APPLIED COMPUTER SCIENCE

Applied Computer Science 2025, vol. 21, no. 3, pp. 137–161
https://doi.org/10.35784/acs_7355

Submitted: 2025-02-27 | Revised: 2025-04-24 | Accepted: 2025-05-06

Keywords: wireless body area networks (WBANs), health monitoring, energy efficiency, WBANs architecture, WBAN communication technologies, applications

Akeel Abdulraheem THULNOON [1], *Ahmed Mahdi JUBAIR* [1*], *Foad Salem MUBAREK* [1], *Senan Ali ABD* [2]

[1] University of Anbar, Ramadi, Iraq, akeelalhadithy@uoanbar.edu.iq, ahmed.mahdi@uoanbar.edu.iq, co.foad.salem@uoanbar.edu.iq,
[2] University of Fallujah, Fallujah, Iraq, senan.a.abd@uofallujah.edu.iq
[*] Corresponding author: ahmed.mahdi@uoanbar.edu.iq

Wireless body area networks: A review of challenges, architecture, applications, technologies and interference mitigation for next-generation healthcare

Abstract

Wireless Body Area Networks (WBANs) are one of the emerging technologies in the healthcare landscape. It enables the non-invasive collection of physiological data to continuously measure health indicators using a network of miniaturized sensors placed on or under the human body. This paper explores a comprehensive study of WBANs, covering all the basic concepts, including their background information and motivation for development, as well as requirements and issues related to their application scenarios and future directions. The paper elaborates on the exclusive characteristics of WBANs compared to Wireless Sensor Networks. It describes health monitoring requirements and energy efficiency challenges with security and biocompatibility as guidelines for comparison. In addition, the paper also highlights various WBAN communication technologies and their relevance in diverse medical and non-medical domains. This paper identifies the critical comprehensive analysis of interference dynamics and mitigation strategies that remain absent in the literature, along with an exhaustive review of the literature. The research shows that WBANs could have a significant impact on healthcare and other industries, while discussing the technical and ethical hurdles to their wider application.

1. INTRODUCTION

Wireless Body Area Networks (WBANs) represent a transformative advance in wireless communication and healthcare technology, enabling continuous physiological monitoring and real-time data analysis through miniaturized sensors placed on or within the human body (Taleb et al., 2021). These networks have significant applications in healthcare, particularly in the management of chronic diseases such as diabetes, Parkinson's, and asthma, where continuous real-time monitoring facilitates early diagnosis of critical scenarios, improves patient health outcomes, and reduces healthcare costs (Talpur et al., 2024).

WBANs play an important role in several other areas. In a common WBAN structure, physiological data collected by body sensors is transmitted via communication protocols to a gateway device. The gateway collects and relays this data to a centralized health monitoring system (Figure 1), where it is analyzed by clinicians or AI-driven diagnostic algorithms (Kalra et al., 2024). This architecture facilitates continuous clinician-patient interaction, enabling real-time health assessments and early detection of emergent conditions such as cardiac arrhythmias or hypoglycemic episodes through automated anomaly detection protocols (Das & Moulik, 2025). WBANs enable real-time health monitoring and rapid response to hazardous exposures. In addition, their potential extends to workplace safety in hazardous industries, elderly care through remote monitoring and fall detection, and integration with augmented and virtual reality applications for immersive experiences (Rameshkumar & Ganeshkumar, 2022). In addition, WBANs are contributing to diverse fields such as research, education, veterinary care, public health, insurance, and lifestyle monitoring, further demonstrating their applicability and transformative impact (Arshad et al., 2024).

The-sensors are expected to become more ubiquitous, offering innovative solutions across a wide range of industries. Emerging applications include monitoring the fitness of athletes during competitions, assessing the health of crops in agriculture, and ensuring the well-being of endangered animals. Future developments may extend WBAN applications into the areas of entertainment, lifestyle enhancement, environmental intelligence, ubiquitous computing, and security (Punj & Kumar, 2019).

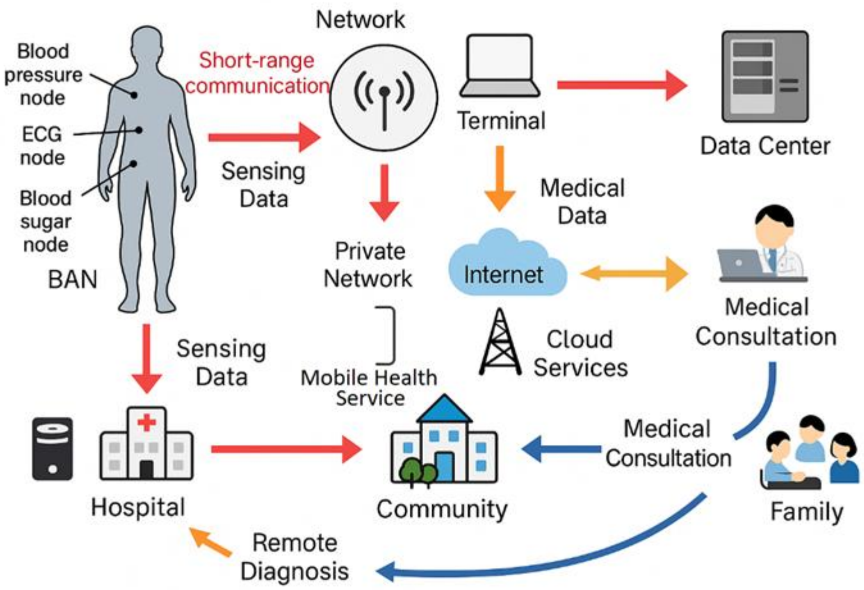

Fig. 1. Wireless body area overview

Given their critical role in medical environments, WBANs must meet stringent Quality of Service and security requirements, particularly when handling sensitive patient data. Recent research efforts (Singla et al., 2022; Kaleem & Rehman, 2024) have focused on optimizing QoS in WBAN applications, emphasizing the need for lightweight security mechanisms tailored to the resource-constrained nature of WBAN nodes. For instance, security protocols such as trust management must be designed to ensure data integrity and confidentiality without compromising network performance (Dhanvijay & Patil, 2021). WBANs also facilitate seamless data exchange with software systems that analyze and present local information through a local processing unit that serves as a gateway between physiological sensors and access points (Khater et al., 2024). In addition, WBAN sensors can interact with the environment and integrate both medical and non-medical data sources to improve patient monitoring and healthcare delivery (Hassan et al., 2024). As technology continues to evolve, WBANs are expected to have a significant impact on healthcare and other industries, providing novel solutions that improve quality of life, operational efficiency and safety in various applications.

Recently, the integration of artificial intelligence (AI) technologies into WBAN systems has received considerable academic interest, especially in the area of processing and classifying the large amount of biomedical data collected by WBAN sensors. Machine Learning Algorithms (Negra, 2022) Artificial Neural Networks (ANNs) (Donghua Jiang et al., 2022a)federated learning systems (Singh et al., 2025)Mobile edge computing is increasingly being used to enhance the intelligence, autonomy, and personalization capabilities of WBANs (Yang et al., 2021). Biomedical signals such as EEG (electroencephalogram), ECG (electrocardiogram), VAG (vaginal acoustic signal), blood glucose levels, and others require complex data processing techniques to extract meaningful information (Popov & Ivanko, 2024).

Particularly, AI is used for classification of biomedical data into different health states in normal and abnormal (Jin & Dong, 2018), anomaly detection to recognize early signs of disease (Abououf et al., 2023; Haechan & Kim, 2024), prediction of disease states such as arrhythmia, epilepsy, or hypoglycemia (Porumb et al., 2020), and personalization of medical care by adapting the monitoring and treatment strategies based on individual patient profiles (Ghanem et al., 2024). In addition to these applications, machine learning techniques have also been employed in the field of orthopaedic diagnostics, particularly for assessing knee health and diagnosing knee-related conditions (Karpiński, 2022; Machrowska et al., 2025). Finally, machine learning classifiers such as support vector machines (SVMs), convolutional neural networks (CNNs), recurrent neural networks (RNNs) (Machrowska et al., 2024)ECG signal classification and arrhythmia detection using decision trees (Çınar & Tuncer, 2021).

There are still many unexplored areas within this technology. In particular, there has been no comprehensive study focusing on interference management in WBANs. This study aims to fill this gap by conducting an in-depth analysis of interference challenges and mitigation strategies in WBANs, thereby contributing to the advancement of research in this area. The contributions of this study are:

- An overview of the needs and research conducted in the area of WBANs.
- A detailed analysis of the three layers of network architecture for WBANs.
- A definition of the WBAN concept based on previous related studies with a proposed new definition.
- A classification of WBAN applications in various medical and non-medical domains.
- A comparison of different communication technologies for WBANs.
- The challenges in WBANs are still open for research. - A collection of WBAN projects.

The paper is organized as follows: Section 2 presents the fundamentals of WBAN architecture, interference dynamics, and existing literature reviews on WBANs, highlighting research gaps. Section 3 discusses optimization strategies for communication technologies, followed by Section 5 which discusses interference mitigation techniques, and Section 6 classifies WBAN applications based on medical and non-medical domains. Finally, Section 7 identifies technical and ethical challenges, and Section 8 concludes the study.

2. STATE OF ART OF WBAN

2.1. Concept of WBAN

Due to the rapid development of the Internet of Things (IoT), WBANs have received significant attention from researchers in various fields (Punj & Kumar, 2019). The integration of WBANs and IoT has enabled a wide range of applications, including remote health and fitness monitoring, rehabilitation, military and sports training, active combat operations, animal husbandry, interactive gaming, personal information sharing, secure authentication, and assisted living. WBANs consist of low-power, miniaturized, and lightweight devices with wireless communication capabilities that operate in close proximity to the human body (Bhatti et al., 2022). These devices can be placed in various locations on the body, including inside the body (in-body sensors or implants), on the surface (on-body sensors), and around the body, to monitor physiological functions and environmental characteristics, supporting a wide range of biomedical applications, particularly in the healthcare industry (Mohamed et al., 2021). The design and deployment of medical sensor networks is tailored to specific applications and scenarios. For example, a sensor network intended for ad hoc deployment on the body during an emergency has different requirements than a network permanently installed in a hospital where fixed, powered gateway nodes can be used to access a wired network infrastructure.

Different researchers have proposed different WBAN architectures, each with unique approaches to health monitoring challenges. The following examples illustrate the diversity of these research initiatives and highlight the breadth of innovation in WBAN technology.

Definition 1: In e-healthcare environments, WBANs are an integral part and play a critical role as information collectors and transmitters (to base stations or portable gateway nodes such as PDAs, cell phones) of medical data to remote healthcare facilities for storage and further processing. In healthcare, this technology enables remote monitoring and disease detection, which improves patient care and reduces healthcare costs by providing continuous, unobtrusive patient monitoring for the elderly or those with chronic diseases (Al-Thobhani, 2022).

Definition 2: WBANs play an important role in modern e-healthcare systems, enabling real-time health monitoring, remote patient management, and timely medical intervention. Data collected by sensors in the WBAN is then either transmitted to personal devices such as smartphones or directly to remote servers via the Internet, where it can be accessed by healthcare providers for continuous monitoring and complex diagnostic services. Technology is enhancing the healthcare landscape to take advantage of increased patient mobility and independence, and also to increase the efficiency of healthcare delivery (Taleb et al., 2021).

Definition 3: WBANs generally consist of a number of small and lightweight devices embedded in the human body that communicate wirelessly with each other. These devices can be placed in or around the body at specific locations to routinely monitor various physiological and environmental parameters. WBAN devices can be classified based on location as internal (in-body sensors or implants), external, which refers to in-body sensors (<5 m distance traveling through vacuum and atmosphere) while carried by a human body. Chaudhary et al. (2024) is similar in meaning but different from the wearable device mentioned above. WBANs are an attractive technology for monitoring vital signs in a wide range of biomedical applications in the healthcare industry due to their low power characteristics (Preethichandra et al., 2023).

Proposed Definition: An interconnected wireless system of devices and sensors designed to continuously monitor a variety of biometric activity information. This includes (but is not limited to) vital signs, habits, patterns, and interactions with the environment, enabling real-time health monitoring, activity tracking, and personalized care solutions. These networks use novel wireless communication protocols to enable continuous, secure, and energy-efficient data transfer between user-wearable devices and external systems.

2.2. Architecture of WBAN

With the growing technology of wireless communication and sensors, WBANs have been identified as a notable advancement in health monitoring and personal care (Krishnamoorthy et al., 2023). A WBAN has developed a three-layer architecture (Fig. 2) for reliable and energy-efficient data acquisition, transmission, and analysis. Layer-One: includes sensors that can be applied to the body surface or placed inside the body. These sensors continuously monitor various physiological signals such as heart rate, body temperature and glucose concentration. The collected information is wirelessly transmitted to the higher level for further analysis. Intermediary devices such as smartphones, PCs and other intelligent electronic systems are in the second layer. These are the gateway devices that transmit the physiological data collected by the sensors to a central data center. This is a wireless communication that allows real-time data transmission, which will provide the impetus for rapid decision making. Remote servers are usually part of the third layer: the terminal data center. It collects, sorts and interprets the data into actionable information. When the system detects abnormal physiological readings, it triggers an emergency by issuing alerts and alarms. Rapid notification is critical to expediting emergency response and facilitating prompt medical care.

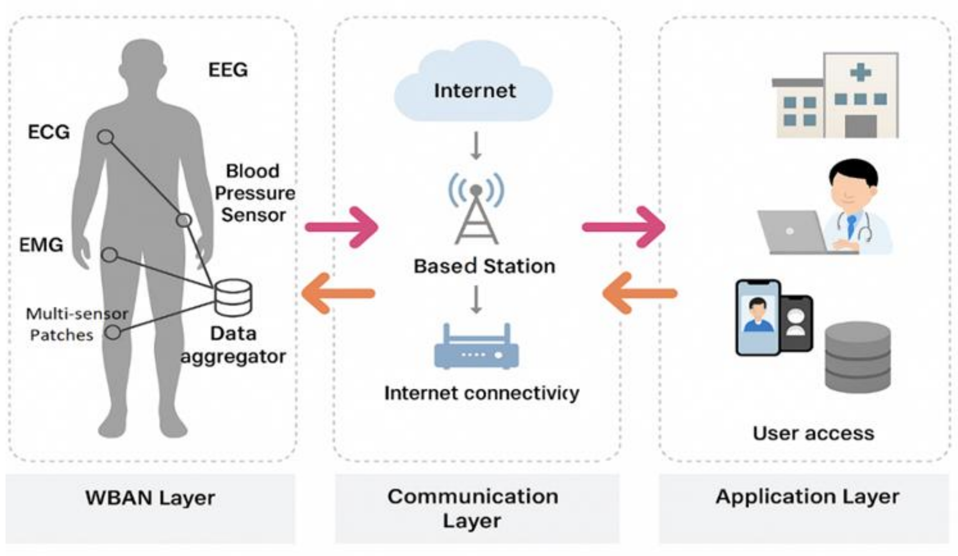

Fig. 2. Three layers architecture for WBAN

2.3. Interference dynamic of WBAN

WBAN is typically deployed for a single human body. However, in many practical environments, the presence of multiple WBANs operating simultaneously is unavoidable (Olatinwo et al., 2021). Since the human body is inherently mobile, the sensor devices attached to various parts of the body, such as arms and legs, also experience localized mobility, as shown in Figure 3. Under such conditions, both intra-WBAN and inter-WBAN interferences can significantly degrade the communication transmission (Shaik et al., 2018). The increasing density of WBAN deployments and their shared operation in limited frequency bands have exacerbated interference challenges (Taleb et al., 2021). These challenges can degrade overall system performance and jeopardize mission-critical applications, particularly in healthcare environments. Interference hinders transmission reliability, resulting in packet drops and frequent retransmissions of both data and control packets (Tusha & Arslan, 2024). These interruptions even cause synchronization problems, sensor-to-hub communication problems, reduced throughput, additional channel conflicts, and unnecessary energy consumption, especially in the scenarios of user mobility and overlapping WBANs, where the validity of the signal is spatially and temporally unstable, causing further noticeable performance degradation in the network. One of the challenges in WBAN is the interference caused by short-range communication. WBAN interference can be divided into three types.

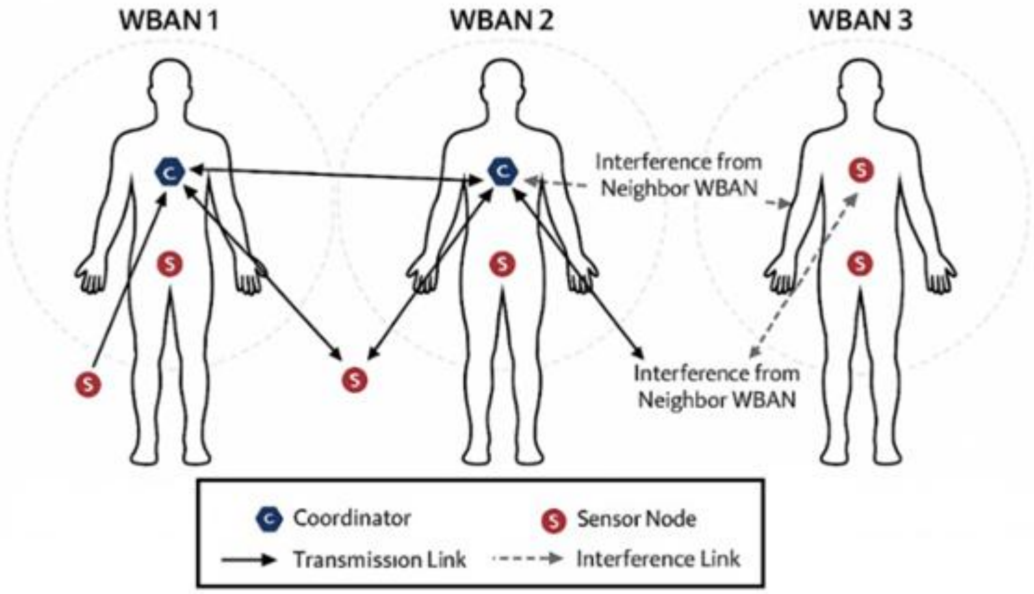

Fig. 3. Transmission and interference links in WBAN

Intra-WBAN communication, a fundamental component of WBANs, supports the continuous collection, processing, and reporting of data across WBANs, such as health monitoring, fitness tracking, and immersive entertainment applications. A typical WBAN consists of multiple small sensor nodes with embedded processing and wireless communication capabilities. Although WBANs inherit the challenges of traditional wireless sensor networks, such as limited node energy and interference in close proximity to the human body, they have their own design requirements. Such challenges are biocompatibility and long-term wearability, and resistance to dynamic body motion, for which specific research beyond the classical WSNs system framework should be addressed. Wearable WBAN sensors used for chronic disease management or health and wellness must operate at ultra-low power levels, often for extended periods of time, and without the risk of false alarms or missing events of interest. To meet these needs, key communication standards have been adapted for wearable applications: IEEE 802.15.4 (Akbar et al., 2022) (Zigbee), IEEE 802.15.6 (Choudhary et al., 2020) (tailored for WBANs) and Bluetooth Low Energy (BLE) (Rangaiah et al., 2023). Notably, while IEEE 802.15.6 was explicitly designed for WBANs that prioritize energy efficiency and channel diversity in body-centric environments, its practical adoption remains limited due to hardware complexity and interoperability challenges.

The impact of inter-WBAN interference, which is critical in multi-user WBANs and results in degradation of network performance due to decreased throughput, high packet loss rates, and reduced reliability (Chaudhari et al., 2022). This interference grows with independent, uncoordinated WBANs, which are common in dynamic environments such as healthcare, such as hospitals, or health monitoring, such as multi-user gyms. Interference management methods can generally be divided into two approaches: centralized and distributed techniques. Centralized solutions use the base station as a coordinator to design Media Access Control (MAC) protocols and sensor transmission power within the WBAN in a way that reduces inter-network interference (Herculano et al., 2024). Although these techniques are efficient for static environments, they are not suitable for WBAN scenarios. Due to the mobility of users and the decentralized, autonomous nature of each WBAN, centralized coordination is not feasible, nor is real-time reconciliation across independent networks.

Inter-domain interference occurs when heterogeneous wireless technologies operating in shared frequency bands coexist in the same physical space. A prominent example is the 2.4 GHz ISM band, where Wi-Fi, Zigbee and WBANs often compete for spectral resources. Such coexistence can severely degrade WBAN performance through channel contention, signal collision, and noise amplification. For example, Fan et al. (2021) Experimentally demonstrated that nearby Wi-Fi and Zigbee devices increase WBAN packet loss rates by up to 40% under overlapping channel conditions, while simultaneously increasing bit error rates and symbol error rates due to cross-technology interference.

2.4. Related work

WBANs have attracted much interest for advanced health monitoring and human-centered services. Many researchers have studied WBANs, focusing on related communication technologies, security protocols and models, energy consumption, architectural designs, and real-world applications. In this section, we review and integrate key contributions from recent works, focusing on dominant themes and placing the work in the broader context of the scientific literature. Table 1 systematically categorizes these studies according to their key contributions.

In the work of Qu et al. (2019)The authors documented a detailed survey of WBAN routing protocols for healthcare systems, describing the unique posture of each protocol in terms of its practical usability. They organized the protocols around the parameters of posture, temperature, clustering designs, cross-layer, and QoS. Focusing on network routing, the study stated that temperature control, energy efficiency, and network dynamics due to body movements should be integrated. The authors proposed to open innovative problem areas in the development of reliable, energy-efficient, low-latency, and persistent WBAN e-health applications, while employing WBAN-tailored routing protocols that focus on efficiency and reliable execution.

In Al-Barazanchi et al. (2019)The researchers reviewed the communication methods used for WBANs, analyzing both short-range methods such as Bluetooth, ZigBee, Ultra-Wideband, and Wi-Fi, and long-range cellular communication. The authors examined the trade-offs between power consumption, data rates, latency, and reliability that are essential for continuous patient health monitoring. The review outlined issues related to power efficiency, secure data transmission, and system scalability. In summary, the paper concluded that technology selection requires careful consideration of application criteria, body mobility, and multiple medical requirements.

In the study Yaghoubi et al. (2022)The authors provided a comprehensive review of the current state of WBANs in terms of architecture, technologies, energy consumption, and security issues related to WBANs. They defined WBANs as networks of wearable or implantable sensors that continuously monitor health conditions. Important issues addressed were the limited energy available, the reliability of data transmission, and the vulnerability of the system to attacks. Various approaches were discussed, such as energy-aware routing protocols, sparse and adaptive security mechanisms, and secure communication strategies. This paper emphasized the need to balance energy optimization with security for weaponized autonomous border surveillance systems.

The authors of Zhumayeva et al. (2023) examined the state of wireless power and information transfer techniques in WBANs, focusing on the role of wireless power transfer and simultaneous wireless information and power transfer as key enablers for sustainable operational functioning. They also separated near-field and far-field WPT methods in the context of energy harvesting optimization techniques. Some of the concerns discussed are device miniaturization, propagation modeling, and security of energy information networks. The study concludes that the merging of communication and energy harvesting is essential for long-term reliable performance in WBANs.

In Shunmugapriya et al. (2022)The authors reviewed the recent research on energy-efficient routing protocols to be used in WBANs and formulated a survey. The categories of routing protocols they derived were cluster-based, cross-layer, QoS-based, postural movement-based, and secure routing protocols. They focused on energy conservation, thermal performance, and network lifetime extension. The survey highlighted the importance of self-configurable protocols that adapt to changing conditions, thereby improving overall system efficiency and reliability for both medical and non-medical applications.

The Authors Hajar et al. (2021) presented a detailed overview of WBANs with special attention to the IEEE 802.15.6 standard, WBAN architectures, their communication layers, and security issues. They reviewed serious security issues such as confidentiality, integrity, and availability, as well as encryption, authentication, trust management, and intrusion detection systems. They noted that "low power," "high reliability," and "strong security" are critical at all levels of communication for sensitive health information and real-time medical needs.

In Bouldjadj (2022) the author reviewed thermal-aware routing protocols for WBANs, focusing on the problems of overheating due to sensor activity. They evaluated sixteen thermal-aware routing protocols and synthesized them in terms of their principles, advantages, and disadvantages. The study described how overheating can cause tissue damage and advocated the construction of routing protocols that provide temperature control in nodes in terms of energy expended. Issues of safe and reliable thermal management in WBANs highlighted open research areas.

In Ayyub (2023) the study examined the impact of WBANs on the healthcare system, with a focus on IoT integration, energy conservation methods, secure data transmission, and real-time patient tracking. They evaluated approaches to increase throughput and reduce latency in WBAN systems and compared other wireless standards to derive optimal strategies for reliable and accurate healthcare data transmission. The study highlighted the need to focus on optimizing the WBAN architecture for healthcare emergencies and the development of eHealth in the future.

In Jian et al. (2024) the authors studied security in WBANs with respect to IoT-enabled healthcare systems. They studied access control methods, protection countermeasure tactics, and strategies for protecting medical information from unauthorized access. After a systematic literature review, the authors examined a number of protocols in terms of communication overhead, energy consumption, and storage efficiency. This study also mentioned that patients should be tracked in real time in the hospital and indicated that WBANs should be highly encrypted, protocols should be secure, and information should be continuously accessible in real time to ensure confidentiality, integrity, and availability in the healthcare sector.

The study Sallabi et al. (2025) provided an analytical study of intelligent network management in healthcare, with a specific focus on WBANs, which are a fundamental part of IoT in healthcare. They studied state-of-the-art network protocols and investigated scalability, device reliability, and health monitoring security that may be related to these protocols. A new reference architecture was recommended that integrates SDN and DL to enhance the intelligent operation of an intelligent healthcare system. They expressed the demand that future healthcare systems should incorporate WBANs and be able to manage patient records in a sustainable, secure, and real-time manner.

In Diane et al. (2025) the authors presented an analytical overview of Low Power Wide Area Networks (LPWANs), focusing on their characteristics, architecture, and applications. Although it was not their primary focus, they considered the applications of LPWANs such as LoRa, Sigfox, NB-IoT, and IoT caregiving. The paper focused on the issues of energy and spectral optimization and scalability, and argued that LPWAN could provide enhanced WBANs by providing remote, low-power communications for continuous patient monitoring.

While numerous investigations have focused on some elements of WBAN, comprehensive and systematically structured analyses that encompass all concepts, applications, characteristics, technologies, and issues are undoubtedly still lacking. The available literature tends to focus on isolated issues, such as interference mitigation and a deep overview of WBAN communication technologies, without promoting the more integrated perspective that is critical for the progress of WBAN research and deployment. This is the gap we aim to fill in this paper by providing a taxonomy-driven review that maps WBAN concepts to actual applications with attributes, classifies system-specific technological advances and emerging challenges, and provides insights with actionable intelligence.

Tab. 1 Comparative analysis of recent studies in WBAN communication

Ref.No.	Year	Type of Study	Focus Area	Key Contributions
(Qu et al., 2019)	2019	Survey	Routing Protocols for Healthcare Applications	Classified WBAN routing protocols by posture, temperature, QoS; analyzed energy-performance tradeoffs and mobility effects on routing stability.
(Al-Barazanchi et al., 2019)	2019	Comparative Survey	Communication Technologies	Compare WBAN communication standards; evaluate Bluetooth, ZigBee, Wi-Fi, UWB; focus on power efficiency, data rate, latency, and suitability for healthcare applications.
(Yaghoubi et al., 2022)	2022	Survey	WBAN Architecture and Security	Reviewed WBAN architecture and challenges, emphasizing power constraints, communication reliability, and lightweight security for medical monitoring applications.
(Zhumayeva et al., 2023)	2023	Technology Review	Wireless Power Transfer	Reviewed WPT and SWIPT in WBANs; discussed near-field and far-field methods, power conversion efficiency, and wireless energy integration for sustainability.
(Shunmugapriya et al., 2022)	2022	Survey	Energy-Efficient Routing Protocols	Reviewed routing protocols in WBANs; identified posture, QoS, and energy-aware strategies; proposed design improvements for efficiency and reliability.
(Hajar et al., 2021)	2021	Survey	WBAN Architecture and Security	Reviewed IEEE 802.15.6 WBAN architecture; analyzed security attacks; proposed IDS, trust models, and countermeasures for secure multi-layer communication.
(Bouldjadj, 2022)	2022	Survey	Thermal-aware Routing Protocols	Classified 16 thermal-aware routing protocols; evaluated energy consumption and node security; proposed design directions for temperature-sensitive WBAN environments.
(Ayyub, 2023)	2023	Review	Healthcare Monitoring	Reviewed WBAN-based healthcare systems; discussed mobility, power, and latency issues; emphasized real-time data handling and emergency response optimization.
(Jian et al., 2024)	2024	Systematic Literature Review	Data Security	Compare security mechanisms in WBAN-IoT; evaluate encryption, authentication, and intrusion detection based on cost, power consumption, and scalability.
(Sallabi et al., 2025)	2025	Conceptual Framework Proposal	Smart Healthcare Network Management	Introduced SDN and deep learning model for intelligent WBAN healthcare; improved scalability, security, and efficiency of patient data management.
(Diane et al., 2025)	2025	Review	LPWANs Overview (Relation to WBAN)	Reviewed LPWAN technologies and architectures; assessed their relevance to WBANs in low-power, long-range medical and environmental monitoring contexts.

3. WBAN COMMUNICATION TECHNOLOGIES

WBANs use state-of-the-art wireless communication technologies to enable unobtrusive health monitoring of a wide range of physiological signals. They use miniaturized sensors on and in the human body connected by various wireless communication protocols to collect, transmit, and analyze important health metrics. Wireless communication technology is essential to achieve energy efficiency, reliability, and successful WBANs. The following are different types of wireless technologies.

Bluetooth operates in the 2.4 GHz ISM band, with data rates of up to 3 Mbps and a range of 100 meters from body-worn sensors connected to central hubs (e.g., smartphones) (Abderrahmane et al., 2024) as shown in Figure 4. With its frequency hopping, it is not easily disturbed and has become a platform well suited for monitoring physical body actions (Zhang et al., 2023). However, Bluetooth's power consumption is a drawback for battery-powered devices. Despite this, Bluetooth is highly compatible and supports many different network topologies, making it a prominent technology in healthcare (Taleb et al., 2021).

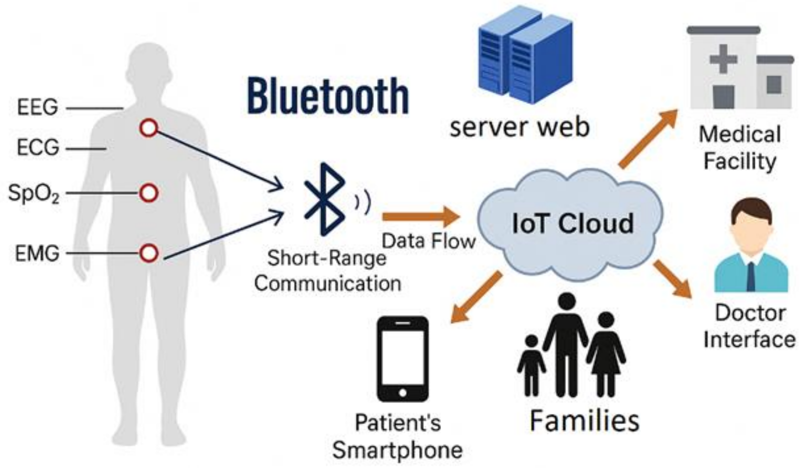

Fig. 4. IoT- Based healthcare monitoring using bluetooth-connected sensor nodes

ZigBee, which is based on IEEE 802.15.4, has been designed for low-power and low-data-rate applications such as WBANs (Al-Sofi et al., 2023). It works on various ISM bands with data rates up to 250 Kbps for use in star-topologies, as well as mesh networks. ZigBee has a multi-hop routing that increases its coverage and reliability. It also allows long latency and is good for continuous health monitoring. While the lower data rate of WBAN is not suitable for high-bandwidth applications, its energy efficiency and more reliable networking are beneficial with respect to almost all practical WBAN purposes (Gavra et al., 2023).

WiFi, with IEEE 802.11 standards enabling data rates up to a few Gbps, provides high transmission bandwidth and is well suited for fast health data transmission in WBANs (Artetxe et al., 2023). WiFi security features ensure the confidentiality of health information as well as operating in two regulated frequency bands, 2.4 GHz & 5GHz, so patients and physicians can feel comfortable about privacy issues when using a WiFi connection for any data transfer (Philip et al., 2021). On the other hand, its high power consumption remains a significant limitation for prolonged use in battery-powered devices. However, the long-range and established infrastructure of Wi-Fi offers considerable flexibility and mobility in healthcare environments (Hasan et al., 2019).

Li-Fi enables the integration of visible light to transmit data, supporting uplink and downlink speeds as high as 10 Gbps, making it a potential replacement for RF communications, also known as Wide WBAN (Subha et al., 2020). It is especially good in environments with a lot of RF interference, such as hospitals. The only drawback is that Li-Fi requires line-of-sight communication, so a body between the transmitter and receiver can interfere with the connection. However, the signal's extremely limited bandwidth and short-range challenges, as well as its ability to potentially be combined with current LED lighting infrastructure, could make it an unobtrusive healthcare communication (Riurean et al., 2019).

LoRa (a low-power wide-area network (LPWAN) technology that operates in sub-GHz bands and can support communication distances of up to 15 km (Mousavi et al., 2022). It is suitable for WBAN applications that require guaranteed long-range communication under conditions such as remote health monitoring. The low power consumption of LoRa devices allows the battery life to last up to years, but it is weaker in data rate compared to other high speed and applications. This star-of-stars topology makes it easier to scale the network so that it can be used for long-term and continuous monitoring (Taleb et al., 2021).

NB-IoT is a low-power wide area network (LPWAN) technology that enables long-range communication with high scalability and minimal power consumption (Nair et al., 2019). NB-IoT operates in the frequency bands below the licensed spectrum and provides data rates as high as 250 Kbps, enough to transmit health metrics within WBANs (Sultania et al., 2021). Its excellent power efficiency allows patients to use it for long periods on a single battery charge, which is essential for continuous health monitoring. Although it stands to reason that its data rate is lower, so NB-IoT may not be suitable for high bandwidth applications), but due to its wide area coverage and secure attributes, which better serve as various reasons why Next Generation Internet of Medical Things (NG-IoMT) should benefit from this technology (Ar-Reyouchi et al., 2022).

WiFi HaLow, based on the IEEE 802.11ah standard in the sub-1 GHz frequency band, supports low-power wide-area network (LPWAN) communications and covers WBANs with long-range service capabilities (Ahmed et al., 2021). With data rates from 150 Kbps to multiple Mbps, it enables the transmission of health metrics over longer distances than standard WiFi. WiFi HaLow security protocols to protect sensitive health data work in large healthcare facilities or outdoor environments due to its long range and low power requirements (Taleb et al., 2021; Zakariya Saleh, 2023).

5G features ultra-high speeds of up to 20 Gbps, low latency (1 ms), and massive connectivity that meets WBAN requirements for fast, real-time data transfer between small devices needed for remote surgery, for example (Garcia et al., 2021) as shown in Figure 5. 5G can operate over multiple frequency bands and handle a large number of connected devices simultaneously, making it an even more useful tool in healthcare. The use of network slicing can improve the quality and safety of various medical applications, but 5G coverage requires extensive infrastructure to be deployed, which may consume more power than previous generations (Khujamatov et al., 2022; Sharmila & Jaisankar, 2021).

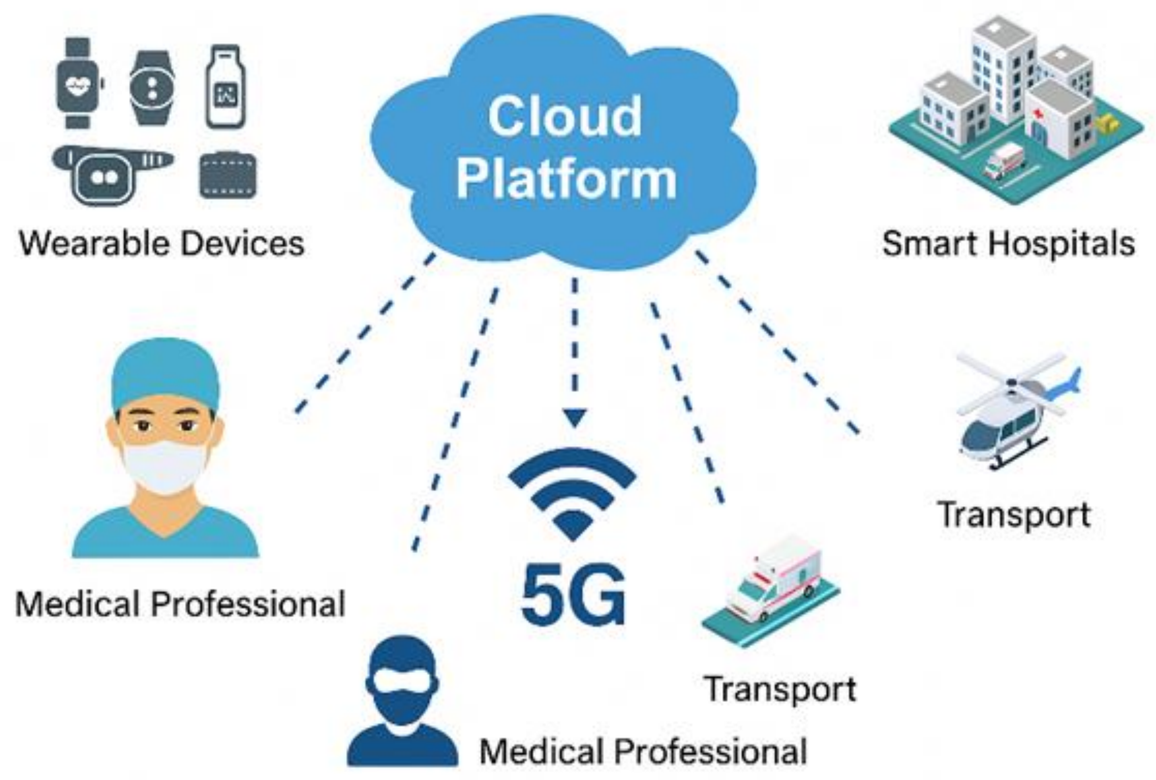

Fig. 5. 5G- Enabled cloud architecture for integrated smart healthcare systems

Body-Coupled Communication (BCC) transmits secure and low-power signals through the human body to transfer data between on-body or implanted devices, making it promising for WBANs where continuous health monitoring is critical (Jang et al., 2019). BCC has higher data rates and much lower latency than BLE, which would be suitable for critical health applications such as glucose or heart rate monitoring. Because it uses the human body, data is secure, but its utility is limited to communication between devices in close proximity, as shown in Figure 6. BCC is very favorable in the presence of high electromagnetic interference (Ormanis & Elsts, 2020).

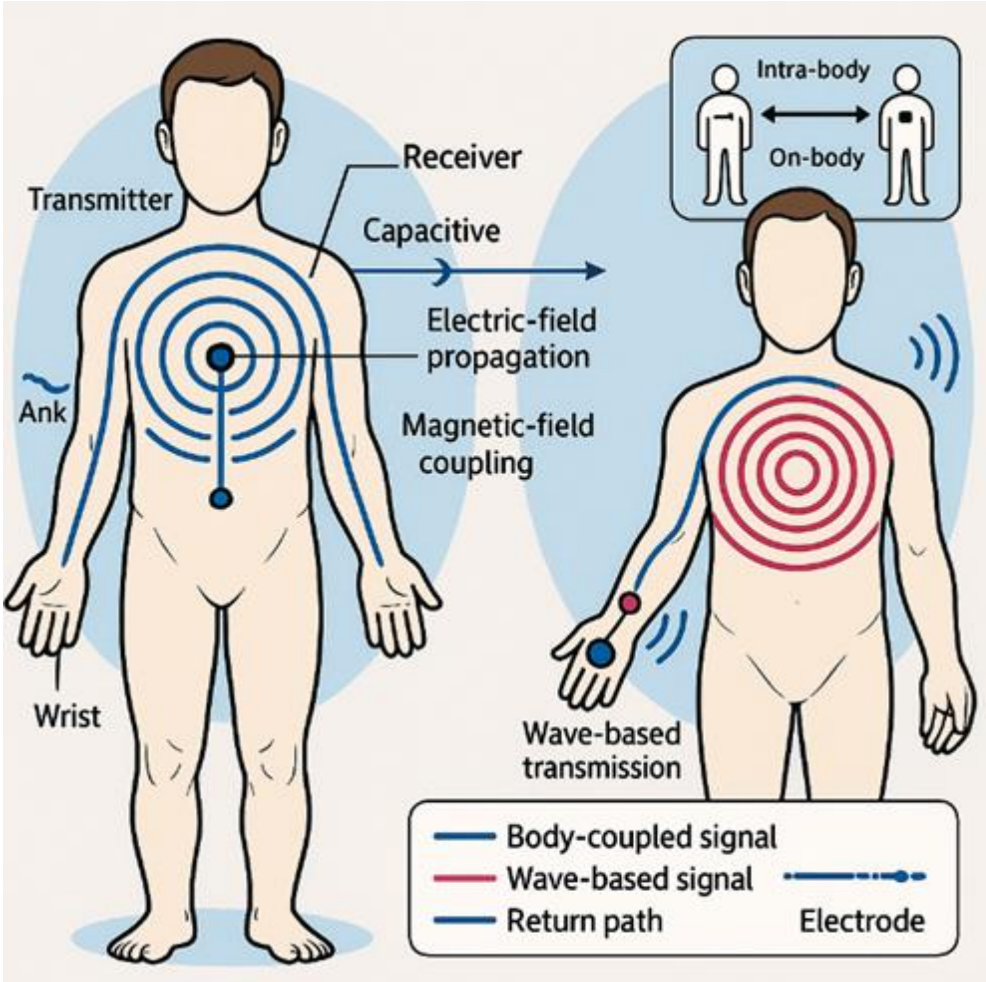

Fig. 6. Body-coupled communication technology

Operating in VLANs of UHF RFID, operates via short-range line-of-sight to retrieve the automatic opinion interrogation and tracking of patients or medical assets. Because of the low power consumption that enables long-term monitoring, RFID is considered a valuable tool for patient care and resource management in WBANs (Mohammad et al., 2022). However, due to the relatively short range of this Technology and its susceptibility to interference caused by metal objects or liquids, it may limit applications where closer proximity is necessary. Although the constraints of RFID technology should not be underestimated, its durability and ability to work within current healthcare systems serve to further legitimate it as a valuable tool in healthcare environments (Bouhassoune et al., 2019).

RuBeeA device for low frequency and magnetic wave data transmission created by IEEE 1902.1 working group (Alejandrino et al., 2021). It has a base frequency in the range of 30 kHz-450 kHz and uses data rates of a few kbps. While RuBee has a low range and data rate, its high immunity to interference from metal and liquids makes it a perfect choice for RF-challenged medical environments. As a result, RuBee's low power consumption and ability to operate in harsh environments make it a strong candidate for secure health monitoring over WBANs, especially in applications such as communicating with implanted pacemakers or defibrillators (Gudnavar et al., 2022).

Table 2 compares WBAN communication technologies by frequency band, data rate, power consumption, range, latency, network topology, security features, and application specificity.

Tab. 2. Comparison between WBAN's communication technologies

Technology	Frequency Band	Data Rate	Power Consumption	Range	Latency	Network Topology	Security Features	Application Specificity
Bluetooth (Abderrahmane et al., 2024)	2.4 GHz	Up to 3 Mbps	Moderate	Up to 100 meters	Moderate	Star	Moderate	General Purpose
ZigBee (Al-Sofi et al., 2023)	868/915 MHz 2.4 GHz	20-250 Kbps	Low	Up to 100 meters	Moderate	Star/Mesh/Tree	Moderate	General Purpose
WiFi (Artetxe et al., 2023)	2.4/5 GHz	Up to several Gbps	High	Up to 100 meters	Low	Star	High	General Purpose
Li-Fi (Subha et al., 2020)	Visible Light	Up to 10 Gbps	Moderate	Line-of-Sight	Low	Star	High	Specialized
LoRa (Mousavi et al., 2022)	Sub-GHz	0.3-50 Kbps	Low	Up to 15 km	High	Star	Moderate	Specialized
NB-IoT (Nair et al., 2019)	700 MHz - 2.1 GHz	Up to 250 kbps	Low	Up to 10 km	Moderate	Star	Moderate	Specialized
WiFi HaLow (Ahmed et al., 2021)	Sub-1 GHz	150 Kbps to several Mbps	Moderate	Up to 1 km	Low	Star	High	General Purpose
5G (Garcia et al., 2021)	Sub-6 GHz mmWave	Up to 20 Gbps	High	Up to several km	Low	Star	High	General Purpose
Body-Coupled Comm. (Jang et al., 2019)	Body Conductivity	High	Low	Short	Low	Star	High	Specialized
RFID (ISO/IEC 18000-6) (Mohammad et al., 2022)	860-960 MHz	Up to 640 Kbps	Low	Several meters	Low	Star	High	Specialized
RuBee (IEEE 1902.1) (Alejandrino et al., 2021)	30-300 kHz	Up to 9.6 Kbps	Low	Up to 10 meters	Low	Star	High	Specialized

4. INTERFERENCE MITIGATION IN WBAN

This section systematically examines current methods for mitigating such interference, emphasizing their theoretical underpinnings and operational frameworks. As shown in Figure 7, existing mitigation strategies are taxonomically organized into four main categories; however, a table summarizing all of the mitigation techniques considered in this paper, along with their detailed descriptions, is presented in Table 3.

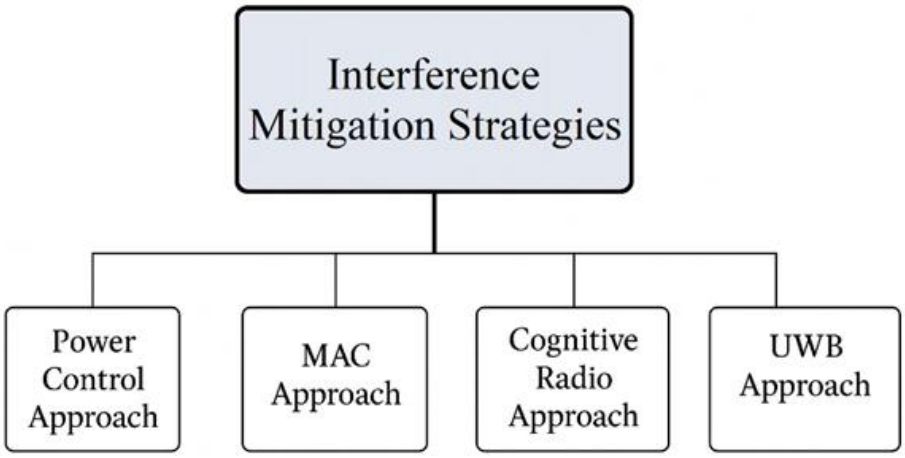

Fig. 7. Categories of interference mitigation strategies

Power consumption is a critical determinant of network lifetime in biosensor systems, as sensor nodes and coordinators operate in close proximity to the human body. Therefore, it is necessary that interference mitigation schemes focus not only on high communication quality and throughput, but also on power efficiency under noisy conditions. Recent studies have proposed novel power optimization approaches to mitigate this dual problem. For example, Chen (2024) present a model-driven approach that combines link adaptation and power control to reduce energy consumption. They use a transmit power threshold table computed based on fine-tuned path loss and receiver sensitivity models, and strategically allocate computational tasks to the WBAN hub to reduce the load on sensor nodes. Motivated by authors, He et al. (2021) proposed a distributed power control scheme for large-scale WBANs. The authors proposed a stacked WBAN architecture coordinated by distributed controllers along with a hybrid in vivo channel model. Their solution uses a Deep Q-Network-based power controller that models power control as a multi-agent reinforcement learning problem. Specifically, the coordinators can adjust the transmission power of the sensors in a feedback fashion to balance energy efficiency and scalability of the network.

The Medium Access Control (MAC) layer plays a fundamental role in achieving energy efficiency and QoS improvement in wireless sensor networks. By providing access to the shared wireless medium, MAC protocols directly affect spectral efficiency, latency, and reliability, and can prevent collisions and interference. A flexible MAC design consideration for various data types such as continuous, periodic and bursty, as well as non-periodic data loads and applications, and the constrained energy consumption of sensor nodes are the conflicting phenomena for an efficient MAC. Traditional MAC protocols for WSNs and short-range devices are usually based on Time Division Multiple Access (TDMA) (Ranjan et al., 2022) or Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) (Matsuda et al., 2024) to achieve fair, medium access with low overhead. By contrast, Frequency Division Multiple Access (FDMA) (Chilamkurthy et al., 2022) and Code Division Multiple Access (CDMA) (Rasool & Gafoor, 2022) are not considered suitable for sensor networks because they require complex hardware and high computational complexity. The state-of-the-art approaches are to adapt the MAC protocols to the requirements of WBANs. For example, the authors Ibrahim & Bayat (2020) Presented a modified MAC (M-MAC) based protocol to categorize biosensor data into normal, low urgency and high urgency data. Based on this, we propose a weight-based energy and QoS (W-QoS) routing algorithm that considers the residual energy, link stability, delay, and proximity to the sink and adapts them before navigating the current packet. As a result, the network lifetime is extended, in addition to prioritizing the routing of critical data. HyMAC, a hybrid CSMA/CA-TDMA protocol designed for body sensor networks, was also introduced in Yang et al. (2018). HyMAC combines the contention-based freedom of CSMA/CA with the deterministic scheduling of TDMA with an Awaiting Orders state to reduce idle listening. This state-centric strategy extends the life of the BSN by reducing energy consumption by up to 33% over traditional solutions.

Cognitive Radio (CR) is a promising technology that, as an extension of Software Defined Radio, can alleviate current wireless communication challenges through dynamic spectrum access. By intelligently scheduling and switching CR transmissions to the underutilized licensed frequency bands, CR alleviates spectrum scarcity and improves usage efficiency. In addition to spectrum agility, the use of CR systems facilitates user cooperation supported by embedded sensing, machine learning, and adaptive decision making, which is particularly important in dense or interference-limited environments. Recent studies demonstrate the importance of CR over WBANs. For example, Suriya et al. (2020) uses PSO to combine CR to design an energy-efficient WBAN framework. The CR-enabled coordinator adaptively switches the best wireless access points based on user movement patterns, connection cost, and time-out limits, which can reduce energy consumption and data arrival time slots. Extending this model Henna et al. (2023) proposed a MAB-BCA algorithm for CRWBANs under the IEEE 802.15.6 standard. Following the Upper Confidence Bound technique, MAB-BCA adaptively combines channels to improve network capacity to overcome the limitation of static channel assignment in dynamic traffic cases.

Tab. 3. Comparative and analysis of interference mitigation techniques in WBAN

Mitigation Technique	Ref	Approach	Finding	Application	Limitations	Future Direction
Power Control Strategies	(Chen, 2024)	Model-driven receiver sensitivity calibration	Achieves energy-efficient, low-complexity link adaptation.	WBAN IoT wearable devices.	Assumes ideal hub-side operations.	Real-world deployment and mobility support.
	(He et al., 2021)	Distributed Deep-Q-learning-based power controller	Improves energy efficiency for massive WBANs with distributed agents.	Massive WBAN environments.	Lacks real-world hardware validation.	Mobility, access management, hardware validation.
Medium Access Control Solutions	(Ibrahim & Bayat, 2020)	M-MAC: Priority-based emergency-aware MAC	Prioritizes critical data to extend network lifetime.	Health monitoring WBANs	Static scenarios only; no dynamic mobility considered.	Mobility-aware MAC schemes; improved slot reuse and fault recovery.
	(Yang et al., 2018)	HyMAC: Hybrid CSMA/CA-TDMA with Awaiting Order state	Reduces collision, saves 6–15% energy compared to QS-PS and CPMAC.	remote health monitoring	Possible inefficiencies with high node density.	Enhanced QoS and Dynamic Traffic Handling
Cognitive Radio	(Suriya et al., 2020)	CR-enabled WBAN coordinator with PSO-based AP selection	PSO optimizes access point selection to minimize energy consumption and delay.	Remote healthcare, mobile WBANs.	CR sensing overhead and latency are not fully analyzed.	Security enhancement s.
	(Henna et al., 2023)]	MAB-BCA: Multi-Armed Bandit-based Channel Bonding in CRWBAN	MAB-BCA improves throughput, reduces BER and dissatisfaction probability.	High-data-rate health monitoring with dynamic environments.	Limited real-world dynamic testing.	Deep contextual learning-based bonding.
Ultra Wideband (UWB)	(Alhawari et al., 2021)	Flexible wearable elliptical UWB antenna for WBAN and breast imaging	High-gain, broadband UWB antenna; safe SAR.	Healthcare monitoring, wearable WBAN	Static indoor scenarios only.	Expand to dynamic/mobile users.
	(Alhawari et al., 2021)	Deep learning-based UWB CIR analysis for user orientation detection	CNNs enable precise angle detection; outperform classical threshold by 9%.	Smart orientation-aware WBAN communication.	Single user tested; generalization across users not proven.	Integrate orientation prediction with network routing.

Ultra-wideband (UWB) technology has been established as an important solution for the next generation of WBAN, achieving high accuracy, low delay and strong immunity to multipath fading. Based on these advantages, UWB was first used in indoor positioning systems and has recently been repurposed for biomedical applications. However, conventional signal processing techniques usually fail to achieve high diagnostic accuracy and reliability, especially when dealing with high-dimensional physiological data. The key to these limitations lies in the inflexible and non-adaptable algorithms, which cannot adapt to the body-centric dynamics of the environment, and necessitates the need for novel signal processing techniques.

Recent advances have been proposed to mitigate the challenges with hardware and machine learning. For example, Alhawari et al. (2021) proposed a metamaterial-inspired UWB antenna for dual-use applications in breast imaging and WBBSNs. The planar and low-profile design of the antenna, implemented through flexible substrates, ensures application on body-wearable parts without sacrificing performance, demonstrating significant efficacy in both diagnostic imaging and body area communication. Complementing this hardware-focused approach, Urwan & Cwalina (2024) addressed signal reliability by integrating deep learning with UWB systems. Using Decawave EVB1000 devices, the authors acquired channel impulse response data under static indoor conditions and trained convolutional neural networks (CNNs) and multilayer perceptrons (MLPs) to detect user orientation relative to antenna geometry. This methodology improves spatial awareness in WBANs and enables adaptive signal processing that mitigates orientation-related performance degradation.

5. WBANS APPLICATIONS

WBANs are being used in a variety of domains that impact multiple domains. These applications range from healthcare to human body monitoring to industrial domains.Table 4 presents a summary of WBAN applications, highlighting their key benefits. The following types of services represent several applications that are diverse uses for WBANs:

Sensor networks will play an increasingly important role in healthcare. Currently, some advanced hospitals are using basic sensors to track patient physiological data, monitor medication adherence, and monitor the activities of both patients and healthcare providers (Shaikh et al., 2023). A key application of these networks is in elderly care, where sensor-based monitoring systems such as sensor-equipped cameras form a sophisticated network capable of tracking muscle movements, detecting falls, identifying periods of unconsciousness, monitoring vital signs, and assessing diet and exercise patterns (Razdan & Sharma, 2022). Experts predict that as technology continues to advance and broadband connectivity becomes widespread, these networks will greatly improve real-time health assessments and provide proactive solutions for diagnosing degenerative diseases (Devi & Kalaivani, 2021). This capability has the potential to save lives while reducing the economic burden on healthcare systems. Patients often seek medical attention only after experiencing noticeable health symptoms, and in severe cases, immediate intervention may be required, often resulting in significant treatment costs. However, the integration of sensor networks in healthcare has the potential to enhance preventive care by continuously monitoring the physiological state of individuals, enabling early disease detection, reducing health risks, and minimizing treatment costs throughout the therapeutic process (Batista et al., 2021).

WBANs have a significant application in sports and fitness, as they serve to enhance an individual's athletic performance and prevent injuries (Demrozi et al., 2023). WBANs support this demand-driven approach by continuously monitoring characteristics such as heart rate, temperature, hydration, and muscle activity, providing athletes/coaches with a real-time basis for tailoring workouts for optimal gains in physical performance. This information is used to assess the stress that athletes are exposed to while exercising and to follow these customized training programs that would improve strength, endurance and overall fitness. In addition, WBAN monitoring helps identify symptoms of fatigue and overtraining that can lead to injury. The inclusion of WBAN in sport and fitness monitoring not only improves performance, but also the overall health and safety of the athlete (Raković & Lutovac, 2015).

In military and defense operations, the health and readiness of soldiers cannot be compromised. Some researchers present an example of the former type, using a WBAN to provide real-time health data such as overall temperature, body temperature, and ECG readings for soldiers (Jayasutha et al., 2024; Prabagar et al., 2023). With continuous monitoring, commanders can see if their troops are fit enough to work or if they need time off. Other capabilities include the detection of early symptoms of health problems such as heat exhaustion, dehydration or hypothermia, allowing for timely medical intervention. The integration of WBANs into the battlefield environment will ensure the safe and effective operation and performance of the warfighter, ultimately leading to mission success and overall mission readiness.

The health and well-being of disaster response teams are fundamental to successful operations (Memon et al., 2023). They provide early detection of monitored signals and physiological parameters at disaster sites, so that the vital signs of medical team members can be continuously monitored to ensure they are in good working condition. Monitoring is critical to detect early signs of illness, exhaustion or stress before they affect their ability to respond effectively. In addition, WBANs can relay environmental data on factors such as exposure to hazardous materials or extreme temperatures, helping to protect response teams from hazards (Anbarasan & Natarajan, 2022). The use and deployment of WBAN in disaster response can indeed contribute not only to the safety and efficiency of response teams, but also to the improvement of post-disaster recovery operations (Damaševičius et al., 2023).

WBANs have the potential to revolutionize the power source for augmented reality (AR) and VR systems, personalizing the experience and making it lightweight and seamlessly integrated at the physiological level (Selem et al., 2019). Enabled by biosensors (e.g., heart rate, stress biomarkers, and kinematic data) for real-time feedback. Mobilizing WBANs provide perceptual gluing within AR/VR environments (Wang et al., 2021). For example, in games or simulation-based training, adaptive algorithms could adjust difficulty levels or activate context-aware haptic feedback in response to a user's physiological state (e.g., level of arousal or fatigue) to optimize engagement and performance (Hong et al., 2024). Therapeutic applications also illustrate such synergy: in exposure therapy for anxiety disorders, WBANs enable closed-loop systems in which physiological measures are used as feedback to modulate therapeutic cues (e.g., from disease-state cortisol levels measured with implantable MR-PET sensors). This capability accounts for inter-patient variability in physiological responses and provides opportunities for precision medicine. The intelligent integration of WBANs with AR/VR is seen as a novel paradigm shift towards interactive, responsive digital ecosystems, our pioneering work, as highlighted in foundational work by Sahu & Pawar (2022).

WBANs can monitor the health and behavior of livestock, which is essential to keeping animals healthy while improving their productivity. The use of WBANs in veterinary care helps to improve the level of animal health management, which will lead to the promotion of overall animal welfare (Postolache et al., 2021). In wildlife research, WBANs provide a less intrusive way to monitor the health and behavior of animals in their natural habitats. WBANs embedded in wildlife wearables is one technique to obtain such cognitive data on physiological parameters, activity routines, and environmental conditions by simulating similarities in the human body through natural habitats. Consider collecting data from animals and learning from it for wildlife conservation to understand health behaviors & ecological interactions within them along with basic animal biology (Dayoub et al., 2024). Figure 8 is an imaginary figure showing how WBAN applications can be used to monitor wildlife for various animals.

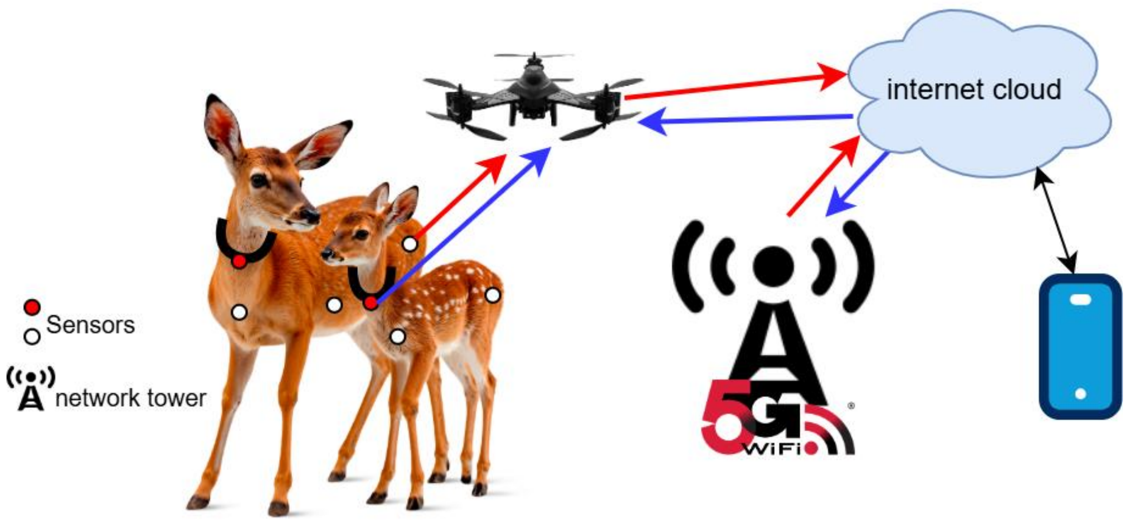

Fig. 8. Employing WBAN's applications for wildlife monitoring

Safety has been enhanced through integration with WBANs, such as Personal Emergency Response Systems, which are designed to provide immediate assistance in the event of an emergency. For example, WBANs are able to monitor vital signs 24/7, while detecting falls and automatically sending distress signals in case of such a health-related crisis (Raza et al., 2016). This real-time management and rapid response capability can also benefit high-risk populations, including the elderly or those with pre-existing conditions, for whom immediate intervention is an added layer of safety. Personal emergency response systems, when embedded with WBANs, provide a more efficient way to monitor safety and quality of life, especially for these at-risk populations (Abdulmalek et al., 2022).

WBANs play a critical role in the delivery of personalized content in the entertainment industry. WBANs continuously monitor physiological responses generated by the user in the form of heart rate, skin conductance, and body temperature, which provide criteria for suggesting content that is precisely tailored to an individual (Bhatti et al., 2022). Instead, the way the individual interacts with the game can be used to increase their immersion. Since gaming is essentially a form of physical activity, it can also be tracked as part of the same health monitoring WBANs. These applications of WBANs for use in an interactive gaming environment represent a major step forward, especially towards real-time adaptive and immersive games (Meharouech et al., 2019).

Tab. 4. fields and applications of WBANs

Application	**Key Benefits**	**Challenges**	**Type of Application**	**Future Trends**
Healthcare and Medical(Zhong et al., 2022)	Continuous monitoring, improved patient outcomes, early detection of health problems	Privacy and security, sensor accuracy, integration with existing systems	Medical	Integration with AI and ML, improved sensor technology, wider deployment in remote areas
Sports and Fitness (Raković & Lutovac, 2015)	Improve athletic performance, prevent injury, optimize training	Portability, data accuracy, device cost	Sports and Fitness	Advanced data analytics, better wearables, increased use in amateur sports
Military and Defense (Jayasutha et al., 2024; Prabagar et al., 2023)	Real-time health monitoring, early detection of health issues, improved operational readiness	Data security, environmental challenges, sensor battery life	Military	Improved device ruggedness, integration with advanced military systems, AI-driven health monitoring
Emergency Response (Anbarasan & Natarajan, 2022)	Continuous monitoring, improved responder safety and efficiency, environmental data collection	Device durability, privacy, operational integration	Emergency	Better integration with IoT, enhanced environmental sensors, AI-driven decision support
Augmented and Virtual Reality (Hong et al., 2024)	Personalized and immersive experiences, real-time feedback, improved user engagement	Technical complexity, ease of use, cost of implementation	Entertainment/Healthcare	More realistic simulations, broader use in healthcare and education, better user interfaces
Animal Health and Monitoring (Postolache et al., 2021)	Improved animal health management, continuous data collection, non-invasive monitoring	Sensor attachment and durability, data accuracy, animal stress	Veterinary/Wildlife	Smaller, more efficient sensors, better data analysis tools, wider adoption in wildlife research
Personal Emergency and Security (Abdulmalek et al., 2022)	Enhanced personal security, real-time monitoring, rapid response capability	Device battery life, false alarms, privacy concerns	Personal Safety	Integration with smart home systems, improved sensor accuracy, AI-driven alerts
Entertainment and Gaming (Mohanty et al., 2023)	Personalized content, enhanced gaming experience, active lifestyle promotion	User privacy, data accuracy, device cost	Entertainment	Enhanced VR and AR integration, more interactive experiences, improved physiological monitoring

6. CHALLENGES IN WBAN

Despite their many benefits, WBANs face several challenges that hinder their widespread adoption and effective implementation. These challenges can be broadly categorized into technical, ethical, and non-technical concerns. The following are some of the key challenges that must be addressed to ensure the successful deployment of WBAN technology. Several key challenges have been identified based on the most common problems encountered in various application domains. These challenges are inextricably linked to the unique characteristics of WBAN within each domain. A comprehensive summary of these challenges, along with the corresponding application-specific characteristics, is presented in Table 5.

WBANs are heterogeneous, with different types of sensors and actuators throughout the network. These differences cause variations in the measurements made by sensor nodes (Selem et al., 2021). Some applications receive real-time data, while others receive periodic readings. Data can also be classified as priority or non-priority. WBANs must support a wide range of data types, from real-time audio and video content to continuous signals such as ECG and EMG (Sagar et al., 2021).

The role of MAC protocols is critical in managing this complexity. Activities such as body movement, posture changes, and environmental changes can cause sudden changes in data context. Therefore, MAC protocols for WBANs should support dynamic resource allocation (Olatinwo et al., 2023). Fixed Slot Allocation in MAC Protocols Does Not Meet the Needs of Heterogeneous and Dynamic WBAN Traffic. Several approaches have been proposed to address context awareness in WBANs. For example, an emergency alerting mechanism is proposed by Rhayem et al. (2021)which operates only when no other node is scheduled to transfer data. Another approach involves using a wake-up signal or wake-up radio (Mikhaylov & Karvonen, 2020; Kim, 2025) to switch nodes from sleep to active mode, although this adds complexity and cost to the hardware. An approach to support context-aware WBANs which have no computational resources to process context is discussed (Wang et al., 2022).

Energy efficiency is a challenging aspect when considering the deployment of WBAN due to the limited power source in sensor nodes. Since WBAN sensors are battery-powered devices, optimizing their lifetime is a must. While low-cost wearable sensors can be easily recharged or replaced, implanted sensors become a significant battery drain problem when replacement is not easy due to complex and expensive surgical procedures. Energy optimization in WBANs can be achieved by several methods, such as optimal design of the physical and medium access control (MAC) layers, efficient communication models (single-hop or multi-hop), and application of adaptive duty cycling to avoid unnecessary power dissipation.

Several studies have investigated approaches to improve energy efficiency in WBANs. For example, Rana et al. (2024) propose a TDMA-based MAC protocol for a multi-class WBAN architecture consisting of three layers: sensor nodes in the first layer, master nodes in the second layer, and a monitoring station in the third layer. In this model, master nodes aggregate data from sensor nodes and forward it to the monitoring station. However, a major limitation of this approach is its stationary network design, which struggles with efficiency when the patient moves. The varying distances between sensor nodes and controller nodes introduce additional energy overhead, reducing the overall efficiency.

In addition, the study in Kareem & Rajesh (2025) explores energy efficiency using a path loss model for WBAN communication over the human body. Addressing energy efficiency in WBANs is critical to ensuring their long-term viability, especially in real-time health monitoring and medical applications. Future research should focus on the development of energy-aware protocols, low-power hardware solutions, and dynamic routing algorithms to further optimize power consumption in WBAN environments.

Secure communication in WBAN is important because data in WBAN must be kept confidential, so only authorized nodes can use and access transmitted information, and the authenticity of incoming data must be verified. Security attacks such as eavesdropping, false alarms, and false data injection can have serious consequences, including patient death. Therefore, Security in WBANs should be addressed at various layers, including the physical, MAC, and network layers (Anitha & Priya, 2024). However, implementing security measures adds overhead and reduces energy efficiency. In Pathak & Singh (2021), A lightweight security scheme based on biometric techniques is proposed to enable low-overhead message authentication in WBANs. This approach proves to be energy efficient. Authentication methods in WBANs include human facial features, hand characteristics, and EEG signals, with ongoing improvements in both academia and industry. An ideal authentication approach involves the use of unique human body characteristics, which can be complex, especially when patients connected to one WBAN come into proximity with another. Identifying which network a patient belongs to is critical. In Demin Jiang et al. (2022), explores node identification based on biometrics. According to Al Barazanchi et al. (2024) by establishing trust between network nodes, WBAN security can be improved.

Quality of Service (QoS) is a critical issue in WBANs that is different from that in Wireless Sensor Networks. QoS requirements in WBANs depend on the sensitivity of the applications and the nature of the data being transported. For example, systems that monitor critical patients require immediate data delivery, as delays can have catastrophic consequences (Sun & Sun, 2024). According to Chen (2024) setting QoS parameters for distributed healthcare systems is challenging due to the unpredictable nature of the WBAN environment. Traditionally, QoS has included metrics such as latency, transmission power, reliability, and bandwidth reservation.

Tab. 5. Comprehensive overview of wearable applications: Characteristics and associated challenges

Application	Characteristics	Challenges
Medical monitoring	• Continuous vital tracking (heart rate, ECG, etc.) • Real-time data transmission• Early anomaly detection • Reliability (low BER, minimal delay) • Energy-efficient implanted nodes• Bandwidth efficiency for mixed data	• Energy constraints (implanted sensors) • Data security and privacy • QoS: prioritizing critical data • Biocompatible, low-power hardware design • Integration with telemedicine platforms
Sports and fitness	• Real-time athlete monitoring (HR, temperature, motion) • Performance feedback for training • Scalability & dynamic deployment • Human-centric, non-invasive design	• Energy-efficient wearable devices • Motion-induced wireless interference • Rugged, durable sensor hardware • Accurate sensing during high activity
Military and defense	• Real-time communication of soldier status • Health, fatigue, and environmental monitoring • Integrated in gear (helmets, uniforms) • Reliable in harsh conditions • Scalable communication across battlefield	• Secure wireless data (data integrity) • Wireless propagation issues (mobility/shadowing) • QoS for real-time alerts • Minimal hardware weight & bulk
Emergency response	• Sensing ambient + physiological data • Alerts for toxins/heat/health risks • Tracks location in hazardous zones • Bandwidth-efficient data handling • Highly reliable and scalable systems	• Sensor heterogeneity (diverse data types) • Timely QoS mechanisms • Energy constraints during prolonged use • Dependable wireless connectivity
Augmented/virtual reality (AR/VR)	• Immersive experience through motion sensors • Wireless streaming of media and motion • Gamified user interaction • High data-rate transmission • User-centric, lightweight wearables	• Sensor diversity handling • Lightweight, ergonomic hardware • Low-latency, high-throughput processing • Battery life constraints for real-time gaming
Animal health monitoring	• Non-human physiological/environmental monitoring • Deployment in natural, uncontrolled settings • Adaptive communication in wild habitats	• Wireless propagation issues due to terrain/animals • Node deployment and durability in nature • Continuous connectivity and power supply
Animal health monitoring	• Monitors physiological signs in livestock/pets • GPS/motion for herd behavior tracking • Deployed in uncontrolled/natural settings • Energy harvesting for longevity • Non-invasive, animal-safe hardware	• Wireless reliability in variable environments • Robust, weatherproof design • Habitat-adapted communication channels
Personal emergency/security systems	• Continuous, non-reactive sensor monitoring • Location + vital sign tracking for vulnerable individuals • Alerts caregivers/medical responders • Simple, human-centric wearability	• High security for personal data • Instantaneous alert mechanisms (QoS) • Continuous operation power demand • Reliable connectivity anywhere
Entertainment and gaming	• Gesture-controlled or motion-based interaction • Real-time data for immersive gaming • Used in AR/VR, music, and social devices • Focused on user enjoyment and ease	• Data privacy for interaction streams • Efficient use of battery for long sessions • Ergonomic, comfortable hardware • Responsive sensor fusion & feedback

Designing appropriate hardware for WBANs, especially sensor nodes attached to or implanted in the human body, is a critical task (Nawaz et al., 2024). The design must be compatible with human tissue and consider the radio frequency environment. Antenna design is particularly challenging, as factors such as antenna gain, polarization, sensitivity, and non-line-of-sight connectivity to access points must be addressed (Arnaoutoglou et al., 2024). Ultra-wideband technologies have attracted research interest due to their ability to improve SNR levels at the receiver.

Wireless propagation is critical to communication between WBAN nodes. Because nodes are attached to the body, patient mobility can affect wave propagation, with devices on the back of the body experiencing shadowing effects. Nodes must also account for dynamic environments with movements such as twisting and walking, as well as multipath propagation. In the case of implanted devices, their position affects wave propagation. Accurate propagation models are needed to predict the impact of realistic channels on network performance, and to help design more effective WBAN architectures and routing algorithms (Ameen et al., 2024). Body area network (WBAN) ultra-wideband (UWB) channel models have recently gained interest, and various simulations and experiments have been conducted to develop appropriate models. While there is a limited literature on WBAN channel models, no general model exists that comprehensively accounts for factors such as gender, age, and application type (Faust et al., 2025).

7. CONCLUSION

Recent wireless communication technologies using networks such as WBANs represent a significant advancement in healthcare systems, as they may offer unique opportunities for continuous and real-time health monitoring, escalating with cycle-by-cycle physiological state estimations. In summary, the purpose of this paper is to present a comprehensive review of WBANs and related works through their characteristics, challenges, and applications. It has shown the fundamental differences between WBANs and other wireless sensor networks, especially in a medical environment where data reliability, energy efficiency of operation and security are critical. The research has highlighted the current challenges and future work of WBAN technology, which require more energy-efficient solutions with strong security mechanisms compliant with implantable biocompatibility. It also highlighted the different types of communication technologies that can be used in WBANs to improve their performance and robustness. The paper also identified important open issues in the field, particularly in the areas of fault tolerance and reliability, as well as interference management, and proposed a new architecture tailored to these needs. These are important advances for promoting the adoption of WBANs in medical and non-medical domains, including sports, military operations, or emergency response. Looking ahead, it is clear that there will be enormous research and innovation challenges to realize their full potential. This will require not only new technologies, but also addressing the ethical and regulatory issues surrounding their deployment. Future work in this area should explore comprehensive WBAN configurations, the compatibility of all types of communication technologies for different environments, and capabilities that can be realized as complete network systems.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

REFERENCES

Abderrahmane, T., Nourredine, A., & Mohammed, T. (2024). Experimental analysis for comparison of wireless transmission technologies: Wi-Fi, Bluetooth, ZigBee and LoRa for mobile multi-robot in hostile sites. *International Journal of Electrical & Computer Engineering*, *14*(3). http://doi.org/10.11591/ijece.v14i3.pp2753-2761

Abdulmalek, S., Nasir, A., Jabbar, W. A., Almuhaya, M. A., Bairagi, A. K., Khan, M. A.-M., & Kee, S.-H. (2022). IoT-based healthcare-monitoring system towards improving quality of life: A review. *Healthcare*, *10*(10), 1993. https://doi.org/10.3390/healthcare10101993

Abououf, M., Singh, S., Mizouni, R., & Otrok, H. (2023). Explainable AI for event and anomaly detection and classification in healthcare monitoring systems. *IEEE Internet of Things Journal*, *11*(2), 3446-3457. https://doi.org/ 10.1109/JIOT.2023.3296809

Ahmed, N., De, D., Barbhuiya, F. A., & Hussain, M. I. (2021). MAC protocols for IEEE 802.11 ah-based internet of things: A survey. *IEEE Internet of Things Journal, 9*(2), 916-938. https://doi.org/10.1109/JIOT.2021.3104388

Akbar, M. S., Hussain, Z., Sheng, M., & Shankaran, R. (2022). Wireless body area sensor networks: Survey of mac and routing protocols for patient monitoring under IEEE 802.15.4 and IEEE 802.15.6. *Sensors*, *22*(21), 8279. https://doi.org/10.3390/s22218279

Al-Barazanchi, I., Abdulshaheed, H. R., & Sidek, M. S. B. (2019). A Survey: Issues and challenges of communication technologies in WBAN. *Sustainable Engineering and Innovation*, *1*(2), 84-97. https://doi.org/10.37868/sei.v1i2.85

Al-Sofi, S. J., Atroshey, S. M. S., & Ali, I. A. (2023). Review of wireless body area networks: protocols, technologies, and applications. *Bulletin of Electrical Engineering and Informatics*, *12*(6), 3677-3689. https://doi.org/10.11591/eei.v12i6.5543

Al-Thobhani, N. G (2022). Implementation wearable WBANs for e-Healthcare. https://doi.org/ 10.13140/RG.2.2.15354.57286/1

Al Barazanchi, I. I., Hashim, W., Thabit, R., Sekhar, R., Shah, P., & Penubadi, H. R. (2024). Secure trust node acquisition and access control for privacy-preserving expertise trust in WBAN networks. *International Conference on Forthcoming Networks and Sustainability in the AIoT Era* (pp. 265-275). Springer Nature. https://doi.org/10.1007/978-3-031-62881-8_22

Alejandrino, J., Concepcion, R., Palconit, M. G., Dadios, E., Bandala, A., & Vicerra, R. R. (2021). Irescue: Tracking device using RuBee–based Technology. *2021 IEEE 13th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment, and Management (HNICEM)* (pp. 1-6). IEEE. https://doi.org/10.1109/HNICEM54116.2021.9732045

Alhawari, A. R., Almawgani, A., Hindi, A. T., Alghamdi, H., & Saeidi, T. (2021). Metamaterial-based wearable flexible elliptical UWB antenna for WBAN and breast imaging applications. *AIP Advances*, *11*(1), 015128. https://doi.org/10.1063/5.0037232

A reliable energy-efficient routing algorithm for WBAN using centrality measure. (2024). In S. Ameen, G. Ahmed, R. S. Malik, S. Siddiqui, M. K. Kamal, & A. Akhunzada, *Innovation and Technological Advances for Sustainability* (1st ed., pp. 309–321). CRC Press. https://doi.org/10.1201/9781003496724-30

Anbarasan, H. S., & Natarajan, J. (2022). Blockchain Based delay and energy harvest aware healthcare monitoring system in WBAN environment. *Sensors*, *22*(15), 5763. https://doi.org/10.3390/s22155763

Anitha, P., & Priya, R. (2024). A novel wireless secure body area network layer protocol for secured patient data transmission. *5th International Conference on Electronics and Sustainable Communication Systems (ICESC)* (pp. 557-564). IEEE. https://doi.org/10.3390/s22155763

Arnaoutoglou, D. G., Empliouk, T. M., Kaifas, T. N., Chryssomallis, M. T., & Kyriacou, G. (2024). A review of multifunctional antenna designs for internet of things. *Electronics*, *13*(16), 3200. https://doi.org/10.3390/electronics13163200

Ar-Reyouchi, E. M., Ghoumid, K., Yahiaoui, R., & Elmazria, O. (2022). Optimized reception sensitivity of WBAN sensors exploiting network coding and modulation techniques in an advanced NB-IoT. *IEEE Access*, *10*, 35784-35794. https://doi.org/10.1109/ACCESS.2022.3163314

Arshad, J., Irtisam, A., Arif, T., Rasheed, M. S., Chauhdary, S. T., Rahmani, M. K. I., & Almajalid, R. (2024). A federated learning model for intelligent cattle health monitoring system using body area sensors and IoT. *Egyptian Informatics Journal*, *27*, 100488. https://doi.org/10.1016/j.eij.2024.100488

Artetxe, E., Barambones, O., Calvo, I., Fernández-Bustamante, P., Martin, I., & Uralde, J. (2023). Wireless technologies for industry 4.0 applications. *Energies*, *16*(3), 1349. https://doi.org/10.3390/en16031349

Ayyub, Q. (2023). Wireless Body Area Network (WBAN) based health care monitoring: A comprehensive review. *Sir Syed University Research Journal of Engineering & Technology*, *13*(2), 85-90.

Batista, E., Moncusi, M. A., López-Aguilar, P., Martínez-Ballesté, A., & Solanas, A. (2021). Sensors for context-aware smart healthcare: A security perspective. *Sensors*, *21*(20), 6886. https://doi.org/10.3390/s21206886

Bhatti, D. S., Saleem, S., Imran, A., Iqbal, Z., Alzahrani, A., Kim, H., & Kim, K.-I. (2022). A survey on wireless wearable body area networks: A perspective of technology and economy. *Sensors*, *22*(20), 7722. https://doi.org/10.3390/s22207722

Bouhassoune, I., Saadane, R., & Chehri, A. (2019). Wireless body area network based on RFID system for healthcare monitoring: Progress and architectures. *15th International Conference on Signal-Image Technology & Internet-Based Systems (SITIS)* (pp. 416-421). IEEE. https://doi.org/10.1109/SITIS.2019.00073

Bouldjadj, S. (2022). Thermal aware routing protocols for wireless body area networks: Review and open research issues. *Karbala International Journal of Modern Science*, *8*(3), 356-374. https://doi.org/10.33640/2405-609X.3244

Chaudhari, S., Aradhya, S. N., Thomas, S. B., Pandey, S., & Durbha, R. P. (2022). A survey on game theory based interference mitigation in WBASN. *International Journal of Sensors Wireless Communications and Control*, *12*(2), 108-121. https://doi.org/10.2174/2210327911666210120120946

Chen, D.-R. (2024). Integrating IoT in WBANs: An energy-efficient and QoS-aware approach for rapid model-driven transmission power control and link adaptation. *Internet of Things*, *25*, 101091. https://doi.org/10.1016/j.iot.2024.101091

Chilamkurthy, N. S., Pandey, O. J., Ghosh, A., Cenkeramaddi, L. R., & Dai, H.-N. (2022). Low-power wide-area networks: A broad overview of its different aspects. *IEEE Access*, *10*, 81926-81959. https://doi.org/10.1109/ACCESS.2022.3196182

Choudhary, A., Nizamuddin, M., Zadoo, M., & Sachan, V. K. (2020). Multi-objective optimization framework complying IEEE 802.15.6 communication standards for wireless body area networks. *Wireless Networks*, *26*, 4339-4362. https://doi.org/10.1007/s11276-020-02342-y

Çınar, A., & Tuncer, S. A. (2021). Classification of normal sinus rhythm, abnormal arrhythmia and congestive heart failure ECG signals using LSTM and hybrid CNN-SVM deep neural networks. *Computer methods in biomechanics and biomedical engineering*, *24*(2), 203-214. https://doi.org/10.1080/10255842.2020.1821192

Damaševičius, R., Bacanin, N., & Misra, S. (2023). From sensors to safety: Internet of Emergency Services (IoES) for emergency response and disaster management. *Journal of Sensor and Actuator Networks*, *12*(3), 41. https://doi.org/10.3390/jsan12030041

Das, K., & Moulik, S. (2025). Wireless body area network for e-health application. *Sensor Networks for Smart Hospitals*, 263-292. https://doi.org/10.1016/B978-0-443-36370-2.00012-8

Dayoub, M., Shnaigat, S., Tarawneh, R. A., Al-Yacoub, A. N., Al-Barakeh, F., & Al-Najjar, K. (2024). Enhancing animal production through smart agriculture: Possibilities, hurdles, resolutions, and advantages. *Ruminants*, *4*(1), 22-46. https://doi.org/10.3390/ruminants4010003

Devi, A. V., & Kalaivani, V. (2021). Enhanced BB84 quantum cryptography protocol for secure communication in wireless body sensor networks for medical applications. *Personal and ubiquitous computing*, *27*(3), 875-885. https://doi.org/10.1007/s00779-021-01546-z

Dhanvijay, M. M., & Patil, S. C. (2021). Optimized mobility management protocol for the IoT based WBAN with an enhanced security. *Wireless Networks*, *27*, 537-555. https://doi.org/10.1007/s11276-020-02470-5

Diane, A., Diallo, O., & Ndoye, E. H. M. (2025). A systematic and comprehensive review on low power wide area network: characteristics, architecture, applications and research challenges. *Discover Internet of Things*, *5*, 7. https://doi.org/10.1007/s43926-025-00097-6

Fan, L., Liu, X., Zhou, H., Leung, V. C., Su, J., & Liu, A. X. (2021). Efficient resource scheduling for interference alleviation in dynamic coexisting WBANs. *IEEE Transactions on Mobile Computing*, *22*(3), 1479-1490. https://doi.org/10.1109/TMC.2021.3110235

Faust, O., Salvi, M., Barua, P. D., Chakraborty, S., Molinari, F., & Acharya, U. R. (2025). Issues and limitations on the road to fair and inclusive AI solutions for biomedical challenges. *Sensors*, *25*(1), 205. https://doi.org/10.3390/s25010205

Garcia, M. H. C., Molina-Galan, A., Boban, M., Gozalvez, J., Coll-Perales, B., Şahin, T., & Kousaridas, A. (2021). A tutorial on 5G NR V2X communications. *IEEE Communications Surveys & Tutorials*, *23*(3), 1972-2026. https://doi.org/10.1109/COMST.2021.3057017

Gavra, V., Pop, O. A., & Dobra, I. (2023). A comprehensive analysis: Evaluating security characteristics of xbee devices against Zigbee protocol. *Sensors*, *23*(21), 8736. https://doi.org/10.3390/s23218736

Ghanem, M., Ghaith, A. K., & Bydon, M. (2024). Artificial intelligence and personalized medicine: Transforming patient care. *The New Era of Precision Medicine*, 131-142. https://doi.org/10.1016/B978-0-443-13963-5.00012-1

Gudnavar, A., Naregal, K., & Patil, B. (2022). Wireless body area network: Communication standards and radio technologies employed. *2022 IEEE North Karnataka Subsection Flagship International Conference (NKCon)* (pp. 1-5). IEEE. https://doi.org/10.1109/ACCESS.2022.3163314

Haechan, N., & Kim, Y. S. (2024). Study on deep learning models for the classification of VR sickness levels. *Applied Computer Science*, *20*(4), 1-13. https://doi.org/10.35784/acs-2024-37

Hajar, M. S., Al-Kadri, M. O., & Kalutarage, H. K. (2021). A survey on wireless body area networks: Architecture, security challenges and research opportunities. *Computers & Security*, *104*, 102211. https://doi.org/10.1016/j.cose.2021.102211

Hasan, K., Biswas, K., Ahmed, K., Nafi, N. S., & Islam, M. S. (2019). A comprehensive review of wireless body area network. *Journal of Network and Computer Applications*, *143*, 178-198. https://doi.org/10.1016/j.jnca.2019.06.016

Hassan, W. H. W., Sarang, S., Ali, D. M., Stojanovic, G. M., Muhammad, W. N. S. W., & Ya'acob, N. (2024). Adaptive medium access control protocol for dynamic medical traffic with quality of service provisioning in wireless body area network. *IEEE Access*, *10*, 35784-35794. https://doi.org/10.1109/ACCESS.2022.3163314

He, P., Liu, M., Lan, C., Su, M., Wang, L., Li, Z., & Tang, T. (2021). Distributed power controller of massive wireless body area networks based on deep reinforcement learning. *Mobile Networks and Applications*, *26*, 1347-1358. https://doi.org/10.1007/s11036-021-01751-3

Henna, S., Meehan, K., & Sakhamuri, M. R. (2023). Multi-armed bandit-based channel bonding for off-body communication in IEEE 802.15.6 cognitive radio wireless body area networks. *2023 34th Irish Signals and Systems Conference (ISSC)* (pp. 1-6). IEEE. https://doi.org/10.1109/ISSC59246.2023.10162083

Herculano, J., Pereira, W., Guimarães, M., Cotrim, R., de Sá, A., Assis, F., Macêdo, R., & Gorender, S. (2024). MAC approaches to communication efficiency and reliability under dynamic network traffic in wireless body area networks: a review. *Computing*, *106*, 2785-2809. https://doi.org/10.1007/s00607-024-01307-9

Hong, F., Wang, L., & Li, C. Z. (2024). Adaptive mobile cloud computing on college physical training education based on virtual reality. *Wireless Networks*, *30*, 6427-6450. https://doi.org/10.1007/s11276-023-03450-1

Ibrahim, A. A., & Bayat, O. (2020). Medium access control protocol-based energy and quality of service routing scheme for WBAN. *2020 international congress on human-computer interaction, optimization and robotic applications (HORA)* (pp. 1-6). IEEE. https://doi.org/10.1109/HORA49412.2020.9152849

Jang, J., Bae, J., & Yoo, H.-J. (2019). Understanding body channel communication: A review: From history to the future applications. *2019 IEEE Custom Integrated Circuits Conference (CICC)* (pp. 1-8). IEEE. https://doi.org/10.1109/CICC.2019.8780224

Jayasutha, D., Hemamalini, V., Sangeetha, S., & Yeruva, A. R. (2024). DIWGAN-WBSN: A novel health monitoring approach for wireless body sensor networks. *International Journal of Communication Systems*, *37*(17), e5934. https://doi.org/10.1002/dac.5934

Jian, W., Tabassum, A., & Li, J. P. (2024). Systematic survey on data security in wireless body area networks in IoT healthcare system. *Frontiers in Medicine*, *11*, 1422911. https://doi.org/10.3389/fmed.2024.1422911

Jiang, D., Njitacke, Z. T., Nkapkop, J. D. D., Tsafack, N., Wang, X., & Awrejcewicz, J. (2022). A new cross ring neural network: Dynamic investigations and application to WBAN. *IEEE Internet of Things Journal*, *10*(8), 7143-7152. https://doi.org/10.1109/JIOT.2022.3228748

Jiang, D., Zhang, G., Samuel, O. W., Liu, F., & Xiao, H. (2022). Dual-factor wban enhanced authentication system based on iris and ecg descriptors. *IEEE Sensors Journal*, *22*(19), 19000-19009. https://doi.org/10.1002/dac.5934

Jin, L., & Dong, J. (2018). Normal versus abnormal ECG classification by the aid of deep learning. *Artificial Intelligence–Emerging Trends and Applications*, 295-315. https://doi.org/ 10.5772/intechopen.75546

Kaleem, M., & Rehman, K. (2024). QoS-aware middleware for WBAN applications. *2024 International Conference on Integrated Circuits, Communication, and Computing Systems (ICIC3S)* (pp. 1-7). IEEE. https://doi.org/10.1109/ICIC3S61846.2024.10603064

Kareem, D. A., & Rajesh, D. (2025). Enhancing WBAN Performance with cluster-based routing protocol using black widow optimization for healthcare application. *Journal of Intelligent Systems & Internet of Things*, *14*(1), 45-58. https://doi.org/10.54216/JISIoT.140104

Karpiński, R. (2022). Knee joint osteoarthritis diagnosis based on selected acoustic signal discriminants using machine learning. *Applied Computer Science*, *18*(2), 71-85. https://doi.org/10.35784/acs-2022-14

Khater, H. M., Sallabi, F., Serhani, M. A., Barka, E., Shuaib, K., Tariq, A., & Khayat, M. (2024). Empowering healthcare with cyber-physical system - a systematic literature review. *IEEE Access*, 12, 83952-83993. https://doi.org/10.1109/ACCESS.2024.3407376

Khujamatov, K., Akhmedov, N., Reypnazarov, E., Khasanov, D., & Lazarev, A. (2022). Device-to-device and millimeter waves communication for 5G healthcare informatics. *Blockchain Applications for Healthcare Informatics*, 81-211. https://doi.org/10.1016/B978-0-323-90615-9.00019-0

Kim, B.-S. (2025). Semantic-aware scheduling for minimizing age of informative data in WBAN-based health monitoring systems. *IEEE Internet of Things Journal*, *12*(11), 15970-15986. https://doi.org/10.1016/B978-0-323-90615-9.00019-0

Krishnamoorthy, S., Dua, A., & Gupta, S. (2023). Role of emerging technologies in future IoT-driven Healthcare 4.0 technologies: A survey, current challenges and future directions. *Journal of Ambient Intelligence and Humanized Computing*, *14*, 361-407. https://doi.org/10.1007/s12652-021-03302-w

Machrowska, A., Karpiński, R., Maciejewski, M., Jonak, J., & Krakowski, P. (2024). Application of EEMD-DFA algorithms and ann classification for detection of knee osteoarthritis using vibroarthrography. *Applied Computer Science*, *20*(2), 90-108. https://doi.org/10.35784/acs-2024-18

Machrowska, A., Karpiński, R., Maciejewski, M., Jonak, J., Krakowski, P., & Syta, A. (2025). Multi-scale analysis of knee joint acoustic signals for cartilage degeneration assessment. *Sensors*, *25*(3), 706. https://doi.org/10.3390/s25030706

Matsuda, R., Tanigawa, Y., & Tode, H. (2024). Random-access MAC protocol applying maximum frame aggregation for delay-constrained packet transfer in wireless sensor networks. *2024 IEEE International Conference on Consumer Electronics (ICCE)* (pp. 1-4). IEEE. https://doi.org/10.1109/ICCE59016.2024.10444427

Meharouech, A., Elias, J., & Mehaoua, A. (2019). Moving towards body-to-body sensor networks for ubiquitous applications: A survey. *Journal of Sensor and Actuator Networks*, *8*(2), 27. https://doi.org/10.3390/jsan8020027

Memon, S., Wang, J., Ahmed, A., Rajab, A., Al Reshan, M. S., Shaikh, A., & Rajput, M. A. (2023). Enhanced probabilistic route stability (EPRS) protocol for healthcare applications of WBAN. *IEEE Access*, *11*, 4466-4477. https://doi.org/10.1109/ACCESS.2023.3235837

Mikhaylov, K., & Karvonen, H. (2020). Wake-up radio enabled BLE wearables: Empirical and analytical evaluation of energy efficiency. *2020 14th International Symposium on Medical Information Communication Technology (ISMICT)* (pp. 1-5). IEEE. https://doi.org/10.1109/ISMICT48699.2020.9152699

Mohamed, M., Maiseli, B. J., Ai, Y., Mkocha, K., & Al-Saman, A. (2021). In-body sensor communication: Trends and challenges. *IEEE Electromagnetic Compatibility Magazine*, *10*(2), 47-52. https://doi.org/10.1109/MEMC.2021.9477235

Mohammad, G. B., Shitharth, S., Syed, S. A., Dugyala, R., Rao, K. S., Alenezi, F., Althubiti, S. A., & Polat, K. (2022). Mechanism of internet of things (IoT) integrated with radio frequency identification (RFID) technology for healthcare system. *Mathematical Problems in Engineering*, *2022*(1), 757256. https://doi.org/10.1155/2022/4167700

Mohanty, R. K., Sahoo, S. P., & Kabat, M. R. (2023). Sustainable remote patient monitoring in wireless body area network with Multi-hop routing and scheduling: A four-fold objective based optimization approach. *Wireless Networks*, *29*, 2337-2351. https://doi.org/10.1007/s11276-023-03276

Mousavi, S. M., Khademzadeh, A., & Rahmani, A. M. (2022). The role of low-power wide-area network technologies in internet of things: A systematic and comprehensive review. *International Journal of Communication Systems*, *35*(3), e5036. https://doi.org/10.1002/dac.5036

Suriya, M., Swathi, R., Surya. P., & Veeralakshmi. R. (2020). Enhancing energy in WBAN through cognitive radio networks. *International Journal of Advanced Information And Communication Technology*, *7*(5), 80-84. https://doi.org/10.46532/ijaict-2020019

Nair, K. K., Abu-Mahfouz, A. M., & Lefophane, S. (2019). Analysis of the narrow band internet of things (NB-IoT) technology. *2019 Conference On Information Communications Technology And Society (ICTAS)* (pp. 1-6). IEEE. https://doi.org/10.1109/ICTAS.2019.8703630

Nawaz, A., Saidi, S., Osman, N., & Hai, N. (2024). A novel methodology for patient prescreening using wireless body area networks (WBANs). *Journal of Medical Artificial Intelligence*, *7*(15). http://dx.doi.org/10.21037/jmai-24-2

Negra, R. (2022). Leveraging machine learning for WBANs. In I. Jemili & M. Mosbah (Eds.), *Distributed Computing for Emerging Smart Networks* (Vol. 1564, pp. 38–59). Springer International Publishing. https://doi.org/10.1007/978-3-030-99004-6_3

Olatinwo, D. D., Abu-Mahfouz, A. M., & Hancke, G. P. (2021). Towards achieving efficient MAC protocols for WBAN-enabled IoT technology: A review. *EURASIP Journal on Wireless Communications and Networking*, *2021*, 60. https://doi.org/10.1186/s13638-021-01919-1

Olatinwo, D. D., Abu-Mahfouz, A. M., Hancke, G. P., & Myburgh, H. C. (2023). Energy efficient priority-based hybrid MAC protocol for IoT-Enabled WBAN Systems. *IEEE Sensors Journal*, *23*(12), 13524-13538. https://doi.org/10.1109/JSEN.2023.3273427

Ormanis, J., & Elsts, A. (2020). Towards body coupled communication for ehealth: Experimental study of human body frequency response. *2020 IEEE International Conference on Communications Workshops (ICC Workshops)* (pp. 1-7). IEEE. https://doi.org/10.1109/ICCWorkshops49005.2020.9145205

Pathak, V., & Singh, K. (2021). Secure and efficient WBANs algorithm with authentication mechanism. *Journal of Intelligent & Fuzzy Systems*, *41*(5), 5525-5534. http://dx.doi.org/10.3233/JIFS-189873

Philip, N. Y., Rodrigues, J. J., Wang, H., Fong, S. J., & Chen, J. (2021). Internet of things for in-home health monitoring systems: Current advances, challenges and future directions. *IEEE Journal on Selected Areas in Communications*, *39*(2), 300-310. https://doi.org/10.1109/JSAC.2020.3042421

Popov, A., & Ivanko, K. (2024). Introduction to biomedical signals and biomedical imaging. *Advances in Artificial Intelligence*. 1-57. https://doi.org/10.1016/B978-0-443-19073-5.00013-6

Porumb, M., Stranges, S., Pescapè, A., & Pecchia, L. (2020). Precision medicine and artificial intelligence: a pilot study on deep learning for hypoglycemic events detection based on ECG. *Scientific reports*, *10*, 170. https://doi.org/10.1038/s41598-019-56927-5

Postolache, O., Monge, J., Alexandre, R., Geman, O., Jin, Y., & Postolache, G. (2021). Virtual reality and augmented reality technologies for smart physical rehabilitation. In O. Kanoun & N. Derbel (Eds.), *Advanced Systems for Biomedical Applications* (Vol. 39, pp. 155–180). Springer International Publishing. https://doi.org/10.1007/978-3-030-71221-1_8

Prabagar, S., Reddy, C. S., Murthy, C. R., & Kumar, G. H. (2023). Cloud based location tracking and controlling parameters system implementation for armed forces in the war field. *2023 Third International Conference on Artificial Intelligence and Smart Energy (ICAIS)* (pp. 471-475). IEEE. https://doi.org/10.1109/ICAIS56108.2023.10073894

Preethichandra, D., Piyathilaka, L., Izhar, U., Samarasinghe, R., & De Silva, L. C. (2023). Wireless body area networks and their applications - A review. *IEEE Access*, *11*, 9202-9220. https://doi.org/10.1109/ACCESS.2023.3239008

Punj, R., & Kumar, R. (2019). Technological aspects of WBANs for health monitoring: A comprehensive review. *Wireless Networks*, *25*, 1125-1157. https://doi.org/10.1109/ACCESS.2023.3239008

Qu, Y., Zheng, G., Ma, H., Wang, X., Ji, B., & Wu, H. (2019). A survey of routing protocols in WBAN for healthcare applications. *Sensors, 19*(7), 1638. https://doi.org/10.3390/s19071638

Raković, P., & Lutovac, B. (2015). A cloud computing architecture with wireless body area network for professional athletes health monitoring in sports organizations Case study of Montenegro. *2015 4th Mediterranean Conference on Embedded Computing (MECO)* (pp. 387-390). IEEE. http://dx.doi.org/10.1109/MECO.2015.7181950

Rameshkumar, C., & Ganeshkumar, T. (2022). A novel of survey: In healthcare system for wireless body-area network. In B. B. V. L. Deepak, D. R. K. Parhi, B. B. Biswal, & P. C. Jena (Eds.), *Applications of Computational Methods in Manufacturing and Product Design* (pp. 591–609). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-0296-3_55

Rana, S. U., Hossain, M. M., Kazary, S., & Rahman, M. O. (2024). Multi-class multi-load handling MAC protocol for WBAN based on IEEE 802.15.6 standard using reinforcement learning. *2024 IEEE International Conference on Computing, Applications and Systems (COMPAS)* (pp. 1-6). IEEE. https://doi.org/10.1109/COMPAS60761.2024.10796374

Rangaiah, P. K. B., Engstrand, J., Johansson, T., Perez, M. D., & Augustine, R. (2023). 92 Mb/s fat-intrabody communication (fat-IBC) with low-cost WLAN hardware. *IEEE Transactions on Biomedical Engineering*, *71*(1), 89-96. https://doi.org/10.1109/TBME.2023.3292405

Ranjan, R., Debasis, K., Gupta, R., & Singh, M. (2022). Energy-efficient medium access control in wireless sensor networks. *Wireless Personal Communications*, *122*(1), 409-427. https://doi.org/10.1007/s11277-021-08905-2

Rasool, S. M., & Gafoor, S. A. A. A. (2022). OMAC: Optimal medium access control based energy and QoS compromise techniques for wireless body area networks. *Wireless Personal Communications*, *123*, 3223-3240. https://doi.org/10.1007/s11277-021-09285-3

Raza, S. F., Naveen, C., Satpute, V., & Keskar, A. (2016). A proficient chaos based security algorithm for emergency response in WBAN system. *2016 IEEE Students' Technology Symposium (TechSym)* (pp. 18-23). IEEE. https://doi.org/10.1109/TECHSYM.2016.7872648

Razdan, S., & Sharma, S. (2022). Internet of Medical Things (IoMT): Overview, emerging technologies, and case studies. *IETE technical review*, *39*(4), 775-788. https://doi.org/10.1080/02564602.2021.1927863

Rhayem, A., Mhiri, M. B. A., Drira, K., Tazi, S., & Gargouri, F. (2021). A semantic-enabled and context-aware monitoring system for the internet of medical things. *Expert Systems*, *38*(2), e12629. https://doi.org/10.1111/exsy.12629

Riurean, S., Antipova, T., Rocha, Á., Leba, M., & Ionica, A. (2019). VLC, OCC, IR and LiFi reliable optical wireless technologies to be embedded in medical facilities and medical devices. *Journal of medical systems*, *43*(10), 308. https://doi.org/10.1007/s10916-019-1434-y

Sagar, A. K., Banda, L., Sahana, S., Singh, K., & Singh, B. K. (2021). Optimizing quality of service for sensor enabled internet of healthcare systems. *Neuroscience Informatics*, *1*(3), 100010. https://doi.org/10.1016/j.neuri.2021.100010

Sahu, G., & Pawar, S. S. (2022). Smart healthcare in smart city using wireless body area network and 5G. In P. Singh, O. Kaiwartya, N. Sindhwani, V. Jain, & R. Anand, *Networking Technologies in Smart Healthcare* (1st ed., pp. 1–21). CRC Press. https://doi.org/10.1201/9781003239888-1

Sallabi, F. M., Khater, H. M., Tariq, A., Hayajneh, M., Shuaib, K., & Barka, E. S. (2025). Smart healthcare network management: A comprehensive review. *Mathematics*, *13*(6), 988. https://doi.org/10.3390/math13060988

Selem, E., Fatehy, M., & Abd El-Kader, S. M. (2019). E-Health applications over 5G networks: challenges and state of the art. *6th International Conference on Advanced Control Circuits and Systems (ACCS) & 2019 5th International Conference on New Paradigms in Electronics & information Technology (PEIT)* (pp. 111-118). IEEE. https://doi.org/10.1109/ACCS-PEIT48329.2019.9062841

Selem, E., Fatehy, M., & Abd El-Kader, S. M. (2021). mobTHE (mobile temperature heterogeneity energy) aware routing protocol for WBAN IoT health application. *IEEE Access*, *9*, 18692-18705. https://doi.org/10.1109/ACCESS.2021.3054367

Shaik, M. F., Komanapalli, V. L. N., & Subashini, M. M. (2018). A comparative study of interference and mitigation techniques in wireless body area networks. *Wireless Personal Communications*, *98*, 2333-2365. https://doi.org/10.1007/s11277-017-4977-6

Shaikh, T. A., Rasool, T., & Verma, P. (2023). Machine intelligence and medical cyber-physical system architectures for smart healthcare: Taxonomy, challenges, opportunities, and possible solutions. *Artificial Intelligence in Medicine*, *146*, 102692. https://doi.org/10.1016/j.artmed.2023.102692

Sharmila, A. H., & Jaisankar, N. (2021). Edge intelligent agent assisted hybrid hierarchical blockchain for continuous healthcare monitoring & recommendation system in 5G WBAN-IoT. *Computer Networks*, *200*, 108508. https://doi.org/10.1016/j.comnet.2021.108508

Shunmugapriya, B., Paramasivan, B., Ananthakumaran, S., & Naskath, J. (2022). Wireless body area networks: survey of recent research trends on energy efficient routing protocols and guidelines. *Wireless Personal Communications*, *123*, 2473-2504. https://doi.org/10.1007/s11277-021-09250-0

Singh, H., Patidar, S., Pratap, A., & Yasumoto, K. (2025). Maximizing utility and quality in smart healthcare with incentive driven hierarchical federated learning. *2025 17th International Conference on COMmunication Systems and NETworks (COMSNETS)* (pp. 120-125). IEEE. https://doi.org/10.1109/COMSNETS63942.2025.10885703

Singla, R., Kaur, N., Koundal, D., & Bharadwaj, A. (2022). Challenges and developments in secure routing protocols for healthcare in WBAN: A comparative analysis. *Wireless Personal Communications*, *122*, 1767–1806. https://doi.org/10.1007/s11277-021-08969-0

Subha, T., Subash, T., Rani, N. E., & Janani, P. (2020). Li-Fi: a revolution in wireless networking. *Materials today: Proceedings*, *24*, 2403-2413. https://doi.org/10.1016/j.matpr.2020.03.770

Sultania, A. K., Blondia, C., & Famaey, J. (2021). Optimizing the energy-latency tradeoff in NB-IoT with PSM and eDRX. *IEEE Internet of Things Journal*, *8*(15), 12436-12454. https://doi.org/10.1109/JIOT.2021.3063435

Sun, J., & Sun, X. (2024). Design a patient monitoring system in health care using cluster-based hierarchical routing for green communication. *Measurement: Sensors*, *31*, 100990. https://doi.org/10.1016/j.measen.2023.100990

Taleb, H., Nasser, A., Andrieux, G., Charara, N., & Motta Cruz, E. (2021). Wireless technologies, medical applications and future challenges in WBAN: A survey. *Wireless Networks*, *27*, 5271-5295. https://doi.org/10.1007/s11276-021-02780-2

Talpur, M. S. H., Abro, A. A., Ebrahim, M., Kandhro, I. A., Manickam, S., Arfeen, S. U., Dandoush, A., & Uddin, M. (2024). Illuminating healthcare management: A comprehensive review of iot-enabled chronic disease monitoring. *IEEE Access¸ 12*, 48189-48209. https://doi.org/10.1109/ACCESS.2024.3382011

Tusha, A., & Arslan, H. (2024). Interference burden in wireless communications: A comprehensive survey from PHY layer perspective. *IEEE Communications Surveys & Tutorials*, 1-1. https://doi.org/10.1109/COMST.2024.3487068

Urwan, S., & Cwalina, K. K. (2024). User orientation detection in relation to antenna geometry in ultra-wideband wireless body area networks using deep learning. *Sensors*, *24*(7), 2060. https://doi.org/10.3390/s24072060

Wang, K., Yap, L. W., Gong, S., Wang, R., Wang, S. J., & Cheng, W. (2021). Nanowire-based soft wearable human–machine interfaces for future virtual and augmented reality applications. *Advanced Functional Materials*, *31*(39), 2008347. https://doi.org/10.1002/adfm.202008347

Wang, L., Xu, B., Cai, H., & Zhang, P. (2022). Context-aware emergency detection method for edge computing-based healthcare monitoring system. *Transactions on Emerging Telecommunications Technologies*, *33*(6), e4128. https://doi.org/10.1002/ett.4128

Yaghoubi, M., Ahmed, K., & Miao, Y. (2022). Wireless body area network (WBAN): A survey on architecture, technologies, energy consumption, and security challenges. *Journal of Sensor and Actuator Networks*, *11*(4), 67. https://doi.org/10.3390/jsan11040067

Yang, X., Wang, L., & Zhang, Z. (2018). Wireless body area networks mac protocol for energy efficiency and extending lifetime. *IEEE Sensors Letters*, *2*(1), 7500404. https://doi.org/10.1109/LSENS.2018.2795566

Yang, X., Yi, X., Khalil, I., Luo, J., Bertino, E., Nepal, S., & Huang, X. (2021). Secure and lightweight authentication for mobile-edge computing-enabled WBANs. *IEEE Internet of Things Journal*, *9*(14), 12563-12572. https://doi.org/10.1109/JIOT.2021.3138989

Zakariya Saleh, Z. (2023). A review of emerging low power networks in Internet of Medical Things (IoMT). In K. Rabie, R. Kharel, L. Mohjazi, T. Elganimi, & W. U. Khan (Eds.), *IoT as a Service* (Vol. 506, pp. 23–37). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-37139-4_3

Zhang, F., Yu, F., Zheng, X., Liu, L., & Ma, H. (2023). DFH: Improving the reliability of LR-FHSS via dynamic frequency hopping. *IEEE 31st International Conference on Network Protocols (ICNP)* (pp. 1-12). IEEE. https://doi.org/10.1109/ICNP59255.2023.10355600

Zhong, L., He, S., Lin, J., Wu, J., Li, X., Pang, Y., & Li, Z. (2022). Technological requirements and challenges in wireless body area networks for health monitoring: A comprehensive survey. *Sensors*, *22*(9), 3539. https://doi.org/10.3390/s22093539

Zhumayeva, M., Dautov, K., Hashmi, M., & Nauryzbayev, G. (2023). Wireless energy and information transfer in WBAN: A comprehensive state-of-the-art review. *Alexandria Engineering Journal*, *85*, 261-285. https://doi.org/10.1016/j.aej.2023.11.030