



Enhancing WBAN Performance with Cluster-Based Routing Protocol Using Black Widow Optimization for Healthcare Application

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Abstract

Research on wireless body area networks (WBAN), also known as wireless body sensor networks (WBSN), has been increasingly important in medical applications recently and is now crucial for patient monitoring. To create a dependable body area network (BAN) system, several factors need to be considered at both the software and hardware levels. One such factor is the designing and implementation of routing protocols in the network layers. Protocols for routing can detect and manage the routing paths in a network to facilitate efficient data transmission between nodes. Therefore, the routing protocol is crucial in wireless sensor networks (WSN) to provide dependable communication among the sensor nodes. Different clustering methods can be used in WBAN systems. However, these techniques often produce many cluster heads (CHs), which leads to higher energy consumption. Increased consumption of energy reduces the lifespan of WBANs and raises costs of monitoring. This research proposes a recent metaheuristic algorithm to select the optimal clusters to provide an energy-effective protocol for healthcare monitoring. This research aims to minimize the energy utilization of WBANs by choosing the most suitable CHs based on the BWO. The proposed BWO-based routing protocol demonstrates superior performance in WBANs based on energy consumption, packet loss, packet delivery ratio, network lifetime, end-to-end delay, and throughput. It optimizes energy consumption by effectively selecting CHs and routing paths, leading to balanced energy usage and prolonged network operation. The BWO model significantly reduces end-to-end delay by ensuring data packets follow the shortest and least congested routes, which is significant for real-time health monitoring. It achieves a high packet delivery ratio, typically between 95% and 98%, indicating reliable data transmission, while maintaining a low packet loss rate, generally between 1% and 5%. Additionally, the BWO-based routing protocol extends network lifetime by preventing early node depletion and enhances network throughput by reducing congestion and packet collisions, thereby supporting continuous and robust health data monitoring.

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1. Introduction

The physical and mental health of people is a crucial need for the health of societies, making healthcare an essential requirement for society that must be provided. If the number of older people rises, it is quite probable that the standard of medical treatment will decline, leading to a significant rise in healthcare expenses and medical expenditures. In contrast, cardiovascular disease is the primary factor behind mortality worldwide, comprising 30% of all fatalities. Based on statistics, around 17.5 million individuals worldwide die of heart disease annually. Furthermore, there are around 246 million individuals globally who are afflicted with diabetes, and this figure is projected to expand to 380 million by the year 2025 if adequate healthcare and essential preventative measures are not implemented. The provision of healthcare can decrease the prevalence of several diseases like kidney disorders, Parkinson's disease, anxiety disorders, Alzheimer's disease, and infant syndrome. One of the healthcare approaches is to employ the latest developments in the field of medicine. The BAN is an emerging innovation that enables the monitoring of an individual's health [1]. WBAN is a subset of WSN that has received

significant interest due to its substantial potential use [2]. WSNs are widely employed in several domains such as engineering, military, agricultural, surveillance, and healthcare applications in the present day. WBANs, based on WSN, are crucial in the healthcare sector [3]. WBANs have the potential to mitigate or resolve societal issues such as the prevalence of chronic illnesses, the growing elderly population, and the pressure on medical staff and facilities. Consequently, there is a growing demand for the quick use of WBAN technology by a larger number of individuals. Despite the fast advancement of sensor technology and communication technology, WBAN is still in its initial stages of development, and several challenges and issues need to be addressed in its research and implementation [4]. WBANs consist of a set of body sensors that are energy-efficient, either non-invasive or invasive, and lightweight sensors. These sensors can be placed on the human body or inside the body. The structure of WBAN is categorized into three stages: Stage-1, known as Intra-BAN, Stage-2, known as Inter-BAN, and Stage-3, known as Beyond-BAN, as seen in Figure 1 [5]. Intra-WBAN: In stage 1, the biosensors or sensor nodes (SN) utilize radio transmission to connect, within 2 meters of range. The SNs relay the recorded biological data to the coordinator. Point-to-point linkages were created between the sensors to facilitate communications among the body sensors and the coordinator, and between the sensors themselves. Inter-WBAN: Stage-2 is an intermediate layer located between several Access Points (AP) and the coordinator. Several APs could be utilized to facilitate the communication of sensor nodes. The coordinator transmits the compiled and analyzed data to many APs. Stage-2 facilitates the connection of WBANs across multiple networks, enabling convenient everyday access. These networks might either be the Internet or cellphone networks. The ZigBee could serve as a stage-2 communication protocol. Beyond-WBAN: This communication layer serves as an intermediary between a WBAN and other networks, such as the internet in Tier-3. Both BC and APs could establish direct communication with the external network. Tier 3 is designed for a specific purpose. APs collect and communicate all the data to physicians or doctors. Therefore, an emergency could be readily communicated to patients or clinicians [6].

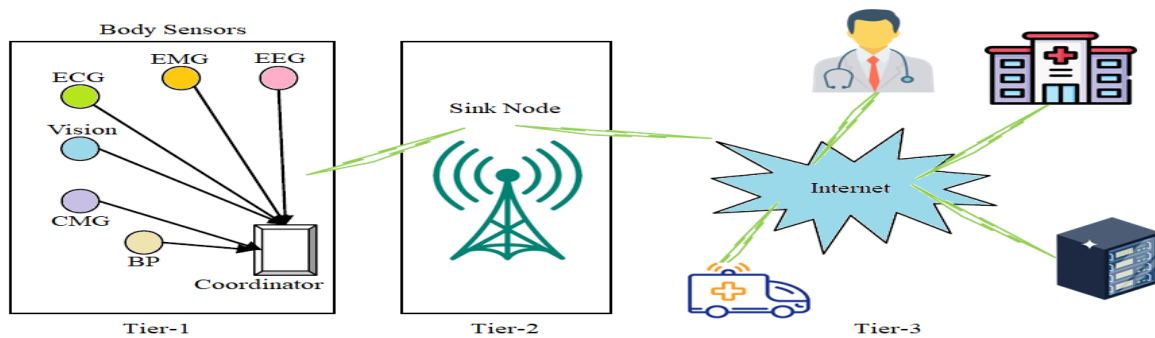


Figure 1. WBAN General Architecture

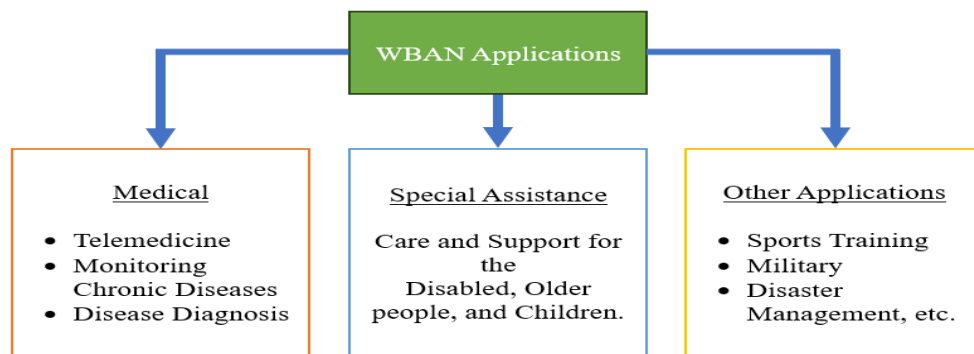


Figure 2. WBAN Applications

Sensors and wearable devices are connected to the APs, such as a mobile phone or PDA. The integration of wearables with other personal digital assistants (PDAs) facilitates convenient access for users and clinicians to health information, allowing them to assess health conditions and environmental state. The information may encompass physical fitness, emotional state, and temperature. In healthcare applications, the biofeedback system provides decision assistance by triggering alerts anytime the monitored physiological condition exceeds or falls below the predetermined health limits (threshold). Decisive actions are made based on the prognostic or biofeedback data to prevent any casualties from occurring [7]. The data rate of a WBAN typically falls within the level of 10 kilobits per second to 10 megabits per second, while the distance among nodes is limited to a range of 2 to 5 meters. Nodes may be added or removed in under 3 seconds. A single WBAN could accommodate 256 nodes. The latency value was minimum than 125 ms for clinical applications and minimum than 250 ms for all others [8]. WBAN utilizes the human body as an interface of communication, integrating it into the network and enabling widespread connectivity and services. This technology is crucial in several applications, as seen in Figure 2 [4].

1.1. Problem Statement

Due to the unique nature of WBAN, the working group called IEEE 802.15 established a working group TG6 for WBANs in 2007. The purpose of this group was to investigate the standardization of WBAN technology. The initial WBAN standard, IEEE802.15.6, was formally published in 2012. The establishment of this protocol also accelerated the quick advancement of WBAN. WBAN is a technology that is used on the human body. As a result, the network environment for WBAN is highly intricate [9]. Designing a routing system for the BAN is crucial due to the significant influence that physiological data collection has on human life and health. There is a requirement to develop routing protocols particularly designed for WBANs to address the specific problems and challenges faced by WBANs [10]. The specific routing problems and difficulties encompass network architecture, body motions, resource constraints, quality of service measurements, radiation and disruption, global network lifespan, and diverse environments. The primary challenge to be examined in both WSNs and WBANs is the restricted energy supply. Therefore, several effective cluster-based strategies are suggested for both networks to minimize power consumption and maximize network longevity. The biosensor nodes in the cluster-based protocol are divided into many clusters. The CH is a designated node that transmits information to the base station (BS) or sink node [11]. Clustering methods enable the cluster head to vary dynamically between cluster members within network operation based on various parameters. For instance, at any given time, the node with a larger residue energy inside the cluster automatically assumes the role of the CH. The cluster-based protocol enhances the longevity of the networks, increases energy efficiency, and improves the accuracy of data transmission by utilizing the self-healing features of the network [12]. Most of the cluster-based protocols exhibit scalability. CH selection and end-to-end route selection are optimized using efficient techniques [13].

1.2. Research Contribution

WBANs are a very influential technical innovation that offers significant advantages to both nonmedical and medical sectors. WBAN is a communication technology specifically developed to monitor the internal or external areas of the human body to gather health data from a patient. It is used to transmit important physical or critical data from SNs to a medical server for further analysis and study. The main issue with WBANs is that the limited battery lifetime restricts the power of the sensors. Additionally, several routing protocols were particularly created to transmit the collected data to a BS for further investigation, which might differ depending on the architecture of the network [14]. In this research, an optimal clustering algorithm is proposed for WBANs to improve energy efficiency and lifetime of the network. The major contributions of this research include:

- An efficient clustering method is proposed to implement the energy efficiency routing protocol of WBANs to monitor patient health.
- The protocol transforms the problem of selecting the best (Optimal) cluster into a mathematical model.
- The optimal clusters are chosen to decrease the energy utilization and improve the lifespan of WBAN.
- The optimum clustering issue is solved using the Black Widow Optimization (BWO) method, which is a recent metaheuristic algorithm.
- The results evaluated from BWO are compared with other metaheuristic methodologies and routing protocols to validate performance.

The subsequent sections of the paper are structured in the following manner. Section 2 provides a concise overview of the current literature on WBANs, focusing on recent models and summarizing previous research on protocols for routing in WBANs. The mathematical model for implementing a routing protocol with energy-efficiency for WBANs and the mathematical representation of BWO are described in Section 3. Section 4 comprises the simulation outcomes and discussion, while Section 5 serves as the conclusion of the research.

2. Literature Review

This literature review explored various energy-efficient and secure routing protocols for WBANs and WBSNs. It highlights approaches like clustering, optimization algorithms, and machine learning (ML) approaches, focusing on their application scenarios, advantages, and disadvantages. Routing is widely acknowledged as a resource-intensive task among other activities. Consequently, it is crucial to develop a protocol with energy-efficiency for WBAN. The work [15] proposed a Secure Optimal Path-Routing protocol (SOPR) to address the concerns of dependability, energy efficiency, and security in WBAN. This approach-enhanced security in WBANs by detecting and preventing black-hole attacks, while also ensuring communication security through the encryption of data packets. Implementing this protocol has several key benefits, such as enhancing network performances by extending the PDR and lowering the detecting attacks overhead, consumption of energy, detection time, and latency. A secure routing method for WBSN in healthcare was proposed in [16], which was based on the league championship algorithm (LCA). The method established a balance between energy use and security. The methodology employed two crucial algorithms: the routing procedure and the communication security mechanism. At first, each CH utilized the LCA to select the most appropriate next-hop CH. The research [17] defined the Optimal Path of Energy

Consumptions (OPEC) in WBAN by analyzing factors like node's importance level, node's residual energy, path energy differences and path cost ratios. The OPEC based on an Artificial Bee Colony (ABC) protocol was proposed. A performance simulation conducted an efficiency assessment of the OEABC. The simulation findings indicated that the OEABC exhibited superior energy efficiency and achieved quicker convergence.

The WBSN comprises a limited number of sensors or nodes that monitor the essential characteristics of the patient and transmit them to the desired destination using intermediary nodes, using the most optimal routes. The study [18] presented a Cluster-based routing Protocol that utilized reinforcement learning with a Q-Learning technique to attain an optimum route. When the packets were transmitted over the most efficient route, the amount of energy used to transport them was relatively lower, resulting in improved throughput. A heuristic-based energy-efficient routing method was designed in the WBAN to optimize energy conservation [19]. The study utilized a hybrid red piranha and egret swarm algorithm (RPESA) to determine the best selection of the CH. After selecting the CH ideally, the optimum routing was done using the RPES algorithm. The transmitted data was employed for detecting disease utilizing an Adaptive dilated cascaded recurrent neural network (ADC-RNN) in this optimum routing method. The settings of the ADC-RNN approach were chosen ideally using the RPESA algorithm. The classification of disease was acquired from ADC-RNN. In this context, the model should have prioritized the longevity of the network. The opportunistic routing (OR) protocol provides enhanced dependability and efficient energy for transmitting packets in WSN. The research [20] – [23] utilized an intelligent opportunistic routing protocol that used an ML approach to select a relay node from a list of prospective forwarder nodes. The protocol enhanced network dependability by effectively connecting many healthcare network devices, hence facilitating the provision of high-quality healthcare services. Furthermore, the protocol conserved energy, hence enabling remote patients to access healthcare services for an extended period by integrating IoT services [25] – [28].

Table 1: Comparative Analysis of Reviewed Works

Ref	Approach Used	Application Scenario	Advantages	Disadvantages
[15]	SOPR protocol	WBAN	Enhances security, detects, and prevents black-hole attacks, increases PDR, and reduces energy consumption and latency.	Additional computational overhead.
[16]	LCA and symmetric/asymmetric encryption	WBSN	Balances energy use and security, uses LCA for optimal CH selection and ensures secure communication.	Potential complexity in managing dual encryption mechanisms.
[17]	OEABC	WBAN	Superior energy efficiency, and quicker convergence, consider multiple factors like residual energy and path cost.	Requires frequent updates for optimal path selection.
[18]	Cluster-based routing using Q-Learning	WBSN	Improved throughput, and lower energy consumption through optimal routing.	Requires training and learning time.
[19]	Hybrid RPESA with ADC-RNN	WBAN	Optimizes CH selection integrates disease detection, and enhances network longevity.	Complexity in hybrid algorithm integration.
[20]	Intelligent OR protocol with ML	Healthcare WSN	Enhances network dependability, conserves energy, and supports remote patient access.	Machine learning models require training and updates.
[21]	IEPSO and fuzzy-based trust inference model	WBSN	Optimizes network longevity, secure routing with trust inference, and reduces network congestion.	Fuzzy logic and multiple algorithms add complexity.
[22]	EEDLABA protocol	WBSN	Efficient in healthcare settings, incorporates path loss and energy usage models.	Limited scalability and potential dependency on node placement.
[23]	PSO-based uneven clustering and routing	WBAN	Enhances network lifespan, and considers multiple factors for CH selection.	PSO fitness function complexity.
[24]	HEESR	WBAN	Enhances security and routing efficiency, prioritizes data, compresses, and encrypts data.	Hierarchical structure causes delays.
[25]	ECSO and BO	Healthcare WSN	Ensures security and privacy, reduce energy requirements, effective for healthcare systems.	Complexity in implementing multipath

				and optimization algorithms.
[26]	GSA and hybrid PSO-GSA	WSN	Minimizes energy consumption, prolongs network lifetime, and expands stable zone.	Computationally intensive.
[27]	PSO-based routing for heterogeneous WBANs	WBAN	Optimizes residual energy and distance, superior performance in terms of residual energy.	Dependence on accurate distance and energy measurements.
[28]	RLTD	WBSN	Considers multiple QoS factors, and improves performance.	Requires real-time monitoring of node dependability and temperature.

3. Proposed Methodology

BAN is a communication network that focuses on the human body. It includes equipment, including sensors that are placed both within and around the body. WBAN enables the installation of intelligent and energy-efficient sensor nodes on the human body to monitor bodily processes and the surrounding environment. The WBAN holds a prominent place in healthcare advancements. An illustration of this concept is the WBAN, which enables patients to carry out their regular activities without any limitations while their health condition is being monitored over a specific duration. The human body undergoes many physiological changes that could be observed by monitoring specific nodes like EEG (electroencephalography), ECG (electrocardiogram), and so on. Once the specialized nodes capture changes in physiology from the body, they transfer this information immediately to the medical server for health status analysis. Figure 3 illustrates the operational concept of the proposed WBAN model, which encompasses both in-body and on-body. The purpose of an "in-body" network was to enable communication between a BS and its matching stationary devices that are implanted within. The primary purpose of an "on-body" area network was to enable communication between a BS and external fixed devices that are placed on the body [19].

3.1. Network Modelling

The proposed WBAN model involves the deployment of six biosensor nodes (S1, S2, S3, ..., S6) on the human body. Each biosensor node has identical power and computational capacities. The BS was positioned in the center of the human body. All the SNs in this model carry out distinct functions. S1 was utilized for electroencephalography (EEG), S2 was utilized for electrocardiography (ECG), S3 was utilized for blood pressure (BP) monitoring, S4 was utilized for continuous glucose monitoring (CGM), S5 was utilized for insulin pump control, and S6 was utilized for motion sensing, as shown in Figure 3. The assumptions made following were based on the biosensor nodes that were installed on the body.

- Each node in the WBAN is stationary and utilizes bi-directional links.
- First, the energy allocated to every biosensor node is uniform.
- All the biosensor nodes are well aware of their distance from other nodes and the sink.

3.2. Energy Modelling

Each node in the WBAN operates continuously, requiring energy for tasks like as detecting, processing, and transferring data. The energy model presented has been utilized for the actual implementation of the protocol. The energy expended in transmitting the data could be determined by utilizing Equation (1).

$$E_{Tr} = E_{TrE} \times p + E_{amp} \times p \times d^2 \quad (1)$$

The consumed energy in obtaining the data could be determined using Equation (2).

$$E_{Rc} = E_{RcE} \times p \quad (2)$$

Within the WBAN model, data is sent across the human body, which might result in potential signal degradation. Path loss refers to the decrease in signal strength as it propagates from one SN to other, caused by the depletion of the human body. Therefore, to account for route loss, the term 'n' has been incorporated into the condition to calculate the total energy. The overall consumed energy in transferring the data, considering route loss, could be estimated utilizing Equation (3).

$$E_{Tr} = E_{TrE} \times p + E_{amp} \times n \times p \times d^2 \quad (3)$$

The following notations are used in this context: E_{Tr} refers to the energy used during transmission; E_{Rc} refers to the energy consumed during reception; E_{TrE} refers to the energy necessary by the electronic circuit of the transmitter; E_{RcE} refers to the energy necessary by the electronic circuit of the receiver; E_{amp} refers to the energy consumed by the amplifier. 'p' represents the packet size, 'n' represents the path loss coefficient, and 'd' represents the distance from a source node to a destination node [22].

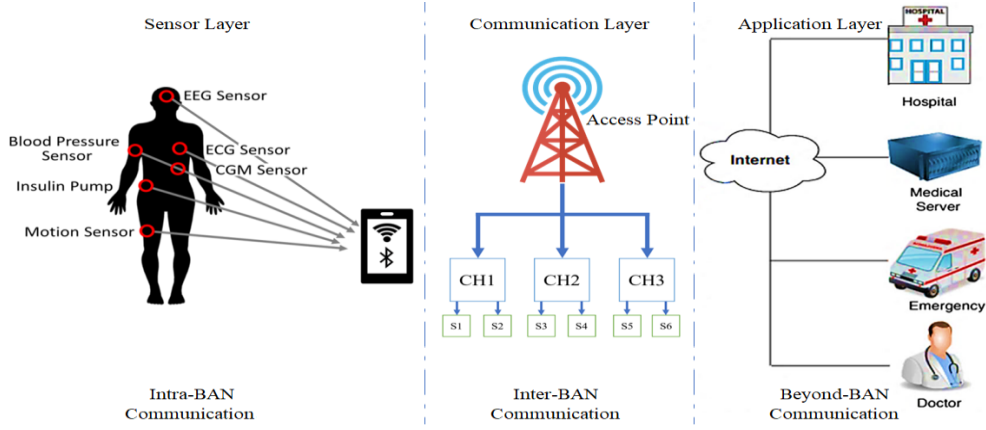


Figure 3. Proposed WBAN Model Architecture

3.3. Path Loss Modelling

The path loss is influenced by several factors, including the varying thickness, characteristic impedance, and dielectric constant of the human body. This might result in significant loss owing to the frequency spectrum used by the nodes for communication. Path loss encompasses the effects resulting from the distance of transmission and the interactions between the physical obstacles and wave during propagations. The overall path loss incurred in the transmission of data could be computed by employing Equation (4).

$$P_L = P_{L_0} + 10 \log_{10} \left(\frac{d_1}{d_0} \right) \quad (4)$$

Where,

$$P_{L_0} = 10 \log_{10} \left(\frac{4\pi d_0}{\lambda} \right) \quad (5)$$

Here, P_L refers to the phenomenon of path loss. The variable d_1 represents the distance of the path, while d_0 represents the threshold distance, which is assumed to be 0.1. The value of wavelength, denoted by λ , is set at 0.125 meters [24].

3.4. CH Selection using Black Widow Optimization

The BWO algorithm imitates the inherent behaviour of black widow spiders, renowned for their adeptness in allocating resources and executing hunting activities. These spiders are efficient predators that organize their resources, particularly when it comes to collecting prey, with accuracy and effectiveness. The BWO algorithm plays a crucial role in the suggested study for creating a cluster-based routing protocol for WBAN. This algorithm addresses key concerns such as energy efficiency, network longevity, resilience, flexibility, dependability, and scalability. The BWO algorithm ensures a balanced energy utilization and extends the lifespan of the networks by optimizing CH selection using factors like node connection, distance to the BS, and residual energy. The method improves routing efficiency by calculating decreased energy usage, ideal multi-hop paths, and adapting to changing network conditions, hence ensuring network resilience and efficiency. The scalability of BWO allows it to effectively handle extensive networks and a wide range of WBAN applications. Furthermore, the BWO plays a role in ensuring the reliable and secure transfer of data, guaranteeing that health data is sent to healthcare practitioners without fail. Therefore, the BWO algorithm greatly improves the performances of the WBAN, leading to improved healthcare outcomes by enabling effective and dependable monitoring. Figure 4 illustrates a visual depiction of the BWO [29].

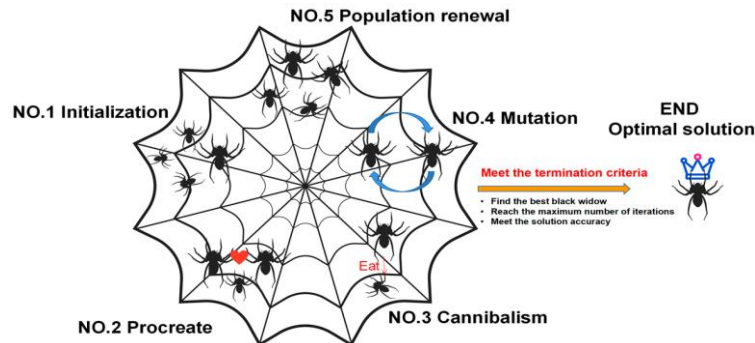


Figure 4. Processes of BWO Algorithm

Initialization: The initial population comprises N_p black widows, where each black widow (Wd) represents a potential solution. The spiders can be imagined as one-dimensional arrays, as seen in equation (6):

$$Wd = [z_1, z_2, \dots, z_{M_{var}}] \quad (6)$$

All the variables, labelled as $z_1, z_2, \dots, z_{M_{var}}$, was expressed as a stochastic real number, with $z_{M_{var}}$ indicating the size of the optimization problem. In this setting, each black widow could calculate its fitness value, represented as FF in equation (7):

$$Fitness = FF(Wd) = FF(z_1, z_2, \dots, z_{M_{var}}) \quad (7)$$

During the initialization phase, a group of N_p black widows are generated, leading to the formation of a matrix of size $N_p \times M_{var}$ consisting of black widows.

Procreation: This phase involved a worldwide exploration that encompassed several sequential actions. At first, the populace is organized according to their degrees of fitness. Therefore, the black widows that engage in reproduction are identified based on the procreation rate, which is referred to as PCR. Parents for procreation are selected randomly using Equation (8). Within the framework of this method, the act of procreation is simulated by producing α arrays.

$$\begin{cases} x_1 = \alpha \times y_1 + (1 - \alpha) \times y_2 \\ x_2 = \alpha \times y_2 + (1 - \alpha) \times y_1 \end{cases} \quad (8)$$

The equation (8) represents the parents as y_1 and y_2 , and the children as x_1 and x_2 . This entire operation is repeated $M_{var}/2$ times. Cannibalism is a feature of the BWO algorithm that includes three specific forms: child-eat-mother cannibalism (CMC), sibling cannibalism (SB), and sexual cannibalism (SC). SC occurs when female spiders, who possess much greater physical condition, consume male black widows with inferior physical condition, either after or during the mating process. Sibling cannibalism occurs when dominant spiders prey on their weaker siblings. Cannibalism occurs when a child spider swallows its mother. This algorithm effectively regulates SC by removing the male parent and selecting and eliminating certain children based on the cannibalism rate (CBR) to reduce SB.

Mutation: The mutation stage involves a search procedure that is limited to a certain area. In the BWO method, the quantity of black widows is selected at random based on the mutation rate (MR). During this phase, each black widow undergoes a mutation process in which two eigenvalues within its array are randomly swapped to aid the mutation behaviour.

Population Update: Black widows with higher levels of fitness after going through the previous four stages are selected as the new starting population for successive cycles until the termination requirements are satisfied. Figure 5 depicts the flowchart of the BWO [30].

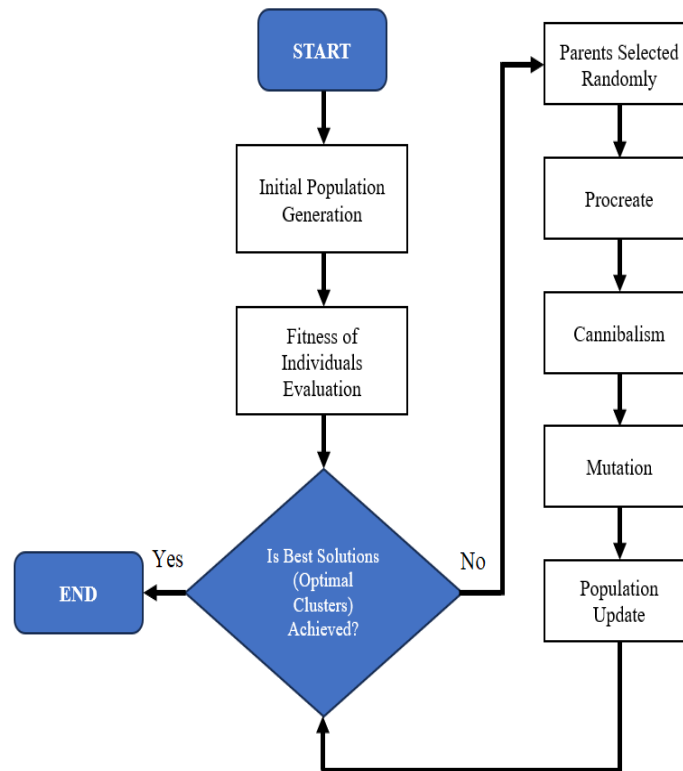


Figure 5. Workflow of BWO Algorithm

Input: Max_number of iterations, PCR, CBR, MR
 Output: The CH position with fitness value according to the termination condition
 Initialization
 Initial population (P) of CH
 Each CH population is a D-dimensional chromosome array
 Loop till the terminal condition
 Using PCR, compute the reproductions NR;
 Choose the best reproduction solution in the CH population and store it in P1;
 PCR and CBR
 For i=1 to NR do
 Choose two solutions randomly as parents from P1;
 Create D children using (8);
 Destroy father;
 According to CBR, eliminate some of the children;
 Save the remaining solutions in P2;
 End for
 Mutation
 According to MR, compute the mutation of children's NM;
 For i=1 to NM do
 Choose a solution from P1;
 Mutate a chromosome solution randomly and create a new solution;
 Save the new solution in P3;
 End for
 Updation
 Update $P=P2+P3$;
 Returning to the best CH;
 Return the optimal CH position from P;

This research aims to minimize the energy utilization of WBANs by choosing the most suitable CHs based on the BWO. Given that every node is mobile and randomly move, it was presumed that each node has an equal probability of occupying any location in the search space and being chosen as a header node under normal circumstances.

4. Simulation and Experimental Analysis

4.1. Simulation Setup

The simulation features a crucial part in thoroughly evaluating the performances of WBANs. Simulation offers a regulated and replicable environment for assessing a research model, enabling researchers to study its influence on different network characteristics. The research model was evaluated using simulation, considering many characteristics. The effectiveness of the model was assessed to establish its overall efficiency. The experiments are performed using the MATLAB 2018A simulation program on a computer equipped with a 64-bit CPU, an i5 processor, and 12GB of RAM. Table 1 presents the simulation parameters that were utilized.

Table 1: Parameters for Simulation

Parameters	Values
Simulator	NS-2.34
Simulation Area	100x100m
No. of Nodes	250
Initial Energy	0.5 J
$E_{T_{RE}}$ Transmitter Energy	16.7 nJ/bit
$E_{R_{CE}}$ Receiver Energy	36.1 nJ/bit
E_{amp} for Amplified Circuit	1.97 nJ/bit
Packet Size	512 bytes
No. of Rounds	6000

4.2. Performance Metrics

This comprehensive analysis focuses on the efficacy of the proposed novel routing protocols in WBANs, considering various metrics such as Energy consumption, PDR, PLR, E2E Delay, Throughput, and NLT.

Energy Consumption: This parameter measures the amount of energy utilized by SNs during the operation of the WSN. Lower energy consumption is desirable as it contributes to prolonged NLT and reduced environmental impact.

E2E Delay: This parameter measures the time taken for data to travel from the source node to the destination node. Minimizing E2E delay is crucial for applications requiring timely data delivery.

PDR: PDR measures the ratio of successfully delivered packets to the total number of packets sent. A higher PDR indicates a more reliable network [25].

PLR: This parameter assesses the proportion of packets that failed to reach their destination, reflecting the reliability and robustness of the routing protocols. A lower packet drop/loss ratio is preferable.

NLT: NLT represents the duration for which the WSN can operate effectively before a significant number of nodes deplete their energy. Extending NLT is essential for sustainable and long-term deployment.

Throughput: Throughput measures the rate at which data is successfully transmitted through the network. Higher throughput is indicative of improved network efficiency and data delivery capabilities [28].

4.3. Simulation Results Analysis

This section presents a detailed analysis and discussion of the research model’s evaluated performances based on energy consumption, E2E delay, PDR, PLR, NLT, and throughput. Table 2 presents the results comparison of energy consumption using BWO-based protocol with other current models discussed in the literature review section. The BWO’s results were compared with models like IEPSO, OEABC, RPESA, PSOBAN, and ECSO-BO. Energy consumption in WBAN was an significant metric that affects the lifetime of the networks and overall performance of the model. In WBAN, the energy consumption commonly includes factors such as energy utilized for communication, and maintaining the operational state of the network. As shown in the table, the results are evaluated based on the nodes ranging from 50 to 250. The research model has attained lower energy consumption in all the node ranges with the best performance. The research model consumed 0.082 J at 50 nodes, which is lower than the compared models with a difference of 0.008 to 0.021 J. In 100 nodes, the model has a maximum difference of 0.028J, 0.032J in 150 nodes, 0.04J in 200 nodes, and 0.051J in 250 nodes. Figure 6 represents the graphical plot of energy consumption comparison.

Table 2: Comparison of Energy Consumption

No. of Nodes	Proposed BWO	IEPSO	OEABC	RPESA	PSOBAN	ECSO-BO
50	0.082	0.090	0.093	0.095	0.100	0.103
100	0.157	0.165	0.170	0.173	0.180	0.185
150	0.225	0.233	0.240	0.245	0.250	0.257
200	0.290	0.300	0.310	0.315	0.325	0.330
250	0.350	0.362	0.375	0.387	0.390	0.401

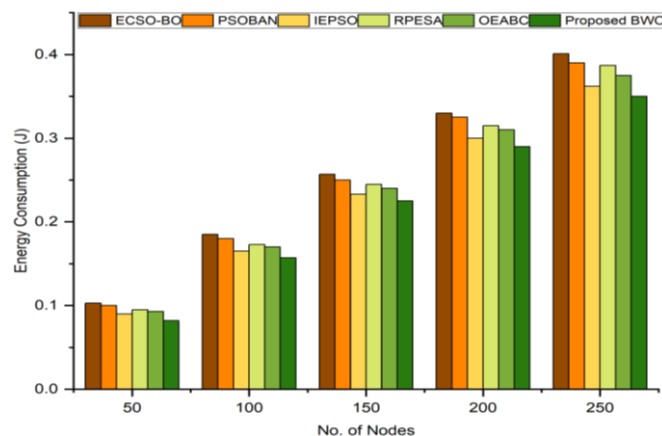


Figure 6. Graphical Plot of Energy Consumption Comparison

Table 3 presents the results comparison of PDR using BWO-based protocol with other current models. PDR in WBAN measures the reliability and efficiency of communications in the network. The research model improves the PDR by optimizing the CH selection and the routing paths, making sure that the packets are effectively delivered from sensor nodes to the BS. The BWO model minimizes packet loss and energy consumption, which leads to a higher PDR performance. As shown in the table, the results are evaluated based on the total nodes ranging from 50 to 250. The research model has attained higher PDR in all the node ranges with the best performance. The research model attained a PDR of 98.3% at 50 nodes, which is higher than the compared models with a difference of 1.6 to 8.5%. In 100 nodes, the model has a maximum difference of 8.8%, 9.3% in 150 nodes, 9.2% in 200 nodes, and 9.3% in 250 nodes. Figure 7 represents the graphical plot of the PDR performance comparison.

Table 3: Comparison of PDR

No. of Nodes	Proposed BWO	IEPSO	OEABC	RPESA	PSOBAN	ECSO-BO
50	98.3%	96.7%	94.5%	92.4%	91.2%	89.8%
100	97.5%	95.6%	93.2%	91.0%	90.1%	88.7%
150	96.8%	94.3%	92.0%	90.2%	89.3%	87.5%
200	95.7%	93.5%	91.1%	89.0%	88.0%	86.5%
250	94.6%	92.2%	90.0%	88.2%	87.1%	85.3%

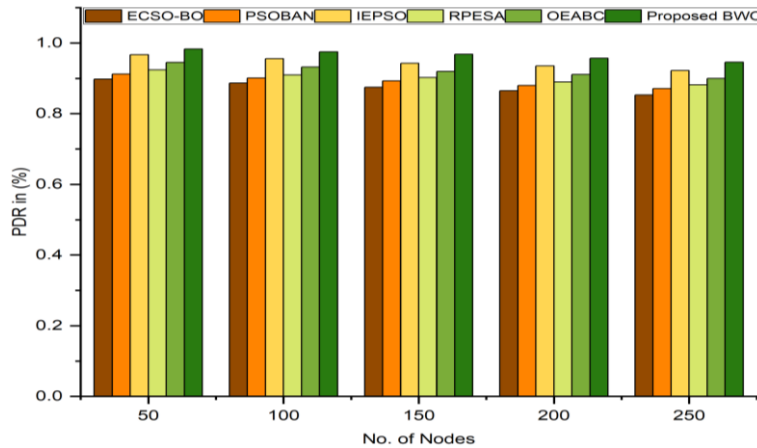


Figure 7. Graphical Plot of PDR Comparison

Table 4 presents the results comparison of PLR using BWO-based protocol with other current models. PLR in WBAN is a crucial parameter, which represents the reliability and efficiency of data communication in the network. The research model reduces the PLR by optimizing the CH selection, which minimizes the congestion and energy depletion between the nodes. As a result, the research model's PLR is effectively lower than the other models in the comparison. As shown in the table, the results are evaluated based on the total nodes ranging from 50 to 250. The research model has attained lower PLR in all the node ranges with the best performance. The research model attained a PLR of 1.7% at 50 nodes, which is less than the compared models with a difference of 1.6 to 8.5%. In 100 nodes, the model has a maximum difference of 8.8%, 9.3% in 150 nodes, 9.2% in 200 nodes, and 9.3% in 250 nodes. Figure 8 represents the graphical plot of the PLR performance comparison.

Table 4: Comparison of PLR

No. of Nodes	Proposed BWO	IEPSO	OEABC	RPESA	PSOBAN	ECSO-BO
50	1.7%	3.3%	5.5%	7.6%	8.8%	10.2%
100	2.5%	4.4%	6.8%	9.0%	9.9%	11.3%
150	3.2%	5.7%	8.0%	9.8%	10.7%	12.5%
200	4.3%	6.5%	8.9%	11.0%	12.0%	13.5%
250	5.4%	7.8%	10.0%	11.8%	12.9%	14.7%

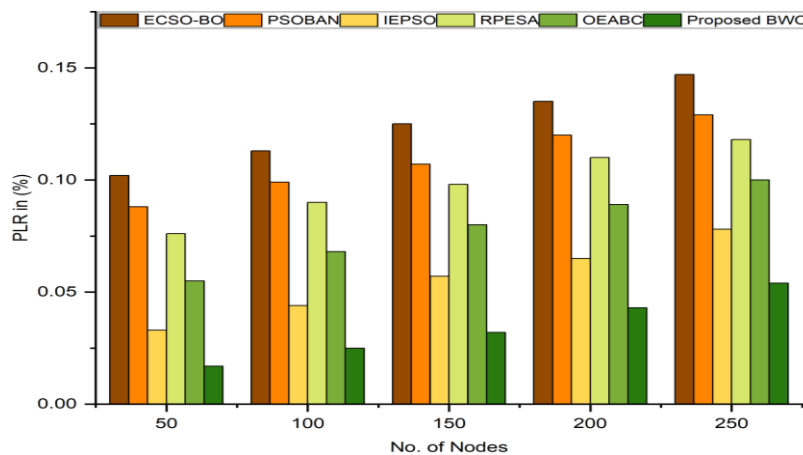


Figure 8. Graphical Plot of PLR Comparison

Table 5: Comparison of End-to-End Delay

No. of Nodes	Proposed BWO	IEPSO	OEABC	RPESA	PSOBAN	ECSSO-BO
50	0.18	0.22	0.25	0.21	0.24	0.23
100	0.23	0.27	0.30	0.26	0.29	0.28
150	0.28	0.32	0.35	0.31	0.34	0.33
200	0.32	0.37	0.40	0.36	0.39	0.38
250	0.36	0.41	0.45	0.40	0.44	0.42

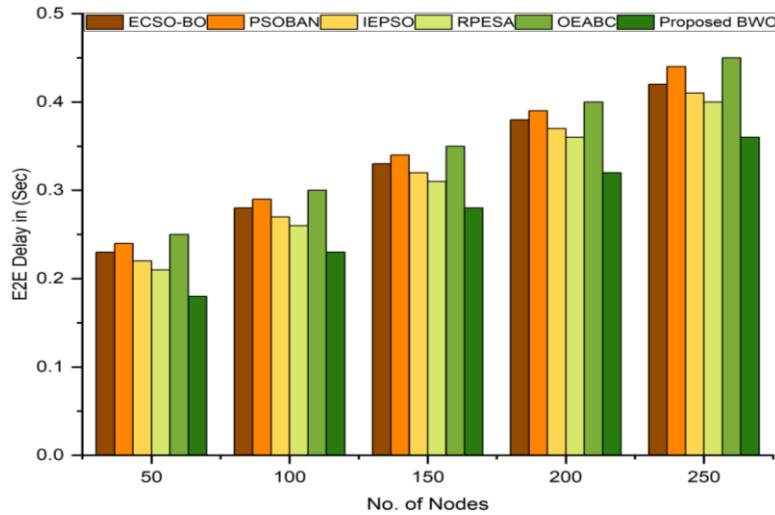
**Figure 9.** Graphical Plot of E2E Delay Comparison

Table 5 presents the results comparison of E2E delay using BWO-based protocol with other current models. The E2E delay in WBAN refers to the total time used for the data packet to travel from the source to the destination node. The BWO model reduces the E2E delay by effective CH selection and optimizing the routing paths, which reduces the distance and the number of hops a packet should travel. The proposed BWO model makes sure that the data packets are delivered quickly, which is significant for time-sensitive applications like healthcare. As shown in the table, the results are evaluated based on the total nodes ranging from 50 to 250. The research model has attained lower E2E delay in all the node ranges with the best performance. The research model attained an E2E delay of 0.18 sec at 50 nodes, which is less than the compared models with a difference of 0.03 to 0.07 sec. In 100 nodes, the model has a maximum difference of 0.07 sec, 0.07 sec in 150 nodes, 0.08 sec in 200 nodes, and 0.09 sec in 250 nodes. Figure 9 represents the graphical plot of the E2E delay performance comparison. Table 6 presents the results comparison of network lifetime using BWO-based protocol with other current models. The network lifetime in WBAN is utilized to measure how long the network can operate efficiently prior to the initial node depleting its energy. The research model increases the lifetime of the network by optimizing the CH selection and the routing paths, which balances the energy consumption between nodes and minimized the energy cost. This results in an effective distribution of energy consumption, avoiding early energy depletion of nodes. As shown in the table, the results are evaluated based on the total nodes ranging from 50 to 250. The research model has attained a higher network lifetime in all the node ranges with the best performance. The research model attained a network lifetime with 5890 rounds at 50 nodes, which is higher than the compared models with a difference of 88 rounds to 502 rounds. In 100 nodes, the model has a maximum difference of 528 rounds, 570 rounds in 150 nodes, 540 rounds in 200 nodes, and 510 rounds in 250 nodes. Figure 10 represents the graphical plot of the network lifetime performance comparison.

Table 6: Comparison of Network Lifetime

No. of Nodes	Proposed BWO	IEPSO	OEABC	RPESA	PSOBAN	ECSSO-BO
50	5890	5802	5670	5544	5472	5388
100	5850	5760	5592	5460	5406	5322
150	5820	5718	5550	5412	5358	5250
200	5730	5640	5466	5340	5280	5190
250	5640	5512	5400	5292	5196	5130

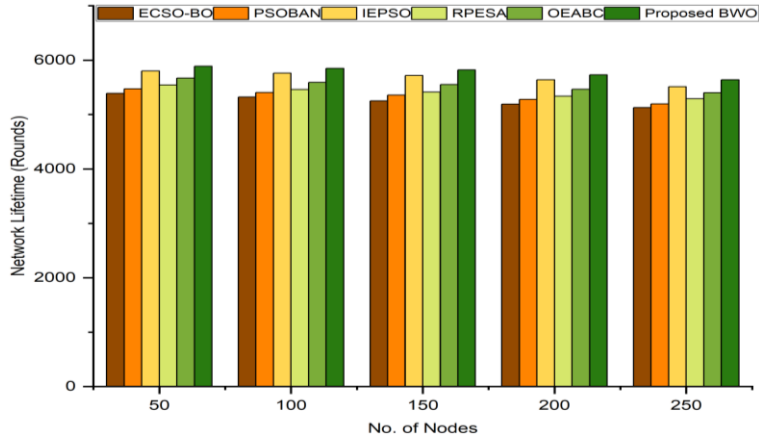


Figure 10. Graphical Plot of Network Lifetime Comparison

Table 7 presents the results comparison of network throughput using BWO-based protocol with other current models. The network throughput refers to the rate at which the data packets are transmitted successfully from the source to the destination in a provided time. The research model improves the network throughput by optimizing CH selection and routing paths, hence reducing packet collision and congestion, and making sure effective data transmission and aggregation. This leads to higher throughput, making the research model reliable and timely delivery of health data in healthcare applications. As shown in the table, the results are evaluated based on the total nodes ranging from 50 to 250. The research model has attained higher network throughput in all the node ranges with the best performance. The research model attained a network lifetime of 0.95 at 50 nodes, which is higher than the compared models with a difference of 0.03 to 0.12%. In 100 nodes, the model has a maximum difference of 0.11%, 0.10% in 150 nodes, 0.10% in 200 nodes, and 0.11% in 250 nodes. Figure 11 represents the graphical plot of the network throughput performance comparison.

Table 7: Comparison of Network Throughput

No. of Nodes	Proposed BWO	IEP SO	OEABC	RPESA	PSOBAN	ECSO-BO
50	0.95	0.91	0.92	0.90	0.88	0.83
100	0.92	0.88	0.89	0.87	0.85	0.81
150	0.89	0.85	0.86	0.84	0.83	0.79
200	0.88	0.84	0.83	0.82	0.80	0.78
250	0.86	0.81	0.82	0.79	0.77	0.75

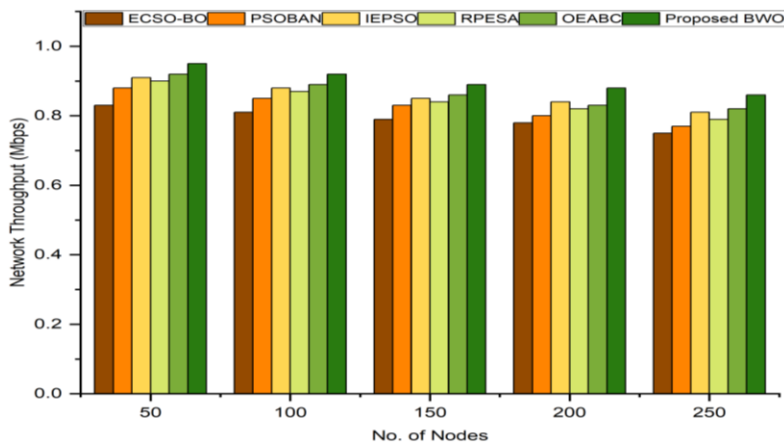


Figure 11. Graphical Plot of Network Throughput Comparison

The proposed routing protocol based on the BWO algorithm provides exceptional performance in WBANs in terms of all the important parameters. It enhances energy efficiency by efficiently choosing CHs and routing pathways, resulting in a well-balanced energy distribution and extended network lifespan. The BWO model effectively minimizes end-to-end latency by prioritizing data packets to travel the shortest and least congested paths, which is crucial for real-time health monitoring. It attains a high PDR, normally ranging from 95% to 98%, which indicates dependable data transfer, while simultaneously retaining a low packet loss rate, generally ranging from 1% to 5%. In addition, the BWO-based routing protocol prolongs the lifespan of the network by preventing nodes from running out of power too soon. It also improves network efficiency by minimizing congestion and packet collisions, which in turn supports uninterrupted and reliable monitoring of health data.

5. Conclusion

WBANs have a significant part in the modern digital world, being utilized in diverse sectors including healthcare. Furthermore, WBANs operate in an environment with limited resources, including restricted battery power, limited processing capabilities, and reduced memory capacity. In conventional data transmission methods that have limited resources, the efficiency is compromised owing to the significant consumption of energy and expense. Hence, an energy-efficient clustering methodology was required to provide quick and uninterrupted transmission of sensitive information from the source to the destination in WBANs. However, it is necessary to efficiently control the energy to enhance the longevity and data transfer capacity of the network. Cluster-based routing algorithms are effective in enhancing the longevity of the network, optimizing network capacity, and alleviating the network's load to enhance the total performance of the networks for better analysis and performance. In this research, a new metaheuristic algorithm was proposed to select the optimal clusters in WBANs to provide a routing protocol with energy-efficiency for healthcare monitoring. The key objective was to minimize the energy utilization of WBANs by choosing the most suitable CHs based on the BWO. The proposed BWO-based routing protocol demonstrated superior performance in WBANs based on energy consumption, end-to-end delay, PDR, network lifetime, packet loss, and throughput. The results of this model were compared with the current routing protocols for validation, in which the research model outperformed all the compared models with less energy consumption, minimal delay, high network lifetime, high PDR, less PLR, and higher throughput. In future, the proposed research can be improvised by proposing a hybrid algorithm for designing the routing protocol to further enhance the result. The main aim will be to optimize the energy utilizations and increase the lifetime of the networks by selecting optimal CHs. Moreover, the research may include more biosensor nodes to monitor the health conditions, which will be challenging to find the optimum path using a hybrid optimization algorithm.

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