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Enhancing sustainable healthcare practices through energy-efficient wireless body area networks

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Abstract

This paper explores how the integration and performance of Wireless Body Area Networks (WBANs) contribute to sustainable healthcare practices. WBANs play a crucial role in reducing the environmental footprint of healthcare systems by providing continuous monitoring that can prevent unnecessary hospitalizations and reduce the consumption of disposable medical supplies. Additionally, the design of WBANs using environmentally friendly materials, low-power devices, and recyclable components is discussed to optimize the sustainability of healthcare practices. To enhance infrastructure, services, and quality of life, new technologies have been integrated to improve WBANs. Patients' essential health data may be continuously and instantly collected thanks to these networks, and healthcare providers can receive the data right away for quick analysis and action. WBANs have healthcare benefits, but there are also major drawbacks. Technologies that can combine low power consumption, minimal delay, and high enough data rates are needed for WBANs in order to support a variety of medical applications. The effectiveness of the LoRaWAN and IEEE 802.15.6 technologies in WBAN is assessed in this paper. With the use of seven crucial metrics which are throughput, arrival rate, delay, energy consumption, residual energy, network lifetime, and packet delivery ratio (PDR), this paper seeks to study which technology is appropriate with WBANs using NS3 as a simulation program. With network parameters, 1000 seconds, and 50 nodes, the paper evaluated the performance of each technology. The results show that IEEE 802.15.6 is superior in terms of throughput, PDR, and arrival rate whereas LoRaWAN is superior in terms of energy consumption, residual energy, network lifetime, and delay.

Keywords: Energy efficiency, Sustainable healthcare, Healthcare optimization, Medical resource management, Low-power devices

1. Introduction

Wireless Body Area Networks (WBANs) have the potential to significantly reduce the environmental footprint of healthcare systems through several mechanisms. First, WBANs enable remote patient monitoring [1], reducing the need for physical visits to healthcare facilities. This decrease in physical visits diminishes the necessity for large healthcare buildings, which are resource-intensive to build and maintain, and lowers the associated energy consumption and carbon emissions from travel. Moreover, WBANs are designed for low power consumption, particularly those based on standards like IEEE 802.15.6 and LoRaWAN. These standards reduce the overall energy demand of healthcare systems. For instance, LoRaWAN's long-range and low-power capabilities make it suitable for continuous monitoring with minimal energy use, enhancing the sustainability of healthcare operations.

Another significant benefit of WBANs is the reduction of waste. Traditional healthcare methods often involve substantial paper use for records and prescriptions. WBANs facilitate digital record-keeping and electronic prescriptions, reducing paper waste. Additionally, the automation of medication delivery via WBANs ensures precise dosages are administered, thus minimizing pharmaceutical waste. WBANs also contribute to the extended lifespan of medical devices. By employing energy-efficient protocols and low-power technologies, WBANs extend the operational life of sensors and monitoring devices [2]. This reduces the frequency of replacements and the associated electronic waste, further enhancing the sustainability of healthcare practices. Optimized resource utilization is another advantage of WBANs. They improve the efficiency of healthcare delivery by enabling real-time monitoring and early detection of health issues. This leads to more efficient use of medical resources, reducing the overuse of medical supplies and minimizing unnecessary diagnostic tests and treatments.

Lastly, WBANs decrease hospital admissions by allowing continuous remote monitoring and early intervention [3]. This not only lessens the burden on healthcare facilities but also lowers the environmental impact associated with inpatient care, such as energy use for lighting, heating, and cooling, and the consumption of medical supplies. The integration of WBANs in healthcare systems supports a more sustainable and environmentally friendly approach by enhancing efficiency, reducing waste, and lowering energy consumption.

The population of our world is growing at a rapid rate, and people's average longevity is also rising. A World Health Organization (WHO) study projects that by 2050, there will be about 2.1 billion people over the age of sixty. Another WHO report indicates that the percentage of fatalities resulting from chronic illnesses (including diabetes, Parkinson's, asthma, etc.) is rising and is expected to reach 66% by 2030. The patients' delayed diagnoses are one of the causes of this rise. Healthcare expenses would be reduced and the effects of such diseases would be lessened with early detection and efficient monitoring [4]. The average life expectancy has increased globally as a result of the world's population constantly expanding, particularly in industrialized nations like Spain, Germany, Italy, Japan, and so on. Unfortunately, the average death rate of a person rises since lethal and chronic conditions like cancer, asthma, cardiovascular disease, etc. are frequently recognized extremely late. Early detection of these conditions may be able to lessen their effects and lengthen the lives of those who suffer from them. Due to its benefits, which include ease of patient monitoring, mobility, and flexibility, smart healthcare has attracted a lot of interest [5].

WBAN technology provides real-time monitoring of patient conditions, medical parameter measurement, and the mitigation of serious disease and health concerns. The WBAN system is a wireless technology based on radio frequency (RF) that measures various physiological characteristics such as glucose levels in sanguine, temperatures of the body, rates of the heart, and so on. It is made up of tiny, intelligent sensors that are either implanted or attached to the human body. Medical staff can interpret and evaluate a patient's status using the recorded data, and then treat him accordingly. In other situations, fluid drugs like insulin require tiny actuators, and the WBAN system used for diabetes and similar disorders automates the procedure so that the medication is injected whenever a physiological parameter reaches its threshold.

When WBAN was first developed, it was only intended to be used for treating sick patients. However, because of numerous advancements in its auxiliary technologies, WBAN is currently employed in nearly every industry where human body testing is necessary. Healthcare, sports, yoga and fitness, the military and armed forces, astronaut training, testing, and research are a few common industries [6]. In contrast to its early years, WBAN is today more efficient and comfortable. Patients may view their own health status and are more aware of their health thanks to real-time monitoring and medical care [7].

To monitor vital signs, a WBAN combines tiny, intelligent electronic devices that people wear. It permits people to use healthcare applications for ongoing health monitoring without putting any restrictions on their regular daily activities. Data rates in videos range from a few thousand bits per second (simple information) to several thousand bits per second depending on the scope of each application. Data in WBAN can also be transmitted in batches to ensure faster data transmission [8]. WBANs have nodes distributed throughout the body and one of these nodes acts as a hub for the rest of the distributed nodes called the Body Central Unit (BCU). This distribution of nodes and BCUs in WBANs leads to a star topology pattern, thus the most commonly used topologies in WBANs are star topologies. The BCU acts as a bridge between sensors and other body area networks or between sensors and external networks which the Physiological signals are sent from the sensors to BCU. These physiological signals are electrocardiogram (ECG), electromyography (EMG), electroencephalography (EEG), body temperature, blood pressure, and glucose levels. The BCU then uploads each of these signals to the hospital's or healthcare facility's medical server for additional examination and analysis. If a more in-depth examination of a particular body part is needed, the medical staff can also issue a direct order to the BCU. As seen in Figure 1, the architecture itself is divided into three tiers: the intra-WBAN communication layer, the inter-WBAN communication tier, and the beyond-WBAN communication tier [9].

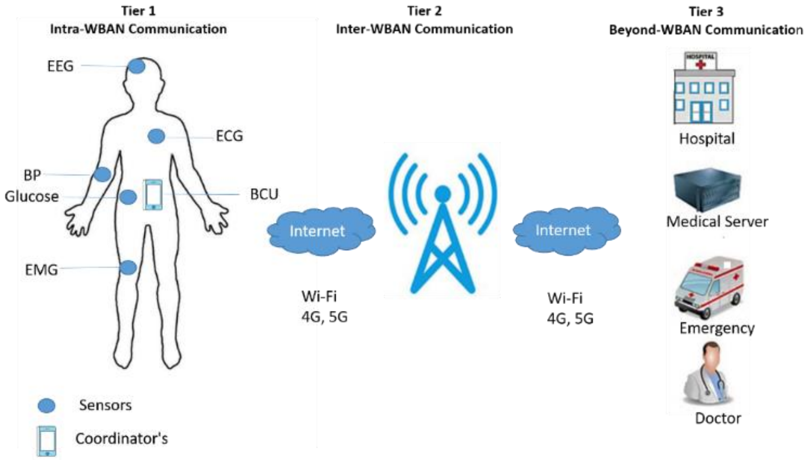

Figure 1. The three tiers of WBAN

Medical communication rules and standards are not met by the present standards, such as IEEE 802.15.4 [10], since they do not address various application needs, including those related to power consumption, reliability, low power, and traffic concerns. Consequently, a new Task Group (TG6) put forth IEEE 802.15.6 [11], a new communication standard that primarily targets a range of applications, including sports, medical, and military applications. The goal of this standard is to achieve ultra-low power, low cost, and extremely dependable wireless communication [12]. Because of enormous potential, Low Power Wide Area Networks (LPWAN) [13] networks are starting to emerge as the technology that makes smart ecosystems like smart cities possible. The low power, minimal data rate, and long-term (as far as 15 km externally) of the LPWAN is an emerging network technology that is making its way into the smart city space. It is already utilized for waste management, pollution monitoring, livestock management, smart lighting, packet delivery, parking availability monitoring, and even pest control because of its easy setup. These qualities make LPWAN an excellent choice for establishing communication between distant devices with challenging access circumstances. These days, LoRaWAN [14] technology is a good option for IoT long-distance communication. This is because LoRaWAN allows IoT devices to be controlled and managed over long distances with very low power consumption, significantly increasing the devices' battery life [15]. In order to assess the appropriateness of IEEE 802.15.6 and LoRaWAN technologies for different WBAN applications, this paper's goal is to use the NS3 simulation program to simulate WBANs that use the two technologies and measure the throughput, arrival rate, delay, energy consumption, residual energy, network lifetime, and PDR and then make a comparison between the two technologies.

In Section 2, related works are reviewed and various MAC protocols and comparable technologies' performance metrics are compared. In Section 3, the topic of multiple access protocols is explored, along with the principles of MAC approaches as they relate to networking. The IEEE 802.15.6 technology is covered in Section 4, with a focus on how it is used in WBANs. In Section 5, the architecture and communication paradigm of LoRaWAN are introduced. The NS3 simulation setup is explained in Section 6, together with the MAC layers, routing protocol, and network settings. Section 7 compares the effectiveness of each LoRaWAN and IEEE 802.15.6 by examining a number of metrics to assess each technology's dependability and efficiency. Finally, Section 8 shows the conclusion of the paper.

2. Related work

Wireless Body Area Networks (WBANs) optimize the use of medical resources and reduce waste through various innovative methods. By providing continuous monitoring, WBANs enable early detection and intervention [16], preventing unnecessary hospitalizations. This proactive approach ensures that health issues are addressed promptly, often before they escalate into conditions requiring intensive care or prolonged hospital stays. Consequently, the demand for inpatient services decreases, which in turn reduces the consumption of resources associated with hospital admissions, such as energy for lighting, heating, and cooling, as well as the use of disposable medical supplies. Continuous monitoring through WBANs also enhances the efficiency of medical resource utilization. With real-time data, healthcare providers can make informed decisions regarding patient care, tailoring treatments based on accurate and up-to-date information. This precision reduces the likelihood of redundant tests and procedures, which not only conserves medical supplies but also decreases the overall burden on healthcare facilities. For instance, instead of ordering multiple diagnostic tests to track a patient’s condition, continuous data from WBANs can provide a comprehensive overview, enabling more targeted and efficient use of medical interventions.

Moreover, WBANs facilitate the automated delivery of medication, ensuring that patients receive the correct dosages at the right times [17]. This precision minimizes medication errors and reduces pharmaceutical waste. Traditional methods often involve a degree of guesswork and approximation, leading to over-prescription or underutilization of medications. WBANs eliminate this inefficiency by providing accurate, real-time data on patient needs, thereby optimizing medication use and reducing waste. The use of WBANs also extends the lifespan of medical devices by incorporating energy-efficient protocols and low-power technologies. This prolonged operational life decreases the frequency of device replacements, thus reducing electronic waste. In healthcare, where devices often require frequent updates and replacements due to high usage, WBANs offer a sustainable solution by enhancing the durability and longevity of these essential tools.

WBANs support the transition to digital record-keeping and electronic prescriptions, significantly reducing paper waste. Traditional healthcare systems rely heavily on paper for maintaining patient records, prescriptions, and administrative tasks. By digitizing these processes, WBANs not only streamline operations but also contribute to environmental sustainability by cutting down on the use of paper and related supplies. WBANs optimize medical resource utilization and reduce waste through continuous monitoring, which prevents unnecessary hospitalizations and ensures precise medication delivery [18]. They enhance the efficiency of healthcare operations by providing real-time data, extending the lifespan of medical devices, and supporting digital record-keeping. These advancements collectively contribute to a more sustainable and environmentally friendly healthcare system.

The authors [19] use CASTALIA software to mimic the amount of energy used, speed of transmission, and dependability for each of the Zigbee and the IEEE 802.15.6 used in health use cases. They then examine and contrast the simulation's output. These findings demonstrate that the novelty of this work lies in providing key elements that determine which MAC protocol is best in a medical setting based on energy usage, node count, and sensor data rates. According to the authors' findings, when it comes to medical applications, Zigbee technology works better for sensors that have less than 40 kb/s as the minimum required rate. These sensors benefit from Zigbee's crucial dependability with low rates of data, which can increase their lifespan by up to 72%. IEEE 802.15.6 is more advantageous to employ for sensors that require high data rates that are higher than 40 kbps due to its dependability at high rates.

Research [20] identified the advantages and disadvantages of both IEEE 802.15.4 and IEEE 802.15.6 over WBAN by comparing average data latency and network lifetime in the Castalia simulator. It was concluded that IEEE 802.15.4 uses less power and extends device battery life due to its simpler network architecture and lower data rate but has a longer average data latency due to its protocol architecture and lower data rate. The authors conclude that IEEE 802.15.6 offers low latency due to its high transmission data rate and its highly efficient architecture. Despite its high transmission rate, it consumes a lot of power, which leads to a shortened battery life. The appropriate choice of protocol depends on the application requirements, where IEEE 802.15.6 is a suitable choice for applications that require low latency, while IEEE 802.15.4 is more suitable for applications that require longer battery life. The authors [21] examined and compared NB-Fi, Sigfox, and LoRaWAN by focusing on the evaluation results they obtained rather than the default specifications of each technology. The authors evaluated the performance of the technologies by calculating performance metrics under different conditions. These metrics are average delay, packet loss rate, and packet error rate. These results serve as a guide for choosing the appropriate technology for a given set of conditions. The authors' results showed that LoRaWAN is a very reliable transmission technology for larger data volumes, however, NB-Fi is best suited for transmitting small pieces of acknowledged data, but Sigfox performs better in situations where devices communicate with small pieces of data without duplication and acknowledgments.

The authors [22] analyzed the data transmission performance of LoRaWAN and ZigBee technologies by using them in buildings under identical operating conditions; for each, they assessed the interaction abilities of a pair of networks by preparing three situations for experimentation: line-of-sight, sideways, and upright and they also varied the rate of baud and the length of the packet and took into account the price and amount of energy used. According to the findings, LoRaWAN networks are the ideal option for constructing networks of communication because they usually perform better than ZigBee networks. The authors’ results provided data validation and engineering guidance for the use of LoRaWAN and ZigBee technologies in buildings by experimenting with their work in buildings under special conditions. The authors' contribution and novelty are reflected in their discussion of how three experimental situations, utilizing the rate of packet loss and time for a round trip, as metrics, affect the performance of ZigBee and LoRaWAN transmissions in relation to the length of the packet, rate of baud, separation, and various places inside a structure. The energy efficiency of Wireless Body Area Networks (WBANs) is a pivotal factor in supporting sustainable energy use in healthcare. WBANs are designed with several features and technologies that significantly reduce energy consumption, making them an environmentally friendly choice for modern healthcare systems.

Firstly, WBANs operate using low-power communication protocols. Standards like IEEE 802.15.6 and LoRaWAN are specifically tailored for low-power, short-range communication. These protocols ensure that the sensors and devices used in WBANs consume minimal energy while maintaining reliable data transmission. For instance, IEEE 802.15.6 is optimized for medical applications, ensuring efficient energy use without compromising the quality of service [23]. Similarly, LoRaWAN's long-range capabilities combined with its low-power nature make it ideal for continuous monitoring over extended periods without frequent recharging or battery replacements.

Additionally, WBANs incorporate advanced power management techniques to enhance energy efficiency. These techniques include duty cycling, where the sensors are active only when necessary and remain in a low-power sleep mode otherwise. This approach drastically reduces the energy consumed during inactive periods.

Moreover, energy harvesting methods, such as solar power or body heat conversion, are increasingly being integrated into WBANs. These methods capture and utilize ambient energy sources to power the devices, further reducing reliance on external power supplies and enhancing sustainability.

Another aspect of WBANs' energy efficiency is their ability to facilitate remote monitoring and telemedicine [24]. By enabling continuous health monitoring from a distance, WBANs reduce the need for patients to travel to healthcare facilities for routine check-ups and consultations. This reduction in travel not only decreases carbon emissions associated with transportation but also alleviates the energy burden on healthcare facilities, which otherwise would have to accommodate more patients physically. WBANs also contribute to energy efficiency by minimizing the operational energy demands of healthcare facilities. With real-time monitoring and data transmission, healthcare providers can optimize the use of medical equipment and resources. For example, continuous data from WBANs can inform healthcare providers about the exact time when medical devices are needed, allowing them to power up equipment only when required. This targeted usage reduces the overall energy consumption of medical devices and equipment.

Moreover, WBANs support the implementation of smart healthcare infrastructure. By integrating WBAN data with hospital management systems [25], healthcare facilities can optimize lighting, heating, and cooling based on real-time occupancy and patient needs. For instance, rooms can be heated or cooled only when occupied, and lighting can be adjusted based on the presence of patients and staff. Such smart management significantly reduces the energy footprint of healthcare facilities. Lastly, WBANs' role in preventive healthcare and early diagnosis also contributes to energy efficiency. By detecting health issues early, WBANs can help avoid energy-intensive treatments and prolonged hospital stays. Preventive care typically involves less energy consumption compared to acute care, which requires extensive use of medical equipment and facilities.

In conclusion, WBANs support sustainable energy use in healthcare through their low-power communication protocols, advanced power management techniques, and the integration of energy harvesting methods. They reduce the need for patient travel, optimize the use of medical equipment, and enable smart healthcare infrastructure, all of which contribute to a significant reduction in the overall energy consumption of healthcare systems. By facilitating preventive care and early diagnosis, WBANs further enhance energy efficiency, supporting a more sustainable and environmentally friendly healthcare model.

3. Multiple access protocols

The term Medium Access Control (MAC) describes a technique for allocating the usage of a medium amongst a network's devices; it serves a purpose like that of a meeting chairman, who must identify every talker in their part and guarantee that only a single talker is talking at a time. When it comes to networking, MAC is essential for allocating access to the device when the medium distribution process and avoiding collisions, and MAC significance grows with the quantity of devices involved [26]. The most basic random-access MAC protocol is thought to be ALOHA. Protocol execution is simple and requires little effort to prevent packet collisions. A node must send a packet repeatedly until it receives an acknowledgment (ACK) from the destination. If the ACK does not arrive, it indicates a collision or data distortion. ALOHA protocols are useful in networks with long relative propagation delays because of their consistent performance. Examples of networks that use ALOHA are satellite communications systems and underwater acoustics. ALOHA is the most important protocol for underwater acoustic networks that suffer from very long propagation delays [27].

The IEEE standards for wireless local area networks (LANs) widely use a distributed media access control protocol known as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [28]. Several investigations have been made to enhance the effectiveness of CSMA/CA, one of the recent investigations was founded upon the best contention window (CW) appreciated by considering the circumstances of the traffic at the station. CSMA/CA searches for data packets ready to be sent by the station by detecting the channel state, whereby a data packet is sent immediately if the channel is idle for the period of the distributed inter-frame space (DIFS). The station waits till the channel becomes vacant if it is busy. The station initiates the backoff process when it finds an idle channel during a DIFS period. A random number between 0 and the CW value is chosen as the backoff number. The backoff counter is lowered by one if the channel is not in use during a slot period. When the backoff counter hits zero, the station transmits a packet. The station halts the retract process and holds off till the channel is empty if another station sends data during the retract procedure. Upon a short interframe space (SIFS) period, the gateway that gets the packet broadcasts an acknowledgment (ACK) packet, and the gateway that receives the packet of ACK presumes in which the packet was transmitted was completely transferred. The gateway that transmitted the data considers it a malfunctioning transmission and reconfigures the retract value before retransmitting it if the ACK packet is not received in a predetermined amount of time. To lower the likelihood of stations choosing the same backoff number during retransmission and avoid collisions, the station doubles the CW value. Schedule-based MAC protocols that do not engage in idle listening, like Time Division Multiple Access (TDMA), are inherently collision-free and need less energy. On the wireless medium, contention-free protocols are commonly constructed. All sensor nodes are assumed to be time-synchronized by TDMA. Unfortunately, because of transmission latency and network topology changes, this strategy usually has unfavorable experiences. During the initialization phase, these methods allocate the collision-free links to neighboring nodes. There are slots inside the time. After that, time slots are allocated to every neighboring node. However, a timetable regulates the participant's ability to use the resources at specific times [29].

4. IEEE 802.15.6

A communication protocol designed especially for WBANs, devices that are located on, near, or inside the human body, is IEEE 802.15.6. These networks can be used for a variety of purposes, such as private entertainment and medical monitoring. Within or near the human body, the standard creates a structured framework that is safe, dependable, and efficient for the transfer of data [30]. IEEE 802.15.6 network structure stands out for emphasizing energy-efficient, short-range communications intended for health, wellness, and medical applications. Personal digital assistant (PDA) is crucial to enable management, monitoring, and communication in WBANs [31]. WBANs have three types of nodes where implantable devices fall under the first group which are devices used for condition monitoring and management and are typically embedded in the body and contain a number of medical sensors that monitor physiological factors such as blood pressure, glucose levels, and heart rate. A subset of WBANs are fitness trackers, smartwatches, and other wearable devices with health monitoring sensors that represent wearable technology devices. Other devices can act as nodes in WBANs which act as controllers or data collectors for other nodes. The hub, also referred to as the BAN coordinator, is the most important controller and lies at the heart of the WBAN design. The hub plays a critical role in exchanging data between nodes by acting as the main communication channel within the WBAN. These central nodes are essential for managing media access because they organize network operations and ensure the integrity and confidentiality of data carried within the network in addition, they can collect data from each node in the network and then process, store, or send it later to other networks, such as the Internet or a local area network (LAN), for further examination or exchange.

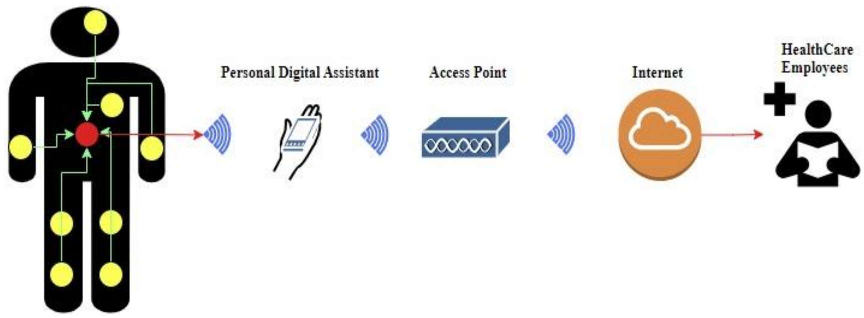

Figure 2. Network topology of IEEE 802.15.6.

5. LoRaWAN

An open networking protocol called LoRaWAN allows for safe, two-way communication. The LoRaWAN architecture consists of four main parts: application servers, gateways, network servers, and end devices. It is implemented in a star topology. Messages are forwarded to or from the application server by a central network server via gateways between endpoints. The gateways function like a clear bridge, only translating radio wave data to IP data and conversely, are connected to the network servers via regular IP connections. Utilizing the long-term properties provided by the LoRa physical layer, wireless communication establishes a one-hop connection between the end device and one or more entry points. The LoRaWAN network server is in charge of overseeing the whole system and dynamically adjusting network settings to adjust to constantly shifting circumstances. Any device within radio range can send LoRa packets to the LoRaWAN Gateway, which then transmits them to the network servers via the IP backbone. There can be more than one gateway in the radio frequency range serving each end device. The relationship between an end device and the gateway is not fixed. The relationship greatly lowers the usage of the power for mobile end devices and lowers the packet error rate because there is a greater chance that the packet will be received by at least one gateway [32]. Figure 3 shows the LoRaWAN network topology.

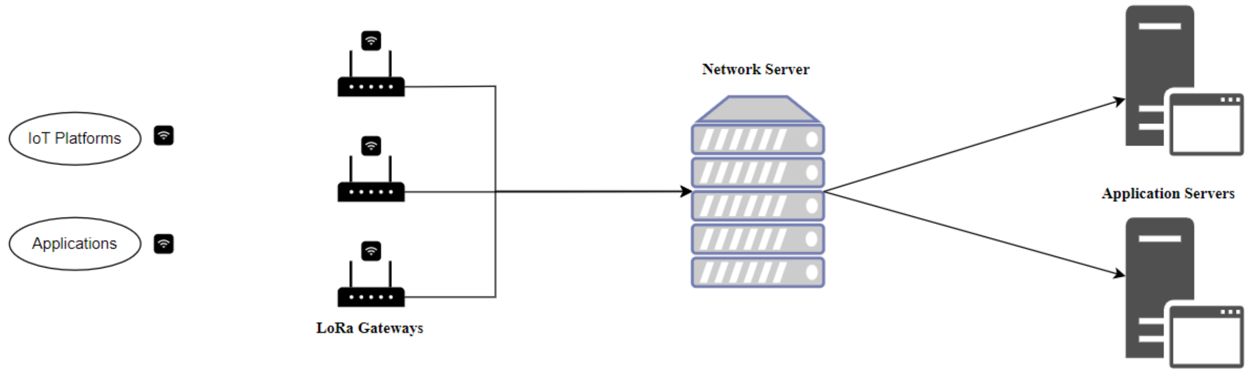

Figure 3. Technology topology of LoRaWAN

6. Network simulation

The IEEE 802.15.6 and LoRaWAN network configurations were put up using the network simulation (NS3) environment. In the simulation, every node has a Hyper MAC made up of two distinct MACs. The network parameters of IEEE 802.15.6 and LoRaWAN are shown in Table 1. ALOHA and CSMA/CA are used at the first MAC layer in the first network device in each node for LoRaWAN and IEEE 802.15.6, respectively. TDMA is used at the second MAC layer in the second network device in each node for LoRaWAN and IEEE 802.15.6. The use of Hyper MAC for LoRaWAN and IEEE 802.15.6 helps to increase the efficiency and reduce the collision rates in nodes by dynamically adjusting their access techniques in response to network conditions.

The Low-Energy Adaptive Clustering Hierarchy (LEACH) routing protocol [33] is used in the simulation network where it schedules nodes into clusters to transmit data in the simulation and distributes the energy usage equally among the cluster heads. Each network device within the simulation is allocated a certain amount of energy to ensure resource management and monitor the network's lifetime. The simulation consists of 50 nodes and one gateway and there are two network devices within each node or gateway where the first network device in LoRaWAN uses the ALOHA protocol and in IEEE 802.15.6 the CSMA/CA protocol and the second network device uses the TDMA protocol in both LoRaWAN and IEEE 802.15.6.

The nodes are connected via a logarithmic distance propagation loss function to facilitate communication within the network and the nodes move in a 200 m × 200 m area in a randomly distributed manner while the gateway acts as a fixed central point where packets can be received from the nodes at all times. TDMA protocol is dedicated to sending packets related to important data such as electrocardiograms (ECGs) while packets dedicated to CSMA/CA or ALOHA represent less important data such as temperature measurements. Each network device within the nodes contained an initial power of 250 joules to support the transport and movement functions within the network. The simulation was performed with a runtime of 1000 seconds and the metrics results were stored for analysis and performance evaluation of LoRaWAN and IEEE 802.15.6 technologies.

Table 1. Network parameters of IEEE 802.15.6 and LoRaWAN network

Parameter	Value
Simulation Time	1000 sec
Simulation Area	200m x 200m
Number of Nodes	50
Number of Gateways	1
Packet Size	19 Bytes
Channel Loss	Logarithm Distance Propagation Loss
Channel Path Loss Exponent	3.76
Mobility Type	Random Rectangle Position
MAC Protocol in LoRaWAN	Hyper MACs: ALOHA and TDMA
MAC Protocol in IEEE 802.15.6	Hyper MACs: CSMA/CA and TDMA
Routing Protocol	LEACH
Energy	250J For the Two Net Devices
TDMA and CSMA/CA Tx Current	0.028 A
TDMA and CSMA/CA Rx Current	0.0112 A
TDMA and CSMA/CA IDLE Current	0.0013 A
TDMA and ALOHA Tx Current	0.028 A
TDMA and ALOHA Rx Current	0.0112 A
TDMA and ALOHA IDLE Current	0.0013 A and 0.0000015 A

7. Performance comparison

In this section, the IEEE 802.15.6 and LoRaWAN are compared based on our results obtained from the simulation. We evaluated each technology by examining the capabilities using network performance metrics. We used throughput, arrival rate, delay, power consumption, remaining power, network lifetime, and PDR as network performance metrics which are calculated over a simulation time of 1000 seconds with 50 nodes to determine the ability of each technology to adapt to the network over time. Our aim from the evaluation was to present the results of WBAN network performance metrics using the two technologies to help determine which technology performs best in WBAN networks.

7.1. Throughput

One of the essential metrics for evaluating network capacity is throughput or the speed at which data is transferred. The throughput of IEEE 802.15.6 may be better than LoRaWAN because the IEEE 802.15.6 architecture focuses on short-range communications and the bandwidth is more efficient. Applications that involve video streaming from wearable devices are particularly important for data transfer rate. The data transfer rate is calculated in kilobits per second using Equation 1.

$$Throughput = \sum_{n=1}^{Total\ packets} \frac{Packet\ Size * 8}{(Packet\ Receive\ Time_n - Packet\ Send\ Time_n) * 1000} \quad (1)$$

Figure 4 shows the throughput of IEEE 802.15.6 and LoRaWAN. Our results show that IEEE 802.15.6 throughput increases from 0 to higher levels which means that the network handles data transfer well, with throughput continuously increasing during the session. The continuous improvement in throughput demonstrates the efficiency and stability of IEEE 802.15.6 in supporting high-speed data transmission over short-range wireless networks. However, LoRaWAN throughput increases over time as the throughput starts at 0 and grows rapidly to high values early in the monitoring period. A slower growth rate indicates a gradual increase in throughput compared to the IEEE 802.15.6 standard. This behavior is identical to LoRaWAN, which is designed for long-range communication with low-power devices and has lower throughput than IEEE 802.15.6 but has better coverage and energy efficiency.

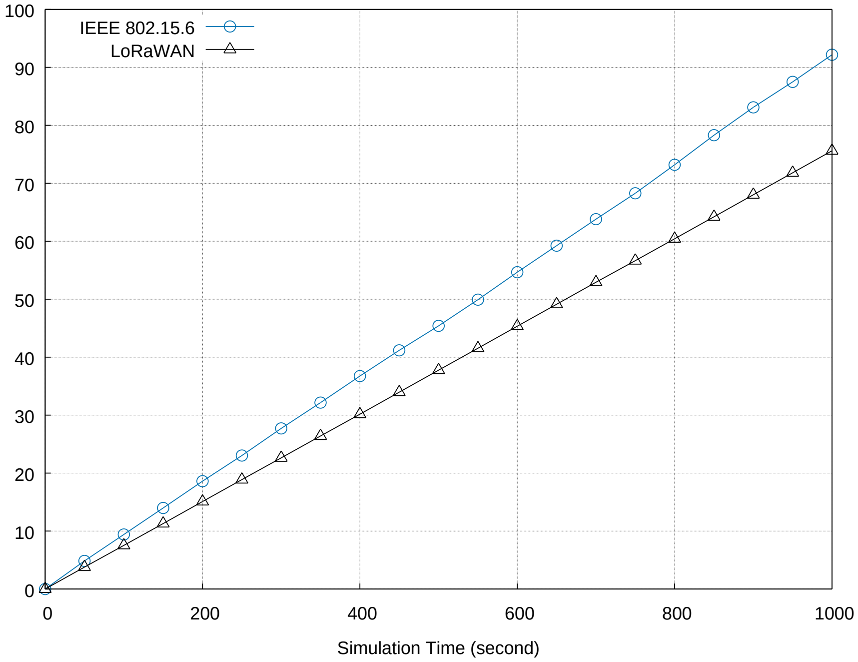

Figure 4. Throughput changes over time

7.2. Arrival rate

The rate at which requests or data packets are created and added to a network is known as the arrival rate. It gauges how frequently new users join network nodes and is frequently used to describe the volume of traffic or workload in a network. Arrival rate management is essential to ensure that sufficient network resources are available to handle incoming data and maintain desired performance levels. Equation 2 calculates the arrival rate. Our results show that there are small differences in arrival rate between IEEE 802.15.6 and LoRaWAN as shown in Figure 5.

$$Arrival\ Rate = \sum_{t=1}^{Total\ Time} \frac{Number\ of\ Received\ Packets\ at\ time_t}{t} \tag{2}$$

The arrival rate in IEEE 802.15.6 has shown a time-varying pattern characterized by fluctuations between high and low values the fluctuating pattern of the arrival rate indicates variations in traffic within the network that can be affected by factors such as device usage, data transfer needs, or environmental conditions. The arrival rate for both technologies gradually decreases which indicates a decrease in demand for network resources or a stabilization of communication activity over a period of time. The variation in arrival rates in IEEE 802.15.6 networks emphasizes the technology's ability to handle varying levels of traffic load because IEEE 802.15.6 is flexible and adaptable.

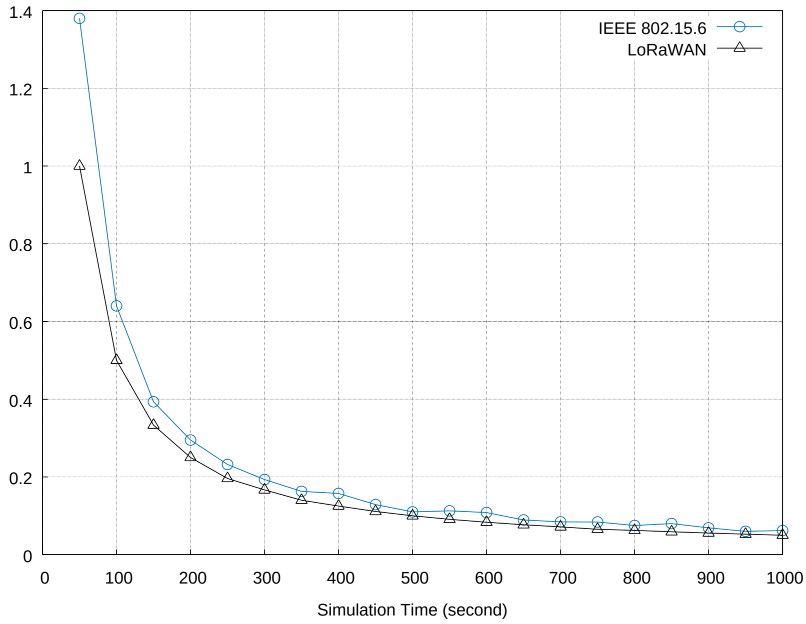

Figure 5. The arrival rate changes over time

7.3. Delay

Delay is an important metric in WBANs because most applications are time-sensitive. Delay is the time it takes for a packet to travel from the source node to the destination node. Delay is calculated in seconds using Equation 3. Figure 6 shows the results for the delay metric in IEEE 802.15.6 and LoRaWAN. LoRaWAN delay values start low and are stable before rising. This indicates an efficient network connection where data packets are transmitted with generally constant Delay in the early stages. Over time, the delay increases, indicating network congestion or traffic stress. Increased delay values indicate longer transmission or waiting times for data packets, which may impair network responsiveness and performance. Early IEEE 802.15.6 delay values increase rapidly, indicating a slowness in the protocol's communication mechanism. Our results show that high delay values in IEEE 802.15.6 indicate longer transmission or waiting times than LoRaWAN

$$Delay = \sum_{n=1}^{Total\ packets} Packet\ Receive\ Time_n - \ Packet\ Send\ Time\ _n \tag{3}$$

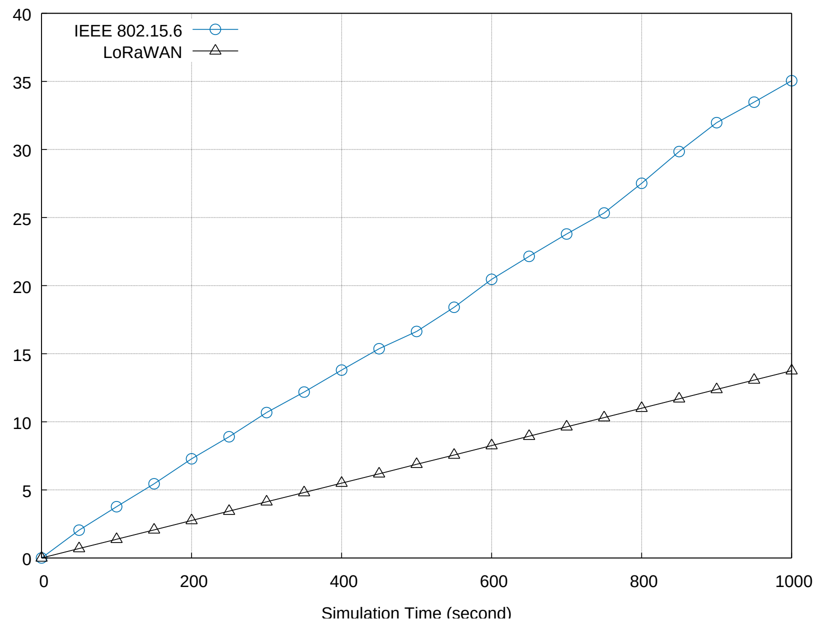

Figure 6. Delay changes over time

7.4. Energy consumption

IEEE 802.15.6 and LoRaWAN are intended for battery-operated devices that do not require recharging. Energy consumption affects the cost of operations and network maintenance. Selecting the best application energy limitation mechanism is aided by comparing energy use. The calculation of energy consumption in joules is shown in Equation 4.

$$Energy\ Consumption = P * T \tag{4}$$

P: The Energy consumed at Tx, Rx, or IDLE.
T: Time taken for Tx, Rx, or IDLE.

The analysis of our results demonstrates notable disparities in power usage between the two technologies, as depicted in Figure 7. IEEE 802.15.6 demonstrates the progressive rise of power usage as time passes. This behavior is typical of protocols that are specifically intended for high data rates and short-range communications. Such protocols usually necessitate higher power consumption in order to sustain the connection and for efficient data flow. Conversely, LoRaWAN exhibits very consistent and reduced energy usage over the studied period.

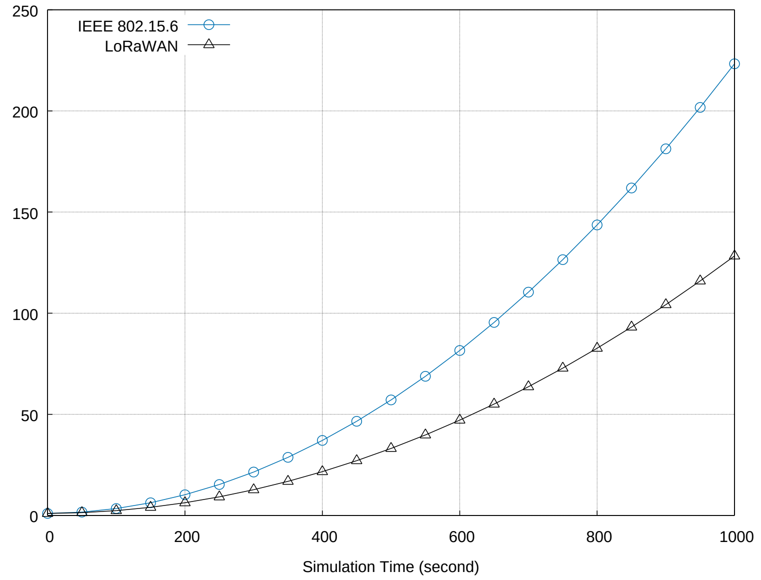

Figure 7. Energy consumption changes over time

7.5. Residual energy

The amount of energy that nodes or devices in a network have left over after completing certain jobs or activities is referred to as residual energy. Remaining energy is the capacity of energy in nodes or devices after completing different jobs or processes. In networks with limited energy, residual energy is a crucial metric since it talks about the resources that will be available for operations and communication in the future.

To extend the lifetime of the node and maximize network performance, residual energy levels must be monitored and managed. Equation 5 shows the calculation of residual energy in joules. Examining the results, it becomes clear that both IEEE 802.15.6 and LoRaWAN show a gradual decrease in residual power over time as shown in Figure 8, which is expected due to the continuous power consumption during communication activities.

$$Residual\ Energy = Initial\ Energy - Energy\ Consumed \tag{5}$$

However, there are notable differences between the two protocols in terms of the rate of energy exhaustion. Our results showed a sharp reduction in residual energy for IEEE 802.15.6 compared to LoRaWAN. This observation is consistent with the power consumption characteristics discussed previously, emphasizing the higher power requirements associated with IEEE 802.15.6 due to its intended use case of transmitting data over relatively short distances at high speeds. The steady decline in residual power reflects the constant demand on the power supply, which may limit the operational life of devices using this protocol.

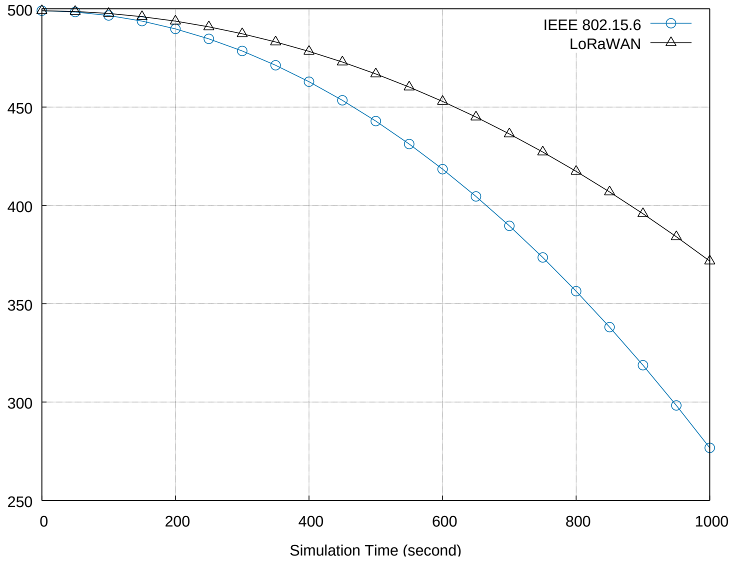

Figure 8. Residual energy changes over time

7.6. Network lifetime

The amount of time until a node fails from energy exhaustion is known as its network lifetime. For deployments that are unreachable, it is crucial. The protocol selected can have a big influence on how often batteries need to be replaced and recharged. Equation 6 is used to calculate the network lifetime in hours. IEEE 802.15.6 and LoRaWAN have different network lifetime trends as shown in Figure 9. Our results show that IEEE 802.15.6's network lifetime reduces over time, signaling resource depletion or performance degradation. Devices in an IEEE 802.15.6 network may need more energy to communicate due to the lowering network lifetime. In contrast, LoRaWAN has a more reliable and long-lasting network lifetime. The protocol conserves energy and maintains communication over long durations, while the network lifetime fluctuates little. LoRaWAN is optimized for low-power, long-range communication and applications that require long battery life and low maintenance. LoRaWAN networks have a consistent lifetime, suggesting devices can run for longer without battery replacement or recharging.

$$Network\ Lifetime = \frac{Initial\ Energy}{3600 * Energy\ Consumption/Sec} \tag{6}$$

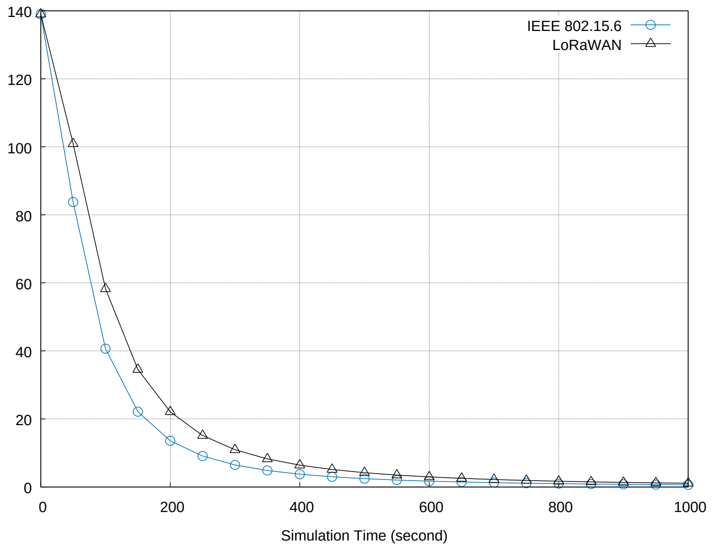

Figure 9. Network lifetime changes over time

7.7. Packet delivery ratio

The PDR measures the effectiveness of network packet delivery. Reliable communication is necessary for critical applications, as demonstrated by high PDR. The PDR for both operations must remain high even in operating circumstances. Although IEEE 802.15.6 networks can function in or on the body's face body shadowing and mobility, long-distance LoRaWAN networks must contend with signal attenuation and interference. The resilience and dependability of a protocol may be demonstrated in several PDR scenarios. The PDR calculation is shown in Equation 7. Figure 10 shows different PDR values for IEEE 802.15.6 and LoRaWAN. Our results show that IEEE 802.15.6 has a better PDR than LoRaWAN. The PDR of LoRaWAN starts at 0 and increases over time. Package delivery performance improves slowly but steadily throughout the calling session. The increasing PDR trend shows that the network is stabilizing and becoming more reliable over time. IEEE 802.15.6 has rapid growth initially followed by a stable plateau. The PDR values of IEEE 802.15.6 peak early in the monitoring time and remain constant, indicating a strong and reliable connection.

$$Packet\ Delivery\ Ratio = \frac{Number\ of\ Received\ Packets}{Total\ Packets} * 100 \tag{7}$$

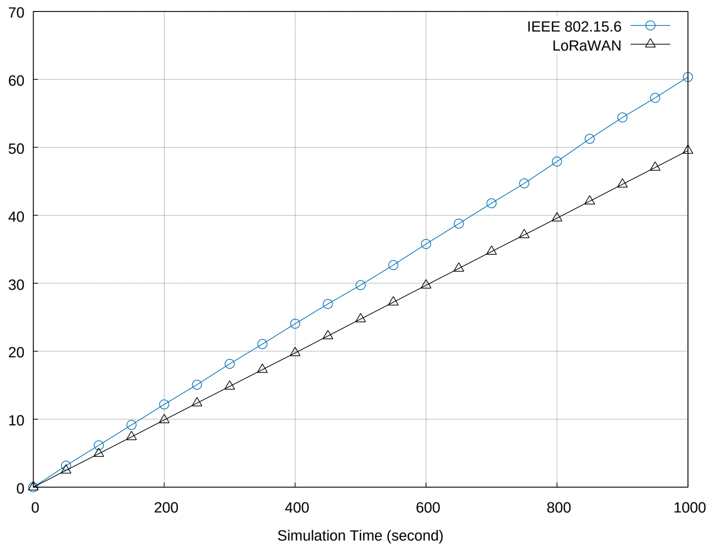

Figure 10. PDR changes over time

The design of Wireless Body Area Networks (WBANs) incorporates several strategies to enhance environmental sustainability. These include the use of environmentally friendly materials, the development of low-power devices, and the integration of recyclable components. These design considerations help minimize the environmental impact of WBANs while maintaining their functionality and reliability in healthcare applications. One of the primary considerations in designing WBANs is the use of environmentally friendly materials. This includes selecting materials that are non-toxic, biodegradable, and sourced sustainably. For instance, the casings of sensors and wearable devices can be made from biodegradable plastics or natural fibers, which decompose more easily and reduce environmental pollution. Additionally, the use of non-toxic materials ensures that the devices do not pose a risk to human health or the environment during use or disposal. Low-power design is a critical aspect of WBANs, aimed at reducing energy consumption and enhancing the sustainability of these systems. Low-power devices rely on energy-efficient microcontrollers and communication protocols. Technologies such as IEEE 802.15.6 and LoRaWAN are specifically designed for low-energy consumption, ensuring that sensors and devices operate efficiently without frequent battery replacements. Moreover, energy harvesting techniques are increasingly being incorporated into WBANs to power devices using ambient energy sources. For example, sensors can be equipped with small solar panels to capture solar energy, or thermoelectric generators to convert body heat into electrical energy. These methods reduce reliance on conventional batteries, further minimizing the environmental impact of WBANs.

The design of WBANs also emphasizes the use of recyclable components to reduce electronic waste. This involves selecting materials and components that can be easily recycled or repurposed at the end of their life cycle. For example, metal components such as electrodes and connectors can be designed for easy disassembly and recycling. Printed circuit boards (PCBs) can be manufactured using recyclable substrates and solder materials that are free from hazardous substances like lead. In addition, modular design principles can be applied to WBANs, allowing individual components to be replaced or upgraded without discarding the entire device. This not only extends the lifespan of the devices but also reduces waste by enabling the reuse of functional parts.

The manufacturing processes for WBANs can also be optimized for environmental sustainability. This includes adopting green manufacturing techniques that minimize energy consumption, reduce waste, and limit the use of harmful chemicals. For example, advanced manufacturing methods like additive manufacturing (3D printing) can be used to produce WBAN components with minimal material waste. Additionally, using renewable energy sources in the production process can further reduce the carbon footprint of WBAN manufacturing. Designing WBANs with a focus on durability and longevity also contributes to environmental sustainability. By ensuring that devices are robust and reliable, the need for frequent replacements is minimized, which in turn reduces the generation of electronic waste. This can be achieved through the use of high-quality materials, rigorous testing, and incorporating protective features that enhance the durability of the devices under various conditions.

Finally, the packaging of WBANs can be designed to be environmentally friendly. This includes using recyclable or biodegradable packaging materials, reducing the use of plastic, and minimizing packaging size to reduce waste. Eco-friendly packaging not only reduces the environmental impact but also aligns with the growing consumer demand for sustainable products. Incorporating environmentally friendly materials, low-power devices, and recyclable components in the design of WBANs significantly enhances their sustainability. By focusing on these design principles, manufacturers can reduce the environmental impact of WBANs throughout their life cycle, from production to disposal. This approach not only supports the broader goals of environmental conservation but also aligns with the increasing emphasis on sustainability in healthcare technology.

8. Conclusion

In order to determine if IEEE 802.15.6 and LoRaWAN protocols are suitable for network applications, this study compares and contrasts them. Utilizing measures for throughput, arrival rate, delay, energy consumption, residual energy, network lifetime, and PDR to evaluate performance revealed the two protocols' unique benefits and drawbacks. For applications like healthcare monitoring that demand quick connections and rapid data transmissions, IEEE 802.15.6 excels in throughput, PDR, and arrival rate. IEEE 802.15.6 has better throughput, PDR, and access rate than LoRaWAN but IEEE 802.15.6 is not preferred for long-range and battery-powered devices. LoRaWAN performs better than IEEE 802.15.6 in terms of delay, residual power, network lifetime, and power consumption due to its long-time architecture which is suitable for applications requiring wide coverage and low power consumption. Specific application requirements, power capacity, and network lifetime are the considerations to be taken into account when choosing between the two technologies. This study helps in choosing the best technology between LoRaWAN and IEEE 802.15.6 which is suitable for efficient wireless communication in WBAN scenarios.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

Author contribution

This research has been done by Soleen Jaladet Al-Sofi, who is a Ph.D. Student. Salih Mustafa S. Atroshey, Ismail Amin Ali were responsible for supervising and reviewing the research.

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