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Enhancement of cluster based routing protocol for wireless mesh networks with modified chicken swarm optimization

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Abstract:

Wireless Mesh Networks (WMNs) offer a promising approach to pervasive communication with efficient network coverage using minimal infrastructure. However, current WMN routing protocols are inefficient due to high energy consumption. This is caused by limited battery life of nodes, uneven distribution of traffic (load imbalance), and long data transmission distances, all of which shorten network lifetime. This paper proposes a new routing protocol for WMNs called Modified Chicken Swarm Optimization-based Efficient Cluster Head Selection (MCSO-ECHS). The MCSO-ECHS leverages the network gateway to select optimal Cluster Heads (CHs). An objective function, considering both residual energy and node distance, is used for CH selection. The MCSO algorithm then refines the selection process to ensure balanced energy consumption among these energy-constrained nodes. This approach prolongs the network lifetime and improves overall energy efficiency. Simulation results demonstrate that MCSO-ECHS outperforms existing protocols in terms of energy consumption, network lifetime, throughput, end-to-end delay and packet delivery ratio, significantly enhancing the energy efficiency of WMNs.

Keywords: Wireless Mesh Networks (WMNs); Cluster head selection; Modified Chicken Swarm Optimization (MCSO); Energy-efficient routin

1. Introduction

The future of communication is all about connecting everyday objects to the internet using the Internet of Things (IoTs). This lets us gather information from these devices and use it in things like ad-hoc networks, wireless sensor networks (WSNs) and Wireless Mesh Networks (WMNs) with no fixed infrastructure [1, 2]. WMN is a game-changing technology that promises a more user-friendly, efficient, and affordable way to connect through a widespread wireless network. WMN features radio nodes that self-organize in a mesh pattern, forming a network where devices automatically connect with each other and work together to maintain the overall connection. The combined signal range of radio nodes acting as a unified network is referred to as a mesh cloud. Access to this mesh cloud relies on seamless collaboration between the nodes to establish a radio network. Mesh networks boast resilience due to redundancy. If a node fails, communication continues between the remaining nodes, either directly or via alternative paths involving one or more intermediaries. WMNs are made up of two nodes: Mesh routers for data forwarding and mesh clients for user access. Mesh routers go beyond the standard routing functions for gateways and bridges found in traditional routers. They include additional routing protocols specifically designed to optimize data flow within the mesh network, ensuring seamless connectivity across all its nodes [3].

Most wireless network applications need to be time saving and reliable for efficient data communication. The limited lifespan of batteries in wireless nodes restricts their operation due to the need for frequent recharging or replacement. This is especially problematic in areas like dense forests, battlefields, and disaster zones where access to charging or spare batteries is difficult [4–8]. To ensure efficient data flow and extend network lifespan, routing protocols manage traffic distribution and network balancing. These protocols are of two main categories: Flat and hierarchical. The flat protocols treat all devices equally, but struggle with large networks due to challenges in managing traffic, ensuring seamless connections, and scaling effectively [9–11].

The hierarchical routing protocol was introduced to tackle the scaling and network balancing issues in the flat routing. This method is known as cluster-based routing. This method organizes nodes into clusters based on their energy levels. Within each cluster, there is a leader called Cluster Head (*CH*) responsible for communication with other *CH*s or Base-Station (*BS*) and Cluster Members (CMs) that send data to the leader [7, 12]. In large-scale applications such as in precision agriculture, WSNs benefit from clustering protocols for efficient data communication. This method is more efficient than a flat routing protocol. It uses fewer resources, conserves sensor node energy, works well on large scale networks, transmits smaller data packets, and distributes tasks evenly across the network [13]. There are two approaches to energy conservation for ad-hoc networks in WMNs, this includes Energy-Aware Routing (EAR) [14] and Cluster-Based Routing Protocol (CBRP) [15].

In the EAR protocol, the energy spent by the equipment is of utmost importance when considering the routing and traffic-engineering decisions to reduce the energy consumption of a network. CBRP is a different routing system that creates groups of devices in the network. Each group has a leader that collects data from its members and relays it to other group leaders. This way, CBRP reduces energy use, avoids traffic jams, and allows the network to grow bigger while saving even more power [16].

However, for sensor networks, grouping nodes into clusters with efficient Cluster Heads (*CH*s) is essential for maximizing network life. *CH*s play a key role in saving energy by taking over communication tasks for other nodes. Also, this efficiently impacts the data routing process to achieve the goal of the WSN. Hence, the selection action of the *CH*s becomes crucial and challenging to solve [17]. *CH*-selection is considered an optimization problem that is Non-deterministic Polynomial-time hardness (NP-hard) in nature [17, 18].

Recently, many bio-inspired meta-heuristic optimization algorithms have been proposed to solve this type of problem [10] among them is the chicken swarm optimization (CSO) [19]. Inspired by how chickens peck for food in a social hierarchy, the CSO algorithm uses a similar structure to solve complex engineering problems. The flock of chickens is divided into smaller groups with a rooster as the head. Each member follows its own movement patterns, and these groups compete within a defined social structure. However, the drawback of the CSO algorithm is its tendency to converge slowly and potentially get stuck in sub-optimal solutions instead of finding the globally optimal solution [20, 21]. To address these problems, there is a need to improve the behavior of the chicken swarm structure to dynamically adjust to the present situation [21].

Some of the works that have employed bio-inspired algorithms to ECHS are discussed herein. Rao et al. [17] developed a method called Particle Swarm Optimization based on an Energy-efficient Cluster Head Selection (PSO-ECHS) to choose energy-efficient *CH*s in WSNs. This method uses a technique called particle swarm optimization. To pick the best *CH*s, the method considers factors like distance within clusters, distance to the main receiver, and remaining energy in the sensor nodes. The method also includes a way for sensor nodes to join their chosen cluster head. Result showed that the method outperformed existing ones in various network setups. However, the protocol is limited in guaranteeing optimal solutions due to its slow convergence rate and can get easily trapped in large dimensional search space [22].

Kaviarasan et al. [11] worked on distributing network traffic or computational tasks evenly among numerous nodes to avoid bottlenecks, optimize resource usage, improve performance, and decrease latency. The protocol improved the performance of the network using an improved Lion optimization, However, the energy consumed in the processing of the data in the network was not considered. Jadhav and Shankar [23] proposed an energy Efficient Cluster Head Selection using Whale Optimization Algorithm (WOA-ECHS). The algorithm selected the best *CH*s with good energy aware behavior with the fitness function comprises of the node's residual energy and that of adjacent nodes. The simulation result obtained showed that the WOA-ECHS protocol outperformed other standard contemporary routing protocols but suffers slow convergence rate and computational complexities. Awan et al. [24] developed a method to save energy of constraint nodes in WSNs. This method grouped sensor nodes into clusters of varying sizes, with factors like remaining battery life and distance to the main station considered. This distributed approach extended the network lifespan through reduced energy use. The result confirmed the effectiveness of the method. Conversely, only the life span performance of the network was considered.

The author in [13] presented a location aware routing protocol for WSNs named gateway clustering energy-efficient centroid (GCEEC). The protocol improved the energy efficiency by choosing *CH*s based on a central location and assigned special gateway nodes to forward data to the *BS*. Simulation showed that GCEEC outperforms existing methods, making WSNs more practical for monitoring purposes. The reviewed works show that the existing routing protocols consume excessive energy. This is due to factors such as long transmission distances, uneven workload distribution and undefined network topology. These factors strain the battery-powered mesh nodes, reducing network lifespan. Consequently, those works experienced low data rates, limited throughput, high energy consumption and end-to-end delay. Therefore, the contributions of this paper are summarized as follows:

i. Propose a scalable, energy-efficient WMN routing protocol with cluster-head gateways.

ii. Optimize CH selection in modified chicken swarm optimization-based efficient cluster head selection (MCSO-ECHS) using an objective function that considers residual energy and node distances.

iii. Use MCSO with roulette wheel selection to optimize the problem and improve exploitation.

The paper is structured as follows; section 2 represents the proposed model, section 3 shows the simulation result, and section 4 concludes our work.

2. Efficient energy-aware routing protocol for WMN

The MCSO-ECHS routing protocol for WMN was achieved in two phases namely: The cluster formation phase and the CH selection. In the first phase, the weighed function which comprises of distance, residual energy and CHs node degree were considered. For the second phase, CSO algorithm was employed in the selection of the optimal CH. The diagram of the proposed cluster-based routing protocol is as depicted in Fig. 1.

2.1 Cluster formation for the MCSO-ECHS protocol

In the proposed routing protocol, the cluster formation employed weighted function 'CHw' used by mesh nodes to be assigned a cluster. The weighed function used is as discussed:

2.1.1 *CH* residual energy

A mesh node $'m_i'$ joins a CH_j with higher residual energy $'E_{res}'$ than other CH in the coverage area of the mesh node. The CHw is proportional to the residual energy of the CH_j and is expressed as.

$$CHw(m_i, CH_j) \propto E_{res}(CH_j) \tag{1}$$

2.1.2 Distance between mesh node to *CH*

To reduce the energy consumed, a mesh node must join a CH_j nearest to it and within its communication range. The CHw is inversely proportional to the Euclidean distance between the mesh node and the CH_j;

$$CHw(m_i, CH_j) \propto \frac{1}{\text{eucdis}(m_i, CH_j)} \tag{2}$$

2.1.3 Distance between *CH* to *BS*

The CH_j pass on the data aggregated from the mesh nodes to BS. The mesh nodes are joined to the CH_j closer to the BS and the CHw is inversely proportional to the Euclidean distance between the CH_j and the BS;

$$CHw(CH_j, BS) \propto \frac{1}{\text{eucdis}(CH_j, BS)} \tag{3}$$

2.1.4 *CH* node degree

A mesh node m_i joins a CH_j with a node degree lower to other CH in the coverage area of the mesh node. The CHw is inversely proportional to the node degree of the CH_j;

$$CHw(m_i, CH_j) \propto \frac{1}{\text{node degree}(CH_j)} \tag{4}$$

The cluster formation weighted function is then obtained by combining equations (1) to (4) which yields.

$$CHw(m_i, CH_j) = NL \times \frac{E_{res}(CH_j)}{\text{eucdis}(m_i, CH_j) \times \text{eucdis}(CH_j, BS) \times \text{node degree}(CH_j)} \tag{5}$$

where, $NL = E_o/E_{m_i}$ is the lifetime of each mesh nodes, E_o is the initial energy and E_{m_i} is the energy consumed by the mesh node in transmitting its data packet.

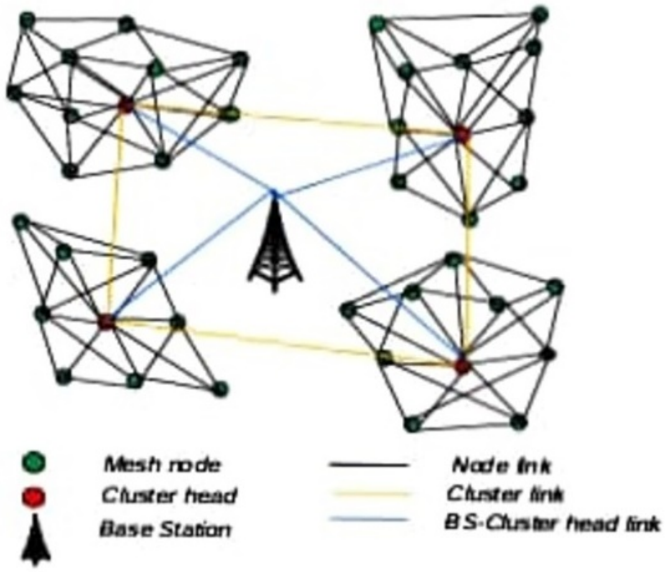

Figure 1. Proposed cluster-based routing protocol.

In the WMN, every node will compute its CHw using equation (5) and then join a CH which has the highest weighted value. The goal of the weighted function is to provide a cluster that makes non-CH mesh nodes to join a CH which helps in ensuring energy balance in the network. Unlike existing protocols, where the non-CH mesh nodes solely join the CH by using the distance, resulting to imbalance load at the CHs and consequently, deteriorates the energy efficiency.

2.2 Cluster head selection for the MCSO-ECHS protocol

In the second phase of the proposed MCSO-ECHS protocol, the choosing of the optimal CHs among the potential mesh nodes with an efficient energy characteristic for the prolongation of the lifetime of the WMN is of crucial importance. Both the distance of each of the mesh nodes which includes the average intra-cluster mesh nodes distance and BS distance as well as the energy consumption in transmitting the data packets are considered.

2.2.1 Intra-cluster distance of the MCSO-ECHS

The intra-cluster distance $'d_{\text{intra}}'$ is the average sum of the Euclidean distances of all the mesh nodes to their selected CH and is expressed as.

$$d_{\text{intra}} = \frac{1}{l_j}\sum_{i=1}^{l_j} \text{eucdist}(m_i, CH_j) \tag{6}$$

where, l_j is the number of mesh nodes in the cluster j. All the mesh nodes in the network consume a certain proportion of energy in transmitting the data packets to the selected CH in the intra-cluster communication range. For energy consumption to be reduced significantly, reducing the average intra-cluster communication distance is crucial.

2.2.2 Average sink distance of the MCSO-ECHS

The average sink distance $'d_{\text{avg-sink}}'$ is taken to be the ratio of the Euclidean distance between a CH_j and the BS to the number of mesh nodes in the cluster j which is expressed as.

$$d_{\text{avg-sink}} = \frac{\text{eucdis}(CH_j, BS)}{l_j} \tag{7}$$

Here, it is essential that the data packets are aggregated via the CHs and then routed onward to the BS in the data routing phase. The CHs must be with minimum distance to the BS. This implies reduced intra-cluster and average sink distance of all the CHs. This is obtained by minimizing the total distance which is dependent on the intra-cluster and the average sink distance of the CHs in equations (6) and (7) over number of clusters, which yields.

$$D^T = \sum_{j=1}^{q} (d_{\text{intra}} + d_{\text{avg-sink}}) \tag{8}$$

2.2.3 Energy consumption model of the MCSO-ECHS

In this section, the energy consumption model is a function of the energy used by each CHs selected in passing the data to the BS. The total energy $'E^T'$ of all the chosen CHs is expressed as.

$$E^T = \sum_{j=1}^{q} E_{CH_j} \tag{9}$$

where, E_{CH_j} is the energy consumed by each selected CHs and can be further expressed as.

$$E_{CH_j} = E_{tx} \times K \times d_r^{\alpha} + E_{rx} \times K \times N + E_{rx-CH} \times K \tag{10}$$

where, E_{tx} is the nodes' transmitter electronics energy, N is the overhearing node number, E_{rx} is the overhearing nodes receive energy, E_{rx-CH} is the cluster's transmitter electronics energy, K length of data packets and α is the path loss exponent expressed as the Radio frequency (RF) propagation path loss experienced over the wireless channel at distance d_r, where $d_r, \in \{d_{intra}, d_{\text{avg-sink}}\}$. Therefore, the energy parameter model can be obtained by minimizing the total energy consumption.

2.3 Problem formulation for the CH

The objective function for the proposed MCSO-ECHS protocol is formulated by transforming equation (8) and (9) into a single objective function presented in equation (11)

$$\begin{aligned} &\min FC = \beta_1 D^T + \beta_2 E^T \\ &(s.t. C1 : \text{eucdis}(m_i, CH_j) \le d_{\max}, @ \\ &\qquad \forall 1 \le i \le p; 1 \le j \le q \\ &\quad C2 : \text{eucdis}(CH_j, BS) \le R_{\max}, @ \\ &\qquad \forall 1 \le j \le q \\ &\quad C3 : CHw(m_i, CH_j) \le 1 \\ &\quad C4 : E_{CH_j} < E_{TH}, \forall 1 \le j \le q \\ &\quad C5 : \beta_1 + \beta_2 = 1 \end{aligned} \tag{11}$$

The objective function minimizes the combination of transmission distance and energy consumed in transmitting the data packets from the mesh node to the BS via the selected CHs. Constraint $C1$ defines mesh nodes as being within the intra-cluster coverage area with the CHs. The constraint $C2$ describes the BS as being within the maximum coverage range of the CHs. $C3$ describes the cluster formation weighted function must be less than unity. Likewise, the constraint $C4$ pronounces that the combined CHs energy must surpass the threshold value. The constraint $C5$ established β as a weight that controls the objective function, and it guarantees the non-existence of 0 or 1 weight on either of them.

2.4 Solution to the formulated problem

The solution to the formulated problem in (11) was solved using the algorithm presented in Algorithm 1.

The computational complexity of the proposed protocol was determined as follows. The complexity of a regular node is denoted as $O(N)$ and that of a cluster head (CH) as $O(K)$. The fitness function's complexity is $O(K \times N)$, while the sorting and ranking process within the while loop has a complexity of $O(K \log K)$. Updating the roosters, which takes $O(K/3 \times (K \times N) + C)$ time, where C represents a constant, contributes a complexity of $O(2K/3)$. Each hen update, involving roulette wheel selection, random number generation, and fitness evaluation, has a complexity of

$O(K \times (K \times N) + C + K)$. Similarly, updating each worker, which involves $O(K/3 \times (K \times N) + C)$ operations, has a complexity of O (expression) due to random number generation and fitness evaluation. Updating CH's solution has a complexity of $O(K)$. The total complexity of the proposed MCSO-ECHS protocol is derived by summing these individ-

Algorithm 1. Modified CSO based efficient energy-aware *CH* selection (MCSO-ECHS).

```
Input: Set of mesh nodes $M = \{m_1, m_2, \ldots, m_p\}$
       Predefined swarm size: $N_c$
       Number of dimensions of a $CH : D = q$
Output: Optimal positions of cluster heads $CH = \{CH_1, CH_2, \ldots, CH_q\}$
       Initialize $CH$ Ck = [RN = CN = MN = HN] $\forall i, j, 1 \leq i \leq N_c$, $1 \leq j \leq D = q$, number of $CH$s,
       G (maximum generation)
       $x_{i,j}(0) = (x_{i,j}(0), y_{i,j}(0))$ /* position of the mesh nodes */
       Evaluate the $CH_N$ fitness values (Ck).
       t = 0;
       while (t < G) do
         if (t mod G=0) then
           Rank the 'cluster head' and divide the swarm into different groups
         end if
         for i = 1: $CH_N$
           if i = rooster then
           $x_{i,j}^{t+1} = x_{i,j}^{t} * (1 + randn(0, \sigma^2))$ /* update its solution/location */

           $\sigma^2 = \begin{cases} 1, \text{ if } f_i \leq f_k \\ e^{\frac{f_k - f_i}{|f_i| + \varepsilon}}, k \in [1, N], k \neq i \end{cases}$

         where $randn(0, \sigma^2)$ is a gaussian distribution with mean 0 and standard deviation
         $\sigma^2$. $\varepsilon$ is used to avoid zero-division-error. $k$ is a rooster's index, $f$ is the fitness
         value of the corresponding $x$.
         End if
         if i = hen then
         Update its solution/location using roulette wheel selection.
             $p_{s1} = rand \leq \frac{f(x_{r1,j}^{t} - x_{i,j}^{t})}{\sum_{i=1}^{N} f(x_{r1,j}^{t} - x_{i,j}^{t})}$

             $p_{s2} = rand \leq \frac{f(x_{r2,j}^{t} - x_{i,j}^{t})}{\sum_{i=1}^{N} f(x_{r2,j}^{t} - x_{i,j}^{t})}$
           $x_{i,j}^{t+1} = x_{i,j}^{t} + S1 \times p_{s1} + S2 \times p_{s2}$
             $S1 = e^{\left(\frac{f_i - f_{r1}}{|f_i| + \varepsilon}\right)}, \; S2 = e^{f_{r2} - f_i}$
           where rand is a uniform random number over [0,1]. $r1 \in [1, \ldots, N]$ is an index
           of the rooster, $r2 \in [1, \ldots, N]$ is an index of the $CH$ (rooster or hen)
           end if
           if i = CH then
           Update its solution/location
           $x_{i,j}^{t+1} = x_{i,j}^{t} + FL(x_{m,j}^{t} - x_{i,j}^{t})$
           where $x_{m,j}^{t}$ stands for the position of the $ith$ cluster head's mother ($m \in [1, N]$).
           $FL(FL \in (0, 2))$ is a parameter
           end if
           Evaluate the new solution/location.
           If the new solution/location is better than its previous one, update till it converges.
         end for
       end while
```

ual complexities and simplifying the resulting expression.

$$O((N+K)+(K\times N)\times(K\log K+K/3\times N+C)+K\times(N+C+K)+K/3\times(N+C)+K)=O(N^2K^2) \tag{12}$$

3. Simulation results

In this section, the simulation of the MCSO-ECHS routing protocol is presented. The simulation was carried out with randomly generated mesh nodes with different seed values on MATLAB R2020a software. Also, the *CH*s are selected among the mesh nodes based on their proximity to the *BS* and their residual energy. The specification of the computer used is described as follows: Intel core i5 processor with chipset 2600, 2.5 GHz CPU 4 GB RAM on Microsoft Window 10 operating system. Comparison was performed with CSO-ECHS, PSO-ECHS, GCEEC and ILO routing protocols. The parameters used for simulation are as presented in Table 1 and scenarios considered in Table 2.

The graphs shown in Fig. 2 to 8 illustrate the performance of the MCSO-ECHS protocol with network area of 100 x 100 m^2 with varying number of nodes. The graph in Fig. 2 illustrates how energy consumption increases with the number of nodes in all routing protocols tested. However, the MCSO-ECHS protocol consumes less energy in transmitting data from mesh nodes to the *BS* through *CH*s. This advantage stems from the reduced transmission distances and the energy-efficient design of the MCSO algorithm used for optimal *CH* selection. At 150 nodes, MCSO-ECHS achieves a 15.29%, 17.81%, 20.50% and 28.82% reduction in energy consumption compared to CSO-ECHS, PSO-ECHS, GCEEC and ILO protocols, respectively at configuration of 9 clusters. Similarly, with 300 nodes, MCSO-ECHS reduces energy consumption by 10.08%, 14.38%, 25.05% and 38.34% compared to CSO-ECHS, PSO-ECHS, GCEEC and ILO, respectively. This demonstrates the energy efficiency of the proposed MCSO-ECHS protocol in selecting energy saving *CH*s compared to existing protocols.

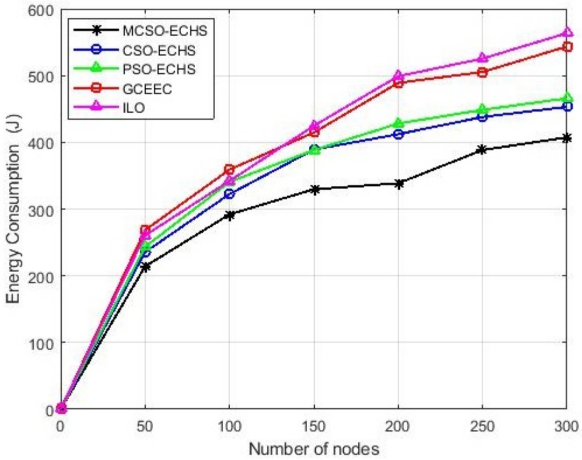

Figure 2. Energy consumption against number of nodes.

Fig. 3 shows that the network lifetime increases with the number of communication rounds for all protocols. Notably, the MCSO-EHCS protocol significantly extends network lifetime by 1.01 seconds, 0.70 seconds and 0.98 seconds when compared to GCEEC, PSO-EHCS and ILO at 1100 rounds at the nodes set to 200 at configuration of 9 clusters. This improvement stems from MCSO-EHCS selecting *CH*s with the highest remaining energy from the mesh nodes. In contrast, CSO-ECHS, PSO-ECHS and GCEEC protocols prioritize *CH* selection without considering residual energy, causing quick energy depletion and reduced network lifespan. Fig. 4 illustrates the network lifetime and the number of nodes at configuration of 9 clusters. As the figure shows,

Table 1. Simulation parameters.

Parameter	Value
Number of nodes	50:50:300
Number of cluster heads	3, 6, 9
Initial energy	1 J
Pathloss exponent	3
Data packet size	512 bytes
Transmission rate	500 bps
Round time	2 sec/round
Transmission energy	50 nJ/bit
Reception energy	20 nJ/bit

Table 2. Scenario parameters.

Parameter	Network area	Nodes
Scenario 1	100 x 100 m^2	150
Scenario 2	200 x 200 m^2	200
Scenario 3	300 x 300 m^2	300

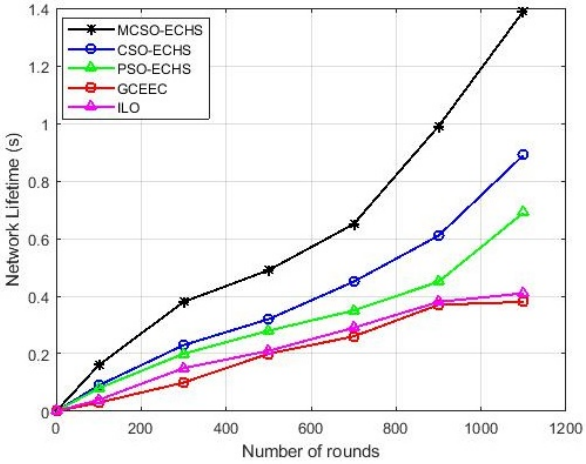

Figure 3. Network lifetime vs number of rounds.

the network lifetime increases with a greater number of nodes. The MSCO-ECHS protocol outperforms other protocols in terms of network lifetime extension. It achieves a 62.26% longer network lifetime than CSO-ECHS, 48.8% longer than PSO-ECHS, 74.45% longer than GCEEC, and 74.59% longer than ILO protocols.

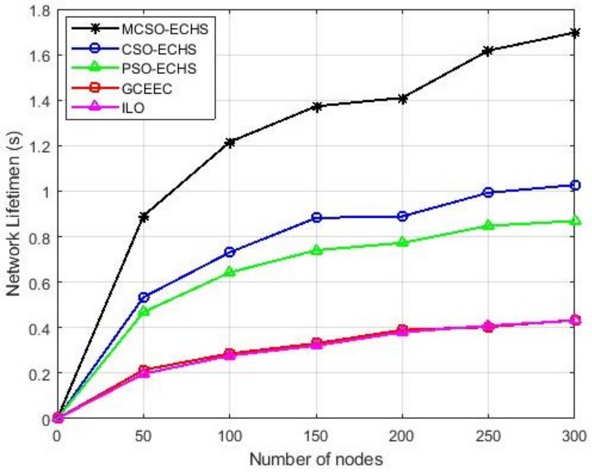

Figure 4. Network lifetime vs number of nodes.

Fig. 5 shows the throughput with the varying number of nodes in the network at configuration of 9 clusters. The graph indicates that all protocols experience increased throughput as the number of nodes increases. However, the MCSO-ECHS protocol consistently outperforms CSO-ECHS, PSO-ECHS and GCEEC, especially in networks with over 100 nodes. This is because the proposed protocol utilizes a time saving and energy-efficient routing strategy. For example, at 100 nodes, MCSO-ECHS achieves a throughput improvement of 22.08%, 27.66% and 51.69% compared to CSO-ECHS, PSO-ECHS and GCEEC, respectively. However, it suffers a loss of 5.32% as compared to ILO which is throughput and response time oriented. This advantage grows at 300 nodes, where MCSO-ECHS boasts a 23.48%, 25.70% and 110.58% throughput increase over CSO-ECHS, PSO-ECHS and GCEEC, respectively. The efficient fitness function employed by MCSO-ECHS is responsible for its superior performance in selecting the optimal CHs.

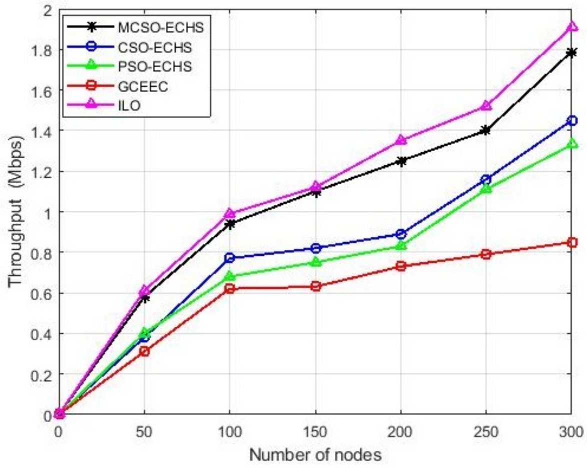

Figure 5. Throughput against number of nodes.

Fig. 6 illustrates the plot of end-to-end delay with number of nodes with 9 clusters. With the number of nodes increased, the end-to-end delay gradually increased for all protocols. Notably, the MCSO-ECHS protocol outperforms both CSO-ECHS, PSO-ECHS and GCEEC protocols. At the highest number of nodes, MCSO-ECHS achieves a reduced end-to-end delay of 3.6 milliseconds, compared to 4.4 milliseconds for CSO-ECHS, 4.6 milliseconds for PSO-ECHS and 5.7 milliseconds for GCEEC but shows a loss of 0.2 milliseconds against ILO. The improvement in MCSO-ECHS is attributed to its high data rate transmission and the choosing of optimal CHs, which facilitates the shortest possible path to the BS which was not considered in ILO.

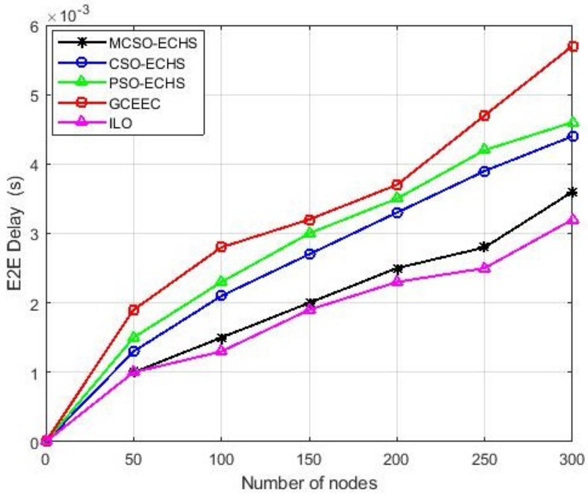

Figure 6. End-to-end delay against number of nodes.

In Fig. 7 the plot of the PDR and number of nodes in the network with 9 clusters is shown. The plot shows that protocols have their PDR increased with increased number of nodes. However, the MCSO-ECHS protocol significantly outperforms the other three except ILO. For instance, at 100 nodes, MCSO-ECHS achieves a PDR of 91.93%, compared to 80.68% for CSO-ECHS, 79.70% for PSO-ECHS, 74.71% for GCEEC and 92.88% for ILO. This trend continues at 300 nodes, where MCSO-ECHS reaches 97.52% PDR, while CSO-ECHS, PSO-ECHS, GCEEC and ILO only reach 88.25%, 83.70%, 80.15% and 99.42%, respectively. The reason for MCSO-ECHS's superiority is its ability to efficiently aggregate and route data packets. This is achieved through a cluster formation function that minimizes energy consumption by finding the shortest paths to the *BS*. Furthermore, the MCSO-ECHS routing protocol incorporates energy and distance factors into its optimization problem, leading to better overall network performance. Additionally, the MCSO algorithm specifically addresses energy imbalances, further contributing to improved network efficiency.

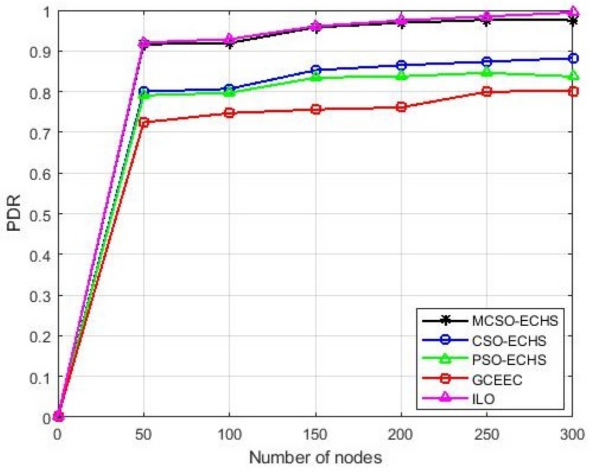

Figure 7. PDR against number of nodes.

Fig. 8 depicts the plot of throughput for different protocols under various clustering configurations at maximum node of 300. In this regard, ILO shows the highest throughput performance of 1.91 Mbps compared to other protocols because it employs a congestion control mechanism to manage network traffic and prevent congestion thereby aiding high data rates. Conversely, this shows that clustering effectively enhances data transmission efficiency of the proposed MCSO-ECHS over all other protocols with a throughput of 1.79 Mbps compared to CSO-ECHS, PSO-ECHS and GCEEC which has 1.46 Mbps, 1.33 Mbps and 0.85 Mbps, respectively at 9 cluster configurations. The proposed MCSO-ECHS protocol distributed the network load more evenly among nodes, preventing congestion bottlenecks by employing more of intra-cluster communication rather than inter-cluster transmission to improve overall throughput in transferring data from the nodes to the *BS* via the selected optimal *CH*s.

The plot in Fig. 9 demonstrates the network lifetime of various protocols under different clustering configurations at maximum number of nodes. MCSO-ECHS consistently achieves the longest network lifetime in all the clustering scenarios, with 0.23 seconds for 3 clusters, 0.46 seconds for 6 clusters and 1.70 seconds for 9 clusters. This highlights its superiority in energy efficiency and network longevity over other protocols and suggests that clustering effectively optimizes energy consumption and extends network lifetime. GCEEC and ILO exhibit significantly shorter network lifetimes at all cluster configurations compared to other protocols. For instance, at 9 clusters configurations, MCSO-ECHS extended the network lifespan by 39.45%, 48.81%, 73.36% and 74,45% over CSO-ECHS, PSO-ECHS, GCEEC and ILO, respectively. This indicates an effective and efficient energy management strategies in proposed routing protocols by minimizing unnecessary transmissions and selecting routes through selected *CH*s that minimize energy expenditure to the *BS*.

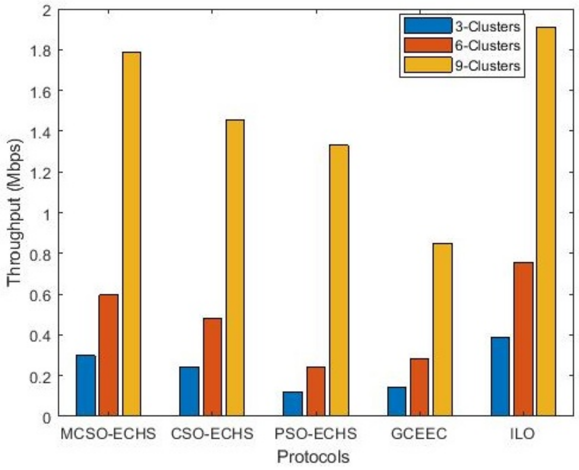

Figure 8. Throughput of all protocols at 300 nodes.

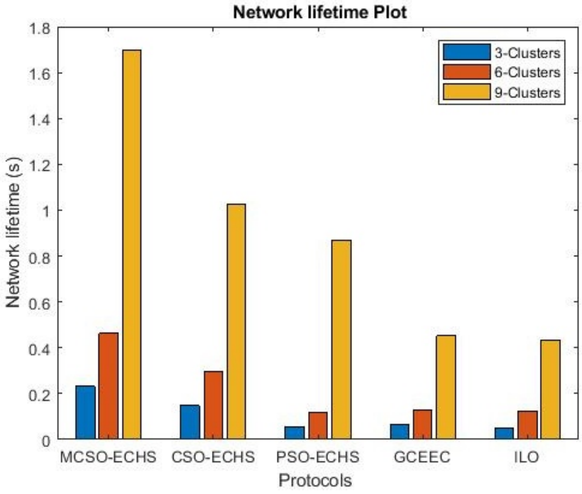

Figure 9. Network lifetime of all protocols at 300 nodes.

Fig. 10 illustrates the plot of PDR for different protocols under various clustering configurations. The result indicates that increasing the number of clusters generally enhances the PDR for all protocols, suggesting clustering's effectiveness in improving communication efficiency. The proposed MCSO-ECHS consistently outperforms other protocols in PDR, except for ILO which shows an improvement of about 23.36%, 7.25% and 2.00% for cluster configurations of 3, 6 and 9, respectively at 300 nodes. CSO-ECHS and PSO-ECHS demonstrate similar performance, with CSO-ECHS slightly edging out PSO-ECHS in some instances. GCEEC exhibits the lowest PDR than other protocols, with a reduction of 17.81% against MCSO-ECHS indicating its less efficient packet delivery mechanisms. This shows that clustering contributes to reducing interference between nodes and enables more efficient routing protocols by prioritizing intra-cluster communication and minimizing inter-cluster transmissions. This ultimately leads to improved communication reliability.

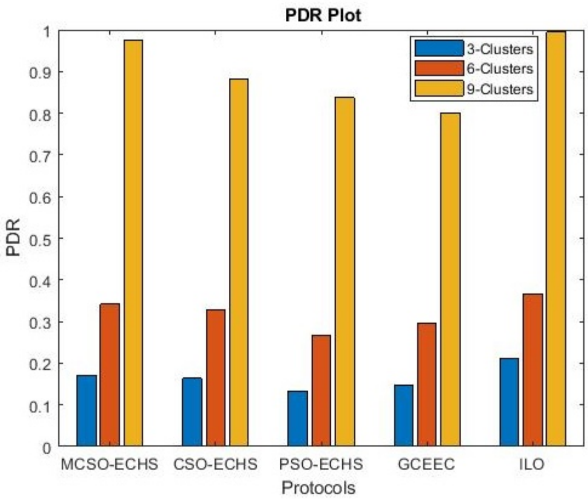

Figure 10. PDR of all protocols at 300 nodes.

Fig. 11 demonstrates how the number of clusters affects network throughput. It shows that as the number of clusters increases, the network throughput performance improves, especially with more nodes. At 100 nodes, the throughput obtained for 3, 6 and 9 clusters were 0.1285 Mbps, 0.3915 Mbps and 0.9400 Mbps, respectively while the corresponding values obtained for 200 nodes were 0.2189 Mbps, 0.4716 Mbps and 1.200 Mbps. In addition, the 300 nodes recorded 0,2989 Mbps, 0.5966 Mbps and 1.7900 Mbps for 3, 6 and 9 clusters, respectively. This implies that increasing the clusters is a good strategy for balancing the data distribution more evenly among the nodes, leading to higher overall throughput performance.

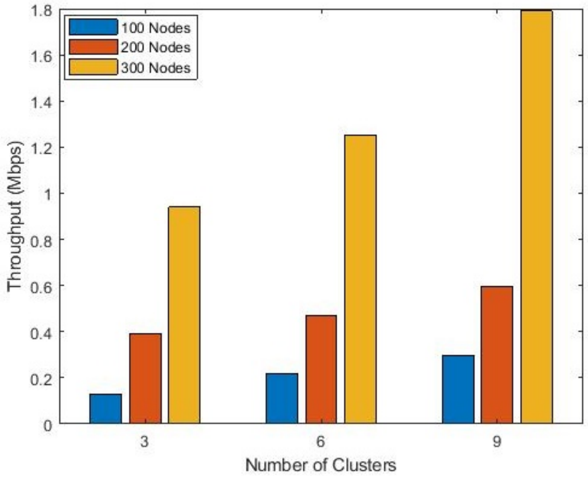

Figure 11. Throughput against number of clusters.

The plot in Fig. 12 depicts the effect of the number of clusters on the lifespan of the network with varying numbers of nodes. Generally, it was observed that increasing the number of clusters extends network lifetime most especially for maximum number of clusters. At 100 nodes, the lifetime obtained for 3, 6 and 9 clusters were 0.1900 seconds, 0.3712 seconds and 1.2160 seconds, respectively while the corresponding values obtained for 200 nodes were 0.2196 seconds, 0.4175 seconds and 1.4100 seconds. In addition, the 300 nodes recorded 0.2317 seconds, 0.4633 seconds and 1.6969 seconds for 3, 6 and 9 clusters, respectively. This is attributed to the more equitable balancing of energy load among the nodes, resulting in longer battery life. The plot implies that clustering is particularly advantageous for networks with a substantial number of nodes.

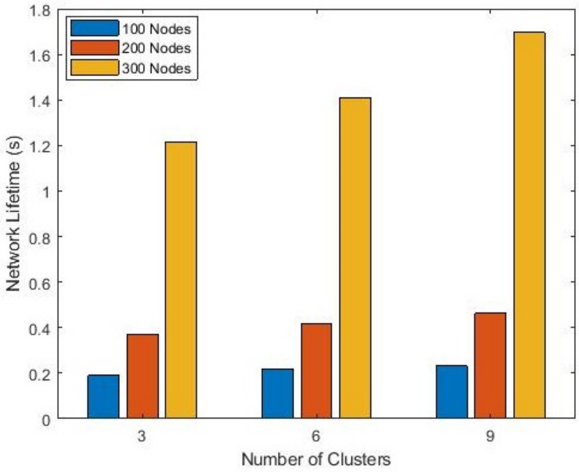

Figure 12. Network lifetime against number of clusters.

The plot in Fig. 13 presents the effect of the number of clusters on PDR in the network at different node numbers. The result reveals that increasing clusters generally enhances the packet delivery. At 100 nodes, the PDR obtained for 3, 6 and 9 clusters were 13.13%, 29.91% and 91.93%, respectively while the corresponding values obtained for 200 nodes were 15%, 31.14% and 96.89%. In addition, the 300 nodes recorded 17.18%, 34.21% and 97.52% for 3, 6 and 9 clusters, respectively. This improvement stems from the ability of more clusters to distribute traffic more evenly, leading to less congestion and higher delivery success rates.

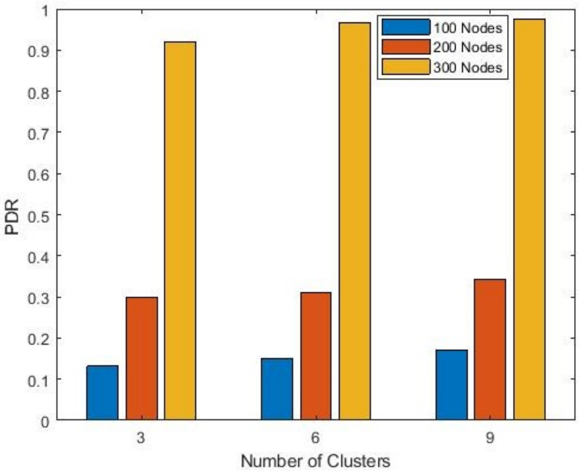

Figure 13. PDR against number of clusters.

The performance of the proposed MCSO-ECHS protocol across different network areas is illustrated in Fig. 14-16, using the scenario parameters defined in Table 2. Focusing on throughput in Fig. 14, although ILO performs well initially, MCSO-ECHS achieves significant improvements in all scenarios. Critically, as the network scales and more nodes are added, the selection of optimal *CH*s in MCSO-ECHS ensures efficient packet delivery by reducing the transmission distance between mesh nodes and the *BS*. Fig. 15 demonstrates the impact of different scenarios on network lifetime. The proposed MCSO-ECHS protocol consistently outperformed all other protocols across all investigated scenarios. Its advantage was most pronounced in Scenario 3, the largest network configuration with 300 nodes. This result suggests that MCSO-ECHS efficiently manages energy consumption even with the increased routing load associated with a larger network, leading to a longer network lifespan. Fig. 16 presents the PDR for the same scenarios. Here, MCSO-ECHS again demonstrated significant improvements compared to the energy-efficient protocols CSO-ECHS, PSO-ECHS, and GCEEC. Quantitatively, MCSO-ECHS enhanced network lifetime by 11.7%, 34.6%, and 33.3% relative to CSO-ECHS in Scenarios 1, 2, and 3, respectively. Although ILO showed slightly better PDRs by 2.6%, 5.1%, and 5.1% in the respective scenarios, these improvements were not statistically significant.

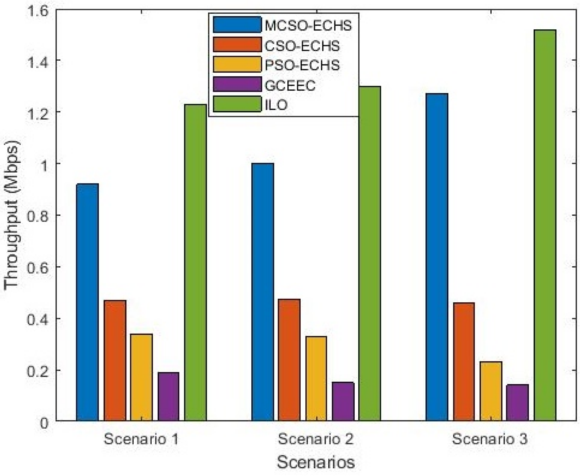

Figure 14. Throughput against scenarios.

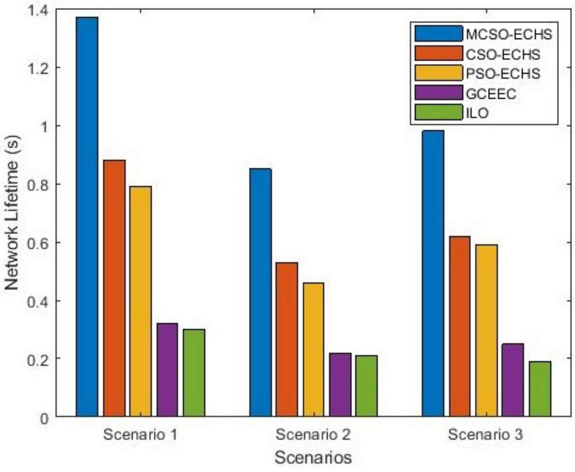

Figure 15. Network Lifetime against scenarios.

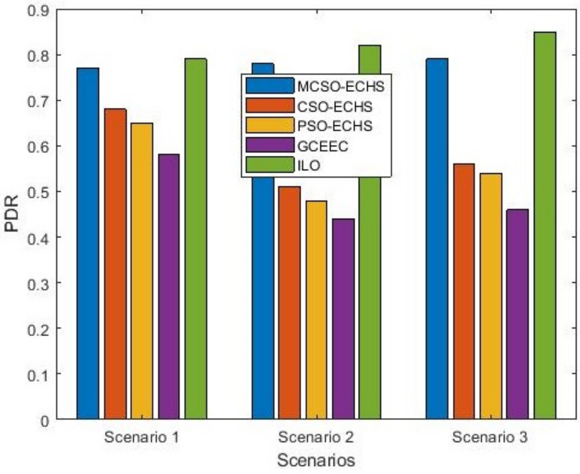

Figure 16. PDR against scenarios.

4. Conclusion

This paper proposes an energy-efficient routing protocol for WMNs that utilizes a MCSO algorithm for optimal CHs selection. The proposed protocol addresses the problem of high energy consumption and long-distance transmission path by selecting optimal cluster heads that act as gateways between mesh nodes and the base station. The selection process considers both distance and energy consumption as factors in a specially designed fitness function for the optimization problem. Simulations show MCSO-ECHS routing protocol significantly outperforming existing protocols in energy consumption, throughput, end-to-end delay, network lifetime, and packet delivery ratio.

Authors contributions
Authors have contributed equally in preparing and writing the manuscript.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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