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Comprehensive Review on Routing Protocols for Wireless Body Area Networks

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Abstract
In today's era, the deployment of wearable and implantable devices and sensor nodes is expanding, giving rise to new research directions in Wireless Body Area Networks (WBANs) to address the various challenges such as efficient routing, security, interoperability, power consumption, energy optimization, fault-tolerance, reliable communication, etc. Among all the challenges, routing is one of the most important factors that needs consideration for data transmission. With the use of wearable (on-body) or implanted (in-body) sensors, WBANs are utilized in e-healthcare systems to retrieve physiological parameters from the human body, and systematically route them to a remote server. High network performance and effective communication depend on the routing protocol's design. Consequently, the primary objective of this work is to provide a comprehensive taxonomy of the most advanced routing protocols used in WBANs. This review paper discusses the different WBAN routing protocols from recent years, reported from 2019 to 2024. The different categories related to WBAN routing are addressed while highlighting their objectives, problem specifications, advantages, disadvantages, simulation tools, and performance metrics. These routing protocols are evaluated and compared in terms of performance parameters like energy, congestion control, data priority, scalability, latency, Packet Delivery Ratio (PDR), node temperature, network lifetime, throughput, security, path loss, etc. Finally, the research gaps are summarized from the reviewed protocols, and future research aspects are discussed.

Keywords- Networking, Wireless body area network, Routing protocol, Healthcare, Energy-efficiency, Network lifetime.

1. Introduction

Wireless Body Area Network (WBAN) is a wireless technology that enables networking between various wearables and computable implantable devices having sensors placed in or around the human body. It has gained a lot of importance in the last decade due to the health issues caused due to lifestyle changes and increased public awareness of monitoring physical health (Akyildiz et al., 2002; Lont et al., 2014). Thus, the demand for body area network technology is growing exponentially with the increase in smart wearable devices for fitness tracking, and managing emergency conditions and long-term diseases. Healthcare and medical systems gained importance with this technological advancement and have made our lives much more convenient (Ananthi & Jose, 2021; Fu et al., 2012). Moreover, the improvement in wireless communication is a major driving factor for enhanced WBAN performance. The global demand for digital healthcare is being driven by increased smartphone adoption and use, wearable technology acceptance, mHealth apps, usage of telemedicine, and other factors. The huge investments in the remote healthcare industry are one of the prominent factors that support WBAN market growth and hence the remote healthcare market is seeing more investments, which is fostering WBAN expansion.

WBAN connects independent nodes widely known as sensors either in the form of wearable like smartwatches, implants like pacemakers, ingestible sensors like capsule endoscopy in the form of pills, embedded like in smart clothes, etc (Tavera et al., 2021). It uses these sensors to gather health-related data (human vital sign information) and transmits the gathered data to the server by the use of wireless technology (Leu et al., 2018; Patnaik & Prasad, 2023). It is a crucial component of WSN and has a wide range of uses at home and in industries for home health monitoring, ambient living, sports, defense, hospitals, military, games, etc (Arefin et al., 2017; Kumar et al., 2023). It is gaining demand and is becoming an emerging technology as it improves the quality of life and provides better healthcare facilities. **Figure 1** represents the block diagram of a typical WBAN:

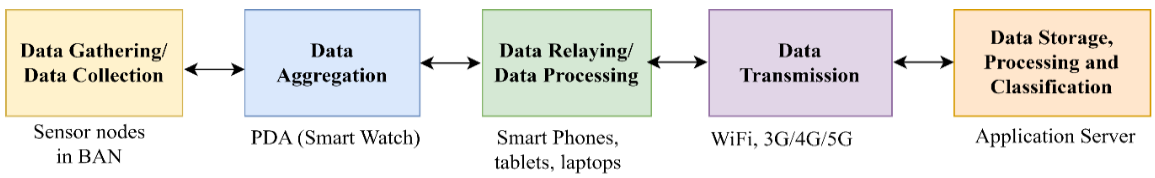

Figure 1. Block diagram of WBAN.

This survey paper gives an overview and insights into the current routing protocols available in WBAN from 2019 to 2024. A comparison in the form of a table is done considering different parameters and WBAN performance metrics. The objective, characteristics, simulation tool used, and various performance metrics for each routing category are discussed in the study. The paper explores and uncovers all of the advantages, disadvantages, applications, and research opportunities of various WBAN routing protocols to provide a comparative study for various kinds of routing protocols. Various problems have been identified from the existing routing protocols that can be considered as part of future studies for further enhancements by different researchers. The prior survey articles did not provide this kind of in-depth analysis of WBAN routing methods. This article will help to understand the current scenario of the research related to WBAN routing as it focuses on the challenges and limitations of existing protocols.

1.1 Motivation for WBAN

Patients, doctors, physicians, and care providers are increasingly utilizing remote healthcare technologies as a consequence of the COVID-19 outbreak. To avoid going to hospitals while the epidemic was going on; many patients adopted virtual and real-time health monitoring services and platforms (Wu et al., 2017). The demand for real-time health monitoring is expected to expand as virtual health care services including chatbots, audio, and video are becoming more widely used over the world. In addition, it is advised that individuals with chronic illnesses should stay away from hospitals and avoid visiting hospitals to prevent any sort of infection thus encouraging patients and healthcare professionals to use remote patient monitoring services (Kour & Kang, 2019). Increased chronic illness burdens, a growing old-age population, rising healthcare prices, and a lack of healthcare resources all are the driving forces that demand remote and real-time patient monitoring and are expected to put further stress on healthcare organizations (Jones & Katzis, 2018). In addition, the remote healthcare sector is seeing an increase in investments, which is encouraging its expansion internationally.

The major contributions of the article are:

- The article describes WBAN architecture, its importance, related technologies, communication standards, applications, and challenges. A taxonomy of the WBAN routing protocols from recent years under different categories are explored and the working of each routing technique proposed in the literature is discussed.
- A comparative analysis of routing protocols is performed, in terms of the objectives, problem specification, contribution, advantages, disadvantages, routing category, tool used, performance metrics, simulation results, performance evaluation, and future scope.
- An analytical comparison for each routing protocol based on various evaluation metrics which include network partitioning, congestion control, delay, energy efficiency, fault-tolerance, latency, network lifetime, PDR, reliability, priority, use of relay nodes, scalability, security, stability, etc.
- Further, the open issues and challenges have been highlighted with a focus on research gaps found in the WBAN routing domain from the literature analysis. This review serves as a reference for understanding the research gaps and future research directions related to WBAN routing.

This review article is organized as Section 2 provides the background of WBAN with a discussion on different wireless technologies, communication standards, and WBAN architecture. The various WBAN requirements are also presented in this section. This section also outlines the different challenges and provides research gaps associated with WBAN routing. Section 3 elaborates on related work. Section 4 represents the methodology adopted for the selection of the article. Section 5 details the taxonomy used for classifying WBAN routing protocols. Section 6 explores the various existing routing protocols under each category from recent years (2019-2024) and Section 7 compares different routing protocols based on various performance metrics and provides a summary related to each routing category. Section 8 highlights the latest technologies like Artificial Intelligence (AI), 5G, blockchain, etc., and their impact on WBAN. Finally, Section 9 concludes the paper with a summary and the future scope. Refer to Appendix A for the graphical abstract (**Figure 12**).

2. Background of WBAN

2.1 Wireless Communication & Classification of Different Wireless Technologies

During the 19th century, the term "wireless communication" was first used and since then wireless communication technology has also evolved. It is one of the most useful and effective techniques used for transmitting data and information across various types of devices located remotely. Using electromagnetic waves such as Infrared (IR), Radio Frequency (RF), satellites, etc., data may be transmitted through the air by the use of wireless technology, replacing the cables and wires that were used earlier for data transmission. Mobility is the main benefit of wireless communication. Apart from mobility, this communication method is easy to use, flexible, and provides remote access. Wireless technologies based on various parameters like range, technology, communication standard used, application area, power consumption, and modulation (Li et al., 2010; Nelson et al., 2020) can be classified into different categories as shown in **Table 1**. The BAN works in proximity to the human body and has a very short range of approximately 0 to 5 meters, like Ultra-wide Band (UWB), Bluetooth technology, Radio-frequency identification (RFID), etc. The second category is Wireless Personal Area Network (WPAN) having a short range of 10-100 meters and uses Zigbee and Bluetooth technology; followed by Wireless Local Area Network (WLAN) with a short/ medium communication range varying from 100-1000 meters like Wi-Fi networks. Wireless Neighbourhood Area Network (WNAN) has a coverage of approximately 5 to 10 km whereas Wireless Metropolitan Area Network (WMAN) supports medium/long communication ranges covering an area of 20-50 km like WiMAX with data rates of 2-70 Mbps (Ha, 2015). Finally, the Wireless Wide Area Network (WWAN) covers a long range of up to 100 km, like 2G/3G/4G/5G (cellular network), and Low-power WAN (LPWAN). LPWAN technology is one of the most popular techniques used in WWAN networks. It is one of the most used long-range and low-power networks which is suitable for the current IoT era.

Table 1. Classification of wireless technologies.

Parameters	WBAN	WPAN	WLAN	WNAN	WMAN	WWAN
Coverage	0-5 m	10-100m	~100 – 1000m	~5-10 km	~20-50 km	Above 50 km & upto 100km
Standard/ Protocols	IEEE 802.15.6	IEEE 802.15	IEEE 802.11 /a/b/g/h/ac/af/ah	Wi-SUN Zigbee-NAN 802.15.4g	IEEE 802.16	IEEE 802.20 (MobileFi)
Range	Very-Short	Short	Short / Medium	Medium	Medium / Long	Long
Technology	RFID, Zigbee, UWD	Bluetooth, Zigbee, NFC, IR, IrDA, UWB, RFID	WiFi, Zigbee	LoRA, SigFox, 6LoWPAN	WiMAX	2G/3G/4G/5G, GSM, LPWAN, LMTS
Data Rate	10 kbps to 10 Mbps	1 to 2 Mbps	1,11,54,200 Mbps (1-54 Mbps)	2-70 Mbps	<75 Mbps	10Kbps to 100 Mbps (Low to medium)
Modulation	OFDM, GFSK, BPSK, DS-UWB	FHSS, DSSS, O-QPSK	OFDM, DSSS	FSK, QPSK, OFDMO	QPSK, 64-256 QAM	Cellular Access (TDMA, CDMA, OFDM)
Ownership	Private	Private	Private	Private	Private or Public	Private or Public
Area	Within human body	Within room	Within office/ Building	Within university offices	Within city	Within countries (Worldwide)
Application	Smart and medical devices	TV Remotes, Device-to-device, Notebook to PC, Peer-to-Peer	Enterprise networks (Computer to computer and the internet)	Conference table devices (Hotspots)	Internet (Homes and business)	Smart phones, PDAs, Cellular networks
Frequency	2.4 GHz, 800 MHz, 900 MHz, 400 MHz	2.4 GHz	2.4 GHz (802.11 b/g) 5GHz (802.11a/n/ac)	315, 433, 490, 868, 951 MHz	2 to 11 GHz	3G (900, 1800, 1900, 2100 MHz), 4G (2-8 GHz)

2.2 Architecture of WBAN

The increased treatment cost and advancements in technologies have led to demand for the development of new techniques in WBAN. WBAN incorporates extremely small nanosized health sensors or nodes that use low power to monitor specific human vital parameters. The architecture of WBAN is divided into 3-tiers namely Intra-BAN, Inter-BAN, and Beyond BAN communication (Antonescu & Basagni, 2013). The three tiers are formed according to their functionality and service provided. The details of each tier of WBAN are as follows:

Intra-BAN communication **(Tier-1):** It consists of medical sensors that are placed on the human body either in the form of wearable devices like skin patches, smart glasses, jewellery, sweat sensors, smart watches, or implantable like retina implants, pacemakers, tooth implants, etc. or in the form of ingestible sensors; to collect the information regarding the human body health like temperature, heart rate, EEG, ECG, etc. for remote monitoring. The patient's data collected by different sensors is aggregated by the PDAs and forwarded or transmitted to the controller node for further processing. Due to the battery-operated nature of the sensors and their low bit rates, this layer must be configured with a QoS provisioning MAC protocol (Movassaghi et al., 2014).

Inter-BAN communication **(Tier-2):** The data gathered at Tier-1 has to be sent to the remote station at Tier-3, for which a bi-directional link must be established between the hub and off-body or external device, such as an access point (AP). Tier-2 receives the health-related information from Tier-1 and forwards it further to Tier-3. There is a wireless setup at Tier-2 that acts as a gateway to forward the information (Khan et al., 2012). Wireless networking technologies, including Bluetooth, ZigBee, Wi-Fi, WLAN, and GSM (3G/4G/5G), are used for communication over the network. In addition to this, a laptop, tablet, other BAN, or smartphone can be used as a gateway.

Beyond-BAN communication **(Tier-3):** The 3rd tier of the WBAN architecture performs beyond-body communication and is responsible for transmitting data between Tier-2 and Tier-3 and also for storing, processing, and analyzing the information collected through health sensors. The server, usually named a database or medical server, saves the health records and maintains a medical history of the patients electronically to be used as a reference by the concerned authority (Gandhi & Singh, 2020). So, it helps in health data management, which can be used for analysis and decision-making by healthcare providers like caretakers, nurses, doctors, medical staff, and emergency rescue staff to provide better remote patient monitoring facilities. **Figure 2** represents the 3-tier WBAN architecture.

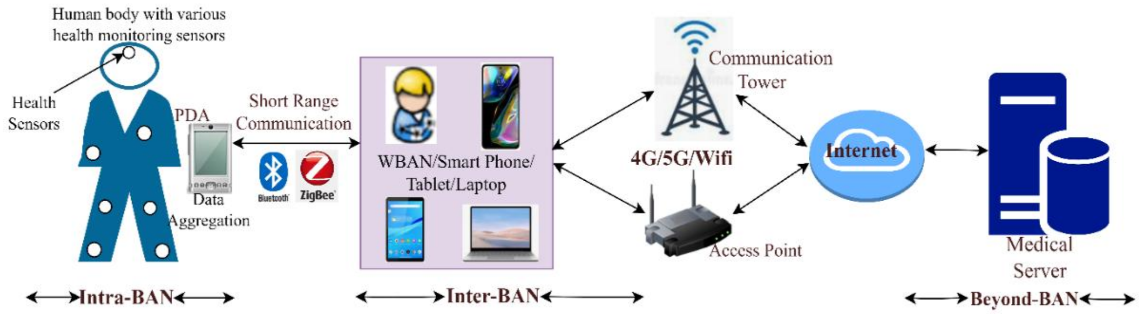

Figure 2. 3-tier architecture of WBAN.

2.3 Requirements for WBAN

The key requirement for WBANs is that the sensors used in this type of network must be small in size and should have long battery life with enhanced security features as these specialized networks carry health-related data of the human body. The data produced by sensors must be error-free and accurate. It should support short-range communication without interference, and the connection must be reliable. The human skin tissues should not be affected or destroyed by the closely placed WBAN devices. Long battery life and low power consumption are the main requirements of any WBAN system, which can be achieved through low-power transmission and duty cycle, which enables lower power consumption in nodes and ensures prolonged battery time (Fu et al., 2012). **Figure 3** shows the main key requirements for a WBAN for its proper functioning.

The different WBAN requirements as shown in **Figure 3** are discussed below in detail (Khan et al., 2012; Shokeen & Parkash, 2019):

- *Interoperability*: The systems need to be scalable and provide constant communication. It must guarantee unhindered data transfers between various networks.
- *Security*: The security of the data is required to protect it against different types of attacks. The WBAN link must be secured because it consists of various nano sensors that measure the patient's vital

information. The security of healthcare data is both crucial and challenging because of the risk of both active and passive attacks.

- *Biodegradability*: WBAN consists of implantable sensors, and the removal of implantable sensors can increase the chances of infection and lead to tissue damage, thus resulting in a longer recovery time. Since the biodegradable sensors do not need to be removed, using them solves these types of issues. Hence, the sensors should be made such that they can completely dissolve into bodily fluids.
- *Low power consumption*: The power consumption must be minimal to prolong the battery life. It's very difficult to remove the sensors from the human body again and again. Different techniques have been developed to reduce power consumption.
- *Self-healing*: For the WBAN networks to operate continuously without interruption, they must possess the ability to self-heal.
- *Low latency*: Latency is the time taken by data to reach its destination from the source and is measured in milliseconds (ms). The latency must be low to reduce energy consumption, and its specifications are different for different data types.
- *Data integrity*: The data generated should be meaningful and in a continuous fashion to be utilized efficiently for real-time applications.
- *Accuracy*: The data acquired by the sensors should be precise and accurate. As it deals mainly with human health data any decision related to the human body is entirely dependent on the data being generated by the sensors.
- *Fault-tolerance*: WBAN networks must have some fault-tolerance mechanism to avoid data loss. A neighboring backup node can assume control of a sensor node's function in the event of failure, preserving critical data.
- *Reliable communication*: The WBAN networks must be highly reliable, preventing network failure. The routing database must automatically update its routing tables and re-plan the path in the case of any failure to provide data throughout, thus making the connection reliable.

Figure 3. WBAN requirements.

2.4 Challenges and Research Gaps in WBAN Routing

Designing an energy-efficient, secure, and reliable protocol for routing the data packets is a major challenge due to the dynamic nature of WBANs. Consideration of postural mobility, node temperature, QoS, priority, data redundancy elimination, and designing an energy-constrained protocol that can ensure end-to-end path reliability are the important aspects of a network that need consideration for efficient routing (Bangash et al., 2014). Satisfying the delay constraints, increased network performance, bandwidth constraints, node temperature maintenance, reliable connection, fault-tolerance, and secured networks are the major research challenges that need exploration to develop efficient routing mechanisms for better communication (Antonescu & Basagni, 2013). Incorporating the latest AI-based machine learning techniques can help achieve better performance and overcome the various challenges faced by WBANs nowadays. The development of an efficient routing protocol is a challenging and quite exciting research area (Menaga et al., 2022). Device mobility also has a great impact on network performance through changes in topology, which lead to link disconnections recursively, energy wastage, reduced throughput, packet delay, and congestion as a result of unnecessary control messages transmission during the route repair phase (Sharma et al., 2021a). The natural energy harvesting techniques like vibration and heat produced by the human body can be utilized to enable autonomous WBAN and extend the network lifetime significantly (Goyal et al., 2023). Moreover, prioritization of emergency and critical packets is required for the successful and on-time delivery of data packets at various access points (Oleiwi et al., 2022). Some of the challenges that have been identified from the literature by comparing different routing protocols are provided below:

i. ***Energy efficient routing*****:** As WBAN, sensor nodes operate on batteries, and it is impossible to remove or recharge the battery in many applications like implantable scenarios; for continuous and long-time monitoring, the sensor's battery power should be saved. Natural energy harvesting techniques like vibration and heat produced by the human body can be utilized to enable autonomous WBAN and extend the network lifetime significantly. Energy-efficient routing techniques need to be developed that ensure energy conservation of sensor nodes to enhance the network lifetime. Moreover, a novel technique and criteria are required to select the forwarder node to make energy-efficient WBAN networks.

ii. ***Congestion control*****:** One of the major threats to WBAN is congestion. It results in a loss of data packets which can drastically affect the network performance entirely. The unpredictable traffic load, limited bandwidth, and power constraints can trigger congestion problems in WBAN. Moreover, the nodes close to the sink get heavily overloaded due to increased use, thus resulting in congestion. Advanced algorithms could be developed that can correctly predict the severity of congestion and, based on that, suggest the sending rate that can be adopted to minimize the congestion. Further network congestion can be avoided by putting limits on the multi-hop scheme. This will also help to keep control over the formation of energy holes in WBAN.

iii. ***Security*****:** The security of the data collected is a major and unsolved concern related to WBAN. The data collected from sensors in WBAN must be transmitted securely. As WBAN carries private and critical data, any tampering with this data can result in adverse effects. Enhanced security-based routing techniques are required to protect WBAN from various attacks while efficiently maintaining data integrity and confidentiality.

iv. ***Mobility support*****:** The link may get broken or lost due to postural change and human body movement resulting in a change of network topology, thus affecting the network performance and resulting in recursive link disconnections, delayed packet transmission, congestion, degraded throughput, and energy waste as more control packets are required for repairing the route. As human behavior depends on certain factors like age, body structure, environment, health conditions, etc., they should also be considered when designing the appropriate mobility models. Human behavior and body pattern recognition should be considered in developing enhanced mobility models for better performance. Current mobility models are not enough to describe the movement of nodes accurately, so there is a need to work on developing better models that consider mobility patterns. Techniques can be developed that could predict human body movement in advance so that the routing path can be refined in advance. Mobility models should mimic the movement pattern of the targeted applications realistically.

v. ***Node temperature management*:** Due to communication radiations, frequent data collection, and circuitry power loss, the sensor node's temperature may rise in the case of WBAN. The researchers must consider the issues related to the node's overheating to avoid human tissue damage. To avoid the radiation absorption problem the energy consumption must be kept to a minimum range. Detecting the hotspot nodes in advance and re-routing can help avoid hotspot node formation and reduce delay in data transmission, thus avoiding high energy consumption. While developing any of the WBAN applications, SAR (Specific Absorption Ratio) must be considered. Mobility support can be combined with temperature-aware routing to provide better and enhanced performance.

vi. ***Delay-sensitive data delivery*:** As WBAN carries critical data related to human vital signs so more practical and delay-tolerant routing techniques are required for the on-time delivery of data packets. There is a lack of an optimal number of relay nodes, due to which there is uneven load distribution among sensor nodes. Improving link quality, and bandwidth, and solving network partitioning issues can help reduce the delay (Guleria et al., 2021). The introduction of more relay nodes will help to distribute the load and timely transmission of sensitive data.

vii. ***Multi-hop limitation*:** To reduce energy consumption and increase network lifetime, there must be a restriction on the number of hop counts. Mostly, WBANs use single-hop topology to limit human body exposure to radiation and to conserve energy, while research is needed to support multi-hop topologies to get high efficiency.

viii. ***Quality of Service* (QoS):** The necessary QoS parameters like delay, throughput, PDR, priority, and reliability need consideration for efficient, error-free, and timely data transmission. Sometimes, the packets are dropped to avoid congestion, resulting in the loss of data packets. The placement of the sink has a great impact on throughput. Better buffer management techniques and reliable routing techniques can be developed to avoid loss of data packets, especially critical data packets, in case of congestion or link breakdown. The reduced dropping probability will result in increased network performance.

ix. ***Fault-tolerance*:** The fault-tolerance is one of the most crucial parameters that influence the quality of patient monitoring. It means maintaining network operations even in case of link or network failures for smooth data transmission. Link failures can occur for various reasons, such as interference, the collision of packets, congestion, etc. There is a need for fault-tolerant routing solutions to avoid link failures to enhance network stability and network lifetime. The fault-tolerant routing protocol that can use ML concepts to identify the nodes that can cause a fault in advance should be designed to fix the errors beforehand to make the network work throughout by ensuring successful data transmission.

x. ***Priority*:** Prioritization of emergency and critical packets is required for the successful and on-time delivery of data packets at various access points. The WBAN demands prioritization of data due to the heterogeneous nature of data generated by the health sensor nodes to provide better QoS.

xi. ***Scalability***: While designing routing protocols, scalability is the most important parameter that needs to be focused in the application development process for WBAN. Scalability is a major challenge in dense scenarios due to performance decreases. Future work can focus on designing the protocol that will be scalable and flexible to various alterations in WBAN like the addition and removal of sensor nodes as per the requirement from time to time. Automatic maintenance mechanisms and routing updates can help to reduce the overheads related to the addition of new nodes and increase overall network performance.

xii. ***Network topology***: WBANs energy consumption & performance are affected by the change in network topology and a node's energy get depleted quickly if the load on sensor nodes is unevenly distributed, resulting in an energy hole. So, network topology should be defined with care focusing on load distribution also (Ahmadzadeh, 2023).

Table 2 highlights the research gaps analyzed from the literature analysis:

Table 2. Research gaps related to WBAN routing.

S. No.	Parameter	Problem identification and solutions
1.	Enhancing QoS	Protocols that reduce latency, increase throughput, consider data priority, enhance reliability, and are scalable can be designed.
2.	Energy harvesting	Energy-efficient techniques and energy harvesting can be developed that can help in conserving energy and decrease the total energy depletion extending network lifetime.
3.	Network partitioning and topology	Minimize the impact of network portioning by developing techniques that consider the dynamic nature of WBANs thus allowing more flexible intra-posture body movements.
4.	Improved security and privacy	Security in WBANs is of utmost importance and it can be achieved by developing new authentication schemes, and security-based protocols that use enhanced technologies like blockchain.
5.	Minimize thermal effects	The routing scheme can be designed based on AI that can detect hot-spot nodes in advance resulting in path change. The new routing techniques can allow for radiation absorption and optimize the heating impact, as a countermeasure for rising temperature.
6.	Minimize interference	The researchers can identify and design the routing mechanisms to make the networks resilient to interferences or to minimize them.
7.	Delay-sensitive data transmission	Emergency data need to be transmitted immediately without any delay so there is a need to develop routing schemes that are efficient enough to send the data without delay and they should also consider data priority for its efficient working.

3. Related Work

WBAN is the growing and most demanding technology in today's era as it enables the remote service of patients, old-aged, and physically disabled persons. It not only operates for healthcare, but it also finds its application in many fields like gymnastics, jogging, sports, assisted living, entertainment, military, and so on. Many challenges in WBAN need to be addressed as it deals with patient data which is very crucial and needs to be handled carefully. The recent years' papers from the literature are considered for WBAN for our study to perform the systematic survey in the WBAN area. Many papers in this domain describe the overall WBAN architecture, its topology, communication standard, routing protocols, layers, applications, etc. So, the below-mentioned survey papers helped to get an overall description of the various terminologies being used in the WBAN domain. These existing papers from the past helped to make a strong understanding of the core concepts of the WBAN that helped to make a strong foundation and base in the area of research while making it easy to explore this area further for future enhancement. The review and survey-based papers by different authors are discussed in **Table 3**, addressing their main concerns, limitations, and future challenges.

Table 3. Summary of the related work from recent years.

S. No.	Reference	Focus area (Summary)
1.	Ullah et al. (2022)	The paper outlines the various WBAN issues and challenges with a focus on different application areas. The various routing protocols are defined and categorized to show their performance analysis while considering various metrics that are important in the WBAN field.
2.	Marandi et al. (2022)	The WBAN concept with IoT, its architecture, and its applications are provided in this paper. The major contribution of work presented by the authors is the discussion of routing protocols and their challenges. The authors categorized and compared the various existing IoT-based thermal-aware routing protocols in detail, thus elaborating on the challenges, advantages, disadvantages, and future implications in this domain.
3.	Hajar et al. (2021)	The authors discussed the various research issues and future research directions in the field of WBAN. The paper gives a brief introduction to the IEEE 802.15.6-compliant WBAN technology and architecture. This comprehensive introduction provides readers with a basic understanding of the field of study. The various security needs and limitations of WBAN are being addressed, particularly in tier-1 and tier-2. Future directions regarding open research issues, challenges, and research opportunities are given.
4.	Taleb et al. (2021)	The paper aims to investigate the wireless technology used in WBAN systems. A comparison is provided that consists of advantages and disadvantages for different proposed wireless technologies used in the field of WBAN. The various WBAN applications are summarized in tabular form based on the type of sensor, wireless technology, and the methodology used. The authors concluded the paper with a discussion of the open research problems in this domain.
5.	Poongodi et al. (2020)	The authors discussed the IoT and its domain, covering the IoT stack in detail. The main aim of the study is to show the relevance of IoT in the WBAN field. The various terminologies and wireless technologies related to WBAN have been focused on. The history of wearable sensors in healthcare is presented thus providing the statistics of global market share by the wearables. The concept localization, data acquisition techniques, and IoT paradigm in WBAN were presented for a better understanding of WBAN and IoT.
6.	Qadri et al. (2020)	It was demonstrated how the system transforms from WBANs to Healthcare Internet of Things (H-IoT) and how this assist in setting the way for future advancements in all current areas such as software-defined network (SDN), blockchain, ML/AI, edge computing, AR/VR, tactile internet and other emerging technologies. The H-IoT systems are being transformed by these technologies, and this article explores how they're accomplishing this. It also offers a potential path for using these new technologies to improve QoS.
7.	Hasan et al. (2019)	The general WBAN communication framework, WBAN classifications, M2M architecture, and applications are highlighted in this review study. To ensure that the survey includes everything, a variety of potential technologies for WBAN is also covered to enhance WBAN system performance. This study also lists several WBAN challenges all of which need to be overcome and can be considered as future work.
8.	Khan & Pathan (2018)	In this paper, the authors explain the basic difference between WSN and WBASN. The existing energy-efficient routing protocols from the past have been presented. The WBASNs application, communication architecture, and security threats are discussed. The different radio technologies & protocols, programming frameworks, challenges, and open research issues are elaborated.
9.	Elhayatmy et al. (2018)	In this, the authors provided an overview of WBAN technology, its architecture, different layers, communication standards used, etc. The various challenges w.r.t physical (PHY) layer, MAC layer, and application layer are provided. Many open research issues in WBANs, their medical applications, and their impact on human life quality are discussed. The authors described different routing protocols in IoT-based WBAN and future work related to it.
10.	Salayma et al. (2017)	The papers provide an overview of WBAN and describe the motivation for the widespread demand for this emerging technology. WBAN's potential applications, standards, and various types of devices present are illustrated with a focus on the WBAN technology challenges. It describes fault tolerance and classifies the faults and different failures. The fault tolerance and the issues related to it are focused on as they are one of the most important requirements for WBAN to achieve reliable communication.
11.	Al-Janabi et al. (2017)	The paper describes the model and the architecture of WBAN with a focus on WBAN security. The various security threats are being discussed with the concern for the requirement of privacy in the WBAN domain. It also presents the latest security measures while presenting the open areas for future research.
12.	Awan et al. (2016)	The routing protocols needed in WBAN have been discussed in the paper. It gives insight into different routing protocol categories. The authors performed a detailed, comprehensive survey of the existing routing protocols in WBANs. The various challenges, and issues associated with routing protocols especially the issues related to energy are highlighted by the authors in this paper.
13.	Negra et al. (2016)	The authors investigated the various technologies and tried to link these with WBAN applications to maximize QoS. The authors presented different applications of WBANs in the medical domain. The paper's major objective is to present adequate wireless technology for different networks.

4. Methodology

Planning is required for the survey, which includes stating its goals, developing a successful search strategy to locate prestigious articles from highly reputed journals, and employing inclusion and exclusion criteria to sift through the papers that fall under the scope. This section describes the methodology adopted for selecting the articles to conduct the review systematically. The paper follows the PRISMA guidelines (Kitchenham et al., 2009) given by Kitchenham to get efficient outcomes from the review.

4.1 Database Source Selection and Search Strategy

The papers included in the survey are selected from reliable and popular database sources like IEEE Xplore, Scopus, ACM digital library, ScienceDirect, etc., and only the articles from these indexed journals are considered for the survey as the key search strategy and source selection effect the research quality. The popular repositories are used to conduct keyword-based searches to find pertinent papers and all e-resources with an emphasis on the titles, abstracts, and keywords were examined. Several constraints are taken into consideration to improve the quality of research.

4.2 Selection Criteria

To do the analysis, a search string is created and a few filters or selection criteria are used to search the top publications from different databases based on the topic of interest. The total number of articles initially retrieved from literature using the Scopus database using the search string: "Wireless Body Area Network" OR "Body Area Network" OR "Body Sensor Network" OR "WBAN*" OR "BAN*" AND "Routing" OR "Routing protocol*" is 429.

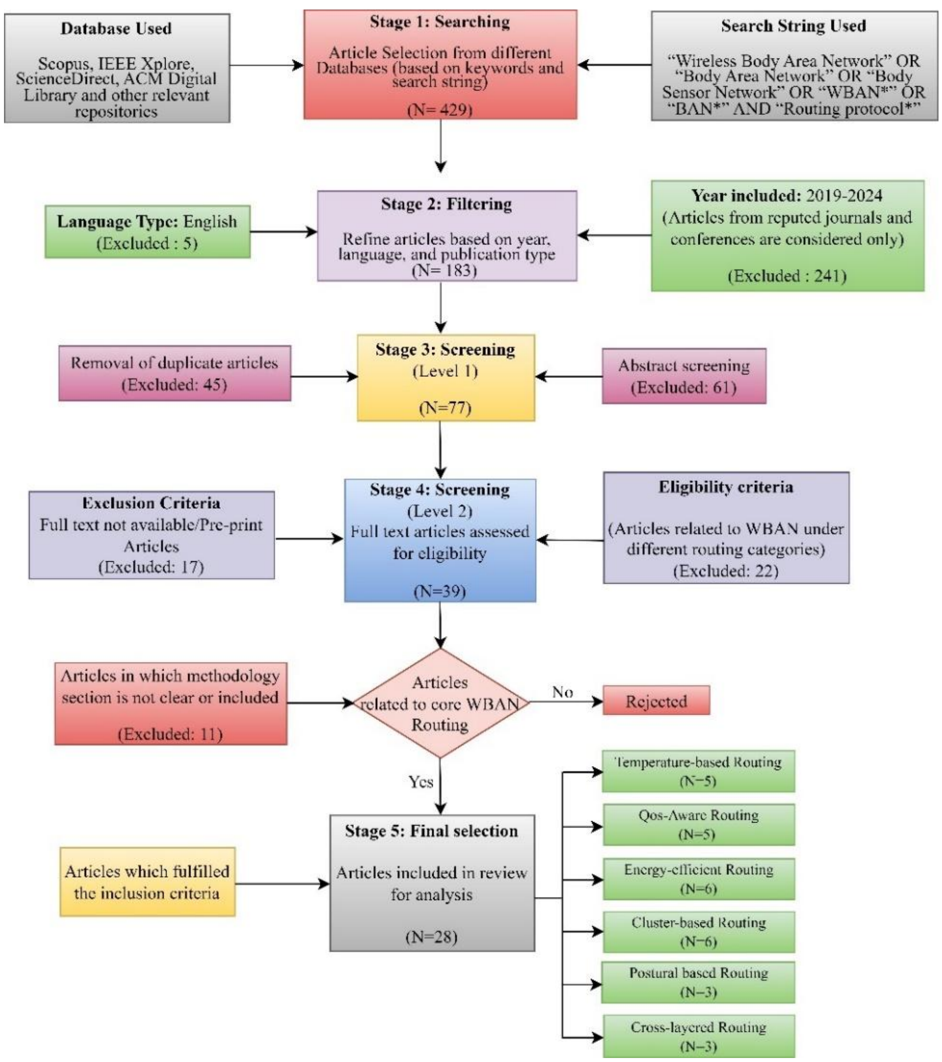

Figure 4. Methodology for article selection.

First of all, the articles are shortlisted based on publication year and the publications from 2019 to 2024 have been selected. The survey excludes the papers written in non-English and which are published before 2019. The articles are refined and those articles that meet the eligibility criteria are only selected to conduct the analytical review related to WBAN routing protocols. This survey excludes all the articles which do not discuss routing in WBAN. **Table 4** highlights the main filtration criteria used to select the articles and the detailed methodology adopted for article selection is shown in **Figure 4**.

Table 4. Search strategy.

Database used	Inclusion criteria	Exclusion criteria
Scopus, IEEE Xplore, ScienceDirect, ACM Digital library, and other relevant repositories	i) Timespan: January 2019 - 2024 ii) Language: English Only iii)Subject Area: Computer science and engineering iv) Articles from reputed journals and conferences v) Articles as per survey scope (Routing in WBAN)	i) non-English papers ii) Non-reputed journal and conference articles iii) Articles before the year 2019 iv) Duplicate articles v) Abstract screening /Full-text screening vi) Full text not available/ Preprint articles vii) Methodology not clear or included

5. Taxonomy on Routing Protocols in WBAN

In the past few years, routing in WBANs has gained a lot of importance and has become a prominent area for research. One of the major challenges of WBAN is routing, which includes the development of new protocols or techniques that can save node energy and increase network lifetime for efficient data transmission. Many protocols have been created to meet the various specifications and needs of WBANs, but still, many problems need to be overcome for enhanced network performance (Khan & Pathan, 2018; Seth et al., 2022). Effective, reliable, and accurate packet routing not only improves the network's lifetime of WBANs but also minimizes energy consumption. The routing in WBAN is categorized into six broad categories based on the functionality and area-focused (Shunmugapriya et al., 2022). The different routing categories are provided in **Figure 5** and are explained below while highlighting their use, functionality, and the type of problem each routing deals with to provide an overview of each routing category:

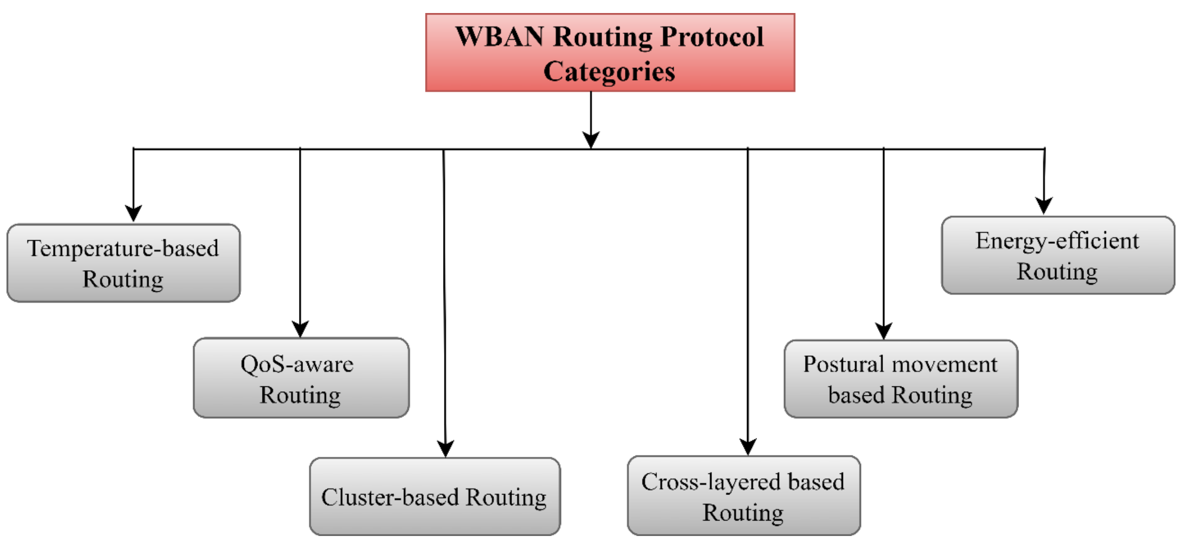

Figure 5. WBAN Routing protocol categories.

5.1 Temperature-Based Routing

One of the major research areas nowadays is to design efficient temperature-based routing protocols which are also known as thermal-aware routing protocols. It considers the node's temperature and the selection of a path based on temperature criteria. The main objective of this routing category is to avoid hot nodes and select an alternate path i.e., the path in which no hot-spot node is available to maintain the node's temperature. The selection of the alternate path prevents the node temperature from rising higher and prevents injury to human tissues as in WBAN the sensors are in direct contact with the human body (Aadil et al., 2019). The main aim of this kind of routing technique is to prevent the sensing nodes from becoming too hot during data transmission and the design a routing protocol that can maintain the node's temperature (Marandi et al., 2022).

5.2 QoS-Aware Routing

The QoS-based routing technique considers multiple factors like reliability, fault-tolerance, delay, data priority, packet loss, and security to ensure data transmission to the destination accurately. WBAN deals with patient monitoring remotely, so the health-related data is transmitted to the server through the network (Kumar & Raj, 2017). As medical data is sensitive and private, so security is also one of the major QoS parameters that need consideration to avoid misuse. The various QoS-related mechanisms are applied to provide accurate, reliable, and timely delivery of data packets at the source and destination (Liu et al., 2021). The priority of data transmission is one of the most important factors for real-time applications that need consideration for the timely delivery of sensitive patient data.

5.3 Cluster-Based Routing

It divides the nodes into various clusters with each cluster having its dedicated Cluster Head (CH), which acts as a central point that collects and aggregates data for forwarding to the base station. Clustering helps to conserve network energy as it reduces the number of transmissions, but on the other hand, it adds overhead due to the requirement of forming clusters and selection of efficient CH (Abidi et al., 2020). Dynamic clustering approach (Rani et al., 2020) can also be used for preserving the energy of the sensor nodes, and the CH can be elected based on various performance metrics such as node energy, throughput, network lifetime, etc as per application requirements. The cluster-based routing aims to preserve the energy of the sensor nodes to increase the overall network lifetime (Mehmood & Aadil, 2021; Shanthi & Sundarambal, 2019).

5.4 Energy-Efficient Routing

Energy is one of the most important parameters and plays an important role in increasing the network lifetime (Verma et al., 2020). As the sensor nodes are powered by batteries having limited energy and also the difficulty is faced in replacing the battery, especially in the case of WBAN networks; there is a need to design the routing technique that can minimize the node's energy consumption. The energy-efficient routing technique considers the sensor's node energy consumption and then selects the optimal path based on energy parameters. The routing protocols based on this type of technique select the optimal routing path that minimizes the network's energy consumption and increases its lifetime (Awan et al., 2016; Bhola et al., 2022). Designing an energy-efficient routing technique that consumes less energy is one of the most prominent areas in which research is going on to make more proficient and energy-efficient routing protocols.

5.5 Postural Movement-Based Routing

A routing strategy based on postural mobility largely considers how sensor nodes move and how people's postures change, altering the distance between the sink and the sensor nodes. In this, the assessment of distinct posture kinds is crucial (Kavitha & SendhilNathan, 2019). The network structure of the human body is examined in several dynamic postures concerning the node behavior, which significantly increases energy consumption and reduces network lifetime. Research is being done to foresee future human behavior to make judgments, analyze data in advance, and adjust the routing path as needed. This helps to eliminate delays, which in turn improves the data transmission rate (Kour & Kang, 2019). The current protocols only function when a scenario arises, which causes a delay that further affects network performance and is undesirable in the case of delay-sensitive applications.

5.6 Cross-Layered Based Routing

As the name indicates, the cross-layer routing technique enables the connectivity of data, information, services, resources, and applications across various layers for more reliable and effective communication. It refers to the sharing of information among different layers for optimal use of network resources and achieving high flexibility and adaptivity. Subsequently, it allows protocols belonging to different levels to collaborate and communicate the network status information. This, in turn, will ensure that the optimum path is taken for routing by taking into account performance needs and energy consumption (Bhanumathi & Sangeetha, 2017). To increase the performance of wireless networks, researchers have created numerous cross-layer WBAN protocols in recent years. Adaptive communication decisions, congestion avoidance, reliable communication, minimal energy usage, scalability, etc., are some of the goals of the cross-layer protocol.

Table 5 summarizes the findings made about the different routing protocol categories (Wali & Abdullah, 2020).

Table 5. Description of each routing category.

S. No.	Routing protocol name	Role of each routing category
1.	Temperature-based Routing	In this routing category; the temperature of the sensor nodes is considered for choosing the appropriate routing path for transmitting data packets.
2.	QoS-aware Routing	Routing is performed based on different QoS requirements like reliability, packet delivery ratio, throughput, delay, latency, etc.
3.	Cluster-based Routing	The sensor nodes are organized to form clusters and a CH is elected to perform data transmission between cluster and gateway.
4.	Energy-efficient Routing	Routing decisions are made to optimize the energy consumption of sensor nodes to enhance the overall network lifetime.
5.	Postural movement-based Routing	This type of routing category considers human postures or body positions or movement for routing data packets.
6.	Cross-layered-based Routing	Routing decisions are made by combining information from multiple protocol layers like MAC, physical, network, etc. to achieve better efficiency.

6. Review on Various Routing Protocols under Different Categories in WBAN

In this paper, several routing protocols have been studied related to WBAN under different routing categories proposed in recent years (2019 to 2024) from the literature.

The different routing protocols category-wise are discussed below that adopt different techniques and methodologies in routing strategy. The detailed taxonomy of WBAN routing protocols is provided in **Figure 6**.

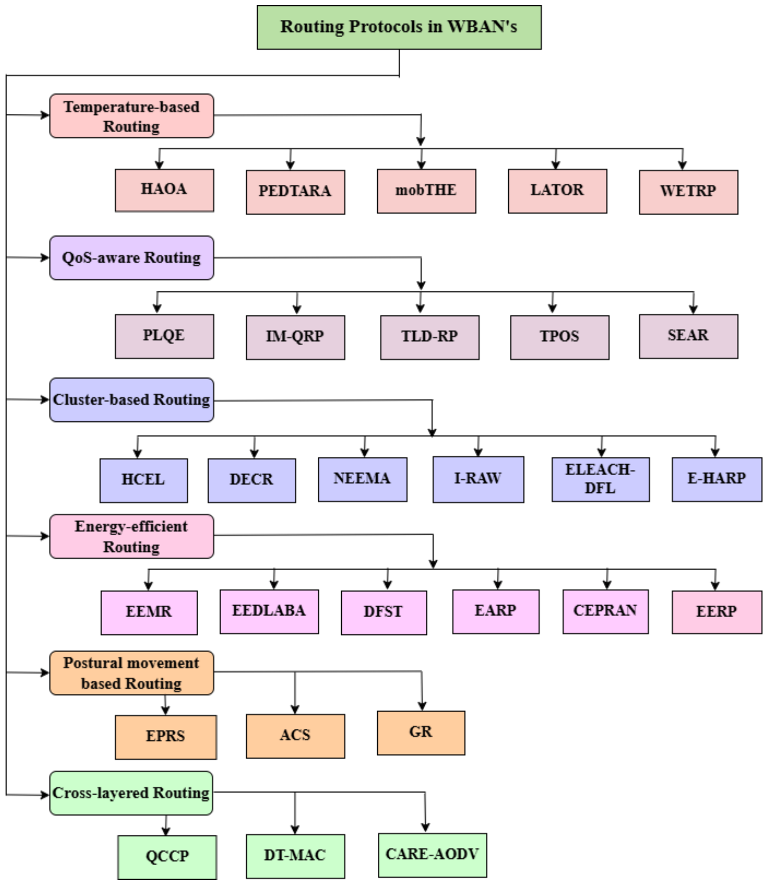

Figure 6. Classification of WBAN routing protocols under each category from 2019-2024.

6.1 Review of Temperature-based Routing Protocols

6.1.1 Hybrid Arithmetic Optimization Algorithm (HAOA)

Javaheri et al. (2023) presented a clustering and routing method for muti-WBANs that prevents temperature rise of the nodes improving the stability, and lifetime of WBANs. It helps to prevent the hot-spot problem caused by the sensor's temperature rise. It is based on a process called data aggregation to reduce data transmission amount to the coordinators. It uses Mamdani-based FLC to form clusters based on different factors like temperature of CH, remaining energy, no. of sensors, no. of similar neighbors, and path loss as shown in **Figure 7**.

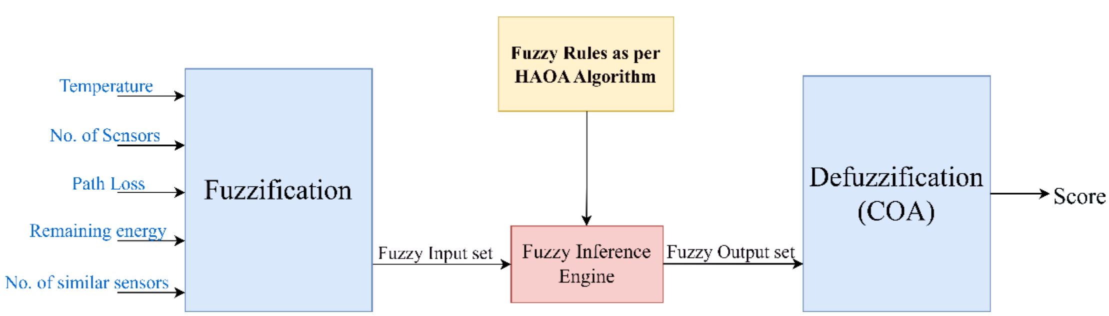

Figure 7. Proposed fuzzy logic controller (FLC) (Javaheri et al., 2023).

In addition to this, a hybrid metaheuristic optimization algorithm called HAOA is proposed, which tunes various FLC parameters and helps by properly selecting fuzzy rules for them. Further, data gathered from sensors are classified as regular and emergency data so that while handling normal data, sensors must adhere to strict temperature thresholds, however, these limitations are somewhat reduced for emergency data. The tool used for implementation is OMNeT++ and simulation results prove that the proposed protocol prevents hotspot problems and improves network stability and lifetime in WBAN by aggregating and sending the messages to the nearest coordinator. In the proposed work, the sensor's average temperature is calculated using the following Equation (1):

$$Avg_{temp} = \frac{1}{N_p} * \sum_{i=1}^{N_p}(\frac{1}{N_{si}}\sum_{j=1}^{N_{si}} Temp(sensor_{ij})) \quad (1)$$

where,
N_p: No. of patients,
N_{si}: No. of sensors in the i^{th} patient,
and,
$sensor_{ij}$: j^{th} sensor in the i^{th} patient.

The power consumption model to compute the sensor node's power consumption is as provided in (Arafat & Moh, 2019) and the following Equation (2) is used to calculate it:

$$E_{tran} = E_{tec} * n + \varepsilon_{amp} * n * disPLoss.$$

where,
ε_{amp} & E_{tec}: Power to run the amplifier circuit and transmitter.

6.1.2 Priority-based Energy Efficient, Delay and Temperature-Aware Routing Algorithm (PEDTARA)

Ahmed et al. (2022) proposed a protocol named PEDTARA, which is formulated by using MGCSMO optimization algorithm for optimal and shortest path selection that solves the problem related to energy, congestion, and temperature. The data classification process is used for grouping and classifying patients' data into different categories based on data priorities. In urgent and crucial situations, the routing procedure is changed based on the priority to meet the time constraints. For the SDN-coupled WBAN PEDTARA has been created for transferring the patient data. The data is categorized, and the set of readings, including the crucial vital signals, is given priority. To reduce the amount of time required for route discovery, the routing process is then started by creating paths using previous routing knowledge. It enables the selection of channels with minimal energy consumption, low congestion, and less heated nodes for handling vital data due to the use of the SDN method that offers a flexible and high-efficiency design. The proposed model calculates the fitness function as given below in Equation (3) with minimization as the objective:

$$f = W_A \times \text{residual energy} + W_B \times \pi\, link\ reliability_i + W_c * pathloss + W_d \times \sum queue\ length_i \quad (3)$$

where,
$W_A + W_B + W_C + W_D = 1$ are weights used to provide priorities to the four parameters defined in the fitness function.

MATLAB tool is used to simulate the proposed protocol that guarantees energy-efficient and congestion-controlled routing. It shows a 2% improvement in transmission rate or throughput; a 12% increase in PDR; an average of 0.2 J less energy consumption than the existing EOCC-TARA routing protocol; and a decrease in the number of overheated nodes by 10%.

6.1.3 Mobile Temperature Heterogeneity Energy (mobTHE) Routing Protocol

Selem et al. (2021); a WBAN-based IoT environment is designed to mitigate the redundancy and packet drop rate. This network is constructed with body sensor nodes and coordinator nodes. Hereby, the coordinator nodes are categorized into neighbor CN and serving CN; these two coordinate nodes act as gateways for routing sensed data packets. In this work, the 'mobTHE' protocol is presented to reduce the non-Light-of-Sight (nLoS) based on enriched LoS for patient mobility. This work mainly focuses on the mobility of nodes to communicate. Then the parent node (PN) is chosen based on 'on demand' based on the estimation of the strongest link capacity. The strength of the link between nodes is predicted by exchanging 'HELLO' packets using an indicator for signal strength. Further, the nodes are classified into three categories based on the data priority that is to be transmitted. The routing is executed concerning the node having high link capacity and transfers the data that is in LOS to the closest CN. Also, synchronization is established to mitigate packet redundancy. The simulation tool used is MATLAB and the simulation results proved that the mobTHE protocol decreases the sensor nodes and average sensor nodes temperature by 20% overall as compared to ''THE'' protocol. It also raises residual energy beyond 35% and 39%; extends lifetime beyond 52% and 58%; enhances throughput beyond 45% and 55%; and average energy consumption beyond 35% and 39% over the protocols namely, ''THE'' and ''iM-SIMPLE''.

6.1.4 Link-Quality Aware and Thermal Aware On-Demand Routing (LATOR) Protocol

Caballero et al. (2020) suggested a protocol named LATOR whose major objective is to maintain latency while preventing overheating for WBAN applications. As control traffic is reduced, it chooses the path based on Link Quality Information. OMNET++ is used in the experiments, and the simulation demonstrates that LATOR enables an improved delivery ratio by selecting an alternative way with better link quality. The LATOR protocol's main contributions to intra-WBAN communication are an improved packet delivery ratio, overheating prevention, and the provision of a backup path if a connection breaks due to overheating or a person moving around, respectively. Each node is in charge of monitoring its temperature to prevent overheating as it performs the route discovery and maintenance stages using a reactive method.

6.1.5 Weight-Based Energy & Temperature Aware Routing Protocol (WETRP)

Bhangwar et al. (2019) proposed a thermal and energy-aware protocol called WETRP, that aims to increase network longevity, total throughput, and route stability. This technique takes energy factors into account in the routing process to increase network lifetime and link-delay estimation to reduce hotspot issues. For distributing traffic load among the sensors, WETRP gives the same weight to link-delay estimation, temperature, and energy. The authors proved how their technique distributes the network traffic among the relay nodes, resulting in a smaller number of hotspots, and compared the results with, HPR and TARA, by varying data rates using the NS2 simulator. It produces better outcomes in terms of throughput, PDR, network longevity, and normalized routing load. In this; an active route might be inactive at any time due to various reasons like hotspot existence, node's energy deficit, etc. RERR is broadcasted to inform the situation of the upstream nodes, and the source node broadcasts a route request packet (RREQ) to find an alternative route.

6.2 Review of QoS-based Routing Protocols

6.2.1 Predicting Link Quality Estimation (PLQE) Routing Protocol

Iqbal et al. (2023) proposed a new protocol named PLQE to address various QoS-related challenges that are not focused on in the existing routing protocols, like link reliability, delay, and the link's probabilistic behavior due to postural body movement. The dynamic link status that occurs due to frequent network partitioning is ignored in existing routing protocols that occur due to postural body movements or node mobility, resulting in low throughput, route breakages, more retransmissions, and delays in data packet delivery. PLQE routing protocol overcomes all these challenges by dynamically identifying the reliable and optimal route for the transmission of data packets. The link between the nodes frequently disconnects as a result of postural body movements, resulting in poor network performance in terms of throughput, routing load, and end-to-end delay. The selection of the optimal route is made by using link quality or link reliability factor (LRF), link delay estimate (LDE), and expected probability (EP), which boosts the performance of the network considerably. To evaluate the performance of the PLQE, the proposed scheme, NS-2 has been used. It performs significantly better against ERRS and MCARMR in terms of normalized routing load, throughput, and end-to-end delay.

6.2.2 Improved QoS-aware Routing Protocol (IM-QRP)

Ahmad et al. (2022) proposed an IM-QRP protocol for WBAN-based HMS for the purpose of remote monitoring of patients with chronic illness or elderly people. The proposed protocol selects the most feasible route among the various routes available and can significantly improve network lifetime. The network's lifetime gets increased due to the arrangement of sensors, and the relay nodes based on the postural body movement of patients. This protocol provides the flexibility of increasing the quantity of sensor and relay nodes based on the requirement of a particular human health condition. The protocol when simulated using MATLAB achieves higher SNR, residual energy, and throughput by enabling a high number of packet transmissions. Convolutional neural networks are also utilized to analyze medical records and diagnose patients remotely for better decision-making. Comparing the proposed protocol to the current routing protocols reveals improvements of 10% in residual energy, 10% in link reliability, 30% in path loss ratio, and 7% in SNR.

6.2.3 Temperature, Link-reliable and Delay-aware Routing Protocol (TLD-RP)

Memon et al. (2021) presented a protocol named - TLD-RP that uses multi-facet routing techniques by considering important QoS parameters like packet drop ratio, link's reliability, path delay, throughput, etc. for the WBAN. It makes better decisions about dynamic channels as data packets are routed using the optimized path that meets the QoS standards. The main contribution of the research is to minimize delay, especially for the critical data packets that integrate factors like temperature, path delay, and link reliability. The proposed scheme is composed of three steps a prediction of path quality using the estimation of QoS, secondly improved route discovery mechanism for optimizing the discovered route in terms of QoS, and thirdly improved route maintenance mechanism that ignores if the routes are not satisfied. The traditional process in AODV routing protocol is followed by sending and receiving route requests and route replies respectively. For estimating path delay and making decisions an exponential weighted moving average function is used. This multi-facet routing technique tries its best to meet healthcare applications' QoS requirements. NS-2 is used to obtain the simulation results and the results show that the suggested scheme outperforms the state-of-art routing protocols of WBANs, namely, ENSA-BAN and P-AODV in terms of routing load, throughput, loss ratio, delay, and delivery ratio. **Figure 8** shows the framework and describes the working of the TLD-RP protocol:

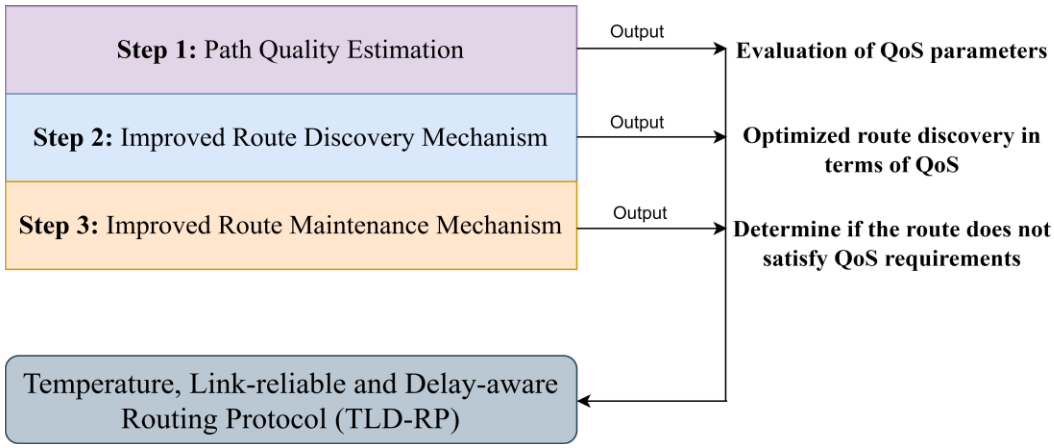

Figure 8. Framework of TLD-RP Routing Protocol (Memon et al., 2021).

6.2.4 Two-Stage Potential Game-Based Computation Offloading Strategy (TPOS)

Yuan et al. (2020) designed a TPOS for edge computing-enabled WBAN for efficient resource allocation by taking into account two priorities such as task and user. The main aim is to maximize Quality of Service (QoS). In the first stage, the game theory computes the utility function and penalty factor, and then the reward is estimated for the tasks in the queue. Further, in the second stage, the penalty factor and reward are updated, and then the computing resources are allocated to the offloaded tasks for processing. The proposed TPOS algorithm is implemented using Python and it achieves low latency and energy consumption even in scenarios with heavy workloads. The working of the algorithm involves two stages and the solutions for each stage. The first stage determines the offload task decisions. In the 2nd stage, the MEC server receives the offloaded task and based on that penalty factor is updated which helps to further allocate the resources.

6.2.5 Simplified Energy-balanced Alternative-aware Routing (SEAR) Algorithm

Mu et al. (2019) proposed a SEAR algorithm to balance energy consumption and minimization of delay. In routing, the next hop is chosen based on the current load and residual energy. Initially, the source node starts with a request packet and if a route exists, then the existing route will be used for data transmission. If there is an absence of a route, then the source node selects two paths for transmission based on the smaller number of hops. The main route and secondary route are R=1 and R=2 respectively, while in case of route failure, it will be R=0. As a result of the failure of both the selected routes, then the routes will be deleted from the routing table and again initiated with the route request. SEAR increases the capacity for data transmission while enhancing the routing request by using the forwarding mechanism to prevent the intermediate node's early death due to excessive traffic load. SEAR achieves higher throughput and network residual while reducing end-to-end delay as per the simulation results which are performed using the NS2 simulator.

6.3 Review of Cluster-based Routing Protocols

6.3.1 Hybrid Clustering Approach for Extending WBAN Lifetime (HCEL)

Helal et al. (2024) introduced an energy-efficient routing protocol called HCEL to address the limitations of existing routing protocols and design a new scheme to enhance WBAN's performance. The main aim is to extend the lifetime of all the nodes present in the network. The proposed protocol selects the parent nodes by leveraging a utility function based on proximity to the sink node, residual energy, energy threshold value, and the RSSI. The simulations are performed using Network and the results show that HCEL outperforms in several key performance metrics like network lifetime and stability, energy consumption, link reliability, throughput, and delays. Network lifespan, throughput, path loss, residual energy, and the projected transmission counts are all significantly increased in HCEL. The remarkable end-to-end delay reductions of 56% and 40% that HCEL achieved in comparison to SIMPLE and ERRS protocols, respectively, are especially significant and demonstrate the efficiency of the proposed scheme as a routing strategy for WBANs. With every transmission, the log-normal distribution-based RSSI value is updated. The cost function is calculated that takes into account each sensor node's proximity to the sink node and for energy efficiency, residual energy is taken into account in the cost function. Hence, the cost function, CF(*i*), for sensor node *i* is calculated as shown in Equation (4) below:

$$CF(i) = \frac{dist \times RSSI(i)}{RE(i)} \tag{4}$$

where,
d is the distance between the sink and node *I*,
RSSI(*i*): RSSI value of node *i*, and
RE(*i*): Residual energy of node *i*.
This assignment of duties keeps energy imbalances between nodes in check and lengthens the lifespan of the network. Incorporating mobility and security issues will be the focus of future work to further expand the capabilities and applications of WBANs in healthcare and beyond.

6.3.2 Distributed Energy-Efficient Clustering and Routing (DECR)

Arafat et al. (2023) proposed a routing protocol based on a two-hop strategy named DECR, which is distributed in nature. It is based on a clustering mechanism; where the information regarding neighbor nodes is obtained within a two-hop range during the cluster formation phase. MGWO, a nature-inspired meta-heuristic optimization algorithm, is used for CH selection and optimization. The use of grey-wolf optimization which is hierarchical in structure helps in data transmission by reducing transmission distance to each CH. The CH is selected based on residual energy and node connectivity in each cluster. To obtain neighbor node information like two-hop connectivity ratio (TCR), node stability factor (NSF), and energy factor (EF); hello packets are used. To measure the energy consumption of nodes, a first-order radio model (Arafat & Moh, 2019) is used and the following Equations (5) and (6) show the transmitted and received energy:

$$E_{Tx}(l,d) = \begin{cases} l * E_{elec} + l * \varepsilon_{fs} * d^2, & if\ d < d_0 \\ l * E_{elec} + l * \varepsilon_{mp} * d^4, & if d \geq d_0 \end{cases} \tag{5}$$

$$E_{Rx(l)} = l * E_{elec} \tag{6}$$

where,
$E_{Tx}(l,d)$: Energy required for transmitting l data bits over distance d.
E_{elec}: Energy required by electronic circuitry
d_0: Threshold distance and can be calculated as follows:

$$d_o = \sqrt{\frac{\varepsilon f_s}{\varepsilon_{mp}}}.$$

The proposed protocol extends the network lifetime as it uses energy-efficient clustering and optimal CH selection mechanism. The simulation results carried out using MATLAB show enhanced results in terms of PDR, control overhead, AE2E delay, cluster lifetime, and building time and energy consumption.

6.3.3 Novel Energy Efficient Hybrid Meta-Heuristic-based Approach (NEEMA)

Sharma et al. (2022) proposed a cluster-based and energy-efficient routing technique named NEEMA that uses a hybrid approach to resolve energy-related issues in WBAN. The meta-heuristic technique is applied which is hybrid in nature as it combines Tunicate Swarm Algorithm (TSA), as well as Genetic Algorithm (GA), called T-GA for delivering high convergence. The selection of CH is done according to the fitness function of T-GA. Various parameters are considered for the selection of CH that helps preserve the node's energy for achieving enhanced network lifetime and low energy consumption. The sensor nodes placed on the patient's body collect the data, and by using multi-hop communication data transmission is done to the healthcare providers. The relay nodes are also used to avoid hot nodes and for data forwarding. This scheme also provides scalability and hence can be applied to specifically large-scale applications like healthcare. The proposed technique NEEMA, implemented using MATLAB, showed enhanced performance in terms of network stability, energy, lifetime, scalability, and throughput as compared to the state-of-the-art protocols.

6.3.4 Intelligent Routing Algorithm for Wireless Body Area Network (I-RAW)

Sharma et al. (2021b) developed a protocol named I-RAW with the goal of improving network lifetime and minimizing the energy consumption of sensor nodes. The network is constructed with two sink nodes placed on the chest and the back to solve and reduce the hotspot problem. It is because of the single-hop communication performed on both sides of the human body i.e., the chest and the back. The nodes in the network are clustered, and a cluster head is elected using the Tunicate Swarm Algorithm (TSA) by taking into account residual energy, path loss model, distance, average energy, and energy consumption rate. The fitness function in TSA is estimated using initial node energy and residual energy. On selection of cluster head, the nodes follow TDMA scheduling for data transmission based on the assigned time slots. The following Equation (7) is defined to determine the residual energy of all the nodes:

$$F_1 = \sum_{i=1}^{n} \frac{E_{res}(i)}{E_{in}(i)} \tag{7}$$

where,

F_1 is the fitness parameter.

To analyze the I-RAW performance, MATLAB is used which takes into account the two scenarios, C1 and C2. In C1, the authors take into a total of 100 nodes with 0.5 J of energy whereas, in the scenario, C2 only 50 nodes are employed with 0.1 J of energy. The proposed protocol performs better in terms of packet delivery, network lifetime, and stability duration due to the efficient CH selection as compared to other state-of-art routing protocols.

6.3.5 Enhanced LEACH using Dual Fuzzy Logic (ELEACH-DFL)

In this paper, Park et al. (2020) proposed a cluster-based routing protocol called ELEACH-DFL protocol based on dual fuzzy logic. In fuzzy logic, Mamdani rules-based membership functions are developed, and the metrics, energy, and distance are taken into account for selecting the CH. After the selection of CH, routing is handled by consideration of energy, and distance between head and base station. The request messages are distributed to the members as per the created TDMA schedules. The fuzzy follows knowledge-based rules and it uses first interference. The proposed protocol maintains energy efficiency even if the first node generated is the dead node which is not in the case of LEACH. The stability factor is given much importance while selecting the cluster and CH selection. Hence, the hierarchical routing protocol is proposed that utilizes fuzzy logic mechanisms for cluster configuration and optimal CH selection to enhance the network lifetime. The proposed ELEACH-DFL is simulated using MATLAB, and its energy consumption is compared to that of the LEACH protocol. The authors used FND (first node dead) value which is typically used to assess energy performance and it is analyzed that FND efficiency increase rate of the proposed protocol over the LEACH protocol is roughly 32% in a 50*50 field. Furthermore, it shows the FND efficiency improvement rate of roughly 159% in a 50 *150 field.

6.3.6 Energy-efficient Harvested- Aware Clustering and Cooperative Routing Protocol (E-HARP)

Ullah et al. (2019) suggested an E-HARP protocol that uses 14 SNs and 2 sink nodes to make a WBAN topology for E-HRAP that is placed on various human body parts. The protocol uses a multi-attribute-based routing strategy for selecting the CH dynamically and it uses the co-operative routing concept. The CH is selected dynamically by considering multiple attributes by computing the cost factor that includes residual energy, transmission power, SNR, and energy loss in the network. For each transmission round, a new CH node is selected. During the first phase, optimal CH is selected by using cost factor metrics. For distributing load; a new CH is selected in each and every transmission round. During the 2nd phase, the cooperative effort technique is used to save the node energy by avoiding redundant data packet transmission. The proposed scheme helps to minimize the delay because of the load distribution mechanism and the use of dual sinks helps to deal with path-loss issues. The total residual energy is calculated using the Equation (8) below:

$$E_{total}(i) = E_{Res}(i) + E_{Harvest}(i) \tag{8}$$

where,
$E_{\text{total}}(i)$: Node's total current energy,
$E_{\text{Res}}(i)$: Residual energy.

6.4 Review of Energy-efficient Routing Protocols

6.4.1 Energy Enrichment Multi-Hop Routing Protocol (EEMR)

The goal of Pradeep & Kavithaa (2024) is to learn more about the behavioral aspects of metaheuristics used to find the best routes. The authors of this research have suggested the EEMR protocol, a complex route selection technique, based on their exploration of a unique metaheuristic method for enhancing network lifespan optimization. To perform CH selection, all sensor nodes on the body are positioned simultaneously, using Optimal K-Means Clustering. There are two phases in which the EEMR is supposed to function. The first stage involves implementing the Enhanced Flower Bee Optimisation Algorithm (EFBOA), whose main goal is to create a network of clusters that will increase the WBAN's network lifetime. The following stage uses the Dynamic Local Hunting and Location Discarding (DLH-LD) technique to determine which path is the fastest out of all the options. As a result, the suggested strategy has been investigated in two stages, using DLH-LD and EFBOA techniques to enhance optimal route selection and prolong the lifespan of sensor nodes, respectively. This way, an ideal approach for the sensor node and the gateway node is precisely determined by the EEMR protocol. The simulation results demonstrate that the proposed EEMR significantly outperformed the traditional methods in terms of path loss, cost estimation, energy consumption, throughput rate, and network lifetime. As per the simulation results the proposed protocol uses 30% less energy than the current procedures, prolonging the network's lifespan.

6.4.2 Energy-Efficient Distance- And Link-Aware Body Area (EEDLABA)

Zaman et al. (2023) proposed an EEDLABA routing strategy for WBAN. The main objective of the suggested protocol is that it must transmit the data with better stability while reducing energy consumption. The proposed routing strategy is hybrid in nature that combines the positive features of DARE and LAEEBA focusing on energy efficiency by using an efficient clustering approach. The clustering mechanism is used as it is the best way to increase the network lifetime thus avoiding delays and path loss. A total of nine nodes numbered 1-9 are deployed including the coordinator node I and the cluster head (CH) node on the human body; as a smaller number of nodes will consume less energy. 1 and 2 nodes are used as CH; 3, 4, and 9 nodes are used for continuous monitoring, while for action-driven monitoring the node 5, 6, 7, and 8 are used. It uses system models that include distance models and route loss while forming the equation. The results are obtained from MATLAB simulations and the proposed routing protocol gives the best results in terms of average path loss (dB), residual energy (j), average stability period, end-to-end delay (ms), and throughput (bits/sec) as tested and compared with the existing systems DARE and LAEEBA protocols.

6.4.3 Dual Forwarder Selection Technique (DFST)

Rahman et al. (2022) introduced DFST to increase throughput and minimize the energy consumption of nodes. The proposed technique uses the concept of dual selection of forwarder nodes in WBAN by grouping the sensor nodes into two groups, A and B, where the nodes are preprogrammed for categorization. This selection of two forwarders is chosen by computing the cost and the cost function is formulated by considering the distance and residual energy of the sensor node. Data transmission is done after the selection of the most suitable forwarder node. The scheduling is assigned for the selected forwarded using TDMA. In case of emergency data, the data is directly forwarded to the sink without selecting a forwarder. The proposed scheme helped to reduce energy consumption and increase the network lifetime, throughput, and stability period. Utilizing MATLAB and simulation results, the effectiveness of the proposed strategy has been assessed in terms of throughput, network stability, and lifetime. DFST has around 50% less number of dead nodes as compared to iM-SIMPLE and RE-ATTEMPT. The average throughput is 51% and 8% greater, and the residual energy is roughly 200% and 120% more than that of iM-SIMPLE and RE-ATTEMPT.

6.4.4 Energy-Aware Routing Protocol (EARP)

Wang et al. (2021) suggested a fuzzy control-based protocol named EARP for the selection of the best forwarder to route the sensed packets. The fuzzy logic operates by following three main functions fuzzification, fuzzy interference engine, and defuzzification. The data transmission is handled by the selection of the best forwarder for transmission from the source to the sink/ coordinator. For the selection of the best forwarder, three main parameters are taken into account, they are hop count, energy, and link quality. The fuzzy rules are defined separately for periodic and emergency data. The neighbour table is updated by the broadcast of Hello packets. The forwarder is elected with the computation of the node's energy, hop count & quality link. The link quality is estimated with the help of a signal strength indicator. The data sensed is categorized into two types periodic, and emergency data. From these parameters, the path benefit is determined and if the probability value is high, then it is chosen as the best forwarder. The best forwarder selection for both periodic and emergency data is based on the predefined 9 fuzzy rules. The following Equation (9) is used in the proposed scheme to calculate the residual energy:

$$RE_i = \frac{E_{res} - E_{th}}{E_{initial} - E_{th}} \tag{9}$$

where,
RE_i: normalized residual energy of node *i*,
$E_{initial}$: Initial energy,
E_{th}: Threshold energy,
E_{res}: residual energy.

The results of the simulation, which are conducted using MATLAB, proved that the suggested EARP performs better than the existing EERDT and M-TSIMPLE protocols in terms of network lifetime extension and data transmission reliability.

6.4.5 Cooperative Energy Efficient and Priority based Reliable Routing Protocol (CEPRAN)
Geetha & Ganesan (2021) presented CEPRAN with Network coding for WBAN. The key goal of this concept is to improve reliability and energy efficiency in WBAN. Cuckoo Search Optimization (CSO), which is one of the optimization algorithms is proposed for the selection of relay nodes for routing and forwarding the data packets. The relay node selection depends on various constraints such as high residual energy, path loss, and distance to sink. The relay node uses the CRL (Cooperative Random Linear) Network Coding method to improve the packet transfer rate. The packets are transferred after encoding which is handled using RP-RLNC protocol. The platform used for simulation is NS3, and the experimental findings demonstrate that the suggested protocol works better than the existing SIMPLE Protocol. At 6000 rounds, the residual energy curves for iM-SIMPLE and SIMPLE, respectively, reach zero. However, because there are fewer dead nodes, the CEPRAN protocol uses less energy. In the proposed CEPRAN protocol, the first dead node is kept at 7897 rounds and initially appears at 6000 rounds. At this point, four to six dead nodes are already visible in the SIMPLE and iM-SIMPLE protocols.

6.4.6 Energy Efficient Routing Protocol (EERP)
Qu et al. (2019) introduced a multi-hop routing protocol that takes into account various metrics like residual energy, available bandwidth, hop count, and transmission efficiency. Based on these metrics, the maximum benefit function is computed for selecting the next hop for transmission. The routing process consists of three stages in the proposed scheme. The first stage is the initialization stage, which initializes all the nodes in WBAN; the 2nd stage deals with the best next-hop selection based on certain parameters, and the last stage transmits and forwards data. The nodes exchange HELLO packets and update the neighbor table, then predict the data priority for selecting the weight value. The nodes having higher weight values are selected as the best nodes for routing. The multi-hop communication helps in reducing the energy consumption that occurs due to direct communication. The MATLAB platform is used to simulate this protocol and according to the simulation results, the suggested routing protocol dynamically chooses the next hop node using the maximum benefit function, which increases data transmission reliability and node energy utilization efficiency while also extending network lifetime. Compared to PERA and NEW-ATTEMPT, the proposed protocol network stability period is 1.36 and 1.24 times better, respectively.

6.5 Review of Postural-based Routing Protocol
6.5.1 Enhanced Probabilistic Route Stability (EPRS)
Memon et al. (2023) proposed an EPRS routing technique to address the issues related to the link's reliability and stability. It uses a cost function LAC to determine whether an active route is good or not for routing by making decisions regarding route reliability and satisfying QoS requirements. Expected Probability E(p) of the link and Route Stability Factor (RSF) are the two factors used to calculate LAC. The link is assigned with a score based on these factors for determining the link connection i.e., the status related to a link. Hence, the multi-facet EPRS performs better as it enhances route stability and throughput, route discovery calls, by reducing re-transmissions and end-to-end delay as depicted by the simulation results performed using NS2. The most reliable links are chosen for packet forwarding, due to which it shows enhanced throughput performance. It is best suited for transmitting emergency data as it requires a stable and reliable connection, and any loss to it may be life-threatening. This protocol provides stable and optimized routes in case of disconnected WBANs that result from postural body movements.

6.5.2 Adaptive Cuckoo Search (ACS)
Samal et al. (2022) proposed a new algorithm, namely, ACS for WBAN based on relay node placement. It uses a fitness function based on optimal sensor coverage, distance, energy consumption, and cost. The fitness function not only considers energy consumption parameters but also the relay node load. To

determine the optimal set of relay nodes a balance between local and global search is maintained in this research work. Additionally, it adopts an adaptable step size to avoid trapping at local optima, and the movement is made dynamic to find the best solution. To examine the scalability of the method, the authors took 80 biosensors randomly placed with 50-300 candidate locations in a rectangular area. The tool used for implementation is MATLAB. According to the simulation findings, the suggested algorithm not only uses less energy than the other state-of-art protocols considered, but it distributes the load also among the various relay nodes.

6.5.3 Geographical Routing (GR)

Savaşcı Şen et al. (2021) proposed a novel surveillance system that predicts coronavirus from its symptoms. This work presents geographic routing based on the improvement of data, delivery ratio, and delay. For routing the GPS is used from which the location information is extracted to find the nearest neighbor and then send data to the gateway node. Eight body sensors have been installed which can be used to monitor people's mask-wearing status and detect symptoms of the COVID-19 pandemic. Through simulation using Riverbed Modeler, the effectiveness of the suggested architecture in addressing people's mobility restrictions has been assessed. COVID-19 symptoms have been visualized using different architectures and simulation tools. In the future, we intend to extract health data using data analytics tools with ML, DL, and cognitive algorithms.

6.6 Review of Cross-layered Routing Protocols

6.6.1 Cross-layer Congestion Control Protocol (QCCP)

Buenrostro-Mariscal et al. (2023) offered a priority-based protocol named QCCP under the cross-layer category with a focus on congestion control. It is managed by transport and MAC layers. The author aims to develop a lightweight, efficient protocol that is TCP/IP compatible, generates no control packets, is decentralized, has less computation, minimum overhead (one bit), and power consumption. It is a multi-objective protocol that provides prioritization and congestion control based on various performance metrics like node balance, packet loss, and latency. QCCP can support multiple applications simultaneously even if they have different performance demands because QCCP categorizes each application into three service classes namely: P1 for urgent, P2 for important, and P3 for best effort. It works in a distributed manner and resolves congestion problems without any control packets and has only a one-bit overhead. QCCP also proposes a packet scheduler to work on congestion control and packet prioritization synchronously. QCCP performs better than other TCP protocols, according to the simulation performed using NS2, with a throughput increase of 64.31%, a packet loss reduction of 18.66%, and a latency reduction of 47.87%.

6.6.2 DT-MAC

Zeb et al. (2022) developed a DT-MAC algorithm for assured data delivery and here virtual clusters are created. The algorithm follows 'make before split', as the clusters are virtual, the dynamic nodes move and join other nearby clusters. Each cluster consists of CH, border, and stationary nodes. The node sets itself as a cluster head and it is supposed to be static in the position. The SYNC message is generated to ensure that a node is not a member in more than a cluster. The proposed protocol, namely DT-MAC, is the enhanced version of MT-MAC developed for the successful delivery of messages. To maintain network integrity, it takes node handover mechanisms across virtual clusters into account. Additionally, it relies on network construction on the idea of the minimal connected dominating set to maximize energy efficiency. It is implemented using the MATLAB tool and simulation results showed an improved packet delivery ratio of 13 to 17% and response time of 15% approximately whereas it leads to increased latency by approximately 3%. The issue related to the gateway is also taken into consideration by planning and reducing the number of nodes in the gateway which helps to improve the response time.

6.6.3 CARE-AODV

Waheed et al. (2021) focused on improving the QoS parameters using a QoS-aware cross-layered solution. It operates based on the relay, multiple metrics, and routing concerning the type of traffic. A CARE-AODV routing algorithm is proposed to select a route based on the estimation of channel condition and link quality. Then a link cost metric is determined by considering hop count, signal strength, and estimated transmission count. According to the availability of the optimized cost function is chosen for routing. This Cross-layered QoS-aware solution proposed is adaptive, relay-based, and multi-metric based on IEEE 802.15.6 standard. The routing is performed based on the traffic type to make it more efficient. The simulation is performed on Castalia for Intra-BAN and the protocol provides good end-to-end reliability. The proposed approach does not use clustering or a dual sink strategy like the other protocols and is developed for single sink intra-WBAN and to optimize path selection, it takes into account the channel conditions.

Table 6 summarizes the recent routing protocols from the year 2019-2024. The table provides an overview and focuses on the objective of each routing protocol. The various parameters considered to perform the efficient routing are analyzed and summarized in **Table 6**. It provides the simulation tools used to implement the proposed techniques and highlights the state-of-the-art routing protocols considered to evaluate the performance. The advantages and limitations of different routing protocols are discussed with a focus on future research scope.

Table 6. WBAN routing protocols.

S. No.	Protocol & year	Objective	Problem specification	Tool used	Parameters considered	Pros	Cons	Comparison protocol	Performance evaluation	Future scope
1.	HAOA (Javaheri et al., 2023)	The objective is to prevent the temperature rise and solve the hotspot problem in WBANs.	The proposed scheme selects the low-heated nodes as CH. The fuzzy approach based on Mandami FLC for clustering helps to keep the average temperature of the WBAN low and prevents the hotspot problem. HAOA is used to improve the effectiveness of FLC's. The proposed method distributes the load and temperature equally on all WBAN sensors.	OMNeT++	latency, packet loss, and node balance.	HAOA protocol prevents hotspot problems and helps to improve the network's lifetime and stability in WBAN. The proposed scheme selects CHs having less temperature. The intra-cluster communication is used to send the data to the near destinations. Fuzzy logic effectively handles the inherent ambiguity in WBANs, especially for clustering, and routing decisions. The protocol promotes fairness by distributing the workload among sensors reducing the hotspot formation. The hierarchical clustering approach simplifies data aggregation and reduces redundant transmissions.	• In the real scenario, it might not be possible for several patients to be near each other (Assumption taken in case of HAOA) • The sensors deployed on different parts of the body are of similar type. • The sensor used in the work contains omnidirectional antennas. • The findings rely on simulation results, and the protocol's effectiveness in real-world deployments remains untested. • The study assumes no malicious nodes in the network, leaving room for vulnerabilities in environments prone to attacks.	iM-SIMPLE, OPOT, LTRT, and WETRP	The proposed technique prevents temperature rise in WBANs in an efficient and better way as compared to protocols considered for comparison. It exhibits a significantly reduced hotspot ratio due to its temperature-aware clustering; enhanced network lifetime, and improved PDR.	The protocol can be enhanced by considering the issues related to network partitioning and congestion thus maintaining the node temperature to avoid the hot spots.
2.	PEDTARA (Ahmed et al., 2022)	To overcome the various WBAN routing challenges like energy constraints, retransmission, increased sensor heat, packet loss, and delay.	A hybrid optimization algorithm MGCSMO is proposed that uses genetic operators to update positions. It assigns different priorities and allocates routes based on priority to data packets while considering the energy efficiency, delay, and temperature factors.	MATLAB	energy, temperature, delay, congestion, and network lifetime.	PEDTARA considers data priorities to achieve emergency transmission on a priority basis. It reduces congestion and delays while providing energy efficiency. The algorithms select forwarding nodes based on energy availability and temperature, reducing the risks of network failures. It maintains reduced queue lengths thereby decreasing transmission delays by an average of 0.1 to 0.2 seconds. The protocol enhances network lifetime by minimizing packet loss and optimizing energy consumption.	• The use of all the operators in genetic algorithms tends to increase the time consumption for the selection of routes for transmission. • The mobility-related issues are ignored that can affect the WBAN performance. • Dividing data packets based on priorities can cause computational overhead and can lead to delayed transmission. • The energy drain rate is not considered. While the model limits energy consumption, critical data transmissions still result in increased SAR values for the selected nodes.	CDR, TAEO, Tripe-EEC, and EOCC-TARA	Based on the simulation performed; it is found that the proposed protocol performs efficient routing in terms of energy, delay, temperature, congestion, and network lifetime as compared to others.	Mobility issues and environmental factors need to be focused on in future work as PEDTARA does not monitor all the activities of the patients. It faces a few challenges in real patient scenarios which can be overcome in future work.

Table 6 continued…

3.	mobTHE (Selem et al., 2021)	The aim is to avoid temperature rise, support mobility and preserve the node's energy.	In the proposed protocol, the disconnectivity problem resulting from the postural change is tackled, and also the node's temperature is kept at a safe level. HO mechanism is used during node mobility. It also minimizes the packet drop ratio due to the minimization of redundant data.	MATLAB	Residual energy, throughput, the temperature of nodes, WBAN lifetime	The use of two CNs overcomes the problem of single CN failure which completely stops data transmission due to the failure of the CN. It can transfer data based on its priority (Emergency). The protocol keeps sensor node temperatures within a safe range, reducing the risk of overheating. The use of the HO mechanism ensures smooth transmission during mobility, preventing data loss. It reduces the chances of dropped packets during mobility due to the use of synchronization between the CNs.	• The excess number of control packets is required for the synchronization of two coordinate nodes, which tends to increase overhead and drains the energy of the nodes. • The one-hop neighbor selection is based on the signal strength, while the neighbor may be at low energy and fail to transfer the data. • The protocol introduces a more complex algorithm for selecting the parent node on demand which increases the processing time and energy consumption. • The HO mechanism, while reducing packet loss, can introduce delays due to data buffering and processing.	THE and iM-SIMPLE	It outperforms in terms of temperature regulation, reliability, improved network lifetime, reduced PDR, enhanced throughput, and increased energy efficiency.	In future work, to get more insightful results, statistical and numerical analysis can be introduced for the proposed work.
4.	LATOR (Caballero et al., 2020)	The objective is to explore the quality of the link and choose a route based on link quality to avoid overheating and get an enhanced network lifetime.	The proposed protocol deals with path loss issues based on the link's quality and also treats topological partitioning resulting from the body. It collects LQI during route discovery which is used by sensors to forward data packets in association with node temperature.	OMNeT++	Packet delivery ratio, node temperature, latency, and network lifetime	• Increase in network lifetime by finding alternative paths incase of weak direct communication or when an intermediate node overheats, ensuring continuous network operation. • It keeps the temperature of the node less and provides secure communication. An increased PDR is obtained in the case of intra-WBAN communication. • An alternative route was discovered in case of link breakage due to human body movement or imminent overheating. • It is adaptive to mobility as it dynamically reroutes data when body movements disrupt direct communication, improving overall connectivity.	• The proposed protocol can further be extended to deal with the different body postures. • It increases overall end-to-end latency in data transmission due to the on-demand route discovery process and temperature-based restrictions on nodes. • The number of packets arriving at the coordinator node is very large in number. • It is primarily designed for intra-WBAN communication with a limited number of nodes. • It does not optimize energy consumption, which is critical for prolonged WBAN operation.	DRR, FRAR, LAOR	LATOR allows better PDR performance and avoids overheating. It also maintains latency for WBAN applications at acceptable values and improves data transmission.	Body mobility and evaluating energy consumption for the sensor's longer battery life need to be focused. A real testbed can be used to test performance in real scenarios.

Table 6 continued…

5.	WETRP (Bhangwar et al., 2019)	The goal is to prevent temperature rise, optimize route, and maximize network lifetime.	A weighted energy-aware, QoS, and temperature-based routing protocol is proposed which uses a composite routing metric for making route selection decisions by considering remaining node energy, temperature, and link-delay estimation.	NS-2	PDR, end-to-end delay, temperature rise, throughput, routing load, and network lifetime	It prevents temperature rise by equally distributing the load between all the relay nodes. It maximizes the network's lifetime by optimizing the route selection process and evenly distributing traffic among relay nodes, thus reducing excessive energy consumption. The network load is distributed equally among the nodes preventing network congestion. By considering link-delay estimation, the protocol minimizes the end-to-end delay for timely data delivery.	• Network overhead gets increased due to the broadcast of RREQ, RERR, and RREP packets. • Packet level priority is not considered to differentiate critical data packets from normal ones. • WETRP assigns equal weights to energy, temperature, and link status which may not be optimal for all healthcare applications. • The protocol does not include specific optimizations for dynamic postural movements, which may affect the performance of mobile patients.	HPR and TARA	It prevents temperature rise, minimizes energy, deals with hotspot nodes in a better way, and maximizes the network's lifetime. Moreover, there is a significantly low routing load in WETRP as compared to HPR and TARA as routes are more stable.	In the future, the work can be further extended to deal with the issues related to postural body movement. Moreover, the integration of packet-level priority can be done to route critical data packets on a priority basis.
6.	PLQE (Iqbal et al., 2023)	To develop a delay-tolerant and reliable routing protocol for WBSNs.	To address network partitioning (due to node mobility) and reliable data transmission PLQE is proposed.	NS2	PDR, routing load, end-to-end delay, and throughput	QoS has improved thus providing a more reliable connection for management applications. Timely transmission of data can be achieved which is the main requirement in healthcare monitoring. The protocol integrates expected probability (EP), and link reliability factor (LRF) which helps to know the future link behavior ensuring more stable route selection and link connectivity. It actively predicts link failures due to mobility, reducing packet loss in dynamic WBAN environments. The use of predictive link quality estimation reduces unnecessary control message exchanges reducing the burden on the network.	• The energy parameter is not considered which is important for WBANs. • It does not include any security mechanisms which are important aspects that need consideration for healthcare applications. • The integration of link reliability and probability-based predictions increases the computational burden on sensor nodes. • It requires frequent hello packet transmissions to update link reliability, which may cause congestion. • PLQE does not explicitly optimize energy consumption which may impact long-term network sustainability. • Although it considers postural movements, it may still face frequent route breakages in highly dynamic environments.	MCARMR, ERRS	It yields better results in terms of load distribution, PDR, throughput, and reducing end-to-end delay.	Future work may focus on the integration of security and privacy mechanisms to protect sensitive patient data. Moreover, energy can be considered along with packet classification for enhancing network lifetime.

Table 6 continued…

7.	IM-QRP (Ahmad et al., 2022)	To propose an improved QoS-aware routing protocol for hospital management systems to remotely monitor chronically ill patients and elderly people in residential environments and hospitals.	IM-QRP selects the new forwarder node in each round based on the cost function. The cost function considers various parameters like distance, residual energy, identifiers (ID), etc. IM-QRP is capable of selecting the most feasible route that improves network lifetime significantly.	MATLAB	residual energy, QoS, SNR, and path loss	Higher SNR, maximum throughput, enhanced network lifetime, and the maximum number of packet transmissions. Improved QoS and residual energy of sensor nodes. It shows a path loss ratio reduction of 30%. The protocol reduced path loss by 30% leading to more reliable data transmission.	• Security which is one of the most important QoS parameters is not considered. • The issues raised from the hot-spot node are not focused in the proposed work. • The protocol is optimized for small-scale WBANS, and its efficiency in large-scale networks with numerous nodes has not been tested. • While the protocol improves the residual energy by 10%; it does not incorporate advanced energy savings mechanisms such as duty cycling or adaptive transmission power control.	CO-LEEBA and QPRD	The proposed protocol has better data transmission reliability, improved residual energy, and packet transmission.	The future work focuses on integrating smart homes with the proposed technique by deploying 6G and IoT frameworks.
8.	TLD-RP (Memon et al., 2021)	To design an improved QoS-aware routing protocol that minimizes delay while maintaining the node's temperature in routing critical data packets in multi-hop WBAN for delay-sensitive applications	It selects the optimal path considering path delay, link asymmetric property, node temperature, and link reliability for forwarding packets.	NS-2	Throughput, delay, packet delivery ratio, loss ratio, network overhead, load, and link stability	It is efficient enough as it has improved WBAN performance by providing link stability and reducing network overhead. It has also considered dynamic channel conditions which are an important part of WBAN. The route is chosen by considering more than one significant parameter which helps to improve the network efficiency. The protocol effectively minimizes packet collisions and ensures effective link selection.	The body's postural movements and the priority of highly sensitive data are not taken into consideration. It consumes more power due to the frequent exchange of packet routing. The problems faced due to congestion in the network and fault-tolerance issues are not focused in the proposed work. The protocol may not perform well in highly dynamic WBAN environments. The focus on avoiding overheated nodes can lead to frequent route changes.	ENSA-BAN and P-AODV	It achieves improved and better performance in terms of throughput, delay, loss ratio, PDR, and routing load.	The future scope includes designing a routing protocol that is both QoS-aware and optimized for postural body movements.
9.	TPOS (Yuan et al., 2020)	The aim is to solve the resource allocation problem for different tasks in WBANs.	TPOS is proposed to optimize the resource allocation that considers both task and user priorities of WBANs.	Python	average processing delay, energy consumption, and network utility	• TPOS can ensure that tasks are completed with less delay, minimal energy utilization, and maximum utility. • It is more suitable for health monitoring as a result of the benefits provided by it. • The problem is solved in a distributed manner which helped to reduce and improve the intelligence and the complexity of the algorithm. • Ensures better utilization of available computing resources and reduces response time for healthcare applications. • The use of a game-theoretic approach balances computational load efficiently.	Different WBAN behaviors, i.e., the mobility of WBAN, were not considered. Temperature rise issues of the heated nodes were not discussed. The proposed scheme faces a problem in the selection of a Mobile Edge Computing (MEC) server. The potential game model demands significant computing resources. Performance may degrade in highly congested networks.	-	The evaluation shows that the tasks can be processed with low delay, high utility, and low energy consumption for different data arrival rates. It ensures efficient task execution, reduces WBAN node workload, and provides a stable and optimized solution.	The paper does not take into account the movements of various WBANs. Our future focus will be on addressing the challenges in allocating computing resources for WBANs that are in motion.

Table 6 continued…

10.	SEAR (Mu et al., 2019)	To balance the node energy consumption, to deal with the harsh environmental conditions, and to reduce the transmission delay for WBANs.	The concept of added path is used as an alternative path to improve the robustness of the proposed algorithm. As human body posture change and if the link gets disconnected; then the source node can send data using the alternative path directly and the source node needs not to reinitiate again the routing request which in turn reduces the delay for data transmission and also reduces network overhead.	NS-2	End-to-end delay, energy consumption, and throughput	• By considering the effect of the node's remaining energy and load, it enhances the routing request forwarding process. • SEAR speeds up connection repairs by incorporating link data into routing tables to identify disconnected links and invalid nodes. • It maintains a backup path to improve the network reliability. • The protocol enhances data transmission efficiency and increases WBAN longevity by optimizing energy consumption.	• The selection of routes with a smaller number of hop counts tends to select intermediate nodes having lesser residual energy that may cause route failure. • In case both routes fail, then the route request has to be forwarded from the initial step, which causes a delay in transmission. • The temperature effect on human skin is not considered. • Moreover, the use of alternative paths adds routing overheads. • The protocol does not differentiate between critical and non-critical data packets.	EERP and ECCRA	It achieves higher residual energy, throughput, and lifetime. The simulation result shows that end-to-end delay is also reduced.	The SEAR protocol can be tested more accurately for real-time and practical application. The temperature effect due to medical sensor's use on human skin needs to be considered in future studies.
11.	HCEL (Helal et al., 2024)	The aim is to overcome the limitations in existing static and dynamic cluster-based routing protocols, optimize energy consumption, and enhance network lifetime.	An energy-efficient routing protocol named HCEL is proposed. In this, the selection of different parent nodes based on factors like distance, residual energy, and RSSI is done after several data transmission rounds considering threshold energy (Th) for all parent candidates.	Networkx	network stability, lifetime, energy consumption, path loss throughput, residual energy, delay, link reliability, transmission count	• By combining dynamic and static clustering; it provides equal distribution of traffic load. • It extends the sensor node's lifetime by optimizing energy use. • Provides improvement in reliability and network performance. • The protocol increases the stability period of the WBAN networks. • It ensures better data delivery by selecting the optimal parent node.	• Only stationary nodes are considered. • The deployment in a wide range of real-world scenarios needs to be tested to check the effectiveness. • Mobility and security are not taken into account which could affect the network performance to a great extent. • The algorithm requires additional calculations for CH selection and requires more processing resources as compared to simpler clustering methods. • It can lead to congestion if too many sensor nodes connect to a single parent node.	SIMPLE and ERRS	Optimized energy management, extended network lifetime, reduced packet drops and gives better performance as it combines static and dynamic routing.	Mobility and security are the key issues that can be considered in the future. Further, the robustness and versatility of WBANs can be enhanced.
12.	DECR (Arafat et al., 2023)	To provide energy-efficient packet delivery from CH to the sink.	A distributed routing protocol for WIoT-enabled WBANs that uses two-hop neighbor information for energy-efficient clustering is proposed as it extends the network's topology local view which helps in handling network topology change and node mobility. MGWO; a nature-inspired meta-heuristic optimization algorithm is applied for selecting the CH as it optimizes average transmission distance.	MATLAB	PDR, delay, energy consumption, Control Overhead (CO), network lifetime, and cluster building time	• The use of two-hop neighbor information helps to handle network topology change and node mobility. • Network lifetime also gets enhanced due to low energy consumption. • For cluster formation factors like Energy factor (EF), Node Stability Factor (NSF), and two-hop Connectivity Ratio (TCR) are used which results in efficient cluster formation. • The use of two-hop neighbor information ensures better node connectivity. • The protocol minimizes redundant transmissions by selecting the optimal routes.	• There is a need to develop robust routing techniques that can solve the issues of data loss. • The inclusion of priority can be considered for transmitting emergency data without any delay. • More optimal solutions need to be focused on that use meta-heuristic approaches to further enhance the network performance. • The use of two-hop neighbor information increases protocol complexity, leading to higher computational overhead. • The use of distributed clustering results in additional control overhead.	ALOC and MT-MAC	The proposed algorithm performed well as compared to existing protocols, namely ALOC and MT-MAC in terms of all performance metrics taken for comparison.	In the future, more optimal solutions can be achieved by using different meta-heuristic optimization algorithms.

Table 6 continued…

13.	NEEMA (Sharma et al., 2022)	The aim is to resolve the issues in WBAN related to energy constraints.	A cluster-based routing technique is proposed to achieve energy-efficiency and enhance network stability. It uses a hybrid approach that uses TSA and GA named T-GA for delivering high convergence. T-GA's fitness function is used for CH selection.	MATLAB	Network lifetime, packet delivery, the stability period	The use of a hybrid approach helps to improve the network performance, energy-efficiency, and stability. Energy consumption has been reduced to a great extent. Scalable WBAN is formed. It selects the optimal relay nodes dynamically and ensures stable and efficient data transmissions. It also helps to distribute the energy consumption across the network nodes.	Fault-tolerance and security-related issues are not considered which are important factors for a WBAN's proper and efficient working. End-to-end delay is not considered which is one of the crucial parameters in WBANs. The dual metaheuristic approach requires more computational power and longer processing time. The cluster formation takes additional processing time resulting in higher initial setup complexity. It may face congestion in large setups.	MS-GAOC, DSCB, OE2-LB and EARP	It shows enhanced performance in terms of higher data transmission success rate, improved energy consumption, and increased network lifetime as per the simulation results when compared with other state-of-the-art protocols.	The security techniques can be incorporated for secured data transmission as part of future work.
14.	I-RAW (Sharma et al., 2021b)	The aim is to elongate the sensor node's life period and to achieve an enhanced network lifetime.	In I-RAW, the CH selection is done based on TSA method to achieve enhanced network lifetime, which considers residual energy, node's distance from the sink, average network's energy, energy consumption, and path loss model. Two sinks are used to mitigate the problem of hot spots.	MATLAB	Network lifetime, packet delivery, the stability period	The installation of a dual sink avoids full dependency on the single sink thus avoiding congestion around a single sink. Due to the second sink's availability, data collection in single-hop communication can be achieved. The proposed technique enhances the network's load-balancing capability. It extends the network stability period and improves overall operational time.	The nodes considered in the proposed work are static; but in a real-time WBAN scenario, it is not possible. Real-time data is not taken into account and priority is not assigned to critical and emergency data. Certain factors like congestion of the radio signals, signal attenuation, radio interference, etc. which affect the network performance are not considered. Despite using two sinks, certain nodes may still experience higher energy depletion.	MS-GAOC, DSCB, and OE2-LB	I-RAW enhances the stability period of the network operational period as compared to the DSCB protocol. It also shows enhanced performance in terms of packet delivery and network lifetime as compared to other state-of-art protocols.	The proposed technique can be used with real data sets to get real-time implementation.
15.	ELEACH-DFL (Park et al., 2020)	To overcome the drawback of traditional LEACH protocols, reduce energy consumption and extend the entire network lifetime effectively.	It uses fuzzy logic to select the optimal CH by considering each node's energy, location, and density. The threshold equation was used and the node with the highest remaining energy among the candidates gets a chance to act as the CH.	MATLAB	Energy consumption and network lifetime	It provides better efficiency through the selection of the appropriate cluster head. It maintains the energy efficiency of the network even after the generation of the first dead node. The proposed technique extends the network lifespan while reducing the energy consumption of the network. The optimal CH selection ensures a more stable network topology. The hierarchical clustering method reduces redundant transmissions and results in low transmission overhead.	The computational overhead is there and reliability is ignored. The traditional problem of the LEACH protocol is the random assignment of the number of clusters, which is supposed to create different sizes of clusters, and hence the energy drain is not similar for all the clusters. The efficiency of CH selection relies on predefined fuzzy rules, which may not always be adaptable to dynamic scenarios. The use of dual fuzzy logic increases processing requirements, which may not be suitable for low-power WBAN nodes.	LEACH	It is more efficient in terms of energy-efficiency, network lifetime, and optimized CH selection as compared to LEACH.	For further work, the reliability of data transmission and computational amounts can be considered simultaneously.

Table 6 continued…

16.	E-HARP (Ullah et al., 2019)	To minimize energy consumption, end-to-end delay and maximize network lifetime.	A novel multi-attribute-based protocol is proposed for dynamic CH selection. Based on the calculated cost factor, optimum CH is selected and redundant data sensed by SNs is omitted by using cooperative effort or routing-based communication.	NS-2	network stability lifetime, throughput, and end-to-end delay	• Multiple parameters are considered for selecting efficient and dynamic CH. • The presence of two sink nodes helped to distribute and balance the load among the sensor nodes. • The communication technique used is both single and multi-hop. • The protocol maintains network stability by ensuring uniform energy consumption across the nodes. • The dual-sink architecture and cooperative routing reduce transmission delays, benefiting real-time medical applications. • Achieves higher data delivery rates and significantly reduces energy consumption.	The selection of CH for each round requires a computation cost factor that depends on multiple attributes. The computation on each round for CH consumes energy that tends to minimize network lifetime. The temperature of the node rises which can lead to damage to human body tissues. During data processing, the power consumption of the nodes was ignored. Frequent updates to CH selection and cluster formation introduce additional control packets, and increased network congestion. Although the protocol accounts for mobility, rapid or unpredictable movements may still cause link failures.	EH-RCB, ELR-W, Co-LAEEBA, and EECBSR	It shows enhancement in terms of network stability, lifetime, PDR, and throughput significantly and also reduced end-to-end delay. The performance of E-HARP is enhanced due to the selection of efficient CH, the presence of an energy harvesting scheme, and the avoidance of redundant data transmission.	E-HARP protocol can be implemented in a real platform to get real-time performance data.
17.	EEMR (Pradeep & Kavithaa, 2024)	To focus is to handle the key problems such as utilization of energy, route loss, and barriers for sending data. The main aim of the work is to identify the optimal paths and gain insights into metaheuristics nature.	A metaheuristic-based approach named EFBOA is developed to lower energy consumption and extend the life span of WBANs and gateway nodes.	MATLAB	Path Loss, cost estimation, throughput, energy consumption, and network lifetime	• The proposed technique provides an accurate and optimal strategy for both the sensor and gateway node selection. • The load balancing algorithm is used for the distribution of traffic in the proposed scheme over the discovered multiple paths. • It uses clustering to extend network longevity. • It reduces unnecessary transmissions, improving efficiency and throughput.	Node prior states are not considered which can affect the network performance to a great extent. There is a huge uncertainty resulting from the physical motions of human beings in parameters. The use of metaheuristic techniques increases processing overhead. The routing strategy does not dynamically adjust to unexpected node deaths.	EECR, EMPR, and M-ATTEMPT	The proposed approach provides maximum throughput, better performance, and energy enhancement.	ML and DL-based techniques can be employed to get the state of the previous node. Features like QoS, security, and congestion can be taken into consideration for further enhancement.
18.	EEDLABA (Zaman et al., 2023)	The objective is to reduce energy utilization and resolve the path loss issue.	To reduce energy usage, distance models and path loss are used that utilize a complex change-of-direction approach while improving the placement of nodes for WBAN. The protocol communicates only if an active sensor is in range and a clustering mechanism is used to solve the energy-related issue.	MATLAB	Average Path Loss, Stability Period, End-to-End delay, residual energy, and Throughput	• It consumes less energy and performs well in terms of throughput, network stability, and lifetime. • The clustering mechanism used in the proposed work enhances the network performance. • The proposed protocol performs well in terms of energy consumption and path loss factors. • It enables reliable data delivery by selecting optimal paths and extends WBAN lifetime by distributing energy consumption.	Mobility, node deployment, and scalability with geography are not considered. Temperature-rise issues of sensor nodes may arise. Congestion control is not considered which can affect the network performance to a great extent. QoS optimization can be done to enhance the network lifetime.	LAEEBA and DARE	The proposed technique provides the best results in terms of all the parameters taken into consideration.	Congestion control mechanisms and energy with reliability along with mobility can be taken into consideration for future work to enhance the WBAN performance. Furthermore, the node scalability can be analyzed to see the effect on energy utilization by decreasing or increasing the number of nodes.

Table 6 continued…

19.	DFST (Rahman et al., 2022)	To improve network efficiency in WBANs by reducing energy consumption, and improving network stability period, and throughput.	It uses the dual forwarder selection technique in WBANs for selecting the forwarder node using a cost function.	MATLAB	network lifetime, stability, and throughput	• The emergency data is immediately transferred directly to the sink thus minimizing the waiting time. • The no. of dead nodes gets reduced to almost 50% in the proposed scheme. • The nodes in the proposed technique are divided into two groups to minimize the data aggregation burden. • Enhanced network lifetime, improved throughput, and increased residual energy.	The selection of two forwarders for each transmission is both cumbersome and energy-consuming due to the frequent exchange of Hello packets. The security techniques can be incorporated to secure the WBAN network for reliable data transmission. More computation is involved due to the use of the cost function and dual forwarder mechanism.	RE-ATTEMP, iM-SIMPLE	Improved Load balancing, reduced node failures, and power consumption	An energy harvesting mechanism can be implemented in the proposed technique to improve network lifetime. Further, security techniques can be investigated and implemented to maintain data privacy.
20.	EARP (Wang et al., 2021)	The goal is to minimize the consumption of energy and provide maximum QoS requirements for a WBAN-based application.	A fuzzy control model that considers link quality and remaining node energy is established in the proposed scheme. Fuzzification, fuzzy inference, and defuzzification rules are used to determine the best forwarder node. It has a higher PDR as it considers the link's quality while establishing an effective routing path.	MATLAB	node energy, link quality, reliability, network lifetime	• The best forwarder node selection based on multiple parameters considering link quality and remaining energy of the node helped to extend the network lifetime. • The use of a fuzzy control model in EARP helps to better adapt to complex WBAN characteristics making it more effective and performing better in terms of energy consumption and network lifetime. • It reduces data loss by selecting stable forwarder nodes.	Priority of data is not considered which is very crucial for a healthcare application. The data type is predicted first and then the fuzzy rules are applied; the time taken for rules-based forwarder selection is critical for emergency data forwarding. The computational complexity of EARP is higher as compared to M-TSIMPLE, and EERDT which leads to an increase in the calculation time. The protocol does not fully optimize sensor movement and requires more transmissions due to frequent link evaluations.	M-TSIMPLE, EERDT	It has better performance, like extended network lifetime, higher PDR, and improved reliability while transmission of data as compared to M-TSIMPLE and EERDT.	For future work, the various green energy technologies can be explored and can be introduced in future routing protocols for better energy saving.
21.	CEPRAN (Geetha & Ganesan, 2021)	The main objective is to enhance the network's energy and provide reliable data delivery in WBAN.	Priority-based, reliable, and cooperative energy-efficient routing with Network coding was proposed to enhance the reliability and energy efficiency of WBANs. An enhanced CSO was used for relay node identification dynamically. It combines both one and multi-hop communication.	NS-3	PDR, throughput, network lifetime	• The addition of RP-RLNC in the relay node increased the packet delivery ratio. It also helped to reduce the retransmissions. • Additionally, it is discovered that at the node level, the residual energy gets considerably increased thus extending the network's life. • Uses cooperative communication to reduce energy consumption and enhance network lifetime. • The Cuckoo search algorithm ensures efficient relay node selection.	The time slot for transmission is assigned by the sink node for the relay node based on the TDMA schedule. This time slot assignment is not favorable in case of the arrival of an emergency message. The traditional issue in the CSO algorithm is slow convergence and failure at the global optimum solution. QoS metrics like delay measures are not focused in this research work. It does not explicitly address load balancing among relay nodes. Relay nodes may become overloaded due to additional forwarding responsibilities.	SIMPLE and iM-SIMPLE	The simulations show increased PDR, throughput, and reduced retransmission in comparison with state-of-art protocols. Enhanced residual energy at the node level and network lifetime with reliable delivery can also be seen in the proposed protocol.	More QoS parameters and delay metrics can also be considered as part of future work. The work can also be extended by considering different mobility scenarios, and the protocol can be tested in real-time, like in a hospital environment.

Table 6 continued…

22.	EERP (Qu et al., 2019)	To provide reliable data transmission in the WBAN.	The maximum benefit function is calculated by normalizing the node's parameter and considering multiple parameters. Based on the different data priorities the weights are dynamically adjusted to get timely and reliable emergency data transmission while satisfying the QoS requirements.	MATLAB	Network throughput, energy efficiency, network lifetime, reliable communication	• It adjusts the weight dynamically for each parameter on a priority basis. • It provides reliable data transmission and also efficient routing based on different priorities. • By optimizing the node selection, the protocols enhance WBAN lifespan. • The protocol dynamically selects the best forwarder node to ensure stable communication.	The consideration of multiple parameters for the selection of the intermediate hop will consume a larger time since each parameter is computed one after the other. The same number of parameters are computed for both critical as well as normal packets, hence the waiting time for the transmission of critical packets is similar for the transmission of normal packets. It does not explicitly handle link failures due to mobility. The dynamic selection algorithm increases node workload.	PERA, NEW-ATTEMPT	The simulation results show that the reliability of data transmission and the energy utilization efficiency of the node significantly improves thus prolonging the network lifetime.	Optimization of the parameter selection can be done to make it more perfect and useful. A better algorithm can be designed to determine the weight's specific value to set reasonable values for data having different priorities to achieve better network performance further.
23.	EPRS (Memon et al., 2023)	To examine and deal with network partitioning issues/effects and route instability in WBAN as a result of postural movement in the human body.	WBAN demands high route stability and timely transmission of critical data packets. The network disconnections in WBAN, due to the postural change, affect the route stability significantly, resulting in unreliable links. The proposed EPRS routing provides stable and optimized routes by considering route stability factors in disconnected WBANs.	NS-2	throughput, end-to-end delay, route stability, and routing load	• The EPRS uses the link's expected positive probability and route stability factor which leads to the selection of the most stable links in WBAN. • Network partition issues are also taken into consideration to avoid delays in transmissions. • The protocol makes a dynamic decision to distinguish unreliable and reliable links in a network. • Meets QoS requirements and lower packet retransmissions.	High control packet overhead. Re-establishing stable routes takes additional processing time. The problem arising due to hot-spot nodes is not considered in the proposed work. The energy consumption of the node has not been focused which can result in poor network performance. The security parameter is not incorporated in the proposed work.	SRE, MCDR, and AODV	The EPRS protocol shows improvement in terms of throughput, stability, and delay.	For future work, the various QoS constraints and parameters related to link quality can be considered for designing an enhanced version.
24.	ACS (Samal et al., 2022)	To minimize the relay node's cost, distribute load on the relay nodes uniformly, and have low energy consumption.	A fitness function based on the sensor's coverage, cost, distance, and energy consumption is formed using linear programming technique formulation.	MATLAB	Energy consumption, computational time, load distribution, and node coverage/distance	• The proposed algorithm distributes the load uniformly among relay nodes. • To find the best set of the relay nodes the proposed ACS makes a balance between global and local search from the set of candidate sites. • Ensures optimal sensor placement for consistent connectivity and provides higher network stability.	It is a time-consuming process to find the optimal no. of relay nodes and can result in delay. The solution size is not been generated adaptively in the proposed scheme which results in increased execution time. The proposed protocol can be enhanced further to make it more energy-efficient.	CSO, EAWD, and modified EAWD	It outperforms in terms of load balancing, and energy consumption than the existing algorithms.	Future work can emphasize reducing the execution time by adaptively generating solution size. More energy-efficient data transmission can be done by integrating it with an efficient MAC protocol.

Table 6 continued…

25.	GR (Savaşcı Şen et al., 2021)	To propose an IoT-based surveillance system with a geographic routing (GR) for pandemic situations based on WBAN architecture.	It uses a GPS-based GR scheme for communication in inter-WBAN. CSMA/CA is used to perform routing.	Riverbed Modeler simulation, InfluxDB, and Node-RED	energy consumption, throughput, delay, and delivery ratio	• Real-time monitoring of health data is made possible with the help of IoT tools for pandemics. The proposed architecture overcomes the mobility constraints of persons. • It works well in dynamic conditions. It uses low-powered GPS making it an efficient scheme for resource or energy-constrained WBANs. • Supports real-time analytics and visualization. Improved data collection for healthcare systems as it enables early detection of symptoms.	The energy and network lifetime are not considered while designing the protocol. The ML-based techniques are not used that can further help to enhance the network performance. It has high hardware dependency as it requires GPS-enabled coordinator nodes. IoT-based data transmissions could face delays in high-traffic scenarios. Dependence on external IoT platforms.	AODV	The results show that the proposed approach works better and yields more effective results compared to AODV including energy, throughput, and delay.	Machine Learning (ML), Deep Learning (DL), and cognitive algorithms can be used in the future for health data mining.
26.	QCCP (Buenrostro-Mariscal et al., 2023)	To provide congestion control and manage heterogeneous traffic based on different priorities for an IoMT network. An efficient, lightweight, and practical solution is required to resolve the congested network problems.	It is a multi-objective protocol that deals with two major network problems, i.e., congestion control and prioritization, which are managed by the MAC and transport layer. It works in a distributed manner and it estimates and resolves congestion problems without generating control packets.	NS2	throughput, latency, and packet loss	• QCCP considers each packet's network load and offers traffic priority. • Even in highly congested networks, it achieves good throughput, low latency, and low packet loss. • It also supports the QoS features for transmitting health signals efficiently by saving time, cost, and human lives. • Minimal overhead as it requires only one-bit overhead, thus reducing the network congestion. • Provides dynamic packet prioritization.	It requires cross-layer congestion control, making integration challenging. The node temperature rise issue and body movements are not focused. No real-time testing is done. The energy efficiency of the network is not focused which is one of the most important parameters in the WBAN setting. The network disconnections occurring due to postural movement of the human body are not considered which can affect the network stability to a great extent.	TCP	Efficient traffic prioritization, low overhead design, and improved reliability	The protocol can be implemented in real scenarios i.e., in physical devices to demonstrate its benefits.
27.	DT-MAC (Zeb et al., 2022)	To provide network integrity by ensuring successful message delivery	It uses the "make before break" concept for network establishment & maintenance. It uses the concept of minimum connected dominating set for network formation for efficient energy utilization. Node handover mechanism is used to ensure network integrity.	MATLAB	average packet delivery ratio, average energy depletion, and network latency or response time	• The algorithm is suitable for real-time applications due to a high packet delivery ratio and better response time. • The number of gateway nodes is reduced in the proposed work which enhances the response time. • The proposed scheme also reduces the packet loss thus enhancing the overall network performance. • It reduces border node energy depletion through a minimum connected dominating set. • It provides better network integrity and enhanced suitability for real-time applications.	The CH are appointed by the node itself which may not have the best features to be elected as a CH. The energy depletion is greater as it uses a greater number of control messages for network establishment. The redundancy of data is ignored which can lead to delay in transmission and can cause inconsistency. It is not fully adaptive to high-mobility scenarios. The protocol is primarily tested in small to medium-sized networks.	MT-MAC	Improved network lifetime, better cluster formation, and reliable packet transmission	Future work can focus on minimizing delay, data redundancy, inconsistency, and network maintenance.

Table 6 continued…

28.	CARE-AODV (Waheed et al., 2021)	To optimize the routing strategy to make them more reliable to carry emergency traffic, especially for Medical BANs.	Traditional AODV is modified to handle emergency traffic by considering the different channel conditions. It is a cross-layered; multi-hop and multi-metric routing protocol that involves information from lower layers for the selection of the best path. Its main focus is on enhancing reliability, reducing delay, conserving energy, and improving QoS-like reliability for a variety of traffic.	Castalia Simulator	Reliability, delay, and energy conservation	• It is a cross-layered and relay-based scheme that utilizes the IEEE 802.15.6 standard. • It is an adaptive approach for intra-WBAN communication that changes the routing path according to traffic type. • It is efficient in terms of reliability. It reduces the number of transmissions and packet loss. • Better emergency data handling by ensuring rapid transmission of critical health information.	The various important factors like energy, heat, and priority are not taken into consideration. The number of nodes deployed in the WBAN scenario used in the proposed work is very few (only 4 sensor nodes). So, there is a need to increase the number of nodes considering the real-time scenario. The proposed technique lacks focus on traffic adaptability and traffic loss factors. The protocol introduces additional control packets. The routing relies on predefined values (fixed cost function) that may not be optimal in all conditions.	AODV	The proposed protocol is efficient enough in terms of reliability and also the packet reception rate is better due to the use of extended 2-hop star topology in CARE-AODV than in Standard AODV.	The temperature of the nodes can be maintained to a particular threshold to avoid human tissue damage.

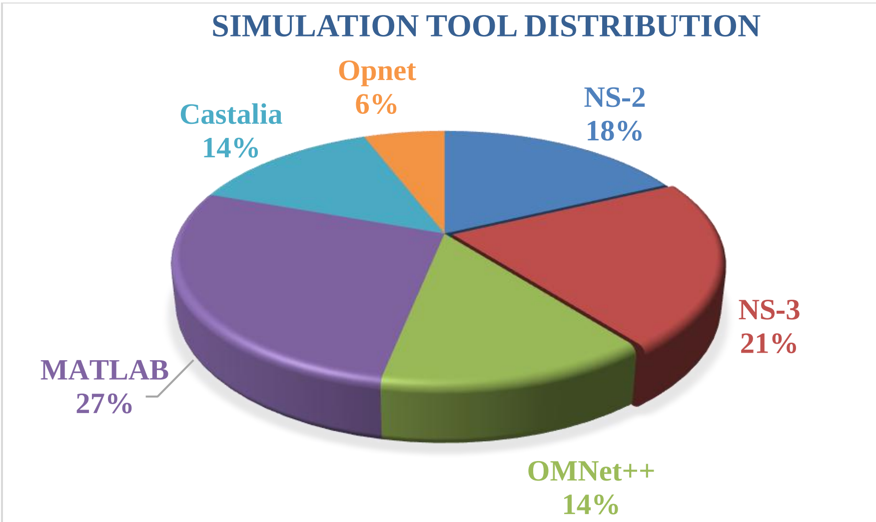

Figure 9. WBAN simulation tool classification to perform WBAN routing.

Based on **Table 6**, it can be observed that there are various existing routing protocols under different routing categories that cover different aspects and parameters depending on the use and application area. It provides an overview of the existing routing protocols with a discussion on problem specification and it summarizes the objective, problem specification, implementation tool, performance parameter used for evaluation, advantages, limitations, constraints, performance aspects, and state-of-art protocols. The objective of the different routing protocols is to know the implications and the aim of developing a particular routing protocol. It also provides the scope of future research by analyzing the limitations in each of the existing routing protocols related to the WBAN domain. It can be seen from the literature review that each routing protocol has challenges associated with it, and those limitations can be considered as part of the research gap to accomplish the research in the WBAN area. It can help researchers easily identify the problem and can provide a way for future research directions. It can also be seen that the most widely used simulation tool in literature for implementing routing protocols in WBAN is MATLAB, followed by NS2 and OMNet++. **Figure 9** shows this distribution as per the literature analysis:

7. Analytical Comparison and Summary of Different Routing Protocols

The paper emphasizes routing protocols under each category from the last 5 years and focuses on performance evaluation based on various performance metrics. This paper compares several routing protocols which helps to classify the best routing protocol that can be applied to the application under consideration. The study presents several current WBAN routing techniques that are affected by the network's structure, node temperature, energy use, QoS, transmission range, human position, and other factors. The various performance features considered for comparison are Packet Delivery Ratio (PDR), energy efficiency, scalability, security, stability, node temperature, throughput, mobility, congestion control, latency, priority, etc. The various performance metrics have their significance depending on the application requirement. For a time-critical application like an emergency condition; delay and reliable data transmission are important parameters, while for normal data; energy efficiency and long-term communication are important factors. The analytical comparison of different routing protocols as shown in **Table 7** will help the researchers to decide and consider the routing protocols based on the application requirement easily as it summarizes the performance metrics focused in various papers by different authors. **Table 7** and **Table 8** provide the quantitative analysis of different routing techniques that are analyzed in the review.

Table 7. Analytical comparison of WBAN Routing Protocols

S. No.	Protocol name	Routing category	Communication mode	Cluster formation	Control packets	Congestion control	Data priority	Data aggregation	Delay	Energy consumption	Energy-efficiency	Fault-tolerance	Latency	Postural-movement	Network lifetime	Network partitioning	Packet delivery ratio	Path loss	Reliable delivery	Relay nodes	Scalability	Security	Stability	Temperature Rise	Throughput
1.	HAOA (Javaheri et al., 2023)	Temperature-based Routing	-	×	×	×	×	✓	×	✓	✓	×	×	×	✓	×	×	✓	×	×	✓	×	×	✓	×
2.	PEDTARA (Ahmed et al., 2022)	Temperature-based Routing	Single-hop	×	×	✓	✓	×	✓	✓	✓	×	×	×	×	×	×	✓	✓	×	×	×	×	✓	×
3.	mobTHE (Selem et al., 2021)	Temperature-based Routing	Two-hop	×	✓	×	×	✓	×	✓	✓	×	×	✓	✓	×	×	×	×	×	×	×	×	✓	✓
4.	LATOR (Caballero et al., 2020)	Temperature-based Routing	-	×	×	×	×	×	×	×	×	×	✓	×	×	✓	✓	✓	×	✓	×	×	×	✓	×
5.	WETRP (Bhangwar et al., 2019)	Temperature-based Routing	Multi-hop	×	×	×	×	×	✓	✓	✓	×	×	×	✓	×	✓	×	×	✓	×	×	✓	✓	✓
6.	PLQE (Iqbal et al., 2023)	QoS-aware Routing	Multi-hop	×	✓	×	×	×	✓	×	×	×	×	✓	×	✓	✓	×	×	×	×	×	×	×	✓
7.	IM-QRP (Ahmad et al., 2022)	QoS-aware Routing	Multi-hop	×	×	×	×	×	✓	✓	×	×	×	×	✓	×	✓	✓	✓	✓	×	×	×	×	✓
8.	TLD-RP (Memon et al., 2021)	QoS-aware Routing	Multi-hop	×	✓	×	×	×	✓	✓	✓	×	×	✓	×	✓	✓	×	✓	×	×	×	✓	✓	✓
9.	TPOS (Yuan et al., 2020)	QoS-aware routing	-	×	×	×	✓	×	✓	✓	×	×	×	×	✓	×	×	×	×	×	×	×	×	×	×
10.	SEAR (Mu et al., 2019)	QoS-aware routing	FMTM	×	×	✓	×	×	✓	×	✓	×	×	✓	✓	✓	×	×	×	×	×	×	✓	×	✓
11.	HCEL (Helal et al., 2024)	Cluster-based Routing	-	✓	×	×	×	×	✓	✓	✓	×	✓	×	✓	×	✓	×	✓	×	×	×	✓	×	✓
12.	DECR (Arafat et al., 2023a)	Cluster-based Routing	Two-hop	✓	✓	×	×	×	✓	✓	✓	×	×	✓	✓	×	✓	×	×	×	×	×	✓	×	×
13.	NEEMA (Sharma et al., 2022)	Cluster-based Routing	Multi-hop	✓	×	×	×	×	×	✓	✓	×	×	×	✓	×	✓	×	×	×	✓	×	✓	×	×

Table 7 continued…

14.	I-RAW (Sharma et al., 2021b)	Cluster-based Routing	Single-hop	✓	×	×	×	✓	×	×	×	×	×	×	✓	×	✓	×	×	×	×	×	✓	×	×
15.	ELEACH-DFL (Park et al., 2020)	Cluster-based Routing	Hierarchical	✓	×	×	×	×	✓	✓	×	×	×	×	✓	×	×	×	×	×	×	×	✓	×	×
16.	E-HARP (Ullah et al., 2019)	Cluster-based Routing	Single & multi-hop	✓	×	×	×	✓	✓	×	×	×	×	×	✓	×	✓	✓	×	×	×	×	✓	×	✓
17.	EEMR (Pradeep & Kavithaa, 2024)	Energy-efficient Routing	Multi-hop	✓	×	×	×	×	×	✓	✓	×	×	×	✓	×	×	✓	×	×	×	×	×	×	✓
18.	EEDLABA (Zaman et al., 2023)	Energy-efficient Routing	One-hop	✓	×	×	×	✓	✓	✓	✓	×	×	×	×	×	×	✓	×	×	×	×	✓	×	×
19.	DFST (Rahman et al., 2022)	Energy-efficient Routing	Multi-hop	×	×	×	✓	×	×	✓	×	×	×	×	✓	×	✓	×	×	×	×	×	✓	×	✓
20.	EARP (Wang et al., 2021)	Energy-efficient Routing	Fuzzification	×	×	✓	✓	×	✓	×	×	×	×	✓	✓	×	✓	×	✓	×	×	×	×	×	✓
21.	CEPRAN (Geetha & Ganesan, 2020)	Energy-efficient Routing	Relay-Assisted	×	×	×	✓	×	×	✓	✓	×	×	✓	×	×	✓	×	×	✓	×	×	×	✓	×
22.	EERP (Qu et al., 2019)	Energy-efficient Routing	Multi-hop	×	×	×	✓	×	×	✓	✓	×	✓	×	✓	×	×	×	✓	×	×	×	×	×	✓
23.	EPRS (Memon et al., 2023)	Postural-based Routing	-	×	×	×	×	×	✓	×	×	×	×	✓	×	✓	×	✓	✓	×	×	×	✓	×	✓
24.	ACS (Samal et al., 2022)	Postural-based Routing	Multi-hop	×	×	×	×	×	×	✓	✓	×	×	✓	✓	×	×	×	✓	✓	×	×	×	×	×
25.	GR (Savaşcı Şen et al., 2021)	Postural based Routing	-	×	×	×	×	×	✓	✓	×	×	×	×	×	×	✓	×	×	×	✓	×	×	×	✓
26.	QCCP (Buenrostro-Mariscal et al., 2023)	Cross-layered Routing	Decentralized	×	×	✓	✓	×	×	✓	×	×	✓	×	×	×	✓	✓	×	×	×	×	×	×	✓
27.	DT-MAC (Zeb et al., 2022)	Cross-layered Routing	-	✓	×	×	×	×	×	✓	×	×	✓	×	×	×	✓	✓	×	×	×	×	×	×	×
28.	CARE-AODV (Waheed et al., 2021)	Cross-layered Routing	Multi-hop	×	×	×	×	×	×	×	✓	×	×	×	✓	×	×	×	✓	×	×	×	×	×	×

Table 8. Quantitative analysis of different WBAN routing protocols.

S. No.	Protocol name	Energy efficiency	Temperature control	PDR	Latency	Scalability	Complexity	Load balancing	Simulation results
1.	HAOA (Javaheri et al., 2023)	High	Very Good	Good	Average	Good	High	Good	In scenarios with 20, 25, and 30 sensors, the protocol consistently outperforms existing schemes in maintaining lower sensor temperatures and extending the network stability. The use of the HAOA algorithm accelerates convergence and reduces the likelihood of suboptimal solutions.
2.	PEDTARA (Ahmed et al., 2022)	Good	Very Good	Very Good	Good	Average	High	Good	It achieves lower energy consumption in comparison to the existing models, reducing energy usage by 0.2 joules and providing 2% higher throughput as compared to EOCC-TARA. The system ensures prolonged usability with an increased network lifespan of 40 minutes with a delivery rate of 97.86% compared to 89.09% in EOCC-TARA.
3.	mobTHE (Selem et al., 2021)	High	Very Good	Good	Average	Good	Average	Good	The protocol increases network lifetime beyond 52% and 58%; throughput by 45% and 55% and overall residual energy is raised by 35% and 39% in comparison to THE and the iM-SIMPLE protocols. Also, the average temperature is reduced by 20% for sensor nodes as compared to THE.
4.	LATOR (Caballero et al., 2020)	Average	Good	Good	Average	Average	Low	Average	LATOR has 73.10% (proposed) PDR as compared to state-of-the-art routing protocols like DRR - 67.53%, FRAR - 70.12%, and LAOR-74.89%. LATOR increases latency, with 2.16% of packets experiencing delays over 500ms, compared to 2.02%in LAOR, 18% in FRAR, and 0.8% in DRR. LATOR dynamically switches routes based on temperature, only 33.55% of the time as compared to LAOR.
5.	WETRP (Bhangwar et al., 2019)	Good	Very Good	Good	Good	Average	Average	Average	WETRP reduces average node temperature rise by up to 30%, preventing sensor overheating. It also achieves lower average latency and higher delivery ratio as compared to HPR and TARA.
6.	PLQE (Iqbal et al., 2023)	Good	NA	Very Good	Good	Good	High	Good	PLQE achieves a PDR improvement of 15-20%, 30-40% lower end-to-end delay, and 25-30% stability as compared to MCARMR, and ERRS. The protocol also lowers routing overhead by approximately 10% and shows higher throughput of 80-100 Kbps.
7.	IM-QRP (Ahmad et al., 2022)	Average	NA	Very Good	Average	Good	High	Average	It shows a 10% higher residual energy improvement; 30% path loss reduction, 10% improvement in the link reliability, and 7% enhancement in SNR as compared to QPRD and CO-LEEBA.
8.	TLD-RP (Memon et al., 2021)	Good	Good	Very Good	Good	Good	Average	Average	Improved PDR by 15% as compared to ENSA-BAN and P-AODV.
9.	TPOS (Yuan et al., 2020)	Average	NA	Good	Good	Very Good	Average	Good	Processing delay was reduced by upto 40% as compared to improved execution of healthcare tasks by 20-30% as compared to traditional methods.

Table 8 continued…

10.	SEAR (Mu et al., 2019)	Good	NA	Good	Average	Good	Low	Average	It shows a 30% increase in WBAN lifespan, higher packet success rate, and lower delays as compared to EERP and ECCRA.
11.	HCEL (Helal et al., 2024)	Very Good	NA	Good	Good	Good	High	Good	Network lifetime extension by 30-40 % over SIMPLE and ERRS; 56% reduction in delay in comparison to SIMPLE and 40% with ERRS.
12.	DECR (Arafat et al., 2023a)	Very Good	NA	Good	Good	Good	High	Good	The proposed protocol has upto 30% energy savings and 35% longer network stability in comparison to other state-of-the-art routing techniques.
13.	NEEMA (Sharma et al., 2022)	Very Good	NA	Good	Good	Very Good	Average	Very Good	It shows increased network lifetime, lower packet loss, and improved energy consumption.
14.	I-RAW (Sharma et al., 2021b)	Good	NA	Good	Average	Good	Average	Good	I-RAW enhances the stability period by 37.7% & the network operational period by 42.7% as compared DSCB protocol. It also shows enhanced performance in terms of PDR and overall network lifetime as compared to other state-of-the-art protocols.
15.	ELEACH-DFL(Park et al., 2020)	Very Good	NA	Good	Good	Good	High	Good	The proposed technique shows FND efficiency improvement of 32% - 159% better than LEACH. It showed reduced energy consumption, improved network stability, and a significant reduction in node energy depletion.
16.	E-HARP (Ullah et al., 2019)	Very Good	NA	Very Good	Good	Good	High	Very Good	It shows a 30-40% reduction in power usage due to the use of energy harvesting and data redundancy elimination. It achieves higher throughput and lower packet loss as compared to ELR-W and EECBSR and lasts upto 16,000 rounds outperforming Co-LAEEBA, and EECBSR.
17.	EEMR(Pradeep & Kavithaa, 2024)	Very Good	NA	Very Good	Good	Very Good	High	Good	EEMR is 30% more energy-efficient and achieves 95% higher throughput and longer network lifetime as compared to the traditional routing protocols.
18.	EEDLABA (Zaman et al., 2023)	Very Good	NA	Good	Good	Good	Average	Good	The first node in LAEEBA and DARE died at 2023 s and 2123s, whereas in EEDLABA, it died at 4205 s, which shows that the proposed routing protocol has a greater operating time as compared to the other two techniques considered for comparison.
19.	DFST (Rahman et al., 2022)	Very Good	NA	Very Good	Good	Good	Average	Good	The no of dead nodes is about 50% less, the average throughput is 51% and 8% higher, and residual energy is approx. 200% and 120% more in the proposed scheme than RE-ATTEMPT and iM-SIMPLE.
20.	EARP (Wang et al., 2021)	Very Good	NA	Very Good	Good	Good	Average	Good	It shows a higher network lifetime, lower packet loss rate, better response time, and reduced delay as compared to EERDT and M-TSIMPLE,

Table 8 continued…

21.	CEPRAN (Geetha & Ganesan, 2020)	Very Good	Average	Very Good	Good	Good	High	Good	It showed a 30-40% longer lifespan, 15-20% higher PDR, and upto 30% reduction in latency as compared to traditional WBAN protocols.
22.	EERP (Qu et al., 2019)	Very Good	NA	Very Good	Good	Average	Average	Good	EERP has prolonged network lifetime by 25% with 30% less low power consumption as compared to existing approaches. Moreover, a 10-15% improvement can be seen in PDR over PERA and NEW-ATTEMPT.
23.	EPRS (Memon et al., 2023)	Very Good	NA	Very Good	Good	Average	Average	Good	EPRS achieves low end-to-end delay and higher network throughput. The end-to-end delay is improved by 15-20% and the packet loss ratio is reduced to 20-30% in the proposed EPRS protocol.
24.	Adaptive Cuckoo Search (Samal et al., 2022)	Good	NA	Good	Good	Good	High	Very Good	The proposed protocol has prolonged WBAN operation time by 30% and has improved transmission success rate by 20%. It consumes upto 35% less power usage as compared to traditional methods.
25.	IoT-Based GPS Routing (Savaşcı Şen et al., 2021)	Good	NA	Good	Good	Good	Average	Average	The simulation results show a higher packet delivery ratio, lower packet loss, and improved network coverage for the proposed GPS-based routing scheme.
26.	QCCP (Buenrostro-Mariscal et al., 2023)	Good	NA	Good	Very Good	Average	Low	Average	It outperforms in terms of 18.66% less packet loss, 64.31% higher throughput, and 47.87% less latency over the state-of-art routing techniques.
27.	DT-MAC (Zeb et al., 2022)	Good	NA	Good	Good	Good	Average	Good	The results obtained after simulation show an increase in latency by 3% roughly, improvement in PDR by 13–17%, and response time by 15% as compared to MT-MAC.
28.	CARE-AODV (Waheed et al., 2021)	Average	NA	Good	Good	Average	Average	Average	The simulation results demonstrate improved data reliability, lower packet loss, higher throughput, and improved efficiency for the proposed protocol.

Table 7 provides an in-depth analytical comparison of routing protocols under various categories based on various performance metrics. The different routing metrics are evaluated and compared based on congestion control, priority, energy consumption, communication model used, fault tolerance, PDR, security, latency, scalability, throughput, network lifetime, etc. **Table 8** provides the quantitative analysis for the various routing protocols based on categories like good, average, very good, low, etc. with a discussion of the simulation results. The various observations have been made from the analysis and are discussed below for different WBAN routing protocols. **Figure 10** provides the overview and the percentage distribution of performance metrics used in WBANs for evaluating routing protocol performance as per the literature analysis:

It is clear from the literature analysis that most of the work done in routing focuses on energy consumption and network lifetime enhancement. As can be seen from the comparison, approximately 15% and 16% of work done in the past focuses on energy consumption and network lifetime, followed by PDR, which makes up 12%. The analytical report showed that though these are the major areas that were focused on in the past, they still need to be focused on in future studies. Other than this, there are a few other parameters that need consideration to enhance network performance further. The following discussion provides a clearer overview of the interpretations made from the literature review.

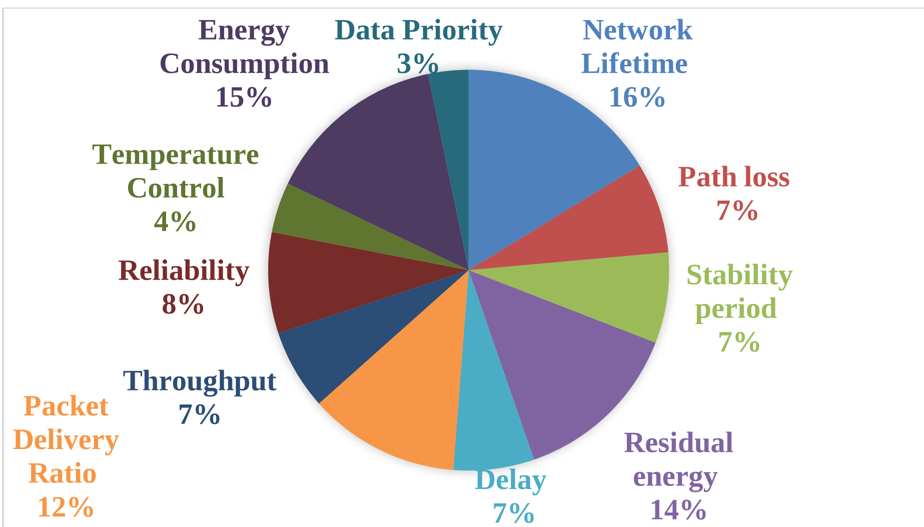

Figure 10. Percentage distribution of performance metrics used for routing evaluation in WBAN.

In Javaheri et al. (2023), the authors used a fuzzy-logic-based technique that can deal with uncertain data and inherent ambiguity. Similar sensors are grouped to form clusters that can do data aggregation in a better way. This scheme prevents the temperature rise of the nodes in multi-WBAN environments by mitigating the amount of data transmission to the coordinators. The protocol considers four different factors such as CH temperature, no. of similar neighbor's path loss, and remaining energy. The drawback of this technique is the assumption made that several patients are near each other. Moreover, postural movements are not considered, which can result in network partitioning and link breakdown. In Ahmed et al.(2022); an SDN-based approach is used that increases the overall efficiency by providing flexibility for data transmission. The main limitation of the PEDTARA model is the issues related to mobility, which it is not able to handle effectively. In Selem et al. (2021); authors proposed a protocol called mobTHE that handles the disconnectivity issue caused by the node's mobility. It considers various parameters like energy, temperature, throughput, and network lifetime. To minimize and solve the problems related to packet duplication and packet drop rate, the authors suggested the use of two coordinator nodes to collect the data continuously from the WBANs by synchronizing the coordinators. The distance of the sink is not considered; due to which the delay can occur. In the literature, no routing protocol performs routing based on link quality for intra-WBAN. LATOR (Caballero et al., 2020) is based on-demand routing, and the routes are selected based on the link's quality, thus overcoming the limitations in previously proposed routing. It also considers partitioning occurring from human body movement and avoids overheating of retransmitter nodes. The major limitation is that energy consumption which is an important factor in WBAN is not taken into consideration. The link status was overlooked in most of the existing routing protocols. So, to overcome this problem, Bhangwar et al. (2019) introduced WETRP, which incorporates relay nodes to enhance the network lifetime for multi-hop communication. Moreover, it was analyzed that the weight factor is an important parameter that needs consideration for routing the data packets. Hence, the proposed WETRP protocol is based on weighted energy and thermal-aware routing that minimizes packet delivery delay and hotspot formation. In comparison to other state-of-the-art techniques, it incorporates energy awareness and link-delay estimates, and it further distributes network load equally among the nodes. However, data priority can be incorporated for the transmission of critical data packets without any delay on a priority basis. In Iqbal et al. (2023), the authors addressed the issues related to network partitioning and reliable data transmission. From the literature, it was analyzed that most routing techniques deal with temperature and energy issues, thus overlooking the dynamic link status caused by postural body movement, which results in network partitioning and, in turn, affects the overall network performance. So, to address these challenges, the PLQE routing protocol was introduced, which identifies the reliable and optimal route dynamically. The main limitation of the work is that the energy parameter is ignored which is one of the most important factors in WBAN routing. So, the work can be extended in the future by considering the energy parameter to maximize the network lifetime. IM- QRP (Ahmad et al., 2022) routing protocol is specifically designed for the WBAN Healthcare Monitoring System. It selects the next hop based on energy and distance. The proposed protocol enhanced the network lifetime and provided higher SNR, increased throughput, and higher energy. The protocols can be integrated with 6G as part of future work by using an IoT-based framework for smart homes. NRL (Normalized Routing Load) is an important factor that determines the overhead involved in data packet routing. In existing schemes, as the network load grows, network interference also grows. This results in more packet losses and transmission disturbance increasing the number of route maintenance calls. This causes an overflow of control packets, namely RREQ, RERR, and RREP, into the network due to which the overhead of the routing protocols increases as more control messages circulate through the network. The authors proposed a new routing protocol called TLD-RP (Memon et al., 2021) to overcome the above-mentioned challenges. It uses a customized route maintenance scheme to make more informed decisions regarding link breakages, thus minimizing retransmissions and improving NRL performance. The limitation of the work is that the postural body movements are not considered, which can result in network partitioning and delayed data transmission.

To form efficient clusters based on various parameters specific to an application, the cluster-based routing protocols (Arafat et al., 2023; Helal et al., 2024; Park et al., 2020; Sharma et al., 2021a, 2022; Ullah et al., 2019) work effectively as they provide good load balancing by distributing the task among various nodes. The main problem with this routing technique is the formation of efficient clusters and the selection of appropriate CH. A sensor node's energy rapidly drains out and gets depleted when demand is distributed unevenly, thus creating an energy hole. In cross-layered protocols (Buenrostro-Mariscal et al., 2023; Waheed et al., 2021; Zeb et al., 2022), the best features or functionalities from different layers of the protocol stack are used for better performance and efficiency, but overhead increases due to the use of a greater number of control messages, which are required to establish a connection. It can also result in increased energy consumption. For time-sensitive and emergency data transmission the QoS-aware routing protocols (Ahmad et al., 2022; Iqbal et al., 2023; Memon et al., 2021; Mu et al., 2019; Yuan et al., 2020) provide better results as they provide a priority-based mechanism for the transmission of critical data on time to avoid any mishappening and loss of life. The QoS-aware routing protocols work well when the concern is to route the data packets urgently and reliably. They are well suited for applications where there is a requirement for a node to work for a longer duration of time and where the replacement of the nodes is a very difficult task. The postural-based routing (Memon et al., 2023; Samal et al., 2022; Savaşcı Şen et al., 2021) is suitable in the case of dynamic networks where the network topology changes very frequently due to changes in human body positions and body movement. It is used to analyze network topology and the dynamic nature of the human body to establish a stable path in various dynamic postures. Postural-based routing can cause network partitioning, resulting in delay-tolerant networks. It has been observed that the temperature-based routing protocols (Ahmed et al., 2022; Bhangwar et al., 2019; Caballero et al., 2020; Javaheri et al., 2023; Selem et al., 2021) deal with hot-spot issues and work well in the case of implanted nodes. As the temperature of implanted nodes rises and eventually harms body tissues, the temperature-based routing protocol helps to maintain the node's temperature at a given threshold by dispersing data among various nodes to prevent temperature rise by selecting different access routes and re-routing the data packets to these nodes. To maintain the energy of the nodes; the energy-efficient routing protocols (Aljaghthami et al., 2021; Geetha & Ganesan, 2021; Pradeep & Kavithaa, 2024; Rahman et al., 2022; Wang et al., 2021; Zaman et al., 2023) play an important role as they use various mechanisms and techniques to preserve the node's energy for a longer duration of time and help increase overall network performance. So, based on the application requirement and use cases, as well as environment and energy constraints, the different routing categories are devised. The choice of routing protocol depends on various constraints like specific application requirements and a trade-off between different factors like reliability, scalability, latency, energy consumption, throughput, delay, security and packet delivery ratio, etc. So, according to the analysis made from various routing protocols, cluster-based routing is best suitable for applications like healthcare monitoring and large-scale environments such as nursing homes and hospitals. Cross-layered-based routing is well suitable for resource-constrained WBANs like multimedia streaming and adaptive transmission where bandwidth is crucial and efficient use of energy is required. QoS-aware routing is suitable for timely and regular monitoring of vital signs, telemedicine applications, and emergency response systems, while postural-based routing is well suited for monitoring elderly people, sports, activity recognition, rehabilitation, and physical therapy. Temperature-based routing protocols help monitor medical conditions like sports hyperthermia and hypothermia, military, etc., and energy-efficient routing is useful in cases where prolonging WBAN's lifetime is the major factor. The WBAN also demands data prioritization due to heterogeneous nature of the data generated by health sensor nodes to provide better QoS. So, certain routing protocols discussed considers priority for transmitting emergency data packets to the destination in case of critical human health conditions. The following **Table 9** categorizes the routing protocols based on their unique feature and application scenarios:

Table 9. Routing protocol with diverse applications.

S. No.	Routing protocol	Applications
1.	Cross-layered routing	Resource-constrained WBANs like multimedia streaming, and adaptive transmission where bandwidth and efficient use of energy are crucial.
2.	QoS-aware routing	Real-time monitoring of vital signs, telemedicine applications, and emergency response systems.
3.	Temperature based routing	Helps in monitoring medical conditions like sports hyperthermia and hypothermia as well as in military applications.
4.	Energy-efficient routing	Monitoring of medical conditions, sports, military i.e. the cases where prolonging WBAN's lifetime is the major factor.
5.	Cluster-based routing	Healthcare monitoring in large-scale environments such as disaster management, nursing homes, and hospitals.
6.	Postural-based routing	Monitoring of elderly people, sports, activity recognition, rehabilitation, and physical therapy.

WBANs have diverse applications in healthcare, fitness tracking, and personal monitoring. A crucial component of WBANs is the efficient routing of data, ensuring that information gathered from wearable sensors is reliably transmitted to the intended recipient, whether that be a mobile device, healthcare provider, or cloud-based server. The key applications of WBANs, highlighting the essential role that routing plays in their operation are:

a) ***Healthcare monitoring and telemedicine***
WBANs are frequently used in the medical field to continuously monitor patients with long-term illnesses like diabetes, heart disease, and respiratory diseases. Vital indicators like blood pressure, heart rate, oxygen saturation, and glucose levels are monitored by sensors built into wearable technology. Timely interventions are made possible by efficient routing, which guarantees that real-time data is transferred without delay. Multi-hop routing is often used to transmit data through multiple devices, such as smartphones or base stations, to the healthcare server to ensure reliable data transmission.

b) ***Emergency medical response systems***
WBANs are extremely important for emergency medical systems, especially when it comes to situations where a prompt reaction to life-threatening situations is necessary. WBANs, for instance, can be used to continually monitor patient vitals in emergency rooms or ambulances. Adaptive routing protocols can be used in emergencies to dynamically choose the optimal path for data transmission even if the environment changes or device mobility occurs.

c) ***Remote health monitoring for the elderly patients***
WBANs are frequently used to monitor elderly patients at home where sensors gather information about their heart rate, mobility, and environmental factors like temperature and humidity. The objective is to identify any anomalous behavior that would necessitate medical intervention, such as falls or aberrant physiological changes. To reduce power consumption and extend the device lifespan, energy-efficient routing methods such as cluster-based routing or spatial routing are used.

d) ***Fitness and sports monitoring***
WBANs are used in the sports and fitness industry to monitor athlete's body temperature, heart rate, muscular activity, and perspiration levels. This real-time data is essential for athletes and coaches to maximize performance and avoid injury. In sporting environments, mesh networks and multi-path routing can be utilized to guarantee that data from several body parts-such as the head, wrist, and chest-is efficiently aggregated and sent to a single location without interruption or data loss.

e) ***Chronic disease management***
WBANs can continuously monitor vital indicators for people with long-term diseases including diabetes, high blood pressure, or obesity. Healthcare providers are better able to manage the disease and modify therapies as required. In these applications, QoS-based routing is frequently used to prioritize vital health data, guaranteeing that crucial information, such as irregular heartbeats or blood glucose rises, reaches medical professionals promptly without any delay.

f) ***Military and defense applications***
WBANs are employed in military contexts to keep an eye on soldier's physiological and general health, especially in harsh surroundings. To avoid fatigue and improve army performance, these networks monitor stress levels, body temperature, and physical exertion. Robust and secure routing is crucial in this situation. Even when soldiers are traveling in uncertain and dynamic environments, hierarchical routing makes sure that the data can pass through different network devices efficiently.

g) *Real-time patient tracking in hospitals*

As patients move from room to room or undergo different medical procedures, WBANs can be utilized to continuously monitor their health. This monitoring guarantees that medical personnel respond quickly to any unexpected changes in health. Dynamic routing algorithms help to manage high-density data traffic and provide dependable, real-time communication between different hospital devices, such as wearable sensors, medical equipment, and the central monitoring system.

For health data to be transmitted reliably, effectively, and securely across a wide range of applications, routing in WBANs is crucial. Routing protocols must be carefully selected to meet the unique requirements of each scenario, whether it be for emergency response, chronic disease management, healthcare monitoring, or sports performance. This ensures that real-time data reaches the right destination with minimal latency, optimal energy consumption, and high reliability. To accommodate the increasing complexity and requirements of WBAN-based applications, future advancements in routing algorithms will concentrate on enhancing network scalability, energy efficiency, and security.

8. Emerging Technologies in WBAN

Recent technological advancements such as 5G/6G, blockchain, IoT (Internet of Things), and Artificial Intelligence (AI) have increased the quality of research in the WBAN field and created new opportunities. To increase the efficiency and accessibility of WBAN systems, these technologies are essential for modern healthcare demand (Aski et al., 2023; Krishna et al., 2023). These technologies are essential for meeting the demands of modern healthcare by improving the accessibility and efficiency of WBAN systems. This technological integration has a significant impact on WBAN's performance as it provides reliable, secure, prompt, and timely healthcare services. The development of new health sensors daily and their easy integration with recent technologies have made a strong foundation for an increase in WBAN demand. Furthermore, to fulfill the requirements of an affordable healthcare system, cutting-edge technologies like edge, cloud, and fog computing provide affordable computational and storage possibilities (Goel et al., 2023). However, several elements must also be taken into account when integrating sensors with other technologies, such as wireless connectivity, battery life of the sensors, interoperability, computational speed, and resilience. The various future trends have been identified for WBAN from the survey and are discussed below, and **Figure 11** illustrates WBAN integration with various emerging domains:

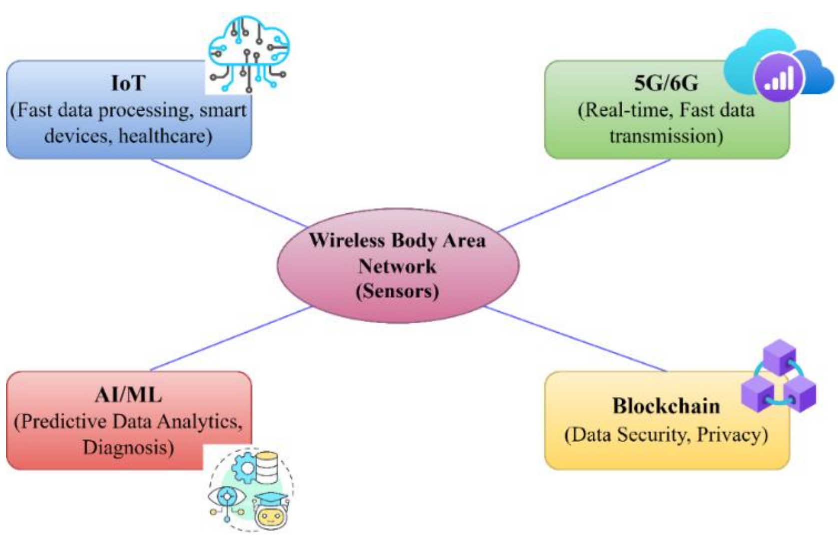

Figure 11. Integration of WBAN with emerging technologies.

a) 5G/6G: With the encouragement of new healthcare monitoring, assessment, and treatment services, 5G and 6G technologies are critical catalysts for revolutionizing the healthcare sector. Better network connectivity is required for the digitization of hospital systems (Dang et al., 2023). The growing demand to increase bandwidth for remote care, IoT setups, telehealth monitoring, e-consultations, and the operation of robotic systems requires fast connectivity, and 5G/6G appears to be the solution to these problems. It facilitates secure data transmissions at extremely high data rates, up to 1Tbps for 6G and 1Gbps for 5G, with a low latency network, enhanced reliability, and reduced power consumption for critical applications (Jones & Katzis, 2018; Taleb et al., 2021; Zhang et al., 2021). Additionally, it supports AI-powered solutions for cutting-edge healthcare systems. It makes it possible to transfer real-time data about the human body to cloud servers and edge devices at high data rates. As a result, it facilitates quick access to imaging systems and medical data, resulting in reliable, efficient, and effective patient care and healthcare delivery.

b) IoT: IoT is a new technological paradigm that has received much interest in various sectors in recent years. The field of healthcare has enormous prospects as a result of the introduction of IoT. To perform effective analyses and complex operations; a smart IoT gateway is required that can expand the applications of WBAN for different activities (Krishna et al., 2023). These intelligent IoT gateways can enhance the functionality of a WBAN by connecting it to cutting-edge technologies like cloud computing. It is expected that these networks would help with early diagnosis, and emergency medical care offering huge potential to improve the quality of healthcare services and cut costs (Ahmed et al., 2017). In addition, it lowers latency in data transmission and enhances storage and data availability. To fully utilize IoT's potential in healthcare systems, a growing number of research institutions are investing in the development of IoT-enabled technologies.

c) Blockchain: To ensure security in WBANs, several cryptographic techniques and methods are available. A growing trend in this age of rapid technical and medical developments is the remote monitoring of patients, especially the elderly. Hospitals and medical facilities are in demand, even under circumstances such as the Covid-19 pandemic. In certain situations, patients in need of 24-hour medical care, as well as elderly individuals, can be allowed to remain in their homes while being watched remotely through the use of a remote patient monitoring system. Networks are used to exchange the collected sensor data with medical facilities and specialists. This data comprises extremely private personal information such as personal details, medical history, vital signs, and so forth. Recently, many projects have been put up to use the newly emerging Blockchain technology to enhance WBAN secrecy, privacy, and security. In this review, we go over several studies that suggested using blockchain technology to guarantee data privacy, security, and integrity in WBAN (Pawar & Kalbande, 2020; Singh & Kumar, 2024). To preserve the confidentiality of personal data, a secure algorithm must be created using the distributed nature of blockchain technology and optimized QoS settings. Benefits of blockchain integration include the ability to promote collaborations with researchers in the diagnosis and treatment of diseases, safe automated patient monitoring, remote patient data storage, and more.

d) AI/ML: With the advancement of AI technology, its application is finding its way in each and every field. AI/ML techniques can be utilized for WBANs to increase network performance thus enhancing overall health services. AI may be used as a strong tool to evaluate the network traffic and consequently to develop better techniques for managing WBAN resources efficiently. WBANs can leverage AI's intelligence to deal with the dynamicity and complexity of these networks. The high demand for advanced diagnostics and health insights has increased the demand for AI in WBANs. Improved data aggregation, node localization, scheduling, routing, sensor fusion, better clustering, improved QoS, and security in WBANs can all be achieved with the application of AI techniques(Al-Turjman & Baali, 2022). The various AI-based techniques like Genetic Algorithm (GA), Reinforcement Learning (RL), Swarm Intelligence (SI), Fuzzy logic (FL), and Artificial Neural Networks (ANN) can be used to enhance the performance of the WBAN to facilitate predictive analytics, optimal selection of data transmission path, health trend analysis, real-time data delivery, and personalized healthcare (Tunc et al., 2021). **Table 10** discusses the importance, demand, advantages, challenges, applications, and scalability features related to the use and integration of these technologies in WBAN:

Table 10. WBAN integration with emerging technologies.

S. No.	Emerging technology	Importance in WBAN	Demand in WBAN	Benefits	Challenges	Applications	Scalability
1.	IoT	Connects WBAN to smart environments (homes, cities, healthcare)	High due to smart home/healthcare integration and its huge adoption	Continuous monitoring, automation, and remote monitoring	Security risks, data standardization (interoperability)	Smart homes, patient monitoring	High
2.	5G/6G	Enables high-speed, real-time data transfer for WBAN	High as it accelerates remote healthcare and telemedicine	Fast data transmission, low latency, real-time updates	Coverage, infrastructure cost, Network availability	Remote surgeries, Remote diagnostics, live monitoring	Moderate, based on infrastructure
3.	Blockchain	Enhances security and privacy for healthcare data, Secures sensitive health data	Growing, with rising concerns and focus on data privacy, data security and compliance	Enhanced security, transparent data sharing, Tamper-proof data sharing, traceability	Integration complexity, scalability	Secure patient record management	High, with technological advancement
4.	AI/ML	Facilitates AI-driven predictive analytics, health trend forecasting, and personalized healthcare	High as AI drives healthcare innovation	Early diagnosis, predictive insights, trend prediction, personalized treatment	Data bias, training complexity Model accuracy, data availability	Predictive health diagnostics	High, dependent on data availability

8.1 Case Studies on Chronic Disease Management and Ankle Fracture Patient Monitoring

a) Case study on chronic disease management (CDM)

Murala et al. (2023) discussed and showed how the combination of the metaverse with blockchain, AI, and wearable technologies can aid the healthcare industries and also demonstrates how these technologies are utilized in the medical area. The authors in this paper proposed an approach used to diagnose and treat chronic patient’s medical issues. Explainable artificial intelligence (XAI) is also used to ensure that the data is analyzed for better diagnosis and forecasting of the progression of diseases mentioning the reasons precisely. To secure the data, blockchain technology, which is decentralized in nature, is used and to collect patient data wearable technology is used. These advanced technologies show a great transition and impact on CDM through a patient-centered framework that helps to control chronic diseases using AI, blockchain, and wearable technologies. Moreover, the proposed architecture depends on the metaverse environment, and to use this both physicians and patients are required to sign up on Blockchain network. A complete record of all the information gathered during doctor-patient interaction, including text, images, videos, clinical data, and audio is compiled, stored, and uploaded to the blockchain. This case study highlights the use of blockchain, AI, and other advanced technologies for chronic disease management thus providing quality of life to the patients and their families.

b) Ankle fracture post-surgery monitoring

Research on post-surgery patient monitoring is beneficial since it is necessary to regularly check on the patient's health to prevent any losses. The study employs the use of the convolutional neural network (CNN), a deep learning-based model, to classify image data and offers a user-friendly platform for detecting ankle mobility in patients who have undergone ankle fracture surgery. (Barua et al., 2020) used deep learning and wireless networking to provide this healthcare monitoring system a cognitive intelligence. This work's primary idea is to capture wireless channel state information when the human body is in motion and use CNN to classify it to detect distinct movements. With the aid of monitoring, the proposed approach assists post-surgery ankle-fractured patients to understand how their ankles are moving.

9. Conclusion & Future Scope

WBAN is a sub-branch of Wireless Sensor Networks developed intending to look after human health remotely through different sensors that are placed on the human body, connected to clothing, or implanted beneath the skin. Miniaturization of electrical components, increased adaptation, knowledge and awareness about the usage of health devices for effectively tracking the physical fitness of patients remotely are the various factors that have increased the demand for WBANs leading to overall global market growth. Various researchers are continuously working to make a better and improved healthcare ecosystem towards improving patient monitoring systems using WBANs. To improve the various QoS parameters, researchers have developed different routing strategies with a focus on enhancing the network's performance, lifetime, battery life, energy efficiency, throughput, etc. This survey provides a detailed taxonomy and a comparative analysis of recent WBAN routing protocols. The research aims to make remote patient monitoring possible in an efficient manner by designing effective routing techniques that overcome the challenges discussed in the article. The various research gaps and the potential future aspects of the reviewed WBAN protocols have been discussed which helps to provide new research directions in the WBAN domain. The various research gaps found from the literature analysis are reduction of node's temperature to avoid human tissue damage, enhancing network lifetime, secured data transmission, prevention of hot-spot nodes, removing or decreasing end-to-end delay, enhancing QoS, etc. Privacy is also one of the major concerns for health-related applications so designing security-based routing protocols can help to minimize the risk of data leakage and can be an emerging area of research. Furthermore, incorporating innovative and new emerging technologies like IoT, blockchain, 5G, Machine Learning (ML), HIoT, Virtual Reality (VR), and Artificial Intelligence (AI) with WBAN provides new growth opportunities for the global digital health market. Advanced ML models can be used more and more by future WBANs to forecast the course of diseases and provide individualized therapies. To provide proactive care as opposed to reactive care, AI can be utilized to evaluate enormous volumes of real-time data from wearable sensors and forecast health emergencies before they arise. Energy harvesting innovations (kinetic, thermal, or solar energy) might provide an alternative for powering WBAN devices without requiring regular battery changes or recharges. WBAN systems can incorporate edge computing to lower latency, computational load, and bandwidth requirements. To provide real-time insights and prompt reactions, edge devices (such as smartphones or local gateways) will process data locally rather than send all raw data to centralized servers or cloud-based platforms. Hence, by combining cutting-edge technology and smart energy harvesting mechanisms, WBANs have the potential to revolutionize many industries, especially healthcare.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AI Disclosure

The author(s) declare that no assistance is taken from generative AI to write this article.

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Appendix A

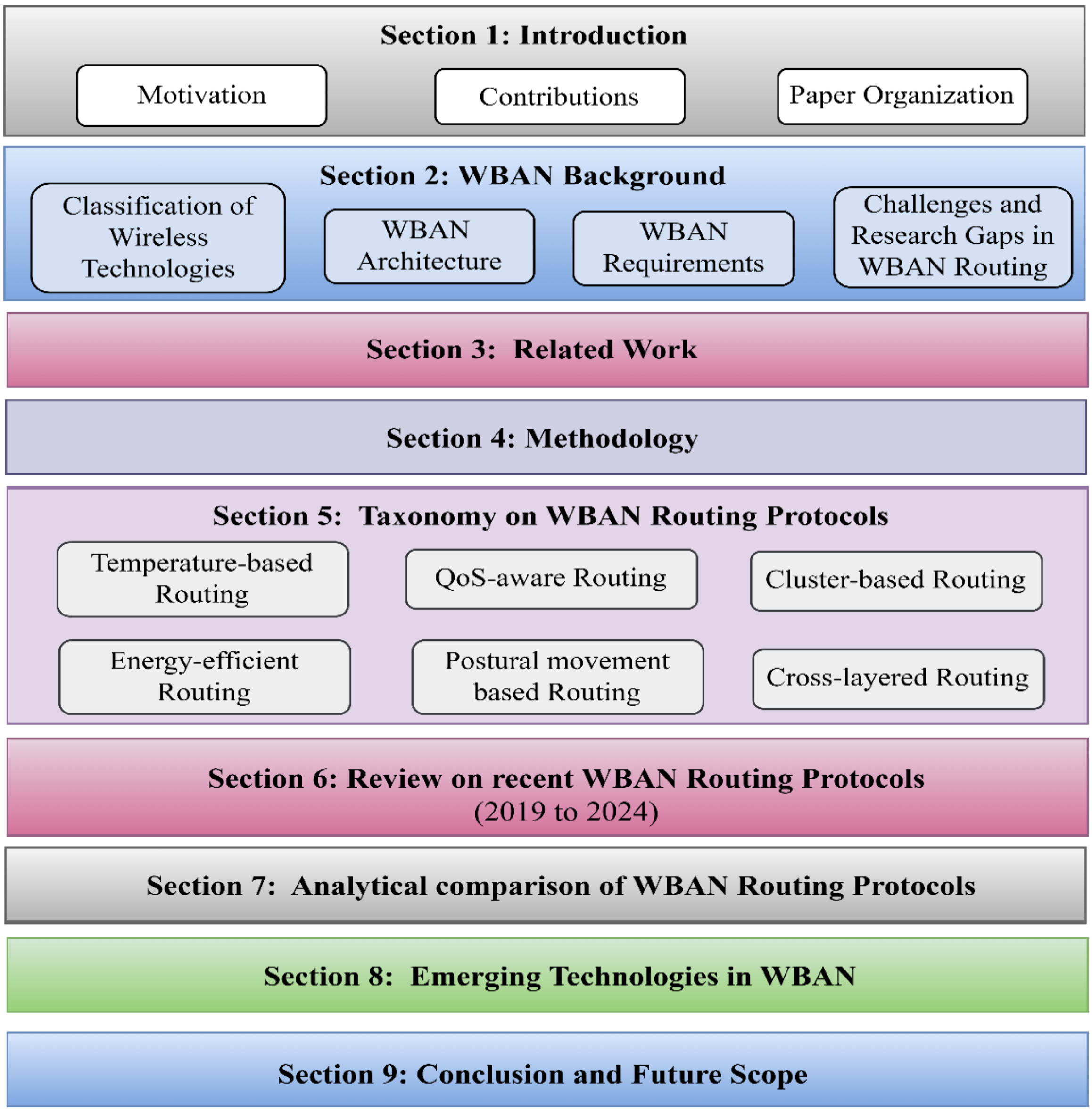

Figure 12. Graphical abstract.

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