconnection between the nodes and problems in routing the data. To cope with these issues, different researchers have established numerous protocols based on the communication cost factor, which is regularly modified. The communication cost factor is defined in terms of energy consumption which is the ratio of total energy consumed in the network to the average packets delivered to the sink [4]. These protocols are focused on the lowest cost of providing the data packets from the patient's body to the coordinator. Different WBAN routing protocols for postural movement are contrasted with other advanced

Table 1: Temperature-sensitive routing protocols.

Reference	Protocol	Objective	Temp. rise	Address policy	Discarding mechanism	PDR	Latency	Energy consumption
Tang et al. [19]	Thermal-aware routing algorithm (TARA)	Reducing overheating risk	Very high	Global	No	Very low	Very high	Very high
Bag and Bassiouni [20]	Hotspot preventing routing (HPR) algorithm	Preventing hotspot creations and reducing average latency	Very low	Global	Yes	High	Low	High
Bag and Bassiouni [25]	Adaptive least temperature routing (ALTR)	Reducing rise in temp, energy consumption, and latency	Low	Global	No	High	Medium	High
Takahashi et al. [26]	Least total-route temperature (LTRT) routing algorithm	To seek routes at low temp	Very low	Global	Yes	Very high	Low	Low
Bag and Bassiouni [25]	Least temperature routing (LTR)	To decrease the rise in temp and energy usage	High	Global	Yes	Low	High	High
Bag and Bassiouni [27]	Routing algorithm for network of homogeneous and ID-less biomedical sensor nodes (RAIN)	Reducing in rise in temp and average latency	Very low	Global	Yes	High	Low	Low
Javaid et al.[28]	Mobility-supporting adaptive threshold-based thermal-aware energy-efficient multihop protocol (M-ATTEMPT)	Reducing rise in temp, energy usage, and average latency	Low	Global	Yes	High	Low	Low
Bhangwar et al. [29]	Trust and thermal aware routing protocol (TTRP)	It was designed to be trustworthy and to avoid hotspot creation	Very low	Global	Yes	High	Medium	Very high

Table 2: QoS-sensitive routing protocols.

Reference	Protocol	Objective	Network throughput	Network size	Latency	Movement	PDR	Energy consumption
Liang and Balasingham [30]	Routing service frame work	To have user specific QoS assistance and routing on priority based	Not applicable	Small	Not applicable	Yes	Average	Not applicable
Djenouri and Balasingham [14]	Localized multiobjective routing (LOCAL MOR) protocol	Assistance for QoS dependent on data design	Not applicable	Medium	Low	Yes	High	High
Liang et al. [31]	Reinforcement learning-based routing with QoS support protocol (RL-QRP)	Large packet ratio and minimal latency	Low	Small	High	Yes	High	Not applicable
Khan et al. [32]	Energy-aware peering (EPR) routing protocol	Reducing network congestion and energy usage	High	Very small	Not applicable	Yes	High	Low
Razzaque et al. [15]	Data-centric multiobjective QoS-aware (DMQoS) routing protocol	Support for QoS	Very low	Large	Low	Yes	High	Average
Khan et al. [33]	QoS-aware peering routing protocol for delay-sensitive data (QPRD)	To minimize latency	High	Very small	Very low	Yes	High	Low
Khan et al. [34]	QoS-aware peering routing protocol for reliability sensitive data (QPRR)	Enhancement of reliability	High	Small	Not applicable	Yes	High	Low

Table 3: Cluster-oriented routing protocols.

Reference	Protocol	Objective	Statistics	Average latency	PDR	Security	Energy consumption
Culpepper et al. [35]	Hybrid indirect transmission (HIT)	Enhancing the network longevity and reduction in direct communication to the sink	Geographical knowledge and nodes remaining energy	Low	Not applicable	Yes	Low
Watteyne et al. [36]	AnyBody	Reduction in direct communication of the nodes to the sink	Density of nodes	Not applicable	Very high	No	Not applicable

and base protocols on the basis of average latency, PDR, mobility, and energy consumption. They are given in Table 4.

4.5. Cross-Layered Routing Protocols. Such protocols attempt to overcome both the network and medium access control (MAC) layers' issues and obstacles concurrently to enhance the overall network efficiency. Several MAC protocols for WBAN have been proposed to address the unique challenges related to collision, delay, reliability, and energy. The design of MAC protocols is based on multiple access techniques. The various MAC protocols for WBANs are mainly divided into two categories i.e., carrier sense multiple access (CSMA) and time division multiple access (TDMA) [37]. CSMA is a contention-based scheme where collision is probable when two sensors try to approach the same channel concurrently. The sensors wait for predefined time and try again until they get the chance to send its data. However, TDMA uses scheduled-based scheme where sensors use assigned time slots to send their data to avoid collision.

The cross-layered methodology improves the interaction of two or more layers without disturbing the layers' actual characteristics. Because of its usefulness in WSNs, it drew the attention of researchers and scientists in WBANs too. Table 5 compares the delay, PDR, and energy consumption for diverse cross-layered protocols for WBANs.

5. Comparative Analysis of Routing Protocols and Future Scope

The goal of the presented paper is to expand on recent WBAN topics for designing routing protocols. For IEEE.802.15.4, it would be beneficial to rebuild the TICOSS [42] protocol to reduce the average latency, which is not taken into account in the current one. The Biocomm protocols [43] and innovative methods to lower node temperature will be the choice if the performance of the entire network is to be optimized. As a result, there is a fairly large window of opportunity for research in this field.

The cluster-based routing protocol hybrid indirect transmission (HIT) [35] tries to maximize network longevity across all routing protocols. However, it ignores the PDR, which is a crucial QoS statistic. Next, the AnyBody [36] protocol takes into account delivery ratio but ignores average latency, mobility, and energy usage. It results in inadequate security checks.

The comparison of some of the WBAN routing protocols is shown in Table 6. The investigation reveals that practically all protocols have used various QoS indicators to evaluate their effectiveness. Therefore, selecting a protocol for a WBAN system relies on the system's specific purpose; it may need to be more reliable, energy-efficient, or it may need to lower the temperature of the node circuits. The benefits and drawbacks of each protocol utilized in WBANs, as well as the application domain, are listed in Table 7. This table aids in selecting a certain protocol based on QoS specifications.

None of the postural movement protocols that were compared to each other took into account both QoS problems and the thermal impacts of nodes. Therefore, enhanced QoS parameters need to be included in the suggested future protocols to lower the node's temperature rise and approach to thwart security assaults. None of the postural movement protocols that were compared to each other took into account both QoS problems and the thermal impacts of nodes. Therefore, future QoS parameters attempt to lower node temperature rise, and approaches to thwart security assaults might all be included in the suggested future protocols. Because of its significance, the review of QoS-based protocols identifies several areas that require additional exploration. Every proposed framework that has been developed is aimed at fixing the flaws in the existing one. For instance, energy usage is not taken into consideration in the reinforcement learning-based routing with QoS assistance [30, 31], unlike in the other existing protocols. Nearly all developed QoS-based protocols exclusively focus on QoS measurements, ignoring changes in human body temperature and the movements of human beings.

Researchers are showing great curiosity in the cross-layered idea because of its adaptability and efficacy in sensor networks. This is the main reason of gaining interest in this concept. CICADA [41] outperforms its other competing cross-layer protocols in terms of average latency and energy efficiency, and future research will focus on making it even more reliable.

Routing protocols in WBAN are compared in Table 6. The results show that the majority of the protocols consider a variety of quality-of-service metrics in their performance evaluation. In consideration of this, protocol selection in WBAN system should be influenced by the system's desired purpose, such as whether it would be used for either more energy-efficient, highly trustworthy, or able to significantly lower the temperature of the node's electronic circuitry. The pros and cons of each protocol utilized in body area networks, as well as the application domain, are listed in Table 7. This table aids in selecting a certain protocol based on QoS specifications. For example, protocols like TICOSS [26] or WASP [48] can be chosen because of their low average delay and high PDR if the proposed system is being used for healthcare monitoring in clinics. The routing algorithms for homogeneous networks and ID-less biosensor nodes, RAIN [27] or Co-LEEBA [47], and TARA [19] can be used if the sensors are entrenched inside the body.

6. Open Research Challenges

WBANs are considered one of the most innovative technologies that have the potential to improve medical care services and life quality. To overcome various routing challenges in WBAN are explained in Section 3, and a significant number of solutions have been detailed in Section 4. However, significant concerns remain unresolved, as outlined in the subsections below, which may limit the widespread use of WBANs.

6.1. Energy Efficiency. The lifetime of the WBAN heavily relies on energy management, as sensors are powered by tiny-formed batteries, which are hard-to-replace, especially for implanted sensors. As a result, when choosing a route

Table 4: Postural-mobility-aware routing protocols.

Reference	Protocol	Objective	Metrics	Mobility	Average latency	Packet delivery ratio	Energy consumption
Quwaider and Biswas [9]	On-body store and flood routing (OBSFR)	Reduction in hop-count and average latency	Link quality	Yes	1.88 s	83-92%	High
Quwaider and Biswas [10]	Probabilistic routing with postural link costs (PRPLC)	Reduction in average latency	Link quality	Yes	3.19 s	82-88%	Small
Quwaider and Biswas [11]	Distance vector routing with postural link costs (DVRPLC)	Reduction in average latency	Link quality	Yes	2.38 s	81-89%	Small
Maskooki et al. [12]	Opportunistic	Enhancement in the lifespan of network	Line-of-sight and non-line-of-sight communication	Yes	Not applicable	Not applicable	Very small
Movassaghi et al. [38]	Energy efficient thermal and power aware (ETPA)	Minimization of energy usage and rise in temperature	Temperature of nodes and quality of link	Yes	High	Up to 95%	Small
Liang et al. [39]	Prediction-based secure and reliable (PSR) routing framework	Reduction in security and reliability	Measurements of past connection consistency	Yes	High	Up to 80%	High
Goyal et al. [4]	Posture aware-dynamic data delivery (PA-DDD)	Efficient and dynamic data delivery	Line-of sight communication	Yes	Very low	Average 73.63%	Very low
Karmakar et al. [17]	Mobility handling routing protocol (MHRP)	Cardiac monitoring, dynamic environment	Fault-tolerant system	Yes	Low	Not applicable	Low
Karmakar et al. [17]	Network management cost minimization framework (NCMD)	Topological fracture treatment, dynamic environment	Link quality	Yes	High	Not applicable	High

Table 5: Cross-layered routing protocols.

Reference	Protocol	Objective	Metrics	Mobility	Average latency	Packet delivery ratio	Energy consumption
Braem et al. [40]	Wireless autonomous spanning tree protocol (WASP)	Reduction in energy usage, PLR, and average latency	Routing and count of hops	No	324 milliseconds	100%	Medium
Latre et al. [41]	Cascading information retrieval by controlling access with distributed slot assignment (CICADA)	Reduction in energy usage and average latency	Routing and count of hops	Yes	<0.3 milliseconds	Not applicable	Low
Ruzzelli et al. [42]	Time zone coordinated sleep scheduling (TICOSS)	Enhancement of IEEE 802.15.4 standard	Routing and count of hops	Yes	Not applicable	Over 92%	Low
Bag and Bassiouni [43]	Biocomm and Biocomm-D	Total network performance optimization	Node temp, count of hops, and delay	No	Average	75-100%	Average

TABLE 6: Comparative analysis of routing protocols.

Reference	Routing protocol	Protocol type	Packet delivery ratio	Energy consumption	Average delay	Average temperature rise	Energy efficiency
Tang et al. [19]	Thermal-aware routing algorithm (TARA)	Temperature-sensitive	Low	High	Very high	Low	Very low
Javaid et al. [28]	Mobility-supporting adaptive threshold-based thermal-aware energy-efficient multihop protocol (M-ATTEMPT)	Temperature-sensitive	High	Low	Low	Low	Medium
Bag and Bassiouni [27]	Routing algorithm for network of homogeneous and ID-less biomedical sensor nodes (RAIN)	Temperature-sensitive	High	Low	Moderate	Low	High
Monowar et al. [44]	Thermal-aware multiconstrained intrabody QoS routing (TMQoS)	Temperature-sensitive	High	Very low	Very low	Moderate	High
Bag and Bassiouni [25]	Less temperature rise (LTR)	Temperature-sensitive	Low	High	High	Low	Low
Takahashi et al. [26]	Least total-route temperature routing algorithm (LTRT)	Temperature-sensitive	Very high	Medium	Moderate	Low	Medium
Liang et al. [39]	Prediction-based secure and reliable routing framework (PSR)	Postural	Moderate	High	Low	NA	Moderate
Movassaghi et al. [38]	Energy efficient thermal and power aware (ETPA)	Postural	High	Low	High	Low	High
Goyal et al. [4]	Posture aware-dynamic data delivery (PA-DDD)	Postural	High	Very low	Very low	NA	High
Razzaque et al. [15]	Data-centric multiobjective QoS-aware routing protocol (DMQoS)	QoS-aware	High	Moderate	Low	NA	Moderate
Ayatollahitafti et al. [45]	Efficient next hop selection algorithm (ENSA-BAN)	QoS-aware	Very high	Low	Very low	NA	High
Khan et al. [46]	Integrated energy and QoS-aware routing protocol (ZEQoS)	QoS-aware	High	High	NA	NA	Low
Djenouri and Balasingham [14]	Localized multiobjective routing protocol (LOCALMOR)	QoS-aware	High	Low	Low	NA	High
Ahmed et al. [47]	Cooperative link aware and energy efficient protocol for wireless body area networks (Co-LEEBA)	QoS-aware	High	Low	NA	NA	High
Liang et al. [31]	Reinforcement learning-based routing protocol with QoS support (RL-QRP)	QoS-aware	High	NA	High	NA	Moderate
Watteyne et al. [36]	AnyBody	Clustered	Very high	NA	NA	NA	NA
Culpepper et al. [35]	Hybrid indirect transmission (HIT)	Clustered	NA	Low	Very low	NA	High
Ruzzelli et al. [42]	Time-zone coordinated sleeping scheme (TICOSS)	Cross-layered	High	Low	NA	NA	High
Khan et al. [34]	Cascading information retrieval by controlling access with distributed slot assignment (CICADA)	Cross-layered	NA	Low	Low	NA	High
Braem et al. [40]	Wireless autonomous spanning tree protocol (WASP)	Cross-layered	Very high	Low	Low	NA	High

Table 7: Application domain with pros and cons of various routing protocols.

Reference	Routing protocol	Pros	Cons	Application domain
Liang et al. [31]	RL-QRP	Adaptable and works well with optimum routing strategies in highly variable scenarios. The average latency is less than 200 ms, making it a good choice even in congested areas.	Ineptitude for multiagent systems and other large-scale networks.	Dynamic biomedical sensor networks.
Khan et al. [46]	ZEQoS	Sustained throughput of 84%, appropriate for all categories including delay, conventional, and sensitive packets.	Negligible progress in reducing energy expenditure.	BAN communication in hospitals.
Liang and Balasingham [30]	Routing service FRAMEWORK	Supports user-defined quality of service (QoS) and prioritised routing for local area networks.	Energy expenditure, a significant limitation of sensor networks, was ignored.	Compact, wireless, dynamic body area networks.
Ruzzelli et al. [42]	TICOSS	Boosts network availability by a twofold increase in high-traffic circumstances, when the packet delivery ratio (PDR) is more than 92%. TICOSS's time-zone coordinated hibernation process extends its battery life to 4 minutes per joule when integrated with 802.15.4, compared to 2 minutes per joule when using 802.15.4 individually.	Not an application-level protocol, hence it will not operate in delay-sensitive networks.	Continual monitoring of vital signs using distributed environmental sensor nodes.
Latre et al. [41]	CICADA	As nodes only wake up to send and receive data, power is only used when necessary, allowing for greater mobility and less energy use.	Interaction between the nodes and the sink is not supported.	In the context of sensors, where processing power is limited.
Braem et al. [40]	WASP	Reduces the time spent in coordination, increasing productivity to 94%. By decreasing the depth of the spanning tree and the amount of power used, it is possible to reduce the delay.	Not suitable for use in dynamic sensor network applications due to lack of mobility capability.	For use in the confines of a hospital for patient monitoring.
Watteyne et al. [36]	AnyBody	A self-organizing procedure keeps the number of clusters stable. About 100% in terms of PDR.	Latency and energy usage are two important parameters that are ignored. As a result, it is not suitable for crucial medical situations.	Monitoring of hospital patients at regular intervals.
Culpepper et al. [35]	HIT	Data collection requires 25% less time than PEGASIS and LEACH; network lifespan is 1.44 and 1.05 times that of LEACH and PEGASIS, respectively.	Although not directly related to any one medical use case, the network's security, reliability, and fault tolerance must be considered.	Bioelectrical computer interfaces, biosensor networks, biomedical signals (such as EEG and EMG).
Ahmed et al. [47]	Co-LEEBA	It takes into account the existence of links. Incorporating a variety of path loss models helps lessen the impact of path loss. Lifespan is increased due to the data's sporadic delivery. When compared to other protocols, which typically achieve throughputs of 2 Mbps, it enhances performance to 36 Mbps.	Optimizes for efficiency at the expense of increased latency.	Elderly patients under surveillance.

Table 7: Continued.

Reference	Routing protocol	Pros	Cons	Application domain
Ayatollahitafti et al. [45]	ENSA-BAN	In addition to satisfying all QoS prerequisites, it also takes into account node energy usage in order to boost network performance. The average delay is less than 16 ms, and the packet delivery ratio (PDR) can be increased to around 96% from DMQoS.	Despite the fact that it is a QoS-aware routing system, it does not take physical motion into account.	Sensor networks for persistent healthcare surveillance.
Tang et al. [19]	TARA	Ability to handle data transmission in areas of high temperature, can reroute packets through cooler regions, can distribute the load more evenly, and causes lesser of an overall increase in temperature.	Larger delays (more than 400 ms) cause more packet loss, and as each node requires its own unique hardware identifier, this approach cannot be used with standardised, nonemergency sensor nodes.	Applications such as retinal transplants and cancer detection rely on embedded sensor networks.
Djenouri and Balasingham [14]	LOCALMOR	The latency is less than 200 milliseconds, the packet reception ratio is greater than 85 percent, and it is compatible with any media access control (MAC) protocol that has an ACK mechanism.	The protocol's scalability with a growing network of sensors necessitates further investigation.	Wide-ranging medical and health-related traffic applications.
Razzaque et al. [15]	DMQoS	By employing a modular architecture, latency and reliability-critical packets to less than 120 ms, compared to 260 ms for existing QoS-aware protocols. In all traffic conditions, the PDR is greater than 92%.	Numerous tuning parameters cannot be estimated analytically. Various simulation experiments are used to fix them.	Resource-constrained BANs.
Takahashi et al. [26]	LTRT	Optimal routing is achieved, resulting in excellent packet delivery ratio and a reduced average temperature increase.	Only the average increase in temperature and rate of packet loss are included in the investigation.	Applications in cardiac patient monitoring and embedded biomedical networks.
Liang et al. [39]	PSR	Data injection threats are mitigated, the PDR potentially reach 80%, and the routing time is reduced.	Incorporates ACK methods for gauging connection quality; however, if ACK count is high, it might put a strain on the network and reduce its lifespan as a whole.	Secure and reliable WBANs.
Movassaghi et al. [38]	ETPA	Facilitating mobility, reduced heat generation, and improved link stability mean that the packet delivery ratio (PDR) can reach 95%, eradicating the previously existing problem of link disconnection caused by the person's own motions.	A slightly longer delay than PRPLC is implemented to counteract the network's temperature increase.	WBAN with persistent communication and limited resources.
Monowar et al. [44]	TMQoS	Using a hotspot avoidance mechanism, this table-driven protocol extends the life of the network, reduces latency between nodes to below 130 milliseconds, guarantees reliability greater than 85 percent, and satisfies quality-of-service requirements without overheating the devices.	To attain the required level of QoS, the average temperature has gone up.	The use of wireless BANS in a living organism.

Table 7: Continued.

Reference	Routing protocol	Pros	Cons	Application domain
Javaid et al. [28]	M-ATTEMPT	In comparison to multihop communication, the advantages of mobility support include a longer network lifetime (29.5%), a longer period of stability (>20%), and a 29% increase in successfully received packets.	A node in transition requires a new parent, and the prospective parent may refuse this request; temperature increase analysis is not included.	Homogeneous and heterogeneous WBANs.
Bag and Bassiouni [27]	RAIN	Effectively directs data from ID-less biomedical sensor networks to a central repository, reduces energy dissipation by an average of 1000 energy units as compared to CFLOOD, PDR is higher than 90% and eliminates hotspots in the network by limiting maximum temperature increases.	Compared to the CFLOOD protocol, PDR is marginally lower, but average latency is marginally longer.	ID-less biomedical sensor nodes, homogeneous in vivo networks.

in WBAN, the routing protocols should take energy into account. Only a few of the studied protocols are energy-efficient. Using characteristics of relay and dynamic power regulation, the enhanced MAC (EMAC) protocol is developed in [49] and is based on the multihop superframe structure of the IEEE 802.15.4 standard. The controller node selects the appropriate relay node for the node if its residual energy is below the threshold energy since the node does not have enough energy to explicitly communicate data to the controller directly. As a result, the network topology is changed from one-hop to multihop, and the superframe is modified to hold this change. To further conserve energy, the protocol also makes use of the idea of a dynamic transmission power control mechanism. In the communication process, the transmission power level is set using the feedback data from the receiver, or RSSI value. EMAC uses the integrated relay, superframe adjustment, and dynamic power regulation as a result to maximize network lifetime while reducing energy consumption. A few of these protocols need the inclusion of extra nodes that serve as relay nodes, like in TTRP [29]. Others attempt to choose the subsequent router node with the largest energy score. Both approaches have shortcomings; the first approach, which makes use of relay nodes, has material overcharging as well as potential effects on the user's comfort. On the other hand, in the second approach, the neighboring nodes need to share the energy level information to update their local information. Therefore, intensive energy will be drained out due to the exchange of additional messages.

In WBANs, energy is a scarce resource but essential. It is, therefore, a challenging task that needs further research to adopt a better approach that increases energy conservation for all nodes in the network and extends network lifetime. Additionally, using energy harvesting from human body sources such as body vibration and body heat, which were not covered in this paper, should significantly extend the lifetime of the network and enable autonomous WBAN.

6.2. Delay-Sensitive Delivery. As WBAN is typically applied in healthcare applications so data must be delivered instantly because any form of delay could have disastrous results. The energy efficiency and minimum delay may be achieved by avoiding idle listening, overhearing, collision, and control packet overhead. In [3], the sensed medical data is categorized into two classes: normal data and emergency data. The body sensors are permitted to interrupt coordinator in case of any emergency data sensed by the sensors so that immediate action can be taken accordingly to avoid life threatening scenario. A MAC protocol for WBAN based on TDMA method is introduced in [50], which leverages single-hop communication to maximize network longevity. This protocol uses TDMA, which is better suited for static networks with a small number of sensors that provide data at the same rate, to reduce idle listening and communication overhead. The primary goal of this protocol is to minimize the amount of time that each sensor spends communicating relative to its power-down state (sleep mode). The protocol includes a few extra slots for retransmission in the event of a communication fault in an effort to improve the duty cycle, which is a crucial factor in energy usage and reliable communication. Protocol transmits redundant data to reduce the likelihood of packet loss, and sensors are permitted to sleep for extended periods of time to save energy. Low channel usage is the shortcoming of the protocol if the sensors have different sampling rates. This is due to lower sampling rates of the sensors which further causes the wastage of the time slots given to them by sending their sampled data after a defined time interval rather than every time frame. A few delay-sensitive routing protocols have been designed [3, 33] so far, but the majority of the thermal-aware routing protocols have selected a thermal-aware technique that is focused on waiting, which raises a conflicting issue in this situation. Therefore, there is a need to identify more practical delay-sensitive strategies which are desperately needed to cut down on delivery delays in future research.

6.3. Mobility Support. The sensor nodes are deployed on the human body in the WBAN setup. Due to body movement or postural change, link may be lost, which further causes the network partitioning or change in network topology. In WBAN, network partitioning may occur more frequently because to short RF transmission ranges and postural motion, creating a delay tolerant network (DTN) [51–54]. Network partitioning is made worse by unpredictable RF attenuation brought on by the signal being blocked by body parts and clothing. Due to this partitioning, communication between on-body sensor nodes is exceedingly unstable. Numerous real-world applications are severely hampered due to unreliable operation of RF around human bodies. A few of the routing protocols take care of network partitioning in WBAN [3, 4]. The mobility-based thermal-aware routing protocols are given much less attention. As a result, it is challenging to create WBAN-specific solutions that combine mobility support with a temperature-aware strategy. This poses a significant research challenge.

6.4. Congestion Control. In many WBAN systems where data is sent to the sink through a multihop strategy, the nearby nodes to the sink are heavily demanded and experience massive overload, which causes network congestion and the formation of energy holes, which may impact the delivery of emergency data. Some authors have devised such protocols which have taken care of congestion control in WBAN [55], but they still do, however, have restrictions in terms of energy usage and charge balancing. Effective solutions are, therefore, urgently needed in this area.

6.5. Radiation Absorption and Overheating. The temperature of WBAN nodes increases during their operation. This increase in temperature is mainly due to the functioning of internal circuitry of nodes and radio transmitter/receiver during data processing. Heat-sensitive human body organs can be harmed by high temperatures, which can cause tissue damage [19]. Therefore, in order to prevent the temperature from rising, energy consumption must be kept to a minimum. The experiments have revealed that there is a considerable danger of tissue injury when the head tissue or torso is subjected to a SAR of 8 W/kg for 15 minutes [56]. Therefore,

Table 8: Open research challenge with their proposed directions.

Open research challenge	Proposed directions to deal with challenge
Energy efficiency	A better approach is required while developing routing protocols that ensure energy conservation for all nodes in the network and extend network lifetime. Additionally, using energy harvesting from human body sources such as body vibration and body heat should significantly extend the lifetime of the network and enable autonomous WBAN.
Delay-sensitive delivery	More practical delay-sensitive strategies are desperately needed to reduce delivery delays, such as by solving network partitioning issues or improving node link quality, which are the main causes of delayed delivery.
Mobility support	WBAN-specific solutions are required that combine mobility support with a temperature-aware strategy.
Congestion control	By putting limits on the multihop strategy in WBAN, network congestion and the formation of energy holes can be kept under control. This is because the nodes close to the sink are heavily used and are overloaded to a large degree.
Radiation absorption and overheating	Energy consumption must be kept to a minimum to avoid the problem of radiation absorption and overheating, which is the main cause of harming human tissues.
Multihop limitation	To increase the network lifetime and to reduce energy consumption, there must be a restriction on the hop count. Also, the WBAN routing protocols must have a plan for the number of hops each packet needs to make the network last longer.
Heterogeneity of the environment	To enhance the WBAN performance as a whole, heterogeneity must be considered by using various types of biosensors.
Reliability and fault tolerance	A reliable and fault-tolerant routing protocol should be designed so as to identify and fix the errors that may be generated due to climate variability (e.g., heat and humidity) and ensure successful data transfer and network functionality continues.
Quality of service (QoS)	An efficient routing protocol should be designed by ensuring the necessary QoS parameters, i.e., delay and reliability.
Security and confidentiality	Effective routing protocols are needed that protect against routing attacks and maintain data security and confidentiality.

researchers should keep in mind the issue of overheating while designing WBAN routing protocols to avoid any type of harm to human tissues.

6.6. Multihop Limitation. According to the IEEE.802.15.6 standard supported for WBANs, one or two hops of communication are suitable in WBANs [57]. However, the WBAN system becomes more reliable as the number of hops grows, leading to better linkage quality or less network partitioning caused by changes in posture or body movement. But as the hop count grows, the energy consumption also increases proportionally. However, the restriction on the packet hop count has not been implemented by most of the WBAN routing protocols.

6.7. Heterogeneity of the Environment. The WBAN employs a variety of biosensors to measure and track various bodily parameters. These biosensors are typically diverse in nature and may also have a range of capabilities in terms of processing speed, data storage, energy usage, and transmission speed. Therefore, this heterogeneity must be taken into consideration while developing the WBAN routing protocol to enhance WBAN performance as a whole.

6.8. Reliability and Fault Tolerance. The reliability and fault tolerance of WBAN are crucial parameters which directly influence the diagnostic quality of patients. The channel quality of the network and end-to-end communication efficiency are two ways to gauge reliability. In WBAN, the term "fault tolerance" refers to the ability of the network to continue operating even if some nodes or links between nodes fail and to limit the impact of failure to a small number of components [58]. Unidentified life-threatening conditions can result in death. The change in environmental factors, such as climate variability (e.g., heat and humidity), can cause biosensors to malfunction. Therefore, a reliable routing protocol should be able to identify and fix these errors to ensure data transfer and the network keep functioning.

6.9. Quality of Service (QoS). The heterogenous nature of the biosensors employed in WBANs necessitates various QoS requirements for the collected data. The QoS is crucial, especially in healthcare applications where delayed or inaccurate information can have fatal consequences, even resulting in death [5]. However, vital information (such as obtained from EEG and ECG) must be transmitted without delay or loss at all times; otherwise, it is worthless. Therefore, the WBAN must have the ability to transmit data consistently and in real time. An efficient routing protocol can fulfil this need by ensuring the necessary QoS (delay/reliability).

6.10. Security and Confidentiality. Security ensures that the recorded data is transmitted securely from source to destination in a hostile environment [59]. Data that has been captured is said to be confidential if only authorized parties are allowed to access or utilize it [60]. WBANs must adhere to a number of fundamental requirements, two of which are security and confidentiality, and can be achieved by standard methods of encryption. Due to the WBANs' limited computing, memory, and energy resources, these conventional procedures are, nevertheless, impracticable. This makes it hard for developers to come up with effective routing protocols that protect against routing attacks [61] and keep data secure and private.

The researchers can work on these open challenges while designing WBAN routing protocols. The summarized open research challenges are specified in Table 8.

7. Conclusions

This survey article classifies and briefly analyzes a variety of current routing protocols used in WBANs from the literature that is currently available. It is clear that the routing protocol is crucial to the development of any effective, dependable, and affordable wireless body sensor network. The routing protocols for WBANs are divided into five categories based on the form and type of networks: cluster-based, cross-layered, postural movement-based, QoS-aware, and temperature-aware protocols. It has been noted that rigorous classification of protocols is not practical. Additionally, it is found that every protocol is application-specific; i.e., distinct protocols are employed for regular tracking and critical medical cases. In this paper, a comparison study of many protocols has been done in order to choose the one that is best for the application being targeted. In order to help the researchers to concentrate on their chosen area of interest, the future directions for each group of protocols are also offered. The open research challenges are also specified, which guides the researchers to focus on various parameters that need to be addressed while designing routing protocols in WBAN. This survey will be helpful to the researchers as they examine the WBAN routing protocols that are currently used in the field of healthcare systems.

The future work will involve developing and implementing a body sensor prototype with a novel routing protocol that will be highly energy-efficient and reliable for the rehabilitation of elderly people using a micro-controller-based system with the appropriate sensors. To obtain the QoS and trustworthy data, future routing protocols for WBANs should be taken into consideration. As a result, data security must be taken into account. Upgrades to network capacity and quality are required for effective data transfer. Hotspot nodes can be avoided by placing more biosensors on the human body. This could be accomplished by creating a routing system that uses the least amount of energy possible. Consequently, the human body's tissues would not be impacted.

Data Availability

There is no available data.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding this paper.

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