Review of implantable-based wireless body area network metrics issues

Rawan Al Majdoubah[1], Yousef Eljaafreh[2]
[1]Department of Medical Engineering, Faculty of Engineering, Al-Ahliyya Amman University, Amman, Jordan
[2]Department of Communications and Computer Engineering, Faculty of Engineering, Al-Ahliyya Amman University, Amman, Jordan

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ABSTRACT

Recent developments in wireless communications, low-power integrated circuits, and biological physiological sensors have led to a new generation of wireless sensor networks. Body area networks are an interdisciplinary field that allows for real-time updates of medical records via the internet and continuous, affordable health monitoring. Several intelligent physiological sensors can be easily integrated into a flexible wireless body area network for implanted use, supporting early disease detection or computer-assisted rehabilitation. This field relies on the feasibility of small, easily implanted biosensors that do not impede daily activities. The body's implanted sensors record various physiological changes to monitor the patient's status no matter where they are. Nonetheless, because they handle health data, these networks ought to use benchmarking criteria to ensure high levels of service quality. Network routing protocols, wireless technologies, quality of service, privacy and security, energy efficiency, and performance are among the challenges being focused on to better satisfy its expectations. This review aims to comprehensively compare implantable wireless body area network metrics issues, seeking to generate a consistent and understandable overview. This study also attempts to address the gaps and provides a current assessment of the metrics concerning a wireless body area network used in healthcare services.

Corresponding Author:

Yousef Eljaafreh
Department of Communications and Computer Engineering, Faculty of Engineering, Al-Ahliyya Amman University
Amman, 19328, Jordan
Email: eljaafreh@gmail.com

1. INTRODUCTION

A biomedical wireless sensor network (BWSN) is a small-size wireless sensor network (WSN) designed for medical applications or healthcare services. With the development of medical technology, biomedical devices are widely used to improve patient healthcare quality and safety [1]. Nowadays, people are becoming increasingly occupied with their financial responsibilities and commitments. As a result, it is not always feasible for many individuals to stay in a hospital for extended periods, nor is it possible for them to attend regular health check-ups due to financial constraints, work obligations, and other reasons. Real-time healthcare monitoring of patients is crucial, and wireless biomedical telemetry systems can play a vital role in achieving this [2]. Wireless body area network (WBAN) devices are becoming increasingly popular with the development of wireless communication technology [3], and these devices are categorized based on their location, either on-body, in-body, or off-body. In the field of WBAN technology, various types of biological sensors are used. These sensors can be wearable or implantable and are placed in different parts of the body.

Biological signals of the patient are sent in real-time to the doctor through a special coordinator node for immediate diagnosis. The primary benefit of WBAN technology is the flexibility and cost-saving opportunities for patients. A WBAN-based wireless medical sensor network system when implemented in medical centers, has significant advantages over the traditional wired-based patient-data collection schemes by providing better rehabilitation and improved patient quality of life. In addition, a WBAN system has the potential to reduce healthcare costs as well as the workload of medical professionals, resulting in higher efficiency. However, implantable medical devices require external communications media. Therefore, when designing implantable devices, it is important to consider specific frequency bands for biomedical applications. There are several commonly used frequency bands for medical applications, including the industrial, scientific, and medical (ISM) band, medical implant communication service (MICS) band, ultra-wide band (UWB), and wireless medical telemetry service (WMTS) band [4].

In this review, we will consider in-body sensor-based WBANs such as pacemakers, neuro-stimulators, insulin pumps, gastric electric stimulators, and others implanted within the human body. These sensors gather and transmit data wirelessly to an external hub. Unlike conventional on-body sensor-based WBANs, the wireless channel between in-body sensors and the hub is highly dynamic and time-varying in nature, and it changes depending on the placement of the sensor node [5], [6]. Whereas human body shadowing is the primary cause of signal attenuation in the case of on-body sensor WBAN, the depth of different tissues and muscles under which the sensor is positioned causes severe attenuation in the case of in-body sensors [7], [8].

Recent research on implantable devices has shown great potential. However, designing these devices for implantable medical applications presents several issues and challenges that must be carefully considered to achieve benchmarking metrics criteria to enforce high levels of quality of service (QoS). The main contribution and novelty of the presented paper is providing a comprehensive comparison of implantable WBAN metrics issues, whereas most previous reviews focused mainly on only a few of them. According to Al-Sofi *et al.* [9], a study investigating the significant features, issues, and challenges in medical applications was performed. Researchers in [10], and [11] confirmed that delays or missing data due to packet collisions or drops have severe negative effects since implant sensors handle extremely important physiological parameters. Furthermore, since implant sensor node replacement or recharging is a laborious procedure, the sensor node should function at ultra-low power. The Federal Communications Commission has designated a distinct MICS band (402-405 MHz) for implant communication to facilitate sophisticated implant communication. Another research was done by Janabi *et al.* [12] focuses on the security and privacy of the WBANs. According to Yaghoubi *et al.* [13] mechanisms for enhancing security and reducing energy usage are discussed, along with sensor network design and functions, communication technology, and security problems. Saleh *et al.* [14] is another research about the preservation of privacy and related security issues. The adaptation of performance-enhancing techniques, like adaptive coding and modulation and link diversity, from miniature wireless electronics to implantable sensors is necessary to achieve the QoS required for biomedical systems in such a propagation medium [15].

Abidi *et al.* [16] provided three networking techniques for in-body and on-body sensors. The application of on-body beacons appears to have the most potential of these. To lessen the amount of power lost inside the human body, the beacons would oversee transmitting data between sensors and back to base stations. Beacons can be utilized as controllers or power sources for the sensors because they have a much bigger power budget than implanted sensors due to their larger size. Ntouni *et al.* [8] concurred with the preceding remark and presented research on the variation in power consumption and QoS of BAN nodes with various locations of on-body beacons.

According to Adarsh and Kumar [17] research was done on intelligent e-healthcare scenarios that make use of developments in the areas of wearable medical sensors and effective body area networks. Priority was given to particularly difficult problems like energy and time-efficient routing protocols. They also carried out a comparison of several body area communication methods. With the use of multi-hop communication, Abidi *et al.* [18] developed a routing protocol that allows for low energy usage, high data transfer rates, and extended system lifetimes.

All wireless systems are not alike. This is particularly true for WBANs, as their requirements for QoS differ from those of other WSNs. It is comprehensible to incorporate QoS in WSNs for WBANs, but it is not accurate. The primary objective of WBANs is not solely to extend their lifespan. It is essential to guarantee that the data transmission rate is kept as low as possible to maintain a high level of security and ensure the overall reliability of the system. This is particularly important for wireless systems, as any errors or malfunctions could potentially harm the individual wearing the system, which would have severe consequences. It is difficult to assign QoS to a healthcare system due to the unpredictable nature of the environment on a WBAN. While aspects like bandwidth reservation, power transmission, latency, and reliability are common for QoS, WBANs require additional QoS considerations [19]–[22].

Many studies [23]–[26] focused on the most commonly used protocol methods like cluster-based routing protocol, the cross-layer routing protocol, the posture-based routing protocol, the QoS routing protocol, and the temperature-based routing protocol. According to Hajar *et al.* [27], the main attention was on the wearable body area network technology, with a primary emphasis on security and privacy concerns, as well as the measures that can be taken to address them.

The rest of the paper is organized as follows. Section 2 describes the wireless body area network, including wireless body sensors network architecture, routing protocols, and prospects for wireless technology. Section 3 presents Quality of Service metrics issues. Section 4 discusses security and privacy concerns. Ensuring the reliability of WBAN's performance is discussed in section 5. Optimizing energy usage techniques are presented in section 6. Finally, some conclusions are drawn in section 7.

2. WIRELESS BODY AREA NETWORK

Miniaturization is transforming implantable electronic devices into more efficient and powerful tools. These devices are equipped with biomedical sensors that monitor various physiological parameters such as glucose levels, blood pressure, and neural activity. Implantable chemical sensors [28], glucose and oxygen sensors for diabetics [29], [2], neural implants [30], [31], and cochlear implants [32] are all examples of such devices.

A WBAN is a WSN applied to the human body and primarily consists of a group of sensors that operate collaboratively within the human body, and they must work together in a network. WBANs and WSNs face similar challenges, but WBANs present specific issues:

a. The human body has limited space, which imposes size constraints on various internal organs and structures.
b. The implant is surrounded by lossy materials that weaken electromagnetic signals used for communication, leading to a decrease in the quality of the connection.
c. The compatibility of a material or device with living tissue or organisms. This is particularly important in medical and biological fields, where the use of incompatible materials can lead to adverse reactions or even harm to the patient or subject.
d. Due to limited available energy, high power efficiency is required whether from batteries or other power sources [33].
e. It is imperative that communications are reliable, as they may convey urgent information about life-threatening conditions.
f. Data safety must be ensured during communications to protect personal and confidential medical information.

Biological tissues absorb energy and release it as heat, which causes a significant attenuation of signal due to the conductive nature of biological tissue. For in-body to in-body, in-body to on-body, and in-body to off-body communications between 2.36 and 2.5 GHz, experimental path loss models were reported in [34]. For implanted sensors to ensure patient safety, networking systems must take tissue temperature increases and the specific absorption rate (SAR) limits into account.

2.1. Wireless body sensors network architecture

Healthcare should be accessible to patients in a safe manner. To achieve this goal, we could aim to connect individual patients to the network. The network will virtually connect a patient's human body to a hospital/doctor's office as shown in Figure 1.

Figure 1. Wireless body sensors network architecture [35]

2.2. Prospects for wireless technology (IEEE.802 standards)

2.2.1. Bluetooth

Bluetooth technology was designed to enable short-range wireless communication through the formation of piconets, which are personal networks consisting of multiple Bluetooth devices [36]. Each piconet comprises a master device that controls up to seven slave devices. While slave devices can only communicate with the master device, they cannot directly communicate with other slave devices. Bluetooth devices function in the 2.4 GHz ISM band, providing a coverage range of 1 to 100 meters. Their maximum data transfer rate is 3 Mbps, and the time required for connection setup and data transfer is approximately 100 milliseconds. However, it may not be the ideal choice in terms of power consumption for sensors with high data rate requirements.

2.2.2. ZigBee-IEEE 802.15.4

ZigBee is a wireless communication technology that offers a long battery life, a low data transfer rate, and secure networking capabilities, [20]. One of the benefits of ZigBee is its ease of installation and configuration. It supports various network topologies and can accommodate many nodes. The equipment can function for several years before requiring a battery replacement, making it a prevalent technology in numerous medical applications within WBAN. ZigBee provides secure networking, offering three levels of security mode to safeguard data from alteration or unauthorized access by attackers [37]. Operating at frequencies of 2.4 GHz, 915 MHz, and 868 MHz, ZigBee has a range of 100 meters and data rates of 250 Kbps, 40 Kbps, and 20 Kbps for each respective frequency band. ZigBee is tailored for WBAN, focusing on medical applications that demand frequent measurements and low-power text-based data transmission. ZigBee's low data rate renders it inadequate for certain WBAN medical applications that demand higher data rates, posing challenges for implementation in hospital settings with multiple patients [38]. Another notable drawback of ZigBee for WBAN applications stems from interference in the 2.4 GHz band, where numerous wireless systems operate.

2.2.3. Wi-Fi IEEE 802.11

Wi-Fi offers dependable, secure, and swift communication, seamlessly integrated into smartphones, tablets, and laptops. Typically equipped with four standards (802.11 a/b/g/n), Wi-Fi operates across both the 2.4 and 5 GHz bands, providing a coverage range of up to 100 meters and data rates of up to 600 Mbps [39]. Wi-Fi is ideally suited for handling large volumes of data transfers with high-speed wireless connectivity, enabling functionalities like voice calls and video streaming. However, in WBAN systems, Wi-Fi is not the preferred choice in the primary tier due to its high power consumption [38]. Instead, it is utilized for communication between personal devices (PDs) and access points (APs) in the secondary tier for certain WBAN medical applications. Like Bluetooth and ZigBee, Wi-Fi operates in the ISM bands, which may lead to significant co-channel interference. A summary of the previously listed IEEE.802 standards is shown in Table 1.

Table 1. A summary of IEEE.802 standards

Criteria / Standard	Frequency Band	Coverage	Data rate	Applications	Features	Drawbacks
Bluetooth	2.4 GHz	100 meters	3 Mbps	Employed for communication between sensors and PDs in the first tier of wearable body area network systems	Free and widely supported by a variety of devices	It is not the ideal choice in terms of power consumption for sensors with high data rate requirements.
ZigBee-IEEE 802.15.4	2.4 GHz, 915 MHz, and 868 MHz	100 meters	250 Kbps, 40 Kbps, and 20 Kbps, respectively, for each frequency band	Medical applications that demand frequent measurements and low-power text-based data transmission. Like body temperature monitoring, pulse monitoring, and various other medical applications	Long battery life, secure networking capabilities, ease of installation and configuration	Low data transfer rate and interference in the 2.4 GHz band, where numerous wireless systems operate
Wi-Fi IEEE 802.11	2.4 and 5 GHz	100 meters	Up to 600 Mbps	Communication between PDs and APs in the secondary tier for certain WBAN medical applications	Dependable, secure, and swift communication, seamlessly integrated into smartphones, tablets, and laptops.	High power consumption, and co-channel interference

2.3. Wireless body area network routing protocols

To successfully create and connect all devices in a network, routing is essential. Additionally, it is necessary to establish a clear path for the transmission and exchange of data [23]. In addition, the primary factors, including the development of a stable and efficient system while enhancing the performance of individual nodes, are of significant importance [40]. Understanding various protocol strategies allows for the effective selection of the appropriate strategy for specific issues [41]. The five most commonly used protocol methods are the cluster-based routing protocol, the cross-layer routing protocol, the posture-based routing protocol, the QoS routing protocol, and the temperature-based routing protocol [23]-[26]. The critical information to be transmitted necessitates the careful selection of routing nodes to prevent malicious nodes from obtaining the data. Several factors can be considered as selection parameters for choosing a node to include in the route. Among these, the trustworthiness of the sensor node is vital; if it is unreliable, the likelihood of delivering accurate data to the destination node decreases significantly, which could potentially pose a threat to a person's life. Several studies discussed various protocol types, as summarized in Table 2.

Table 2. A comparison between various protocol types

Technique	Research Issues	Methodology	Outcome
M-ATTEMPT [42]	Heterogeneous wireless body area sensor networks	Linear programming (LP) model to maximize information extraction while minimizing energy use	Less energy consumption and more reliability as compared to multi-hop communication
M-TSIMPLE [43]	Energy efficient threshold based data transmission	Using the forwarder node technique based on the mobility of nodes	Less energy consumption, path loss, and propagation delay and is also more efficient in terms of stability, residual energy and throughput
Point-to-point communication system [44]	Harvesting radio energy in WBAN	Power splitting protocol in normal circumstances and time-switching protocol in abnormal circumstances at the sensor	Maximize the information throughput from the sensor to the access point (AP), while satisfying energy harvesting (EH) and consumption balance constraint at the sensor
Trust and thermal aware routing protocol (TTRP) [45]	Privacy and confidentiality of patient data	Trust and thermal-aware routing protocol for WBANs that considers trust among and temperature of nodes to isolate misbehaving nodes	Performs better in terms of packet drop ratio, packet delay, throughput, and temperature
iM-SIMPLE [46]	High throughput for WBAN	Select the forwarder; the node with the highest residual energy and the least distance to sink has the minimum cost function value and is selected	Maximizing stability period and throughput of the network
Lightweight encryption algorithm (LEA) [47]	Securing the WBAN	Adds a layer of encryption to the three-tier architecture used by the WABN to encrypt the patient’s vital signs captured by the sensor and sent to a mobile device that a patient carries	More suitable encryption algorithm for the WBAN environment
Energy efficient and reliable data transfer (EERDT) [48]	Power efficient and high throughput routing protocol	Hierarchical routing to minimize energy consumption and single-hop routing to transfer critical data directly to the base station	Enhances the network stability period
Cooperative link aware and energy efficient protocol (Co-LAEEBA) [49]	Collaborative learning and path loss	Learn and select the most feasible route from a given node to sink while sharing each other's distance and residual energy information	Maximizes the network throughput
Hybrid routing protocol for WBAN [50]	Routing nodes selection	Count the trust of the node as an important factor and update the path if it finds any a malicious node in between the route	The throughput and packet delivery ratio are improved, considering the link failure issue due to the mobility factor of nodes.

Furthermore, a comprehensive comparison of routing protocols for WBSNs based on other important metrics, including network lifetime, stability period, throughput, residual energy, and path loss of each protocol, is presented in Table 3. The results show that the majority of the protocols consider a variety of quality-of-service metrics in their performance. In consideration of this, protocol selection in the WBAN system should be influenced by the system's desired purpose, such as whether it would be used for being more energy-efficient, highly trustworthy, or able to significantly increase the network throughput and lifetime evaluation.

Table 3. A comprehensive comparison of routing protocols for WBSNs based on important metrics

Criteria / Protocol	Stability period	Network lifetime	Throughput	Residual energy	Path loss
M-ATTEMPT [42]	11% greater than ATTEMPT	29.5% better network lifetime over varying numbers of rounds	12.5% with ATTEMPT	***	***
SIMPLE [51]	31% more stability period than M-ATTEMPT	0.4% longer network lifetime than M-ATTEMPT	High throughput than M-ATTEMPT	Higher than M-ATTEMPT	Less than M-ATTEMPT
iM-SIMPLE [46]	45% than M-ATTEMPT	Better than M-ATTEMPT	Higher than M-ATTEMPT	Higher than M-ATTEMPT	Reduced path loss in comparison to M-ATTEMPT
Co-LAEEBA [49]	Much greater than M-ATTEMPT	Greater than M-ATTEMPT	Higher than M-ATTEMPT	Higher than M-ATTEMPT	Better than M-ATTEMPT dropping the path-loss to 161.8 dB
EERDT [48]	Increased more than 5000 rounds as compared to ATTEMPT	Better than ATTEMPT	Transfer more data packets compared to ATTEMPT	Higher than ATTEMPT	***
M-TSIMPLE [43]	Greater than that of M-ATTEMPT	Greater than that of M-ATTEMPT	Increased throughput compared to M-ATTEMPT	Higher than M-ATTEMPT	Less path loss compared to M-ATTEMPT

Finally, temperature-based routing protocols are summarized in Table 4. The findings show that each temperature routing protocol is aimed at minimizing the rise in temperature of embedded body nodes. The pros and cons of each protocol are provided through contrast with other state-of-the-art techniques based on the rise in temperature, end-to-end delay, throughput, and packet drop ratio [45].

Table 4. A comparison between temperature-based routing protocols

Criteria / Protocol	Packet drops ratio	Average End-to-End delay	Throughput	Average Temperature rise
TTRP	The lowest	The lowest	The highest	The lowest
Hotspot preventing routing algorithm (HPR)	Less than TTRP	Less than TTRP	Less than TTRP	Less than TTRP
Thermal aware routing algorithm (TARA)	The highest	The highest	The lowest	The highest

3. QUALITY OF SERVICE METRICS ISSUES

Different quality factors, including latency, dependability, bandwidth, and security, must be met for different wireless sensor network applications. QoS requirements are crucial because of some of the issues that WSNs face, including low bandwidth power, erratic communications, and node vulnerabilities. QoS is a crucial issue in WBANs that is distinct from WSN applications. Unlike WSNs, QoS in WBANs is sensitive to the nature of the transported data and the sensitivity of the applications, making it impossible to directly apply WSN QoS to WBANs. Depending on the intended application, the QoS in WBANs can vary. For instance, in critical patient monitoring systems, it is crucial to deliver data instantaneously, as any delay can result in catastrophic situations. [52].

According to Cova *et al.* [53], traditional QoS typically encompasses latency, transmission power, reliability, and bandwidth reservation. To ensure QoS in WBANs, it is crucial to consider several factors. Resource constraints, including battery power, available bandwidth, transmission power, buffer size, and processing capacity, are essential factors to consider for any sensor node application. Unlike traditional QoS approaches for routing and medium access control (MAC) protocols that are not suitable for WBANs, it is crucial to develop solutions that address these constraints to ensure optimal performance. Unpredictable and diverse traffic is common in WSN applications, where QoS is typically defined for periodic traffic. However, because different kinds of applications are used in WBAN, the traffic levels experienced by WBAN vary, including no traffic, data bursts, and occasionally varied amounts of traffic. The diverse traffic increases the complexity and difficulty of QoS requirements and support.

Zhou *et al.* [54] stated that QoS in WBAN can be satisfied by using three different components. These are as follows: i) an asymmetric architecture, where most of the processing is handled by the central node; ii) a virtual MAC that enables it to schedule wireless resources irrespective of the MAC protocol being used; and iii) an adaptive resource scheduler that schedules the remaining bandwidth to meet QoS requirements if radio frequency (RF) interference from patient movement causes a channel failure. The provision of QoS is an essential aspect in the pursuit of a dependable network. A reliable QoS ensures that packets are delivered in the correct sequence and within the allotted timeframe [55]. As per Li *et al.* [56], QoS plays a crucial role in medical information transmission inside WBAN, as vital applications necessitate the greatest possible QoS. To enhance system performance, achieving high QoS necessitates a high throughput. The packet payload and transmission delay are directly correlated with the throughput and inversely so, respectively. To guarantee the effectiveness of the data, QoS also demands a minimum delay. Optimizing the network lifetime by limiting the primary energy loss sources is another prerequisite [57].

Ensuring transmission reliability is paramount in guaranteeing the effectiveness of a WBAN [58]. The monitored data must be received accurately by medical staff, as failure to do so could have fatal consequences, particularly if a life-threatening event goes undetected. Reliability includes the delivery of data in a reasonable time and a guaranteed delivery of data. The unreliability has main causes such as low transmission range, interference, inefficient routing, and others [59]. QoS stands as a fundamental characteristic in establishing a dependable network. A reliable QoS ensures that packets arrive in the correct order and within the specified timeframe [55]. As outlined in [56], QoS plays a pivotal role in the transmission of medical information within WBANs, especially for critical applications that demand the utmost QoS. Achieving high QoS necessitates a high throughput, which significantly enhances system performance. Throughput is directly related to the packet payload and inversely related to transmission delay. Ensuring QoS also entails minimizing delay to guarantee data effectiveness. Additionally, maximizing network lifetime involves managing the primary sources of energy loss [57]. The fifth generation (5G) could indeed be a viable solution for enhancing QoS in WBAN systems, as it promises high data rates, reliability, and extremely low latency. However, it is important to note that this advancement may come at the cost of increased energy consumption. Consequently, striking a balance between these factors becomes imperative to achieve optimal system performance.

5G has the potential to significantly improve the QoS of WBAN systems by guaranteeing high data rates, great dependability, and extremely low latency. However, doing so can result in a rise in energy usage. Thus, to get a satisfactory performance, we must compromise between these factors. The 5G cellular network technology is poised to offer an extremely high data rate of up to 10 Gbps, minimal latency approaching the millisecond range, exceptional reliability, a wide bandwidth exceeding 100 MHz, substantial capacity, effective interference mitigation, support for a vast number of connected devices, and a secure network infrastructure [60]. Within WBANs, 5G has the potential to drive substantial advancements in medical applications, particularly for urgent and critical scenarios demanding real-time data transmission and high data rates. Specifically, 5G stands to significantly enhance telesurgery procedures by enabling robotic platforms equipped with audio, video, and haptic feedback capabilities to operate seamlessly [61]. Additionally, 5G serves as an efficient solution for accurately monitoring patients in real-time continuously and detecting their positions in abnormal situations. Moreover, it facilitates the rapid transmission of medical images and videos [62]. Nevertheless, the power consumption of 5G remains a crucial concern within WBAN, particularly for miniaturized sensors that must operate for extended periods, spanning multiple years [63]. In the realm of beyond-fifth-generation (B5G) mobile communications, the objective is to establish a system with a capacity surpassing that of 5G networks by more than 100 times. This includes achieving data rates in the terabits per second range, minimal latency, and unparalleled reliability. These advancements hold immense promise for healthcare applications within WBANs [64].

The sixth generation (6G) will leverage terahertz signals for transmission, effectively enhancing both bandwidth and data rates. The anticipated prerequisites of 6G communication technology for future healthcare encompass achieving data rates surpassing 1 Tbps, minimizing latency to less than 1 ms, ensuring high reliability, supporting high mobility (exceeding 1,000 km/h), and offering bandwidth three times greater than that of 5G [65]. While 5G and B5G primarily offer 2D communication, 6G is poised to transition towards 3D services utilizing holographic communication. This shift has the potential to revolutionize intelligent healthcare systems, particularly in tele-surgery scenarios where extremely high data rates are imperative. Other applications such as remote patient diagnostic and medical treatment supervising will also be feasible, where doctors can diagnose remotely using holographic communication which can relieve the economic and physical burden for the patients [66].

3.1. Delay

Due to the nature of WBANs, several of their sensors are directly implanted within the body to collect and transmit vital physiological information about the wearer's condition. However, human tissue and body motion can significantly impact the network's performance, which poses a challenge. In particular, the issue of delayed communication is especially significant, as it could become outdated and even crucial for the user if essential information that the healthcare staff receives is delayed [67], [20].

3.2. Latency

Latency is another major challenge that must be addressed. The term "latency" refers to the delay in the arrival of information packets due to high traffic, long queues, or a longer route taken to avoid congestion. As was previously said, appropriate routing protocols are needed to address these problems because the outcome could be just as important as the delay [20], [21]. It can range from less than one millisecond for 5G/6G to a few tens of milliseconds for 3G/4G and can even exceed one second for low-power wide-area network (LPWAN) technologies [21]. The rapid transmission of data is crucial for ensuring the successful real-time transmission of data to a medical center. The applications for WBANs in the medical field can be critical if they are unable to tolerate delays, especially in emergencies where the delay in data delivery could result in fatal consequences for the patient [21]. Health data latency should not exceed 12 ms in applications used for medical purposes, while non-medical applications should guarantee data latency of no more than 250 ms [68]. The reason for the stringent data latency requirements of WBANs is that most medical applications, like emergency medical systems, cannot withstand slow response times. This is because delayed delivery of the collected health data to a medical facility could render it ineffective in emergencies. To address latency in healthcare applications, a few potential WBAN system solutions were suggested by Mahapatro *et al.* [69] and Wang *et al.* [70].

3.3. Reliability

Reliability is defined as the amount by which the succession of an attended computing process is considered. This means that the success rate of a system can be directly correlated with its reliability. The reliability of information can vary depending on various factors, including the type of application and the way users handle it. As a result, it is difficult to determine what is completely reliable in different situations. In summary, a link is considered successful if it can be traversed with exceptional precision and recall. Ensuring prompt retrieval of the genuine representation of resources while maintaining consistency [20], [21].

3.4. Data rate

Data rate can be defined as the quantity of health information as well as the speed (or rate) at which that information can be sent at a given moment over a communication channel. Depending on an application's nature and the kind of application traffic pattern—continuous or periodic—different data rates are needed for WBANs. WBAN sensor devices typically require data rates ranging from a few kbps (<1 kbps) for on-body monitoring to >1,000 kbps (>1,000 kbps) for real-time video feeds [71]. Similarly, while designing WBAN systems, appropriate bit error rates (BERs) must be guaranteed for health data transfer to be dependable. One way to define the bit errors per unit time (data loss) is as a measure of the BER. For instance, sensor devices with a high data rate demand may be used in surroundings with lower BER values to meet the dependability requirements of health data transmission in WBANs [72]. Similar to this, the physical (PHY) layer of a WBAN system can maximize the BER value of a transmission link by taking advantage of various coding and adaptive modulation techniques that are suitable for the communication-channel conditions [73]. The BER, which is often a measure of the quantity of dropped packets, must be provided to define and select the proper data rate. Regarding medical devices, the data rate determines the reliability rate. While some devices that operate at a low data rate can handle a greater BER, other devices operate at a higher data rate but necessitate a lower BER [68].

3.5. Data priority

One of the biggest issues with the right routing protocols within a WBAN is that not all data can be placed on the same priority. For instance, physiological data about body temperature shouldn't have the same priority as information on a life-threatening illness. Because it could potentially result in a patient's death, a suitable routing decision needs to be made quickly and intelligently [74], [75].

3.6. Requirement for throughput

A system's capacity to handle data in a specific amount of time is measured by its throughput. Another way to put it would be the entire quantity of data that a WBAN system can send over a communication channel bandwidth. To improve the health data communication efficiency of WBAN systems, an optimal throughput is required because the majority of WBAN health data are vital and need to be delivered on time to a remote medical center [76]. To do this, the throughput of a WBAN system can be maximized by either maximizing the throughput of each sensor device in the network or by maximizing the throughput of the entire network, which includes all of the sensor devices [21].

3.7. Coexistence in communication bands

As communication systems, WBANs need a communication band (range of frequencies in the RF spectrum) to supply a communication channel(s) for the network devices to use. WBANs are primarily made to operate in unlicensed ISM frequency bands, like 2.45 GHz, which includes 915 MHz, for financial reasons. For example, the ISM bands are used by several standards (such as Bluetooth, Wi-Fi, ZigBee, and others) that are frequently used in WBANs for the transmission of health data. Be aware that the ISM bands are also used by other communication systems besides WBANs. As a result, there is an increasing quantity and variety of these wireless communication technologies, which is overcrowding the band. Interference may arise among the numerous communication systems coexisting on the ISM bands due to their overcrowded character. Therefore, interference-resistant technology implementation is necessary to ensure the reliability of WBAN medical applications, particularly in emergency scenarios [21].

3.8. Low electromagnetic radiation

The increasing prevalence of WBANs is leading to a rise in interference, which presents a genuine challenge [77]. This interference can have a detrimental impact on network performance and may also lead to increased power consumption in sensors due to the repeated re-transmission of data when interference hinders its successful transmission to the intended recipient. WBAN systems can be subject to two types of interference. The first type is intra-network interference, which arises from the asynchronous transmission between nearby sensors. Inter-network interference is the second type of interference that occurs when outside sources use the same WBAN frequency channels [78]. When data is sent simultaneously by two or more WBANs, inter-network interference can also happen. Mitigating or avoiding these two types of interference is essential to ensuring the quality of the signal in WBAN [79]. Because high electromagnetic wave radiation can lead to a variety of health risks, including tissue damage, decreased blood flow, and enzymatic disorders, it poses a serious risk to human health [80]. Designing a WBAN system necessitates considering the electromagnetic waves emitted by sensor devices during data exchange, as WBAN is a body-focused network—that is, a network that has direct touch with a patient's body. It's also important to note that a body sensor device operating at a high-power level will have a high throughput, which is excellent because greater throughput rates increase the likelihood that health data will be sent successfully. The federal communications commission (FCC) regulation defines the acceptable SAR of body tissue for 1 g at 1.6 W/kg. Transmitting at higher power levels by the sensor devices will, however, automatically increase the electromagnetic radiation absorbed by the patient's body tissue. SAR measures the amount of energy or RF energy that is absorbed by human tissue and the body when exposed to RF electromagnetic radiation. Each medical sensor device in a WBAN system is intended to radiate its health data at a transmission power of approximately 0.0001 W, or –10 dBm, and should not exceed a maximum transmission power of <0.001 W or 0 dBm to meet the SAR constraint requirement.

3.8. Patients' mobility

Another essential prerequisite for WBAN systems to deliver ubiquitous healthcare monitoring (HCM) services is patient mobility assistance. Since the majority of WBAN customers are likely mobile consumers who need to access and receive medical services at their convenience, such as at home, the office, the market, and so forth, they are static. As a result, patient movements—whether fast or slow—may cause signal fading or shadowing, which could be detrimental to QoS performance—which includes latency, health data delivery ratio, and other factors. Thus, to address the issue of patient mobility, the existing WBAN solutions need to include some wireless technologies in the systems. Because of this, LPWAN solutions are seen as potential technologies that can facilitate the large-scale delivery of health data to distant medical centers while also enabling patient mobility. For example, when linked to LPWAN systems, a patient's temperature or heart rate can be tracked from any location using medical sensors, alerting the attending physician of the patient's health status [21].

4. SECURITY AND PRIVACY

Two extremely delicate subjects in a WBAN are security and privacy. The ability for the user to govern their own data collection and distribution is what is meant by privacy, whereas protection against bad intent is what is meant by security. Privacy and security are established automatically when data is created, processed, moved, or even kept. The health insurance portability and accountability act (HIPAA) imposes rules and regulations to guarantee that, in a WBAN, every device that currently collects user physiological data is outfitted with security measures to prevent malicious intent, including tampering and unauthorized access. Other QoS like data integrity and throughput are severely constrained by this high level of security and must be taken into account when developing a security architecture [13], [20], [67], [81], [82].

Ananthi and Jose carried out an extensive investigation of the WBAN security issues for applications related to healthcare [83]. To improve security and expedite the dependability of the WBAN, the researchers examined and evaluated various procedures and events. The authors of this paper explored and explained the fundamentals of security and security measures in WBANs, including their applications, challenges, and solutions. They also presented the outcomes of various techniques used for enhancing the security of WBANs. The findings and conclusions of this study indicated that methods such as clustering and choosing efficient router protocols enhance the throughput and lifespan of the network securely and reliably. The researchers in this article presented methods to extend the life of the network and enhance the security of the WBAN to improve high-speed data transmission. Although the authors did not discuss the influence of metaheuristic techniques and artificial intelligence algorithms on enhancing the control parameters, their study was limited in that it did not address the optimization of network quality and energy consumption.

Numerous security prototypes for WBANs have been outlined in the literature. However, despite these efforts, ensuring the security and privacy of medical data in WBANs remains a significant challenge. Addressing these challenges necessitates the development of appropriate mechanisms, which is currently the focus of extensive research. Several open issues persist in this domain, including:

Initially, as WBANs become more pervasive, patient data sharing will extend to family members, doctors, hospitals, pharmacies, and other stakeholders. This necessitates the implementation of robust and consistent policy sets to safeguard patient privacy effectively. Secondly, WBANs could be susceptible to a range of attacks. As described in [84], these security threats are categorized into two types: external attacks and misbehavior. External attacks can typically be addressed using traditional security mechanisms, whereas misbehavior attacks present a more complex challenge requiring further research and study. Thirdly, another critical aspect requiring attention is trust management. Trust reflects the level of reliability, safety, and dependability of a node when interacting with other nodes. Recent research on trust management for WBANs is outlined in a survey provided by [85]. Fourthly, the implementation of complex security mechanisms in WBANs demands additional power resources. Achieving a balance between various factors such as security, power consumption, efficiency, and practicality is crucial for the widespread adoption of medical applications in WBANs. Further research is required to address this challenge effectively. Recent analyses regarding security and privacy issues are discussed in the following references. Moganedi *et al.* [86], presented research elaborates on the security and privacy challenges arising from the growing utilization of the internet of things (IoT). Following the examination of existing solutions tackling these challenges, the authors proposed novel approaches to address the prevailing issues. Additionally, Mehrjou *et al.* [87], analyzed IoT security, focusing on potential threats, identification of countermeasures, and their limitations. Attention is particularly paid to the security mechanisms inherent in IoT protocols. Ingham *et al.* [88], examined common attacks that may impact IoT devices and networks, along with an evaluation of the security measures implemented in LoRaWAN and their vulnerability to compromise. Meanwhile, Beavers [89] explored potential threats targeting pacemakers, aiming to determine the feasibility of hacking modern industrial pacemaker models.

Even after a decade of incredible research, privacy and security for WBAN remain a popular area of study. To create safe WBAN systems, numerous cryptography methods and algorithms are put out in several literature works. Here is a list of some of the most recent research that is relevant.

A random key deployment approach is suggested by Di *et al.* [90]. In this approach, data is sent from node to node (via an ad-hoc wireless network), protecting it against cracker attacks. A safe protocol for WBANs is proposed by Li *et al.* [91], in which a set of nodes establishes confidence by forming an authenticated group that can accurately associate with the intended patient. A secure protocol for communication inside a WBAN called the physiological-signal-based key agreement, or PSKA, is presented by Venkatasubramanian *et al.* [92]. With the acquired physiological signals, PSKA enables nearby sensors in a WBAN to decide on a shared cryptographic key in an authorized way and without the requirement for startup or deployment. Liu *et al.* in [93], a dynamic password-based authentication mechanism is suggested. The system generates a unique, private password for each login using a bespoke password computation technique. Using two secure protocols—one for authentication and another for re-authentication—Almuhaideb and Alqudaihi [94] presented a lightweight technique for WBAN authentication that preserves the anonymity of the sensors using a hash function. The proposed WBAN authentication cryptosystem by Konan and Wang in [95] is based on an algorithm that combines bi-linear pairing techniques with elliptical curve cryptography.

To increase the security of the WBAN, the proposed study in [96] first employs the hash method and key generation procedure (KBS) keys. Second, for inter-WBAN communication, key generation algorithm for inter sensor communication (KAISC) is employed. Using the XOR and basic hash functions, Gupta *et al.* [97] created an anonymous authentication system and safe key agreement protocol for WBAN. A study on the use of biometric traits to enable secure data communication in a WBAN is conducted in reference [98].

The protection of patients' highly sensitive personal data, such as their medical information, is crucial for WBANs. This includes ensuring that this information is not disclosed to unauthorized individuals and is safeguarded during collection, transmission, and storage [21]. False information provided to medical personnel can result in improper treatments, which may lead to patient death.

5. WBAN's PERFORMANCE

Ensuring the reliability of transmission is a crucial aspect of WBAN performance [58], as it is essential to convey the monitored data to medical staff. If a life-threatening event is not detected due to unreliable transmission, the consequences can be fatal. Reliability involves delivering data within a reasonable timeframe and guaranteeing its delivery. There are several causes of unreliability, such as low transmission range, interference, and inefficient routing [59].

Approximately 70% of bodily fluids (tissues) are exposed to the curved surfaces of the body, where a set of radiant elements of WBAN receivers and transmitters for body implants operate. The WBAN signal is attenuated, and the thermal impacts of RF are increased by the absorption qualities of biological tissues. The transmission of signals and other pathways within the biosensor circuit are also impacted by the tissues' absorption qualities. Data and device anomalies, network faults, and modifications to circuit transmissions can affect the way data-acquisition devices operate. Moreover, the signal strength is diminished by signal attenuation brought on by the tissue's absorption characteristics. Furthermore, variations in body motion brought on by various dynamics and WBAN topology impact the RF signal's propagation, altering packet transmission distance and disconnection while also reducing reliability.

Considering the constraints faced by WBANs and the necessity for healthcare in the future, the focus is on enhancing service quality and performance to ensure effective operation in a demanding and resource-constrained setting. Therefore, improving the cost-effectiveness, flexibility, and operational efficiency of current technology is essential to ensuring the quality of services that will shape the future of modern healthcare [99]. To mitigate the impacts of fading in health monitoring systems, researchers in [100] suggested a multifrequency/multichannel communication framework for WBANs. Increasing data rates will enable multimedia data and enhance network performance.

Detecting sleep denial attacks in WSNs required the application of a hierarchical structure built on the distributed collaboration technique [101]. This approach minimizes the chance of an improper incursion by using a two-step anomaly detection procedure. Consequently, an efficient and reliable heterogeneous WSN is showcased.

Mahmoud *et al.* [74] proposed a new routing protocol for WBANs, which utilizes a weighted average optimization function. This protocol is an improved version of the multipath ring routing protocol (MRRP), as it employs a weighted average function to determine the next hop node. The performance of this protocol, as well as other WBAN routing protocols for healthcare applications, has been evaluated in terms of energy consumption, packet reception rate, end-to-end delay, and maximum temperature of the sensor nodes. Liu *et al.* [99] discussed several of the driving and open performance issues related to current and future WBAN application technologies, specifically focusing on improving efficiency through signal processing while addressing concerns such as packet processing and queuing delays, information security, and reliability, all of which have a significant impact on WBAN operational performance.

6. ENERGY EFFICIENCY

Energy efficiency can be defined as a design criterion that aims to reduce or limit energy consumption in a system. Energy efficiency strategies can be integrated into WBAN applications to create a sustainable, environmentally friendly WBAN system. Energy efficiency is essential in a WBAN system since medical professionals are often located at a distance from patients, particularly those with chronic illnesses. Consequently, cost-effective solutions, such as advanced healthcare monitoring and communication technologies, can be utilized to remotely collect and transmit medical data for these patients. Since the sensor devices used in these technologies are primarily battery-operated, they cannot incur additional energy costs for data collection and transmission. Moreover, patients find frequent battery changes to be quite inconvenient, especially for implanted devices that can only be surgically replaced. A WBAN's effectiveness and user satisfaction are directly influenced by its hardware size and battery power limitations. Therefore, energy efficiency is crucial for a well-designed WBAN, and many studies currently focus on optimizing energy usage as a primary goal of WBANs listed in Table 5.

Table 5. A comparison between several studies focusing on optimizing energy usage

Technique	Research Issue	Methodology	Outcome
Priority-aware schedule-based charging algorithm [102]–[105]	Energy efficiency	Medium access control (MAC) protocols are used for inductive powering from the primary unit to the secondary unit in a collision-free centralized scheduling scheme. The proposed algorithm is designed as per carrier sense multiple access with collision avoidance (CSMA/CA) technique	Guarantee the accessibility of more delicate and time-sensitive sensor nodes. In addition to improving the longevity of more sophisticated nodes
Alter IEEE 802.15.6 standard to allow several emergency data to be sent simultaneously [106], [107]	Energy saving techniques	Using PHY or MAC protocols with low power consumption	The suggested protocol performs better in terms of throughput, energy consumption, and packet delivery latency than its equivalents, increasing battery capacity through low-power consumption PHY or MAC protocols on ultra-low-power integrated circuits and enhancing cloud computing environments' virtual machine placement
IEEE 802.15.6 baseband on field programmable gate array (FPGA) [108]	Lower power and lower cost BAN	FPGA-based hardware architecture that complied with IEEE 802.15.6 and supported NB PHY, including baseband processing, radio frequency, and digital-to-analog conversion	This scheme's throughput, working frequency, and energy consumption were confirmed
Hybrid architecture combining coherent and non-coherent receivers [109]	Low power, data rate scalability, and low complexity implementation sensors network	A smart combination between a non-coherent synchronization algorithm and a coherent demodulation one. This architecture was implemented in a complete ultra-wideband impulse radio (UWB-IR) communication system environment	Recommended baseband architecture that supports the IEEE 802.15.6 standard's ultra-wideband (UWB) digital baseband PHY. The FPGA experiment demonstrated the reduced packet and bit error rates of this approach.
Narrowband physical layers (NB PHY) Transceiver of IEEE 802.15.6 WBAN on FPGA [110]	WBAN functionality, power, and data transfer	Building blocks of PHY transceivers, such as CRC, spreader, interleaved, and scrambler were individually designed and integrated. BCH (63, 51, 2) encoder and decoder are integrated into the design. Before modulation, the spreading technique is employed and supports pi/2 Differential-Binary Phase Shift Keying (DBPSK) modulation	Present a full FPGA-implemented NB PHY transceiver made up of baseband transceiver modules
A baseband transceiver implementation in application-specific integrated circuit (ASIC), which meets the 802.15.6-2012 standard requirements [111]	Energy consumption	Three modulation types, DBPSK, DQPSK, and D8PSK, which cover all the modulation methods specified by the IEEE 802.15.6-2012 standard	Completed an ASIC of the baseband processing module in NB to address the energy consumption of WBANs. This ASIC meets the IEEE 802.15.6 standard. This suggested ASIC shows advantages in energy efficiency, small area, throughput, and power consumption, and small area when compared to other known IC design approaches

7. RESULTS AND DISCUSSION

For simplicity and clarity, Table 6 summarizes all the reviewed papers based on various metrics and attributes of the implantable WBAN. Considering the discussions above, it is evident that most reviews primarily focused on security and privacy, while a few addressed data prioritization, performance, and mobility. Hence, to complement the existing studies in the literature and to address the gap in research, this review covers nearly all of the QoS requirements of the WBAN communication network.

Table 6. A comparison between this review and the state-of-the-art surveys and reviews

Reference(s)	Metrics issues											
	Delay	Latency	Reliability	Data rate	Data priority	Throughput	Coexistence	EM radiation	Mobility	Performance	Energy efficiency	Security & Privacy
[10], [11]	✓											
[12]												✓
[13]						✓						✓
[14]												✓
[20]	✓	✓	✓			✓						✓
[21]		✓	✓			✓	✓		✓			✓
[27]												✓
[47]		✓					✓					
[52]	✓											
[53]		✓	✓				✓					
[55]			✓									
[58]			✓									
[60]		✓										
[61], [62] [63]								✓				
[67]	✓					✓						✓
[68]		✓		✓								✓
[69], [70]		✓										✓
[71]–[73]				✓								
[74], [75]					✓							
[76]								✓				
[80]						✓		✓				
[82]–[98]												✓
[58], [59], [74], [99]–[101]										✓		
[102]–[106]											✓	
[107]–[111]											✓	
This review	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

This review compared Bluetooth, ZigBee-IEEE 802.15.4, and Wi-Fi IEEE 802.11 as communication technologies in WBAN as shown in Table 1. From this comparison, it’s clear that for sensors that demand a high data rate, Bluetooth might not be the best option due to its high power consumption. Within WBAN, ZigBee is a widely used technology in many medical applications. It is specifically designed for medical applications that require low-power text-based data transmission and frequent measurements. Still, ZigBee's low data rate makes it unsuitable for several WBAN medical applications that need greater data rates, making it difficult to deploy in multi-patient hospital environments. Also, ZigBee for WBAN applications stems from interference in the 2.4 GHz band, where numerous wireless systems operate. Wi-Fi, however, is not the recommended option for the primary tier of WBAN systems because of its high power consumption and substantial co-channel interference as a result of operating in ISM bands.

Another aspect of the comparison of this work dealt with different WBAN routing protocols as shown in Table 2, where the authors concluded that the lightweight encryption algorithm (LEA) is the most suitable encryption algorithm for the WBAN environment. Furthermore, a comprehensive comparison of routing protocols for WBSNs based on other important metrics, including network lifetime, stability period, throughput, residual energy, and path loss of each protocol, is summarized in Table 3. It is noticed that the protocol selection in the WBAN system should be influenced by the system’s desired purpose: energy-efficient, highly trustworthy, increasing the network throughput, or lifetime evaluation. On the other hand, the study presented a comparison between temperature-based routing protocols as shown in Table 4, where the findings showed that the TTRP protocol is the best compared with HPR and TARA.

Finally, this research provided a comparison between several techniques focusing on optimizing energy usage as shown in Table 5, and the results indicated that Alter IEEE 802.15.6 standard is the best protocol to perform better in terms of throughput, energy consumption, and packet delivery latency than its equivalents, increasing battery capacity through low-power consumption PHY or MAC protocols; on ultra-low-power integrated circuits and enhancing cloud computing environments' virtual machine placement. It can also be noted that a baseband transceiver implementation in ASIC, which meets the 802.15.6-2012 standard requirements technology, presented a completed ASIC of the baseband processing module to address the energy consumption of WBANs.

8. CONCLUSION

The WBAN fulfills its promises in terms of both its supported functionalities and its boundless potential. The WBAN stands out among the other WSNs because of its specially designed architecture and functionality to meet the requirements. Despite being widely used and represented in industries like entertainment and the military, WBAN excels in medicine. In addition to providing patient monitoring, treatment, and consultation, it also serves to safeguard patients' wellness by identifying potential health risks that could progress to life-threatening illnesses or by keeping an eye on blood pressure and glucose levels to guarantee a stable state of health. The wireless network, with its numerous, tiny sensors, is the greatest advantage of these amazing technologies, but it also presents the biggest barrier.

After deeply reviewing previous literature dealing with implantable WBAN metrics, we may conclude that, although improvements in wireless sensor network technology have opened a new era for creating wireless body area networks that enable continuous remote monitoring of patients' vital signs in both hospital and remote home care settings, thereby enhancing the healthcare system, there is still a long way to go in this field as they also present their own set of difficulties. Existing medical applications based on sensor networks are in the first-line potential research for use in the future of WSNs, and their medical device looks extremely promising. However, security issues are one of the main challenges in the design and implementation of WBANs that should be taken into account in future research. Assuring that the QoS benchmarking metrics are as high as feasible involves developing the proper standard, implementing effective protocols, and even enforcing security policies and methods. This enormous effort demonstrates both the struggles WBAN faces and the areas in which it still needs improvement. To illustrate the possible areas that could want further improvement, a thorough comparison between this review and the ones indicated in the relevant work section was provided. One aspect of these future improvements is the connection between bioscience, biotechnology, and nanoscience in the development of sensors, which can enhance the development of placeable, wearable, and implantable biosensors and their networking, which is one of the hot topics at present.

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Rawan Almajdoubah	✓		✓		✓	✓	✓	✓	✓	✓	✓		✓	NA
Yousef Eljaafreh	✓	✓	✓	✓		✓		✓		✓	✓	✓		NA

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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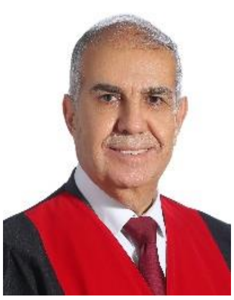
BIOGRAPHIES OF AUTHORS

Rawan Almajdoubah received a B.Sc. degree in biomedical engineering from the Hashemite University, Jordan, in 2007 and an MSc. degree in communications engineering from Al-Ahliyya Amman University in 2023. Currently, she is a lab supervisor and lecturer (part-time) at the Department of Medical Engineering, Al-Ahliyya Amman University. Her research interests include transdermal optical wireless communications, biomedical sensors, and body area wireless networks. She can be contacted at email: r.almajdoubah@ammanu.edu.jo.



Yousef Ghazi Eljaafreh received a B.Sc. in communications engineering from Royal College, United Kingdom, in 1978 and an M.Sc. and Ph.D. in communications engineering from Wales University, Swansea, United Kingdom in 1985 and 1989, respectively. Currently, he is a professor at the Department of Communications and Computer Engineering. His research interests include wireless sensor networks, cellular mobile communications, interference in Bluetooth networks, machine learning, and network intrusion detection systems. He can be contacted by email: eljaafreh@gmail.com.