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Research Article

An Energy Efficient Wireless Sensor Network for Optimal Routing using Hybridized Bio-Inspired Technique: An Integration of Modified Harmony Search and Competitive Swarm Optimization Algorithm

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ABSTRACT

Due to their spatial distribution and energy constraints, the efficiency of Wireless Sensor Networks (WSNs) relies heavily on effective energy management. Optimizing energy consumption can significantly enhance network longevity and performance. While clustering techniques, such as Low Energy Adaptive Clustering Hierarchy (LEACH), help reduce energy usage, they suffer from inefficient local searches and poor exploration-exploitation balance.To address these limitations, this study proposes a hybrid bio-inspired optimization technique—Modified Harmony Search Algorithm (MHSA) combined with Competitive Swarm Optimization (CSO)—for optimal cluster head (CH) selection. The MHSA enhances global search efficiency, while CSO dynamically adapts to network changes, leading to improved convergence rates and balanced energy distribution.Performance evaluation, based on key metrics such as the proportion of alive nodes, residual energy, and throughput, demonstrates that the MHSA-CSO hybrid significantly outperforms existing WSN approaches. The proposed method achieves latency reductions by more than three orders of magnitude and energy efficiency improvements exceeding two orders of magnitude, effectively extending the operational lifetime of WSNs. This approach offers a robust, energy-efficient routing solution for WSNs, contributing to more sustainable and resilient network designs.

Keywords: Optimization technique, clusters, energy consumption, sensor node, residual energy, and throughput.

1. INTRODUCTION

The rapid advancement of wireless communication technologies has spurred significant research interest in Wireless Sensor Networks (WSNs). These networks consist of spatially distributed sensor nodes that communicate wirelessly to monitor physical and environmental parameters such as temperature, humidity, and pollution. WSNs have been widely adopted in military, civil, and healthcare applications. In military settings, WSNs enable enhanced surveillance and threat detection, while in healthcare, they facilitate continuous patient monitoring using wearable or implantable devices. [1, 2,3].

A WSN typically comprises numerous lightweight, low-power sensor nodes capable of sensing, computation, and wireless communication. These nodes can be deployed randomly or in fixed locations for data collection. A standard WSN architecture includes a base station (BS) that aggregates data from sensor nodes and serves as the interface between the network and the end user. Each sensor node consists of a radio transceiver, power module, sensing device, and computational components. Through collaborative sensing and processing, WSNs can monitor extensive areas with minimal infrastructure, making them ideal for applications such as environmental monitoring and industrial automation. [4, 5, 6].

WSN infrastructure comprises a sink or base station acting as the interface between the network and the user. The sensor nodes collect data and wirelessly pass that to the BS where data is aggregated to be available to the users. Each sensor node has a common set of components: radio transceiver, power module, sensing device and computational components [7]. By collaborating together they are able to perform sensing and processing tasks and forward collected data through the network to the BS. Since the WSN node is distributed and lightweight, the nodes can communicate and sense effectively over large areas which enabled environmental monitoring and industrial automation applications [8].

Energy efficiency is the most important challenge of WSNs [9]. Sensor nodes possess limited battery resources and the network lifetime is limited by the battery energy constraints of sensor nodes [10,11]. The challenge of using the available energy resources should be addressed. An example of which are exploration of topology management, optimization algorithms, efficient routing, clustering, scheduling and data aggregation employing all the energy conservation techniques. Clustering is an especially popular energy efficiency improvement technique that groups sensor nodes on clusters, has a cluster head (CH) for cluster communications and to the BS [12, 13].

This research aims to address these limitations by developing an energy-efficient and secure routing mechanism for WSNs. The proposed approach integrates clustering techniques, bio-inspired optimization algorithms, and blockchain technology to optimize energy utilization, reduce redundant transmissions, and enhance network security. The inclusion of blockchain ensures data authentication and integrity, while clustering and optimization techniques minimize energy consumption and extend network longevity.

The core contribution of this research is the introduction of an optimized CH selection technique based on a hybrid bio-inspired optimization algorithm. The proposed method combines the Modified Harmony Search Algorithm (MHSA) and Competitive Swarm Optimization (CSO) to improve convergence rates and achieve better energy distribution among sensor nodes. The results demonstrate that this approach significantly enhances WSN performance by reducing latency, improving data transmission reliability, and extending network lifespan.

In this research, we proposed energy efficient and secure routing methods to tackle the critical challenges in WSNs. This combination of clustering, optimization techniques as well as blockchain technology presents a holistic solution to augment network performance while decreasing energy. However, the proposed approach minimizes the energy consumption and the network's operational lifespan to develop the sustainable and resilient WSNs in various applications. This research leads to future work in advanced techniques to address the changing WSN challenges.

The research article is structured as follows: In Section 2, article present an overview of existing works in Wireless Sensor Networks (WSNs), and how they are significant. In Section 3, article detail the proposed MHSA-CSO hybrid algorithm. The simulation analysis and evaluation of the proposed method are presented in Section 4. In the last section, the article concludes with key findings and future research directions.

2. RELATED WORKS

Wireless Sensor Networks (WSNs), a spatially distributed sensor node system used for environmental monitoring, has greatly evolved due to the development of wireless communication. Applications in WSNs include military, healthcare, and environmental monitoring since these systems are able to acquire and relay the data very efficiently. Nevertheless, network lifetime is still limited due to energy constraints as sensor nodes are usually battery operated. Energy efficient routing and optimization methods are required to address these challenges. In this research, a new hybridized bio inspired technique, MHSA-CSO, is introduced for optimal cluster head (CH) selection, which is a combination of Modified Harmony Search Algorithm (MHSA) and Competitive Swarm Optimization (CSO). The comprehensive analysis is given in Table 1.

Table 1. Comprehensive Analysis of WSN

Reference	Proposed Work	Key Methodology	Main Advantage	Limitations
Pantazis et al. (2013) [14]	Chain routing for WSN	Uses polar coordinates and Greedy algorithm to form chain-like routes.	Reduces energy consumption through compressed data collection and efficient routing.	High dependency on sink node as a central pole.
Rawat et al. (2014) [15]	Optimized cooperative routing	Optimization framework using branch and bound algorithm for cooperative routing.	Minimizes collision probability and reduces computational complexity.	Scalability issues with increased network size.
Rault et al. (2014) [16]	Energy aware distributed routing	Shortest path algorithm to compute the optimal cost of links for better network lifetime.	Provides improved lifetime by minimizing energy consumption.	Limited to predefined routing strategies.
Srbinovska et al. (2015) [17]	Coverage and connectivity preserving route with energy-efficient scheduling.	Minimal sensing range and periodic sensor scheduling to conserve energy.	Reduces energy consumption through distributed scheduling without geographic information.	May face challenges in maintaining coverage in dynamic environments.
Anisi et al. (2017) [18]	Reliable routing scheme using coalitional game theory.	Coalition formation algorithm for secure and trustable routing.	Ensures reliable delivery and enhances route security.	May require high computational overhead for large-scale networks.
Mahmood et al. (2015) [19]	Secure and trustable routing scheme based on active trust mechanism.	Detects black holes in routes to enhance route security.	Enhances network security and trust among nodes.	Performance heavily depends on accurate detection of malicious nodes.
Bhuiyan et al. (2017) [20]	Tree-based diversionary routing to enhance network lifetime and location privacy.	Uses hide-and-seek strategy to create decoy routes and fake events periodically.	Preserves node privacy and extends network lifetime by reducing energy consumption at hotspots.	Increased computational overhead due to creation of decoy routes and fake events.
Jehan & Shalini (2016) [21]	Energy-conserving cluster-based routing with optimal route selection.	Clustering based on energy parameters and cuckoo search algorithm for optimal route selection.	Conserves energy through efficient clustering and routing.	High dependence on initial parameter settings for cuckoo search algorithm.

ABC-SD [22]	Bio-inspired approach for WSN routing.	Artificial Bee Colony optimization for route selection and scheduling.	Improved energy efficiency and network lifetime.	Limited adaptability to real-time dynamic scenarios.
FAMACROW [23]	Bio-inspired WSN approach for efficient routing.	Focused on fast and adaptive multihop clustering.	Achieves better load balancing and reduced energy consumption.	May face issues in large-scale networks with dense node deployment.
Beeswarm [24]	Bio-inspired routing method for WSN.	Leverages swarm intelligence to enhance data aggregation and routing efficiency.	Improves data accuracy and reduces transmission energy.	High computational cost with larger networks.
Beesensor [25]	Bio-inspired WSN routing approach.	Focused on efficient data collection and node clustering using bee colony algorithms.	Extends network lifetime and improves cluster stability.	Limited applicability to heterogeneous WSNs.

Cluster heads (CHs) selection in WSN is the major issue as the main challenge of energy efficient communication, particularly, in minimizing energy wastage, and increasing network lifetime. Poor trade off between exploration and exploitation leads to inefficient CH selection and inefficient data throughput as well as high latency, and that is true for both LEACH and traditional optimization methods. These methods, in contrast, do not account for dynamic nature of WSNs, where energy is dissipated unequally leading to network partitioning. This research proposes to fill these gaps with the hybridization of a bioinspired technique, MHSA-CSO. Competitive Swarm Optimization (CSO) increases dynamic adaptability and the Modified Harmony Search Algorithm (MHSA) enhances global search efficiency.

The proposed method integrates these approaches in order to optimally choose CHs, balance energy consumption, and improve routing efficiency. The hybridization guarantees faster convergence, lower energy consumption across nodes, and better throughput. Through performance analysis, we find that MHSA-CSO outperforms existing approaches in terms of energy efficiency, latency reduction, and network lifetime extension. The proposed method also dynamically adapts to network changes to provide reliable communication in different scenarios. MHSA-CSO overcomes critical limitations of previous techniques, and is demonstrated as an effective energy efficient routing technique for WSNs. The research gap and solution is illustrated in Table 2.

Table 2. Acquired Research Gap in Literature and Solution

Aspect	Research Gap	Proposed Solution	Benefits	Limitations Addressed
Energy Efficiency	Existing algorithms like LEACH lack optimized energy utilization.	MHSA-CSO ensures optimal energy-efficient CH selection.	Extends network lifetime by reducing node energy consumption.	Reduces uneven energy distribution among nodes.
Routing Optimization	High latency and energy usage in existing	Combines MHSA global search with CSO dynamic capabilities.	Improves convergence speed and reduces latency.	Enhances scalability for large-scale networks.

	routing techniques.			
Data Throughput	Suboptimal throughput in traditional clustering approaches.	MHSA-CSO achieves efficient data aggregation.	Increases throughput by minimizing packet loss during transmission.	Mitigates inefficient communication overhead.

3. PROPOSED HYBRIDIZED CSO AND HAS FOR WSN

The proposed WSN technique for clustering is determined as hybrid HSA-CSO is established with the general characteristics of both CSO and HSA algorithms. The algorithm's functioning is broken down into several rounds. The CH gather information from the entire members reside in the cluster and send it to the BS at the end of every round. The following are the steps to follow in order to execute the hybrid HSA-CSO algorithm:

Initialization of Parameter

We initialize the energy levels of the sensor nodes, followed by the generation of velocity and position of particles at random. Then, the particle harmony memory (PHM) is determined and used to specify the harmony memory and size of a particle. The initial value of PHM is arbitrarily generated outcomes for the optimization problem. These outcomes are structured by 'q' index of cluster head (CH) counts. The value of PHM is estimated for the optimization problem.

$$\begin{bmatrix} M_1^l & \cdots & M_q^l \\ \vdots & \ddots & \vdots \\ M_1^{HMS} & \cdots & M_q^{HMS} \end{bmatrix} \begin{bmatrix} f_{obj\_fn\_1} \\ \vdots \\ f_{obj\_fn\_n} \end{bmatrix} = \begin{bmatrix} F^1 \\ \vdots \\ F^{HMS} \end{bmatrix}$$

The PHM value from newly generated ones from the enhanced harmony

Then the vector of harmony $[M_1', M_2', \dots \dots \dots, M_k^{HMS}]$ is generated to enhance the value of Particle Harmony Memory (PHM). The Harmony Memory Considering Rate (HMCR) is used to generate each element of the new harmony vector M_j'.

$$M_j' \leftarrow \begin{cases} M_j' \in PHM with\ the\ probability\ value\ of\ HMCR \\ M_j' \quad with\ the\ probability\ value\ of\ 1 - HMCR \end{cases}$$

The Harmony Memory Considering Rate (HMCR) defines the chances of selecting an element belonging to the Particle Harmony Memory (PHM) members; (1-HMCR) is the chances of generating an element at random. M_j' is selected from the PHM is then modified on the basis of the Pitch Adjustment Rate (PAR). This means the probability of a candidate from the PHM being mutated, the probability of not being mutated is (1 - PAR). Then, the pitch alteration of the chosen M_j' is determined.

$$M_j' \leftarrow \begin{cases} M_j^n \in PHM with\ the\ probability\ value\ of\ PAR \\ M_j' \quad with\ the\ probability\ value\ of\ 1 - PAR \end{cases}$$

In this scenario, the nearest node within the cluster that has an energy level higher than the current Cluster Head (CH) is denoted as M_j^n. The objective value is determined by evaluating the row value, and the worst-performing value is excluded from consideration.

Position and Velocity of Particle Updation

The position of particles is used to identify the best position to place the cluster head (CH) based on the least cost value. Both global and particle best solutions are coordinated by nodes. In each transmission round, the velocity and position of nodes are updated. Here, competition winners are directly passing to the next round and losers learn from winners. Randomly initialized swarms that are termed losers correlate their position based on their velocity. These losers use the position of the winners to update where their position is, therefore they move closer to the winners.

The process of optimization keeps iterating over velocity and position. In each round, we continuously update the velocity and position of these nodes to get better performance and finally find the optimal position of CH.

$$s_{1o}^{r+1} = G_1^r S_1^r + G_2^r (p_{wi}^r - p_{lo}^r) + \emptyset G_3^r (p^{-r} - p_{lo}^r)$$

$$p_{lo}^{r+1} = p_{lo}^r + s_{lo}^{r+1}$$

In this context, rounds are indicated by r, and random vectors are represented by G_1^r, G_2^r, G_3^r, each lying within the range $[0, 1]^n$. The winner swarm is denoted by p_{wi}^r, and the loser swarm is indicated by p_{lo}^r. The mean position is represented by p^{-r}, and the influences are controlled by $\emptyset$ for p^{-r}. The values in the loser swarm will update their position and velocity, resulting in a new position.

4. SIMULATION ANALYSIS

In a 1000×1000 meter network area with 200 sensor nodes, the proposed hybrid MHSA-CSO routing algorithm is evaluated using Network Simulator-2 (NS2). The analysis is conducted with respect to key metrics: Latency, energy consumption, network lifetime, packet delivery rate (PDR). The proposed approach is compared with existing routing techniques, i.e., ABC-SD, FAMACROW, and BeeSwarm, on these metrics.

Performance metrics

Any routing algorithm must maximize the Packet Delivery Ratio (PDR), the ratio of successfully delivered packets over the total transmitted packets. Table 3 shows that MHSA-CSO can obtain higher PDR than existing approaches in all cases due to the selection of optimal CH and reliable route identification. Successful packet delivery is achieved using reliable routes, rather than the use of shortest paths, with PDR improved as the number of nodes increases.

$$PDR = \frac{Successful\ Transmission\ of\ data\ packets}{Total\ count\ of\ packets\ transmitted}$$

Latency is the average time for data transmission from source to destination. As shown in Table 4, the proposed approach has the lowest latency compared to ABC-SD, FAMACROW and BeeSwarm. Frequent routes are stored in the cluster leader to reduce frequent route discovery and reliable routes are used for faster data transmission. Results confirm that MHSA-CSO significantly reduces delays and has a positive impact on network efficiency.

$$Latency = Data\ received\ time - data\ transmission\ start\ time$$

In WSN, energy consumption is of critical importance since the sensor nodes have limited power resources. The MHSA-CSO algorithm is proposed to incorporate the energy efficient principles, i.e., clustering, and optimal route selection to reduce the energy depletion of sensor nodes (Table 5). The experimental analysis shows that the proposed algorithm MHSA-CSO is more effective in reducing energy consumption than other algorithms, and the energy utilization is lower as the number of nodes increases. Efficient CH selection and reliable routes are responsible for reducing energy consumption.

$$E_{consumption} = \sum_{i=1}^{N} (E_{tx}(i) + E_{rx}(i) + E_{idle}(i) + E_{sleep}(i))$$

where $E_{tx}(i)$ is Energy consumed during data transmission by node i, $E_{rx}(i)$ is Energy consumed during data reception by node i. $E_{idle}(i)$ is Energy consumed when node i is in idle mode, $E_{sleep}(i)$ is Energy consumed when node i is in sleep mode, and N is Total number of nodes.

Energy consumption directly affects network lifetime, defined as the time for which nodes remain active. Table 6 shows an extended network lifetime obtained by the proposed approach. The clustering mechanism and optimal routing guarantee uniform energy utilization over nodes so that nodes do not prematurely fail. It is found that MHSA-CSO outperforms ABC-SD, FAMACROW, and BeeSwarm in having more active nodes over time, and thus in having a longer network lifespan.

$$T_{lifetime} = \frac{E_{initial}}{E_{consumption}}$$

where $T_{lifetime}$ is Lifetime of the network, $E_{initial}$ is Initial energy of the nodes, and $E_{initial}$ is Average energy consumption per unit time.

Simulation results show that the proposed MHSA-CSO is to improve the performance of WSNs efficiently. It achieves higher PDR, lower latency, lower energy consumption and longer network lifetime compared to the existing methods. These improvements makes MHSA-CSO a robust solution for energy efficient WSNs based on the integration of clustering and reliable routing mechanisms.

Simulation Illustration

Table 3. Comparison of Packet Delivery Ratio (PDR)

No. of Nodes	ABC-SD	FAMACROW	BeeSwarm	MHSA-CSO (Proposed)
50	92	93	91	**94**
100	92.3	93.5	91.5	**94.5**
150	93	93	93	**96**
200	93.5	94	94	**97**

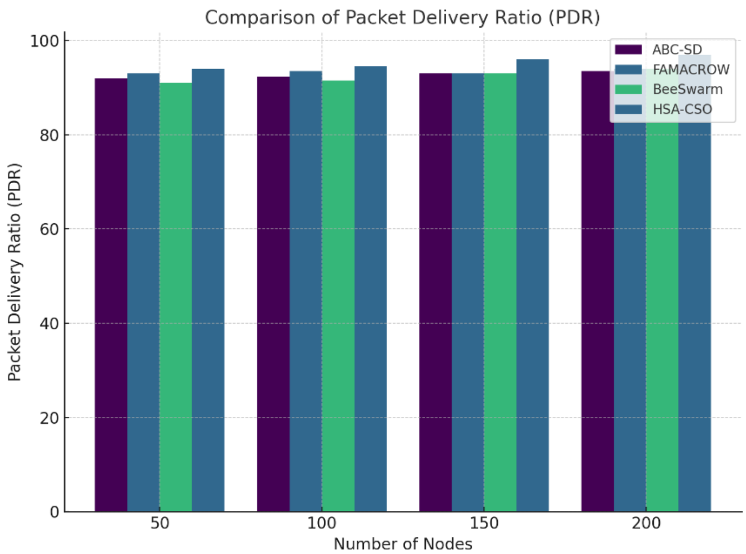

Figure 1. Comparison of Packet Delivery Ratio (PDR)

Table 4. Comparison of Latency (in Seconds)

No. of Nodes	ABC-SD	FAMACROW	BeeSwarm	MHSA-CSO (Proposed)
50	1.2	1.2	1.1	**1**
100	1.5	1.4	1.2	**1.1**
150	1.6	1.5	1.4	**1.3**
200	1.7	1.6	1.5	**1.4**

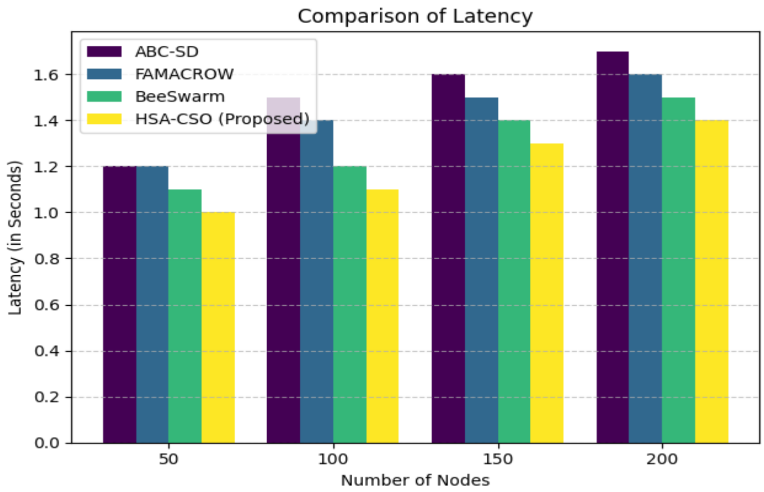

Figure 2. Comparison of Latency (in Seconds)

Table 5. Comparison of Energy Consumption (in Joules)

No. of Nodes	ABC-SD	FAMACROW	BeeSwarm	MHSA-CSO (Proposed)
50	0.3	0.29	0.28	**0.21**
100	0.36	0.31	0.29	**0.19**
150	0.41	0.35	0.31	**0.18**
200	0.45	0.41	0.32	**0.16**

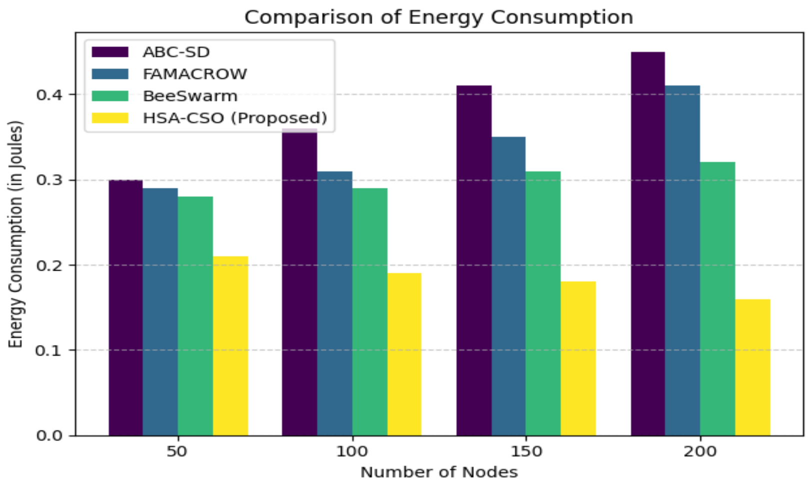

Figure 3. Comparison of Energy Consumption (in Joules)

Table 6. Comparison of Network Lifetime (in Seconds)

No. of Nodes	ABC-SD	FAMACROW	BeeSwarm	MHSA-CSO (Proposed)
50	200	200	200	**200**
100	170	179	180	**195**
150	167	170	175	**190**
200	150	160	170	**180**

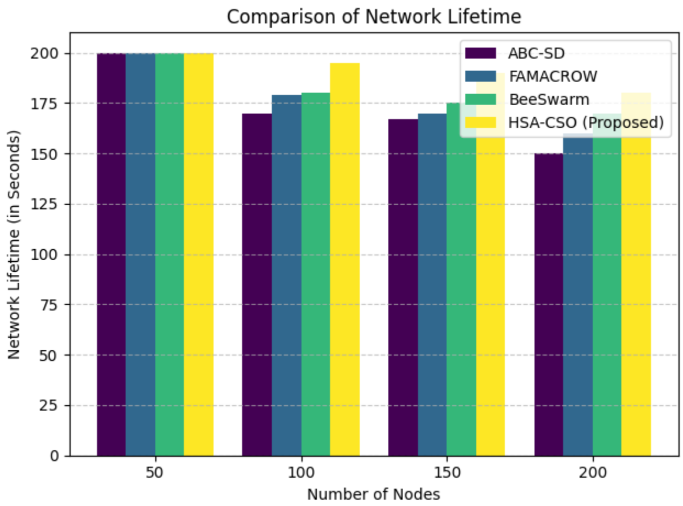

Figure 4. Comparison of Network Lifetime (in Seconds)

Discussion

Results from the simulation show that the proposed MHSA-CSO algorithm outperforms ABC-SD, FAMACROW, and BeeSwarm on Packet Delivery Ratio (PDR), latency, energy consumption, and network lifetime. As Table 3 illustrates, MHSA-CSO beats all other algorithms in terms of PDR for all node counts. As an illustration, with 200 nodes MHSA-CSO is able to obtain a PDR of 97%, ahead of ABC-SD (93.5%), FAMACROW (94%), BeeSwarm (94%). The reason for this improvement is due to MHSA-CSO, with reliable route selection and clustering. Latency performance is shown in table 4 where we find that MHSA-CSO keeps the lowest latency at all node counts. For example, it takes 1.4 seconds for MHSA-CSO to finish, while FAMACROW (1.6), BeeSwarm (1.5), and ABC (1.7). To achieve this latency reduction, frequent paths are stored in the cluster leader, and on the basis of these paths, reliable routes are selected, thus reducing the route discovery delays.

As shown in table 5, MHSA-CSO consume the least energy when compared to the other algorithms. MHSA-CSO consumes 0.16 joules while FAMACROW consumes 0.41 joules, BeeSwarm consumes 0.32 joules and ABC-SD consumes 0.45 joules. Improved performance is due to energy efficient clustering and the optimal route selection strategy of MHSA-CSO. The enhanced network lifetime achievable by MHSA-CSO is shown in Table 6. MHSA-CSO requires 180 seconds of network activity for 200 nodes, whereas ABC-SD, FAMACROW, and BeeSwarm achieve 150, 160, 170 seconds respectively. The clustering mechanism is able to minimize energy consumption and load balancing. We analyze the proposed MHSA-CSO algorithm and show that across all performance metrics it consistently outperforms the existing approaches in routing efficiency in wireless sensor networks.

5. CONCLUSION

This study addresses the critical issue of energy efficiency in Wireless Sensor Networks (WSNs), where sensor nodes operate with limited battery resources. To improve energy-efficient data transmission, we introduce a hybrid bio-inspired optimization technique—Modified Harmony Search Algorithm (MHSA) combined with Competitive Swarm Optimization (CSO). This approach optimally selects Cluster Heads (CHs), balancing global search efficiency with dynamic adaptability to network conditions.Simulation results indicate that the MHSA-CSO hybrid significantly enhances WSN performance by achieving lower latency, reduced energy consumption, and extended network lifespan compared to existing approaches such as ABC-SD, FAMACROW, and BeeSwarm. The proposed technique enables higher packet delivery ratios, ensuring reliable communication and prolonged operational efficiency.Future work will explore advanced machine learning models for dynamic CH selection, further optimizing network adaptability. Additionally, the integration of enhanced security mechanisms will be investigated to ensure secure data transmission while maintaining energy efficiency. The proposed methodology has potential applications in heterogeneous WSNs and the Internet of Things (IoT), where nodes possess varying energy capacities and operational requirements. Real-world validation through large-scale deployments will further assess the scalability and practicality of this solution in diverse environments.

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