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Congestion Control in Wireless Body Area Networks using FIREFLY Algorithm

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Abstract

The healthcare industry is the most widely used application of Wireless Body Area Network (WBAN). WBAN networks have been developed to provide a more flexible experience than traditional wired medical systems using low-power miniature sensors that monitor physiological signals. Some studies have addressed the problem of congestion in body networks and proposed new methodologies to deal with this problem. Recently, in WBAN networks, metaheuristics algorithms have been employed to improve performance and job execution efficiency, which has proven effective in finding optimal solutions, especially for congestion problems. This research applies a metaheuristic algorithm, the Firefly algorithm, to optimize node selection in WBAN. Additionally, the Random Early Detection system (RED) is employed to control network congestion. Two scenarios are applied, the first one represents a network with 20 nodes, and the second one represents a smaller network with 10 nodes. The results were compared statistically. The present paper defines an enhanced congestion handling method for WBANs. For this purpose, the fitness function of the nodes is evaluated based on essential factors: congestion probability, the variables are residual energy, average data rate, node distance, and sink distance. It also improves the routing strategy by introducing the firefly algorithm-based forward-looking node selection approach. This eventually results in improved quality of service.

Keywords— *Metaheuristic algorithms*, *Firefly algorithm*, *RED*, *WBAN, Qos.*

1 Introduction

Certain issues are being resolved in order to enhance the performance of WBAN networks, an important example of which is the congestion issue, which is brought about by large package transfers and is being tackled, leading to an increase in node energy consumption due to overtransmission and node energy depletion. (Kumar M & Raj C, 2017) Qos parameters generally include energy consumption, productivity, reliability, and others.

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Metaheuristic algorithms have attracted a lot of attention lately. They include the genetic algorithm, the ant colony optimization (Dorigo & Di Caro, n.d.), the firefly algorithm, and other algorithms. They are being used in optimization issues and solving complicated problems (Qais & AbdulWahid, 2013). The Firefly Algorithm (FA) is considered stochastic; it is a reliable and effective algorithm that can estimate the global optimum level through a process of preserving the finest solutions from each generation to improve other solutions (Ibrahim et al., 2024) (Xin-She Yang, 2020). In this way, all individuals become better generation after generation.

The Random Early Detection system (RED) is a technique used to lessen congestion in wireless networks. Its operation is based on the idea that the RED gateway calculates for each packet arriving the average size of the queue, then this average size is compared to two thresholds, a minimum and a maximum. Each incoming packet is assigned a probability, which is dependent on the average size of the queue when it falls within the minimum and maximum thresholds (Hassan & Rufai, 2023). However, metaheuristic algorithms have attracted many authors to perform their study work on energy consumption as well as congestion (Sharma et al., 2022). An example of this is ANT colony optimization (ACOBAN), which was suggested to use clustering to observe Body Area Network data in order to improve network lifetime (Rakhee & Srinivas, 2016). As in (Anand & Sethi, 2017) a Threshold-unaware Energy efficient Multi-hop Protocol (NEW-ATTEMPT) mechanism was developed by the authors, in this method, an integral cost function is designed for forwarding the data from one node to node. Different parameters are used for evaluating the cost function; these parameters are the sending data rate, the distance between the nodes, and the remaining energy. The concept of residual energy in WBAN is used to form the energy-efficient protocol.

The authors (Aryai et al., 2023) developed a congestion control mechanism that works on the basis of queue length and delay, but it needed more improvements, such as adding an energy consumption approach to the congestion control method in the network (Yaghoubi et al., 2022). The firefly algorithm was implemented to create an efficient path for transmitting data in the network, where the Fuzzy Logic System has been used with the Sugeno paradigm to manage network congestion.

This study is important since it addresses the issue of congestion in (WBAN) networks, which arises from the collector node's exposure to scenarios in which a large number of data packets are received from multiple nodes. In these scenarios, we must adapt to the situation and implement a particular strategy that lowers energy consumption and congestion. Reducing congestion and the consumption of energy is considered one of the most prominent challenges and problems that exist within networks, especially in WBAN. In addition, one of the multi-solution class's issues is determining which node is the best fit. There are numerous ways and algorithms offered to handle congestion problems.

The present research focuses on the idea of improving the handling process of congestion for WBAN. For achieving this idea, the node’s cost function is evaluated based on key factors such as distance and remaining power. Additionally, the Red (Random Early Discarding) system is used to implement the congestion control model, and the Firefly algorithm-based forward-looking node selection approach is used to improve the routing strategy. The suggested work was evaluated using a MATLAB simulation. In the following stage, two scenarios were applied for two networks, one containing 10 sensor nodes and the other 20 nodes. Then the firefly algorithm was implemented and repeated 100 times. After that, the values resulting from each round were collected, the standard deviation and standard error were calculated, and their normality was tested; based on that, the results were collected. Then the two scenarios were compared using GraphPad Prism software.

The next sections of this study are organized as follows: The second section is the resources and methods; the third section is the employed algorithm; the fourth section is the findings and discussion; and the last section is the conclusions.

2 System Model

2.1 Congestion in WBAN Networks

One of the many uses of WSN in the medical field led to T.G. Zimmerman's 1996 discovery of a new field of study that is now called (WBAN) (Aryai et al., 2023). It is specified in IEEE 802.15.6. WBAN is a new network made up of a set of sensors positioned all over the person body that communicate with a sink or base station known as a Personal Digital Assistant (PDA) (Aryai et al., 2023). Because of the nature of WBAN's handling of heterogeneous data flows, data is divided into three basic groups (Yaghoubi et al., 2022). First one is on-demand traffic which is a form of data that provided when the controller (consultant or doctor) makes the request to diagnose the network's body, Key concerns are latency and reliability. Second one is emergency data traffic which is unexpected, it contains the most vital data and cannot withstand a large data loss or delay. The last type of data is normal data traffic that means data delivered at normal and regular intervals to show the body's normal functioning (Yaghoubi et al., 2022).

At each layer of WBAN, many issues need to be addressed efficiently, especially at the transport layer where the main function End-to-end communication that is free of congestion and dependable. Whether at the source or destination, the entire message's error control, flow management, and congestion control are carefully monitored. Reliable data transfers, flow control, the impact of congestion, packet loss or loss owing to load, traffic categorization, delay, scheduling, security, error control, fault tolerance, buffer management, and quality of service are among the several challenges with the transport layer (Sathya & Evanjaline, 2023).

2.2 RED System

It is a technique for reducing network congestion generally in wireless networks. The RED gateway determines the average queue size (avg) for each arriving packet, which is the basis for its operation. Two thresholds are used to assess the average size of the queue, a minimum threshold and a maximum threshold. The arriving packets are not marked when the queue average size is below the minimal threshold, while every incoming packet is highlighted only when the average queue size exceeds the maximum threshold. A probability is assigned to each arrived packet, when the average queue size falls between the minimum and maximum thresholds (Siregar et al., 2017).

The packets are tagged at reasonably regular intervals and often enough to regulate the average queue size and this is the main gateway's goal Figure 1 (Hamadneh et al., 2019) .

Since the mean varies from $\mathrm{min_{th}}$ value to $\mathrm{max_{th}}$ value, the probability of a packet being flagged ($\mathrm{P_b}$) varies linearly from 0 value to $\mathrm{max_p}$ value.

$$\mathrm{P_b} = \frac{\mathrm{max_p}(\mathrm{avg} - \mathrm{min_{th}})}{(\mathrm{max_{th}} - \mathrm{min_{th}})} \tag{1}$$

Where $\mathrm{min_{th}}$ is the minimum number of queues, avg is the average size of the queue, $\mathrm{max_{th}}$ is the queue maximum number, and $\mathrm{max_p}$ is the maximum value of $\mathrm{P_b}$ (Adamu et al., 2020).

Where Avg is average queue length, max thresh is max queue length threshold, and min thresh is min queue length threshold. The goal is to find a method for routing by selecting the best node and at the same time reducing congestion.

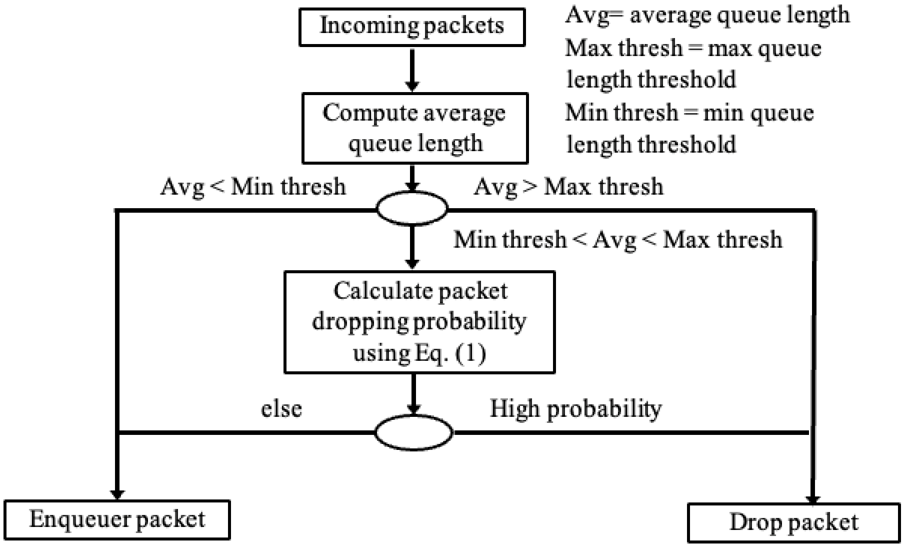

Figure 1: The RED system

2.3 Used Algorithm

Firefly method is a metaheuristic algorithm developed by Dr. Xin-She in 2007 (Yang & He, 2013). It is based on the way fireflies emit light, a process known as bioluminescence; nevertheless, it is still unclear exactly what functions these signaling systems accomplish. Such brightness serves two main purposes: attracting possible prey and mating partners (communication). Furthermore, brightness may also operate as a protective warning system. The signaling system that unites the sexes includes factors such as brightness, the light rate, and duration.

Females respond to the distinct pattern of males in the same species, and we know that the intensity of light at a specific distance r from the light source follows the inverse square law. This means that the light intensity *I* decreases as the distance *r* increases, where $\mathrm{I} \propto \frac{1}{r^2}$. Furthermore, the air absorbs light, which grows weaker as distance increases. These elements make most items only visible from a short distance, generally a number of hundred meters at night, which is sufficient to let objects communicate. The flashing light can be built in such a way that it is related to the objective function to be optimized, allowing you to create new optimization techniques. The process starts with creating a random group of n fireflies to represent appropriate solutions to the problem. Next, the fireflies are classified from best to worst based on how suitable they are for the goal function (suitability), and the best firefly (the most appropriate solution) that achieved the best value for the goal follower is chosen. The other fireflies are then drawn to the best firefly (solution). Finally, the algorithm returns a result when the required condition or maximum generation is reached; if not, the process is repeated (Kumar & Kumar, 2021). FA is described using the two ideal principles that follow for simplicity:

1) The attractiveness of a firefly is directly proportional to its brightness. So for any two objects, the less bright will move towards the brighter. Gravity is directly proportional to brightness and both will decrease as the distance between them increases. If there is no individual brighter than a particular firefly, it will move randomly.
2) The kind and structure of the appropriate function influence or determine the firefly's brightness. In the most elementary situation of maximum optimization issues, the firefly brightness at a given location may be selected as I (x) ∝ f (x). However, Gravity β is based on distance and other variables and is relative r_{ij} between firefly *i* and firefly *j*. In addition, light is absorbed in the medium and loses intensity with distance from its source; gravity must be adjusted to take these effects into account. In its most

basic form, the intensity of light I(r) follows the inverse square rule. $I(r) = I_s/r_2$, where Is represents the intensity at the source (Tilahun et al., 2019).

The intensity of light I in a material with constant light absorption r, varies with distance. Consequently, the relationship that follows expresses the brightness equation:

$$\mathrm{I(r)} = \mathrm{I_0} * \mathrm{e}^{-\gamma r^2} \tag{2}$$

Where I_0 is the original light intensity (brightness at distance r = 0, I(r) is the brightness at a distance r, γ is a constant that represents how gravity changes with increasing firefly distance. Given that the gravitational pull of a firefly is directly proportional to the light intensity perceived by adjacent objects, we can use the following equation to determine the gravity β:

$$\beta = \beta_0 * \mathrm{e}^{-\gamma r^2} \tag{3}$$

β: gravity at distance r. β_0: The value of gravity at distance r = 0, and β_0 represents the criterion based on which fireflies are attracted to the best solution. Distance calculation: The separation of any two components i and j at x_i and x_j , it is the Cartesian distance, respectively.

$$r_{ij} = |x_i - x_j| = \sqrt{\sum_{k=1}^{D} (x_{i,k} - x_{j,k})^2} \tag{4}$$

$x_{i,k}$ is the k^{th} component of the spatial coordinate x_i of firefly i. In 2D case

$$r_{ij} = \sqrt{(x_i - x_j)^2 + \left(y_i - y_j\right)^2} \tag{5}$$

firefly i is attracted to another brighter (attractive) firefly j by

$$x_i^{t+1} = x_i^t + \beta 0 e^{-\gamma r_{ij}^2} * \left(x_j^t - x_i^t\right) + \alpha * \varepsilon_i \tag{6}$$

Where x_i^{t+1} is the new location, and x_i^t is the old one. The second term represent the attraction, while the third term is the randomization term (Wu et al., 2020).

In this paper, the proposed algorithm uses an initialization step, all fireflies (sensors) must calculate to do this, we determine the beginning brightness β_0.

$$\beta_0 = \frac{E_{residual}}{E_{max}} \tag{7}$$

The sensor brightness (s) should not be lower than min, where $E_{eresidual}$ denotes current power and E_{max} represents the maximum power of the sensor battery. This indicates that the brightness will gradually drop until it becomes undesirable (Pakdel & Fotohi, 2021).

As the energy consumption resulting from sensitization increases, we consider the brightness fading coefficient γ (Equation (2) uses the light absorption coefficient of a specific sensor to compute its energy usage to equation (8):

$$\gamma = e_d * b * d^{\alpha} + e_t * b \tag{8}$$

Where e_d the amount of energy wasted per bit, and $\mathrm{e_t}$ the energy consumption of the transmission circuits per bit, values are $100 * 10^{-9}$and $50 * 10^{-9}$for e_d and $\mathrm{e_t}$ respectively (Pakdel & Fotohi, 2021). In addition, b is the number of bits to send or receive, the conventional value of α is 1, and d represents the distance between the sender and the receiver.

2.4 Cost Function (Fitness Function)

The individual node cost function is evaluated to determine the next coming step in the nodes sequence.

$$\text{cost function} = \left(\frac{1}{\mathrm{p}}\right) * \frac{\mathrm{e(i)}}{\mathrm{d} * \mathrm{q}} + \frac{1}{\mathrm{d_{i,node}}} \tag{9}$$

The cost function is evaluated using d (the dsistance between the node location and the sink), q (the average rate of data), $\mathrm{e(i)}$ (the remaining energy at node (i), and $\mathrm{d_{i,node}}$ (the calculated distance between the source node location and the next node). p is the probability of congestion which is calculated using the RED system and varies from 0 to 1. The total energy is calculated as follows (Arafat et al., 2023) (Mehmood et al., 2023):

The first order radio model which proposed by Dr. Wendi Rabiner Heinzelman is used as a radio model, mainly due to its simplicity (Mehmood et al., 2023), The power required to transfer a packet of data of size k (in bits) is calculated concerning the distance between the transmitter and the receiver as well as the antenna gain, packet size in bits, transmitting and receiving energy .

$$\mathrm{E_{tx}(d,k) = k\left(E_{elec} + E_{amp}d^2\right)} \tag{10}$$

Where $\mathrm{E_{elec}}$: the amount of energy required to operate the transmitting or the receiving circuit.

$\mathrm{E_{amp}}$: antenna gain at the transmitter and receiver. In the same way, to receive k bits, the energy required for this is:

$$\mathrm{E_{rx} = k\, E_{elec}} \tag{11}$$

The total consumed energy $\mathrm{E_{total}}$for the sensor node is expressed as:

$$\mathrm{E_{total}(d,k) = E_{tx}(d,k) + E_{Rx}} \tag{12}$$

There are two common types of transceivers; Nordic nRF 2401A and Chipcon CC2420 (Mekathoti & Nithya, 2021), in WBANs technology. The Nordic nRF 2401A is a single chip , low power transceiver and the other one is Chipcon CC2420. The operating frequency of both the transceivers is 2.4GHz. We use the energy parameters of the Nordic nRF 2401A transceiver because it consumes less power than Chipcon CC2420 transceiver (Javaid et al., 2015). The energy parameters of these transceivers are explained in Table 1.

Table 1: Two common commercial sensors with their corresponding power values

Parameter(unit)	**nRF2401A**	**CC2420**
$\mathrm{E_{tx,elec}}$ (nJ/bit)	16.7	96.9
$\mathrm{E_{rx,elec}}$ (nJ/bit)	36.1	172.8
$\mathrm{E_{amp}}$ (nj/bit/mn)	1.97	0.027
Tx current (mA)	10.5	17.4
Rx current(mA)	18	19.7

Figure 2 shows the flow chart of the algorithm.

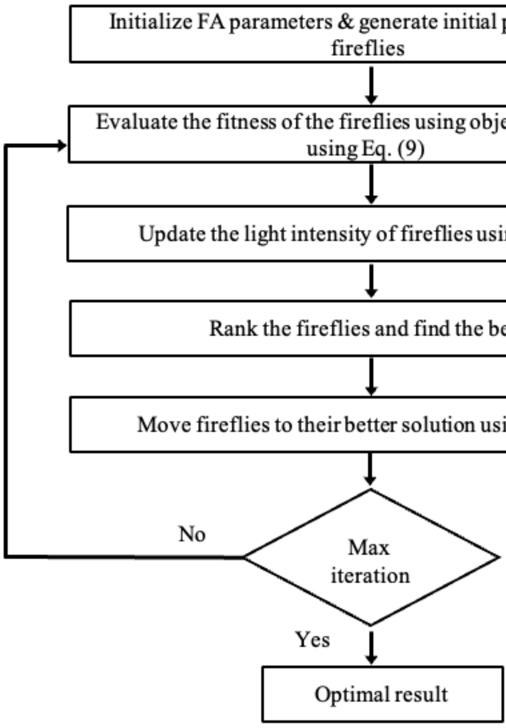

Figure 2: The flow chart of Firefly algorithm

The initiation of the process involves the distribution of the mesh across the designated region with respect to the x and y axes. Crucially, the determination of the network's node cardinality is a prerequisite. Furthermore, this initial phase encompasses the definition of the nodes' baseline energy levels. Subsequent to network deployment, the RED system is implemented, to commence route design, the initial population must first be generated, following this, the cost function is computed through the application of Equation 9. Subsequently, the firefly algorithm is employed to iteratively update the initial population, equation 9 is then utilized to calculate the revised cost function, incorporating the updated population. If the newly computed cost surpasses the preceding cost, the cost function is adjusted accordingly, otherwise, the population undergoes further refinement using the firefly algorithm; the forward-looking node is selected for data transmission, and the optimal solution is identified based on the revised cost. The efficacy of the proposed task is evaluated upon the completion of the data transmission process. The performance of the suggested model was assessed via simulation by executing the algorithm across 100 iterations and analyzing the resulting outcomes. The progression of the current work is illustrated in Figure 3.

2.5 Number of Nodes

According to IEEE standards, that address the technical specifications of WBAN, a WBAN can have as little as a few actuators or sensors interacting with an Internet gateway as its nodes (Benmansour et al., 2020) (Niaz et al., 2020). A standard WBAN-based medical network consists of six nodes with a structure that is scalable and can contain up to 256 nodes (Niaz et al., 2020). The specifications given in (Zhang et al., 2020) also provide a 3 m operating range for WBAN networks, which can support 256 nodes in each network within a 6 m3 cube and reach up to 10 piconets per person. Due to restrictions in the transmission method, only one hub with several nodes ranging from 0 to n MaxBANSize defined as 64 in the IEEE 802.15.6 standard is permitted to exist in a WBAN. However, a maximum of 256 nodes can exist per network because 2-4 WBAN networks are said to cohabit on the same person (per m2). Although there is typically no limit to the nodes number in a WBAN, in real application settings, the number may be limited due to limits in the network's architecture, communication protocols, and transmission methodologies (Zhen et al., 2008) (Movassaghi et al., 2016) (Hanlen et al., 2010).

For example, (Zhong et al., 2022) states that a WBAN can have a maximum of 20 nodes since each main frame of duration one second is divided into no interfering time slots of 50 ms, allowing 20 nodes to broadcast orthogonally.

In this paper, there are two networks, the first one represents a network consists of 20 nodes, and the second one has 10 nodes representing a smaller network.

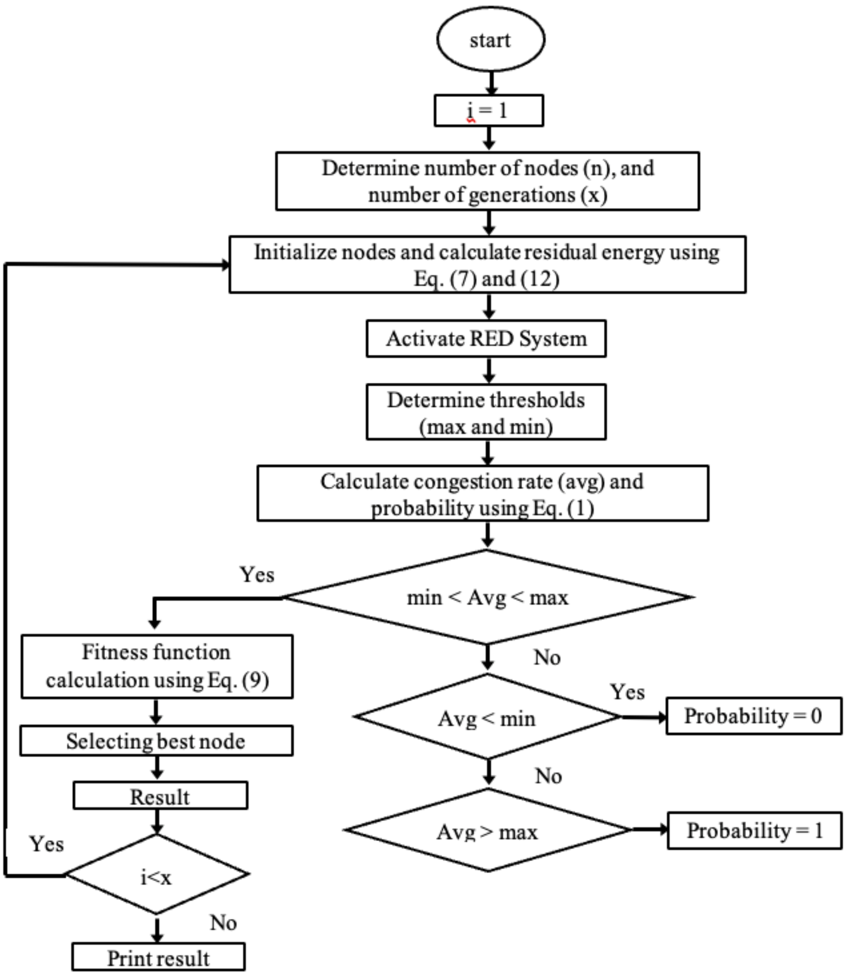

Figure 3: The process by which FA & RED is implemented for congestion control in WBAN

3 Results and Discussion

Numerous tools and software platforms are available to streamline the simulation process, offering environments that closely approximate real-world Wireless Body Area Network deployments. These tools allow for the implementation of algorithms, adjustment of main parameters, simulation environment configuration, and result visualization (Saha et al., 2021).

In this paper, the Firefly algorithm and RED system have been implemented and applied in a WBAN environment using MATLAB. The characteristics and parameters related to WBAN and our proposed algorithm utilized in the simulation are shown in Table 2.

Table 2:Input parameters for simulation in the first scenario

Parameter	Value
Nodes	10
Alpha	1
Theta	0.97
Iterations	100
Eelec	$96.9 * 10^{-9}$
Eamp	$2.71 * 10^{-9}$
Et	$50 * 10^{-9}$
Ed	$100 * 10^{-9}$
Packet Size	4000
Current energy	$0.5 * 10^{-9}$
Min^{th}	30%
Max^{th}	90%

When the algorithm was repeated for 100 generations, the performance was evaluated through simulation experiments and compared with different congestion rates.

3.1 First Scenario (20 nodes)

It can be observed that the Firefly algorithm searched for the optimal solution for the target function represented by equation (9) during 100 iterations or generations and produced curves that express the results of the algorithm’s search. The algorithm's success in determining the best value for the fitness function was shown by the curves in the first case, which were colored green, red, and blue, respectively, for congestion rates of 70%, 60%, and 40%. Figure 4 outlines the algorithm performance with three different congestion rates and 20 nodes.

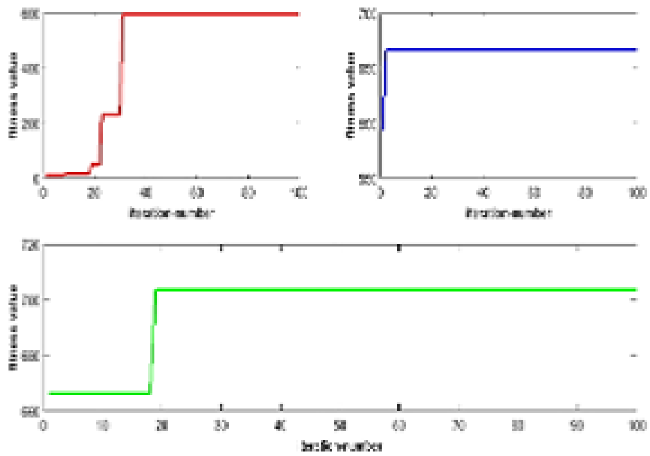

Figure 4: The firefly algorithm performance for each congestion rate in the first scenario

Figure 5 as shown below combines all the previous curves presented in Figure 4 in one form to simplify the comparison.

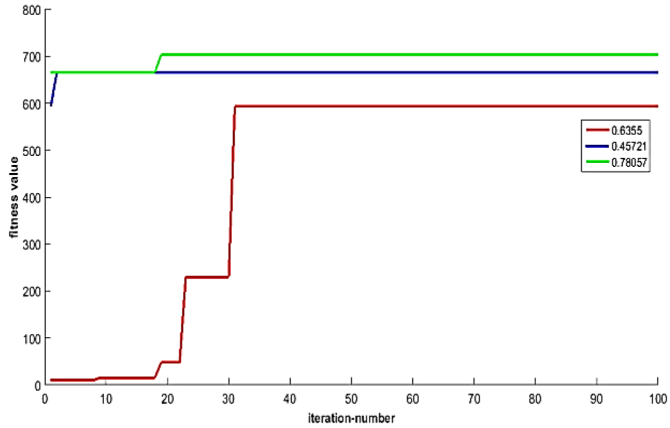

Figure 5: Comparison between the curves according to each congestion rate in the first scenario

3.2 Second Scenario (10 nodes)

In the second case, the algorithm's performance was depicted by curves using green and red, respectively, for congestion rates of 40% and 80%. As for the results, the best values were close to each other. In addition to that, the algorithm returns the coordinates of the node that gave this value, which in our case is considered the optimal node. Figure 6 outlines the algorithm performance with three different congestion rates and 10 nodes.

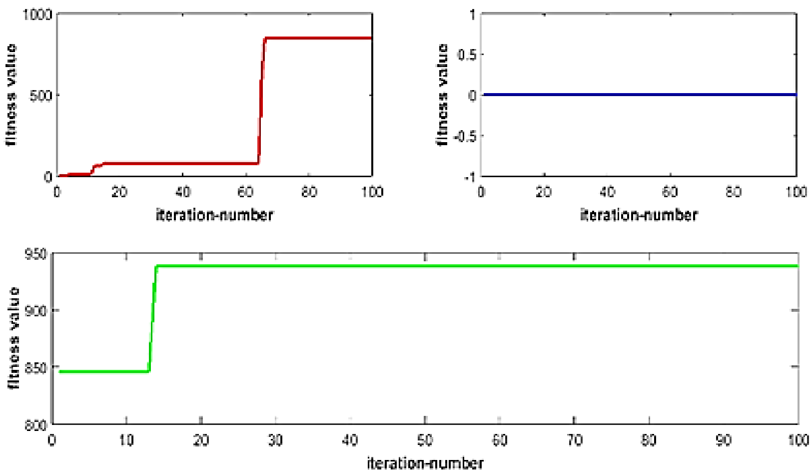

Figure 6: The firefly algorithm performance for each congestion rate in the second scenario

Figure 7 combines all the previous curves presented in Figure 6 in one form to simplify the comparison.

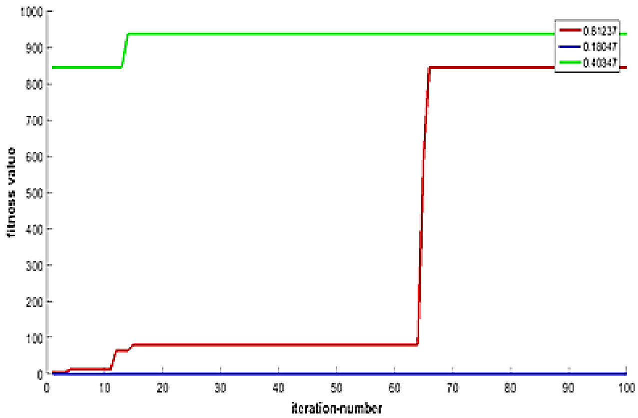

Figure 7. Comparison between the resulting curves according to each congestion rate in the second scenario

We conclude from this that when the congestion rate became between the two pre-determined thresholds, the algorithm began searching for the best node achieving the highest value of the goal function.

However, in the case where the congestion rate is less than the lower threshold, the probability of congestion is zero, or if the congestion rate is higher than the upper threshold, the probability of congestion occurring is equal to one. In both cases, there is no need to perform the algorithm as shown in Figure 8, which shows the green and red curves for a value of 20% representing congestion. We notice that in the case of a value of 20%, which is less than the minimum threshold (30%), the algorithm stops searching, while it completes its work when the congestion rate becomes between the two thresholds.

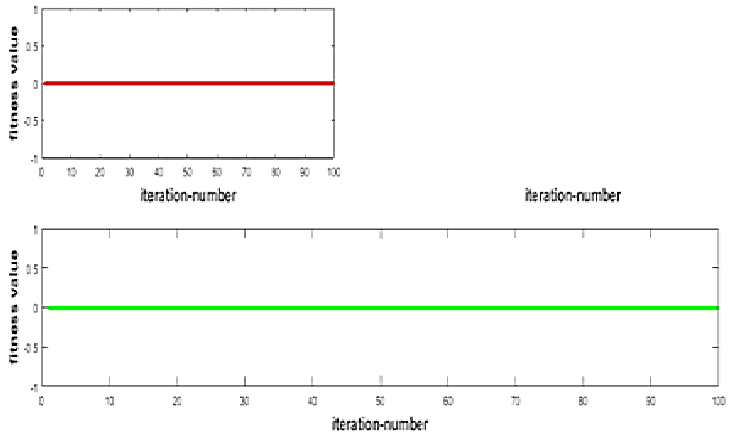

Figure 8: Cases of the algorithm not working

It can be observed that the function (cost function) that represents the final objective function of the optimization process is the most important factor in evaluating the outcome of the whole process.

3.3 Comparison between the two scenarios in terms of statistical criteria

After repeating the execution of the required algorithm 100 times (rounds) in each scenario separately, the results were collected and compared in terms of standard deviation, standard error, and normality testing using the Agostino & Pearson test which is a test for normal distribution, it first computes the skewness and kurtosis to quantify how far from Gaussian the distribution is in terms of asymmetry and shape. It then calculates how far each of these values differs from the value expected with a Gaussian distribution, and computes a single P value from the sum of these discrepancies. It was used because it is a versatile and powerful normality test (DEMİR, 2022). When comparing the two scenarios in terms of statistical criteria such as standard deviation and standard error, we obtain the following representation of data as shown in Figure 9.

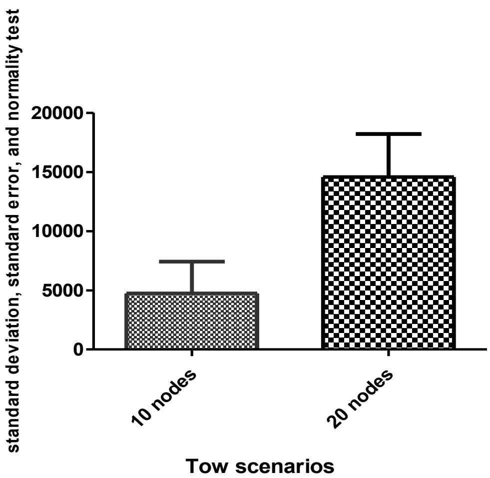

Figure 9: Comparison between two scenarios

It can be observed that:

1- In terms of standard deviation, the scenario (20 nodes) was worse than the scenario (10 nodes), because the values have a larger scattering in comparison with a smaller network.
2- In terms of standard error, the scenario (10 nodes) was better than the scenario (20 nodes).
3- About the normal distribution, the scenario (10 nodes) has a normal distribution in comparison to the other scenario.

4 Conclusions

In this research, the metaheuristics algorithm (Firefly algorithm) and the RED system were applied to control the congestion problem in WBAN. For each congestion rate that falls between the lower and upper thresholds, the algorithm searches for the optimal solution for the goal function, which includes factors (distance, the remaining energy, and congestion probability). If the congestion rate is less than the lower threshold, the probability of its occurrence is zero, and if it exceeds the upper threshold, the probability becomes one, and in both cases, the algorithm does not run. This explains the ability of the Firefly Algorithm to effectively reach optimal solutions in complicated problems. A small wireless body network with an average of 10 nodes is considered more stable than a network with a larger number of nodes, as it gives better results in terms of standard deviation, standard error, and normality testing. These results explain the ability of the Firefly Algorithm to effectively reach optimal solutions to complicated problems. In the future, a more complex target function can be designed that takes into account parameters other than energy and distance. Another recommendation is working on a broader network consisting of many WBANs, such as a hospital, for example.

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