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An Optimal Routing Protocol Using Multi-Objective Whale Optimization Algorithm for Wireless Sensor Networks

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Abstract

Recently, wireless sensor networks (WSNs) have been used increasingly in military and civilian fields, especially for target tracking and environmental monitoring purposes. The main obstacle in the way of broader use of WSNs is the limited charge of sensors used in these networks. Research has shown that the power consumption of these sensors can be reduced through the sensible use of routing protocols and multi-hop communications. While cluster-based multi-hop protocols have shown to be very effective in reducing power consumption of sensors, they tend to suffer from power balance and data conflict problems. This paper applied the multi-objective whale optimization algorithm to develop a cluster-based routing protocol for WSNs. For improving the time division multiple access cycle, a bottom-up continuous time slot allocation scheme was used with the purpose of preventing data collision in multi-hop communications, as well as maximizing the sleep period of all idle nodes, including the cluster heads. Simulations performed in MATLAB demonstrated the ability of the developed protocol in prolonging the network lifespan by almost 100% by balancing the power consumption of its sensors.

Keywords: Multi-Objective Whale Optimization Algorithm, Routing Protocol, Wireless Sensor Networks
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1. Introduction

Networks consisting of large numbers of nodes (few tens to thousands) are termed Wireless sensor networks (WSNs), which have characteristics of self-organizing, low cost, and random deployment [1]–[4]. Sensor nodes are distributed randomly in the monitoring area and sense signals in the surrounding environment through built-in sensors, send then the collected data to base station. These networks can be used in medicine [5]–[8], environmental monitoring [9], forest fire detection [10], military [11]–[13], precision agriculture [14], [15], industry [16]–[18], etc. Thanks to their great potentials, WSNs recently have gained the high interest of researchers [19]–[21]. However, an important factor affecting the application of WSNs is limited energy. Sensor nodes usually carry small batteries, which tend to be difficult to recharge or replace in complex environments [22]–[26]. Therefore, in practical applications, each node in the WSNs is required to consume energy as little as possible for data collection and transmission to increase network lifespan. To maximize network lifetime through energy conservation, routing protocols should be more energy efficient. Therefore, reducing node energy consumption has become the main aim of routing protocols.

The protocol of clustering routing is known to have better energy consumption than other WSN routing protocols. In clustering routing, WSN is partitioned into manifold clusters, each consisting of a cluster head and several common nodes. Cluster heads can form a higher-level network until the highest-level base station. A typical clustering routing is Low energy adaptive clustering hierarchy (LEACH) [27]. LEACH applies a cluster election algorithm to split the WSNs into numerous clusters. The cluster common nodes send the data collected to the cluster head, whereby they are forwarded to base station after a data aggregation procedure. LEACH uses a threshold formula to select cluster heads in every round, which effectively avoids the excessive energy usage of cluster heads. In addition, data aggregation can reduce the amount of communication, thus prolong network lifetime.

LEACH-C [28] is an improved centralized routing protocol based on LEACH. The difference from the LEACH is that the cluster heads selection is the responsibility of the base station, which chooses a group of nodes with higher density as optimized cluster heads by simulated annealing algorithm. However, in the clustering routing, the cluster heads need to be accountable for collecting, aggregating, and transmitting data, which consume more energy than common nodes, resulting in unbalanced energy consumption.

Another routing protocol with the ability to efficiently relay packets in the network is multi-hop routing. In the multi-hop routing protocol, an algorithm is introduced to construct a tree topology, with base station as the root node. According to reports, using multi-hop routing leads to energy saving in WSNs [29]. Common nodes send data to intermediate nodes, which perform data aggregation and then forward data to the succeeding intermediate node until the data is sent to base station. LEACH-based multi-hop protocols include inter-cluster multi-hop protocols, intra-cluster multi-hop protocols, and combination of intra- and inter-cluster protocols. However, LEACH-based multi-hop protocols tend to suffer from imbalanced power consumption and data conflict problems.

Cluster head selection is an optimization problem and turns out to be an NP-hard problem as well [30]. Canonical optimization techniques are ineffective when the network is scaled up. Multi-objective whale optimization algorithm (MOWOA) is an algorithm of bio-inspired optimization capable of solving NP-hard problems. It is easy to implement, gives the high-quality solution, and possesses commendable exploration and exploitation characteristics, leading to quick convergence without getting trapped in local minima.

In this paper, the main emphasis is on the selection issue of the cluster head and a MOWOA based algorithm is presented. The algorithm helps choose the cluster heads among the sensor nodes efficiently while considering the node residual energy. The algorithm is evaluated extensively to show its superiority over contemporary routing techniques.

The remainder of the study is organized as follows. Section 2 introduces related works and analyses current problems. Section 3 goes over our proposed method in detail. In Section 4, we conducted simulation experiments for the protocol we proposed and compared the results. Finally, we made a conclusion based on the experimental results.

2. Related Works

Nabavi et al. propose a routing protocol using a multi-objective greedy approach for WSN. This method first finds the shortest random path in WSN using a greedy search. The greedy local search is known to have higher convergence rate than other similar methods and can reach the optimal solution for some problems. In the proposed method, the nodes have a roughly symmetric power consumption and the network lifetime declines at a gentle slope [31].

In a study by Mukhtar et al., they have introduced a protocol for prolonging network lifetime in WSNs. This protocol, which is called region-based mobile routing, divides the network field into two parts based on distance from base station, which is positioned at the network domain center. Cluster heads in region 1 closer to base station establish a direct link with base station with a normal power consumption rate. Meanwhile, a series of mobile routing nodes follow a specified path in region 2 to collect data from cluster heads of this area and forward them to base station after aggregation. This setup results in less power consumption in the network, which leads to prolonged lifetime [32].

Nabavi et al. present a multi-objective particle swarm optimization algorithm-based energy-aware routing protocol. The fitness function of the particle swarm optimization algorithm is used in the proposed method to select the optimal cluster head based on QoS goals such as residual energy, link quality, end-to-end delay, and delivery rate. Because it balances the goals of QoS criteria, the proposed approach consumes less energy and extends network lifetime than other methods [33].

In a study by Fang et al., these have researchers introduced a protocol to prolong network lifetime and improve its availability and its resistance against attacks. In this protocol, which is called LEACH-TM, energy efficiency has been improved by constraining the size of clusters and controlling residual energy and density of neighbor nodes by using a number of dynamic cluster heads. This protocol is equipped with a trust management scheme, which incorporates the trust-related attributes into the cluster head selection process, leading to higher power efficiency as well as security [34].

To improve the energy efficiency of routing in WSNs, Singh et al. propose a mobile sink protocol based on the genetic algorithm (GA). In this protocol, the network is partitioned into an optimum number of rectangle-shaped clusters. The sink movement path is designed so that it moves through at least one boundary of each cluster, and the best data collection points along the sink movement path through each cluster are detected. These best points, which are called the optimal sink data collection points, have less energy intensive data transmission than the sink and cluster nodes. The method not only optimizes the sink location but also determines the optimum place of each cluster head. In this protocol, cluster head selection is performed in real-time on the basis of each node's residual energy and its distance from the optimal cluster head as well as the cluster head selection count in previous rounds of data transmission. Singh et al. have claimed that this method achieves better lifetime, residual energy, and throughput than the existing state-of-the-art protocols by reducing the average communication distance of the entire network [35].

In another study by Nabavi et al., they have used the multi-objective cultural algorithm to develop a routing protocol in WSNs. In the suggested protocol, individuals are considered as the central sensors of the cluster, the fitness function of which possesses the highest value on the basis of QoS objectives for that sensor. In fact, in each cluster of sensors designed in the region under consideration, the node with the highest fitness value (determined by the fitness function) is chosen as the cluster head, gaining the responsibility to transmit data packets. The protocol proposed in the present paper has lower average consumed energy and longer lifetime compared to other earlier protocols. The lesser use of energy and prolonged lifetime of the proposed protocol suggests balance of consumed energy in this protocol ad the later death of sensor nodes, resulting from precise clustering and observing main network parameters [36].

Jin et al. have analyzed the energy consumption of relay transmission and non-relay transmission and proposed an optimized relay cost model to select the optimal relay nodes. To minimalize the power usage of relay transmission, a multi-start minimum spanning forest algorithm was used for conducting relay node selection simultaneously with network generation. In order to realize multi-hop transmission with data aggregation, reduce data collision and maximize the sleep period of idle nodes, they designed a method of bottom-up continuous time slot allocation and modified the TDMA cycle. The data sending frequency of different cluster heads at the inter-cluster transmission stage were matched at the lowest delay, and the cluster heads could also sleep properly in the non-working time [37].

Radi et al. have used the Multi-Objective Immune Algorithm (MOIA) for developing a protocol called Joint Nodes and Sink Mobility-based Immune Routing-Clustering (JNSMIC) to handle the motion of sink and sensor node simultaneously. In this protocol, a mobile sink is used to deal with the hot spot problem. Also, MOIA is applied to divide the network into a number of clusters and find the temporary location of the mobile sink. This clustering process can be conducted with different objectives, including improved energy saving, link connection time, network coverage, residual energy, and mobility. The protocol initiates the clustering process when the remaining energy drops below a certain threshold to reduce the overhead control packets and computational time. Also, to avoid packet drop owing to the cluster head failure, the protocol selects a deputy cluster head for each cluster to serve as substitute when the first cluster head fails [38].

Nassirpour et al. have proposed a clustering method through memetic algorithm. The proposed method includes two stable clustering and data transmission phases. In clustering phase, clusters are formed and in data transmission phase based on schedule, collected data would be transferred by sensor nodes to cluster head. In this paper, operation of specifying cluster heads is supposed to take place in base station or sink. Base station or sink is a powerful central processing unit with unlimited amount of energy, which is capable of classifying information related to energy and position of network nodes (after receipt) in clusters that are equal concerning energy consumption and total amount of work done, based on memetic algorithm. After formation of clusters, nodes will recognize their own cluster heads and send their own data to related cluster head, based on TDMA schedule specified and sent by cluster heads. Each cluster formation phase and permanent state is called a round. At the end of each round, clustering operation would be performed again; and, new nodes would be selected to play the role of cluster head [39].

A reliable energy-aware routing protocol has been introduced by Ma et al., in which data forwarding is managed based on a parameter called Reliable Energy Cost Based on Distance (RECBD). In order to decide when to forward data from a node, the protocol examines the RECBD value of that node and other nodes that fall inside its communication range. Each node's RECBD value is determined by its distance from the relay node, the distance between the relay node and the sink node, the nodes' current residual energy, and the link quality. The purpose of this protocol is to optimize message delivery rate and power consumption during communication with the sink node [40].

In a study by Hawbani et al., the data routing problem has been modeled as an in-zone random process. In the algorithm proposed by these researchers, the probability of forwarding in each hop is a function of transmission distance, perpendicular distance, direction angle, and residual energy probability distributions. The performance evaluations and large-scale simulations conducted in this study showed the advantage of the suggested algorithm over its state-of-the-art counterparts concerning network lifetime, routing efficiency, and power consumption [41].

3. Methodology

This section provides a description of Multi-Objective Whale Optimization Algorithm (MOWOA), the network model, and the proposed MOWOA-based method.

A) Multi-objective whale optimization algorithm

This algorithm is the multi-objective version of the whale optimization algorithm stimulated by the feeding behavior of humpback whales, which are among the world's biggest mammals and may grow to over 30m long and weight more than 190t. MOWOA is highly similar to WOA in term of how the feeding behavior; it is mathematically modeled to encircle prey, attack with a bubble net, and hunt for prey [42].

Encircling Prey: This technique is based on the assumption that the position of the search space is not known in advance. Thus, it initially treats the current position as the best solution and then updates the position using the equations below:

$$\vec{D} = \left|\vec{C}.\vec{X}*(t) - \vec{X}(t)\right| \quad (1)$$

$$\vec{X}(t+1) = \left|\vec{X}*(t) - \vec{A}.\vec{D}\right| \quad (2)$$

In these equations, $\vec{X}$ is the current position at the current iteration t, $\vec{X}*$ represents the best position ever reached, and $\vec{A}$ and $\vec{C}$ are coefficient vectors, all defined as:

$$\vec{A} = 2\vec{a}.\vec{r} - \vec{a} \quad (3)$$

$$\vec{C} = 2.\vec{r} \quad (4)$$

Here, $\vec{a}$ represents linearly decreasing in the interval $[0,2]$ and $\vec{r}$ indicates a random vector in the interval $[0,1]$.

Bubble-net attacking: In this stage, the algorithm starts to exploit the global solution in the search space. This stage makes use of two mechanisms: shrinking encircling and spiral position update, each with a 50% probability of being activated. Figure 1 shows a diagram of the natural phenomenon from which these mechanisms have taken inspiration.

Both mechanisms are mathematically expressed using the equation below:

$$X(t+1) = \begin{cases} \vec{D}.e^{bl}.\cos(2\pi l) + \vec{X}*(t) & p \geq 0.5 \\ \vec{X}*(t) - \vec{A}.\vec{D} & p < 0.5 \end{cases} \quad (5)$$

In this equation, $\vec{A}$ represents random value in the interval $[-a, a]$ where a represents decreasing in the interval $[0,2]$, b indicates a constant that determines the spiral shape, l is a random value in the interval $[-1,1]$, and $\vec{D}$ is well-defined as:

$$\vec{D} = \left|\vec{X}*(t) - \vec{X}(t)\right| \quad (6)$$

As before, $\vec{a}$ is linearly decreasing in the interval $[0,2]$ and $\vec{r}$ indicates a random vector in the interval $[0,1]$.

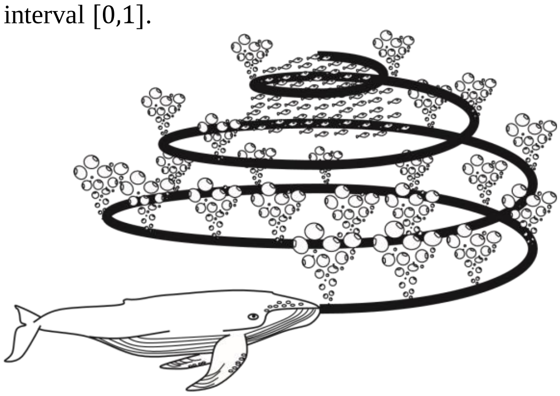

Fig. 1. Attacking and search for prey mechanisms

Search for prey: This stage is inspired by how whales detect locations of other whales and start searching for prey. In this stage, the algorithm explores the search space to find eligible solutions by updating the fitness function by random values than the superlative results.

$$\vec{D} = \left|\vec{C}.\vec{X}_{rand} - \vec{X}\right| \quad (7)$$

$$\vec{X}(t+1) = \vec{X}_{rand} - \vec{A}.\vec{D} \quad (8)$$

In the above equation, $\vec{X}_{rand}$ is a randomly generated position vector. Figure 2 shows a graphical representation of the exploitation and exploration stages.

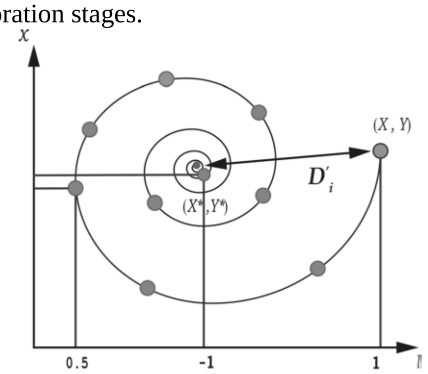

Fig. 2. Spiral updating position

Non-Dominance and Archive Grid: The multi-objective problems are solved by using an archive controller to achieve the non-dominated solutions and then save the best obtained solutions in an archive repository.

Implementation: MOWOA is implemented through the following procedure:

(1) Initializing the whale's population as follows:

$$X = \begin{bmatrix} X_1 \\ X_2 \\ \cdots \\ X_n \end{bmatrix} = \begin{bmatrix} x_{1,1} & \cdots & x_{1,d} \\ x_{2,1} & \cdots & x_{2,d} \\ \vdots & \vdots\vdots\vdots & \vdots \\ x_{n,1} & \cdots & x_{n,d} \end{bmatrix} \quad (9)$$

Where n indicates the number of whales, d indicates the dimensionality.

(2) Computing and evaluating the fitness value of the whale population. Depending on the problem, there will be at least two fitness values to evaluate for each whale. For the problems with two objectives like F_1 and F_2, this evaluation is formulated as follows:

$$FX = \begin{bmatrix} F_1(X_1) & F_2(X_1) \\ F_1(X_2) & F_2(X_2) \\ \vdots & \vdots \\ F_1(X_n) & F_2(X_n) \end{bmatrix} \quad (10)$$

(3) Determining the non-dominated solutions to initialize the archive repository.
(4) Identifying the best whale $\vec{X}*$.
(5) Updating the whale positions.
(6) Preventing the searching whales exiting the search space.
(7) Re-calculating the fitness function.
(8) Updating $\vec{X}*$ if better solutions exist.
(9) Run the algorithm for a fixed number of iterations.

Figure 3 shows the pseudocode of WOA.

```
Set the whale's population X_i (i = 1, 2, ..., n)
Compute the fitness of every search agent
X* = the superlative search agent
while (t < maximum number of iterations)
  for every search agent
    Update a, A, C, l, p
    if1 (p < 0.5)
      if2 (|A| < 1)
        Update the current search agent's position
      else if2 (|A| ≥ 1)
        Choose a random search agent (X_rand)
        Update the current search agent's position
      end if2
    else if1 (p ≥ 0.5)
      Update the current search position
    end if1
  end for
  Check if any search agent goes beyond the search space
  Compute each search agent's fitness
  Update X* if a better solution exists
  t = t + 1
end while
return X*
```

Fig. 3. Pseudocode of the WOA

Theoretically, WOA falls in the category of global optimizers as it makes use of both exploration and exploitation schemes. Furthermore, the hyper-cube mechanism of this algorithm entails defining a search space in the vicinity of the best solution and instructing other search agents to exploit the current best record within this space.

B) Network Model

Model Assumptions: The protocol proposed in this study is on the basis of the following model assumptions:

1. All nodes are distributed randomly in the monitoring region, and the position coordinates are known. At the beginning of each round, a data packet with its own energy and position information is forwarded to the base station.
2. The nodes are consistent, having the same initial energy and data aggregation capability.
3. All nodes are static and do not move during communication.

Energy Consumption Model: This study used the same energy consumption model as in [27]. The energy used by a node to transmits a k-bit data packet to a location at a distance of d consists of the transmission circuit loss and the power amplification loss as formulated below:

$$E_{TX} = \begin{cases} E_{elec} \times k + \varepsilon_{fs} \times k \times d^2 & d < d_0 \\ E_{elec} \times k + \varepsilon_{mp} \times k \times d^4 & d \geq d_0 \end{cases} \quad (11)$$

Once a node receives a k-bit data packet, the energy it consumes is the loss of the transmitting circuit as formulated below:

$$E_{RX} = E_{elec} \times k \quad (12)$$

Node's fuse k-bit data, and the energy consumed is:

$$E_{DA} = E_{da} \times k \quad (13)$$

Where E_{elec} is the circuit energy consumption coefficient, ε_{fs} is the free space amplification coefficient, ε_{mp} is the multipath fading amplification coefficient, E_{da} is the data aggregation energy consumption coefficient, d indicates the transmission distance, and d_0 indicates the transmission distance threshold and is obtained by the following:

$$d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} \quad (14)$$

The above analysis indicates that the transmission distance should be reduced as much as possible so that more data can be sent with lower energy consumption.

C) Proposed Method

The proposed method operates based on a centrally controlled algorithm enforced from the base station. This algorithm operates in rounds. Each round starts with a setup phase similar to the one in PSO-C [30]. Each setup phase begins with all nodes sending their energy and location information to the base station. This information is used by the base station to estimate the mean residual energy and then make the nodes with more residual energy than the mean energy value eligible for being selected as the cluster head. WOA is then executed in the base station to determine the 10 cluster heads that give the lowest (best) fitness function values.

It is assumed that the proposed MOWOA is implemented on a set of randomly deployed stationary nodes in a sensor network. There are n cluster head search agents (whales) in the form of $CH = CH_1, CH_2, \ldots, CH_n$. Since sensor nodes are stationary and the location of search agents (whales) should be imitated, the position of each search agent (candidate cluster head) is represented by CH_i in the 2D space indicating the node's position $[Pos_i(t) = xi(t), yi(t)]$. The method then takes the location of the best search agent and uses it to identify the best solution, base on which the best cluster heads will be selected.

The initial spawn location of the search agent is random and upon spawning the information of the nearest node will be cloned to its position. The next step is to compute every search agent's fitness value and choose the best for reference. Next, the parameters of MOWOA are updated so that other search agents are spawned according to the position of the best agent.

The cluster head selection is performed on the basis of a fitness function. In MOWOA, this function plays a critical role in the exploration mechanism (search for prey). The factors of this function are the attributes of node, including how much energy it has (Er) and how many nodes are positioned in its neighborhood.

The fitness function is formulated as follows [43]:

$$f(CH_i) = p1|N(CH_i)| + p2\,\Sigma(CH_E) \tag{15}$$

In this equation, $p1$ and $p2$ are randomly values between 0 and 1, $N(CH_i)$ is the list of all nodes in the neighborhood of the cluster head CH_i, and CH_E is the neighbor node's residual energy. Here, the larger the fitness value, the better the solution because a node must have many nodes in its neighborhood as well as enough residual energy to become the cluster head.

Once the optimal layout of cluster heads and their associated nodes are determined, the base station broadcasts the IDs of cluster heads throughout the network. Each of these cluster heads turns into a control point for its neighborhood, responsible for data gathering and transmission. Moreover, a Time Division Multiple Access (TDMA) scheme is used to avoid data collision amongst cluster members. This also enables the cluster members to be in sleep-wake cycle where, they need to be awake only in their respective TDMA time slots and conserve energy during its sleep cycle. In the sleep cycle, the nodes may be in a low power state and conserve energy. At each round termination, each cluster head receives and combines the data of all members of its cluster and sends the fused data to the base station. The data between base station and cluster head is done using Carrier Sense Multiple Access (CDMA) approaches which is similar to [44]. The pseudocode of proposed method is given by Figure 4.

```
while1 (r < rmax)
  while2 (t < tmax)
    for each search agent CH_i
      Clone the nearest node to CH_i
      Compute fitness according to (13)
      Calculate the coefficient vectors using (1)-(8)
      Update the whale's position
      Update the X* best position if X is better than X*
      Update the fitness function for all search agents
    end for
  end while2
CH = Nearest node to the X* position
end while1
```

Fig. 4. The proposed MOWOA Pseudocode

4. Result and Discussion

MATLAB 2021a was used to analyse and evaluate network performance and the energy consumption of the proposed protocol. The simulation parameters are shown in Table 1.

Table.1.
Simulation Parameters

Parameters	Value
ε_{fs}	10 pJ/bit/m^2
e_{da}	5 nJ/bit
E_{elec}	50 nJ/bit
Packet size	2000 bits
Message size	200 bits
Node initial energy E_0	0.5 J
Total number of nodes	300
Base station location	(50, 50) m
Simulation area	100 × 100 m^2
Number of iterations	200

The evaluation conducted in this study aimed to determine the improvement that can be achieved with proposed approach. The measures of this evaluation were residual energy, death process, energy consumption and network lifetime. Figure 5 illustrates the sensor nodes' average residual energy in the network.

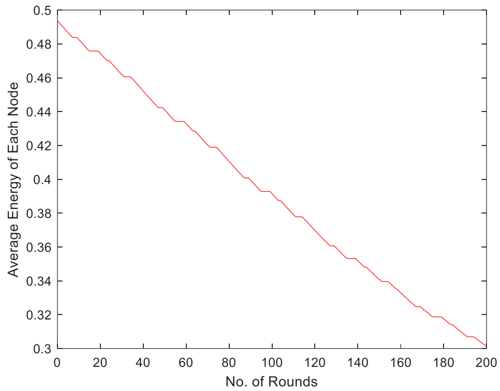

Fig. 5. Average residual energy of sensor nodes

As shown in Figure 5, the network nodes have an almost symmetric energy consumption, which means all node are likely to expire at the same time (rather than some expiring sooner than others). Thus, the power levels of all nodes drop slowly and uniformly, resulting in longer network lifetime.

Figure 6 illustrates the sensor nodes' death process in the network.

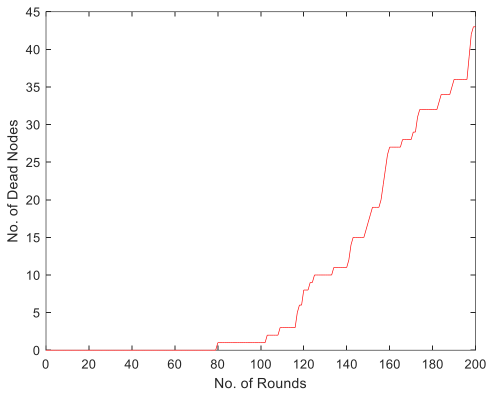

Fig. 6. Death process of the sensor nodes

As shown in Figure 6, the death of the first sensor occurred after 79 rounds. Thus, once the first sensor is dead, the other sensors also are dead increasingly.

Figure 7 illustrates the comparison of prior methods (such as MOPSO [33], Clustering Hierarchy [45], LD2FA-PSO [46], FBUC [47], EAUCF [48], EPSO [49], PSO [50], GLBCA [51] and GA [52]) with the proposed method concerning network lifetime.

In Figure 7, it can be seen that the protocol can have a huge impact on the network lifetime by affecting how much energy it consumes.

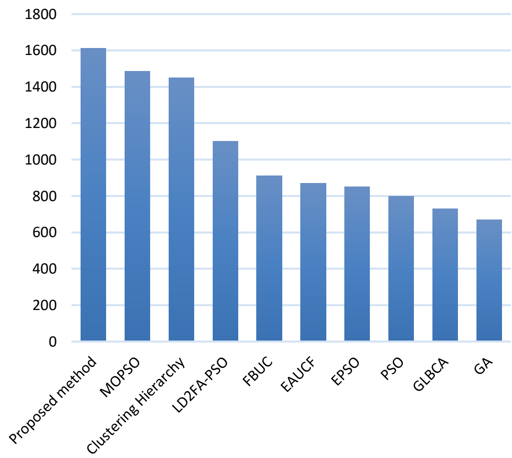

Fig. 7. Comparison in terms of the network lifetime

Figure 8 illustrates the comparison prior methods with the proposed method concerning energy consumption.

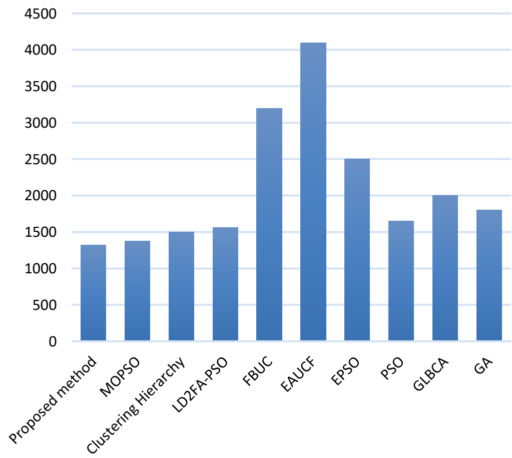

Fig. 8. Comparison in terms of the energy consumption

As shown in Figure 8, the proposed method decreases energy consumption compared with other ones, respectively.

5. Conclusion and Future Works

In the present paper, the multi-objective whale algorithm has been used to develop an optimal routing protocol in wireless sensor networks (WSNs). To reduce the overall energy consumption of the sensor network, the suggested protocol makes energy-aware decisions about which nodes to use as cluster heads using a fitness function that considers the residual energy of each node and the total energy of nodes in its neighbourhood. The performance of the proposed method was evaluated against other standard contemporary routing protocols. The performance of various protocols is evaluated for energy efficiency, network lifetime and throughput. The simulation results showed that the suggested algorithm outperforms other routing algorithms concerning residual energy, network lifetime, throughput and longer stability period. In conclusion, this study presents a robust energy efficient routing algorithm on the basis of multi-objective whale optimization, which has the ability to select cluster heads for maximum energy utilization in WSN. It has been shown that the proposed method outperforms other contemporary routing protocols.

Future works will aim to develop a routing algorithm more efficient by considering more factors in the fitness function like energy balancing. An algorithm that works for heterogeneous WSN can also be developed. The optimization can also be improved by using hybrid optimization techniques to increase the search efficiency in order to converge at optimal solutions quickly.

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