Swarm Intelligence-based Energy Optimization Protocol for Hybrid Routing in Wireless Sensor Networks

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Received: 12 February 2025 | Revised: 17 March 2025 and 27 March 2025 | Accepted: 28 March 2025

 DOI: https://doi.org/10.48084/etasr.10550

ABSTRACT

Wireless Sensor Networks (WSNs) face critical challenges in energy efficiency, scalability, and fault tolerance due to the limited energy resources of sensor nodes. This study proposes a novel hybrid energy optimization protocol that leverages swarm intelligence algorithms, specifically Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO), to address these challenges. This protocol integrates traditional clustering techniques with swarm-based optimization to design an energy-efficient and adaptive routing mechanism. Sensor nodes are self-organized into clusters using PSO, ensuring optimal coverage and connectivity. Cluster Head (CH) selection within each cluster is performed using ACO, considering residual energy, node density, and distance to the base station, ensuring balanced energy consumption. The routing mechanism combines intra-cluster communication with PSO-based multi-hop inter-cluster routing, dynamically optimized using ACO to minimize transmission costs. Reinforcement strategies adapt to environmental changes, such as node failures and energy depletion, while promoting load balance and reliability. This protocol mimics the collaborative behavior of biological swarms, allowing dynamic and adaptive energy-aware routing while addressing the challenges of network scalability and reliability. The proposed Swarm Intelligence-based Ant Colony Optimization and Particle Swarm Optimization (SIACOPSO) protocol offers significant advantages, including enhanced energy efficiency, adaptability to dynamic network conditions, fault tolerance, and scalability for large-scale deployments. Comparative analysis with traditional bioinspired protocols demonstrates the superiority of this hybrid approach in prolonging network lifetime and improving overall performance.

Keywords-Wireless Sensor Networks (WSNs); Ad-hoc On-Demand Distance Vector (AODV); Ant Colony Optimization (ACO); Swarm Intelligence-based Ant Colony Optimization Particle Swarm Optimization (SIACOPSO)

I. INTRODUCTION

In the era of pervasive connectivity and digital transformation, Wireless Sensor Networks (WSNs) have emerged as a cornerstone technology, enabling diverse applications such as environmental monitoring, healthcare, industrial automation, and smart cities. WSNs consist of spatially distributed sensor nodes that autonomously collect, process, and transmit data to central locations, facilitating real-time decision-making and control. However, despite their immense potential, WSNs face significant challenges related to energy efficiency, network scalability, and reliability. The limited energy resources of sensor nodes, coupled with dynamic and often harsh environmental conditions, impose stringent constraints on the design and operation of these networks [1].

In recent years, many studies have proposed energy optimization solutions in wireless sensor networks using different algorithms. In [2], energy optimization was performed using a routing algorithm protocol with swarm intelligence techniques. The proposed Effective Fitness Function-based Particle Swarm Optimization (EFF-PSO) considered parameters such as residual energy consumption, latency, node connectivity, and distance. The limitations of this method are challenges in real-time flexibility and environmental changes. In [3], an improved PSO method was proposed to select the Cluster Heads (CHs), using the Gray Wolf Optimization (GWO) algorithm to find the optimal path in the network. However, this approach faces challenges in real-world scenarios. In [4], a multi-objective swarm intelligence, namely the shuffled frog leaping firefly algorithm, was used for a WSN clustering protocol. This method aimed to optimize energy consumption and efficiency in data transmission, achieving an 11.3% reduction in different network scenarios. However, this algorithm highly depends on the initial tuning parameters. In [5], the Swarm-Intelligence Centric Routing Algorithm (SICROA) was proposed to address WSN problems such as stability, scalability, etc. This method was better than Ant Colony Optimization (ACO) by improving routing performance through collision avoidance and link quality prediction. In [6], different methods on Wireless Multimedia Sensor Networks (WMSNs) were reviewed and compared.

In [7], Chaos Particle Swarm Optimization (CPSO) was used to improve energy and transmission efficiency in WSNs, increasing the lifespan of the network by approximately 55.20%. In [8] a hybrid swarm intelligence based on hierarchical routing was proposed, combining Gray Wolf Optimization (GWO) and Marine Predators Algorithm (MPA). However, this method required significant expertise and computational resources. In [9], two algorithms, namely HOCK and HECK, were combined for WSN applications. HOCK was used for the optimization of cluster positions and HECK focused on the selection of optimal clusters using cuckoo search methods. Simulation results showed that the proposed method was more effective in extending network lifetime than previous ones. However, this method assumes a uniform distribution of nodes. In [10], a Multi-Objective nature-inspired Algorithm (MOSFA) aimed to enable adaptive clustering and routing in WSNs using the shuffled frog-leaping and the firefly algorithms. This method improved network lifetime compared to other protocols but cannot work on specific network scenarios. In [11], Swarm Intelligence (SI) algorithms were proposed to optimize WSNs. In [12], the QoSCRSI offered an improvement in selecting CHs and routine techniques but it was not tested in real-world scenarios. In [13], a method for military WSN applications was proposed. In [14], PSO was combined with fuzzy logic to improve energy efficiency and lifespan in WSN systems. In [15], a hybrid algorithm combined Artificial Bee Colony (ABC) and Ant Colony Optimization (ACO) in CHs selection to improve energy efficiency and lifetime and accelerate packet delivery compared to other existing methods.

In [16], a method was proposed to predict energy consumption in WSNs with intelligent routing. The cluster mechanism integrated PSO to enhance path selection and fault tolerance for dynamic transmission. This method improves the lifetime and energy supply through balanced node scheduling but is difficult to implement in real-time applications. In [17], the Energy-Efficient Distance-based Spectrum aware Optimization (EDSO) was proposed for WSNs, achieving better results compared to existing methods in energy consumption, packet delivery ratio, etc. In [18], the HGWO-Firefly algorithm was implemented for routing in WSNs. This algorithm mainly consists of two sequences, namely the selection of potential CH using K-means and the GWO algorithm. The Firefly algorithm was used to select the best route between the base station and the sensor node. However, this method is not effective under dynamic conditions. In [19], the PSO-EECS method was proposed to improve network stability and operational efficiency. This method achieved a stability improvement of 95.4% compared to GAPSOH (34.8%) and ABE-DE (29.2%). However, this method also does not work better under dynamic conditions. In [20], GA-UCR was proposed to reduce energy consumption and improve network lifetime through different fitness functions. In [21], PSO was combined with fuzzy logic to improve the performance of WSNs in terms of network lifetime and energy consumption. In [22], a hybrid approach combined Artificial Bee Colony (ABC) and ACO to select an ideal CH considering several factors, including residual energy at the nodes, distance to neighbors, distance to the base station, node degree, and node centrality. In [23], PSO-based scheduling was implemented to maximize the lifetime of WSNs formulated as a Non-Disjoint Sets Cover (NDSC) problem. In [24], Cognitive Fish Swarm Optimization (CFSO) was proposed for multi-objective routing and channel selection in WSNs. In [25], the aim was to increase the battery life of nodes with varying distances. However, these studies show that there is scope to improve WSNs using advanced optimization techniques.

The primary objectives of this study are as follows:

- Develop a hybrid energy optimization protocol that uses ACO and PSO for efficient clustering and routing in WSNs.
- Evaluate the protocol's performance in terms of energy efficiency, fault tolerance, adaptability, and scalability.
- Compare the proposed method with bio-inspired and traditional approaches to explore its advantages and limitations.

II. PROPOSED METHOD

The proposed SIACOPSO system consists of sequential steps: the initialization phase, i.e., node deployment and energy assignment, CH selection using the ACO algorithm, a routing mechanism involving the hybrid approach with the help of intra- and inter-cluster communication, and energy optimization using PSO and ACO. PSO optimizes node placement and clustering. The optimal routing algorithm is used for the dynamic re-route paths, ensuring minimal transmission cost and load balancing and avoiding nodes with low energy. The final step offers fault tolerance and scalability enhancement. In case a node or CH fails, neighboring nodes use swarm intelligence mechanisms to automatically reconfigure routes and re-cluster if necessary.

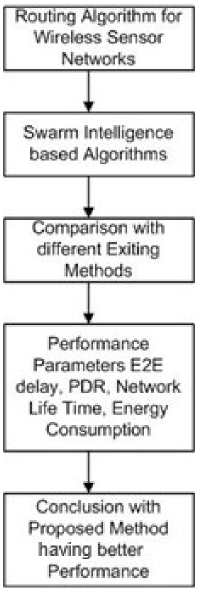

Fig. 1. Sequential diagram of the proposed method.

The following equation shows the node energy assignment.:

$$P_i = \begin{cases} P_0\ 0.5 \text{ if tier is low} \\ P_0\ 1 \text{ if tier is medium} \\ P_0\ 1.5 \text{ if tier is high} \end{cases} \quad (1)$$

Equation (2) gives the cluster formation for the PSO algorithm:

$$Minimize\ function = \sum_{i=1}^{X}\sum_{j\epsilon b_i}|x_i = \mu_i||\text{^}2 \quad (2)$$

where x_i denotes the position of the nodes in the cluster and μ_i is the centroid of the cluster i.

The head suitability score using the ACO algorithm is given by:

$$S_n = \alpha \frac{E_n}{dist(n,BS)} + \beta D_n \quad (3)$$

The formula for the probability of the ACO algorithm is shown in (4), which is defined as the transition probability or v_n for node n.

$$P_n = \frac{\tau_n^{\alpha}.\eta_n^{\beta}}{\sum_{j\epsilon cluster}\tau_j^{\alpha}.\eta_j^{\beta}} \quad (4)$$

Equation (5) provides the update rule:

$$\tau_n = (1-\rho) * \tau_n + delta_{\tau_n} \quad (5)$$

where the notation ρ represents the evaporation rate and $delta_{\tau_n}$ denotes the pheromone increment using the node performance.

In intra-cluster communication, the energy consumption for the transmitting data is given by:

$$G_{tx} = G_{elec} * l + G_{amp} * l * d^2 \quad (6)$$

where the l is the packet length, d is the distance between the transmitting node and receiver, G_{elec} is the energy required for the electronic circuits, and G_{amp} represents the energy required for the signal amplification.

The mathematical representation of the intercluster multi-hop routing, used to minimize the total energy cost, is:

$$Min: \sum_{i=1}^{H} G_{tx}(i) \quad (7)$$

where H represents the number of hops in the routing path.

Energy optimization and fault tolerance are performed by using the cluster centroid update PSO method. The centroid update is performed by dynamically updating the CH based on the nodes. The mathematical representation of the centroid calculation is:

$$\mu_i = \frac{1}{c_i}\sum_{j\epsilon c_i} X_j \quad (8)$$

where C_i represents the number of nodes in cluster i and X_j is the position of the nodes.

Finally, fault tolerance, i.e failed nodes with residual energy, is achieved using

$$G_n \leq G_{min} \quad (9)$$

Compared to other algorithms, the LEACH protocol uses randomized CH selection without energy considerations, unlike the ACO-PSO hybrid approach. AntHocNet applies ACO for routing but lacks clustering efficiency, which is achieved through PSO-based clustering. On the other hand, bio-inspired algorithms focus more on task allocation than the combined routing and clustering strategy of this protocol. This novelty of the proposed approach provides a robust hybrid energy optimization protocol that leverages SIACOPSO to enhance routing efficiency and prolong the network lifetime, with adaptive behaviors inspired by biological systems.

III. RESULTS AND DISCUSSIONS

A. Simulation Setup

The SIACOPSO protocol was implemented using NS v2.34 simulations. The proposed SIACOPSO protocol was compared to two other popular routing protocols, the responsive Ad-hoc On-Demand Distance Vector (AODV) and ACO to examine its energy efficiency and network mobility performance.

B. Performance Metrics

The following key metrics were used to evaluate performance:

- End-to-End (E2E) delay is the average time taken for a packet to travel from the source to the destination, calculated by:

$$E2E\ delay = \frac{\sum_{i=1}^{n}(R_i - S_i)}{n} \quad (10)$$

where n is the total number of packets received by the destination, R_i is the time a packet is received by the destination, and S_i is the time the packet was sent by the source.

- Energy Consumption (EC) denotes the energy consumed by each node during the simulation relative to its initial energy. This is calculated using:

$$C = \sum_{i=1}^{n} in(i) - en(i) \quad (11)$$

- Packet Delivery Ratio (PDR) is the ratio of successfully delivered packets to the total packets sent.
- Network Lifetime (NL) is defined as the time from the deployment of the network to the failure of the first node, signaling the loss of network coverage.
- Throughput (TP) measures the total number of packets transmitted successfully per second during the simulation.
- Routing Packet Ratio (RPR) is the ratio of data packets sent to Routing Packets (RP), where RP represents the packets required to discover nodes in the network. The formula for the Routing Packet Ratio (RPR) is:

$$ROR = \left(\sum \frac{RP}{RP+DDP}\right) * 100 \quad (12)$$

The SIACOPSO protocol was compared to ACO and AODV using the above metrics under varying network conditions, demonstrating significant improvements in energy efficiency, network lifetime, and throughput.

C. *Result Analysis*

Table I shows the parameters utilized in the simulation. Table II highlights the performance comparison for different numbers of nodes. The graphs below illustrate the performance of various configurations on ACOCH protocol scenarios, including consumption-based energy reduction and network lifespan extension.

TABLE I. SIMULATION PARAMETERS

Parameters	Values	Unit
Run Counts	6	-
Queue Size	60	Packets
Mobility Model	Random	-
Packet Size	1024	Bytes
Transmission Range	300	M
Protocols	SIACOPSO, PSO, ACO, AODV	-
Total Area	1350	m^2
Simulation Time	20-90	ms
Node Speed	1-12	m/s
Traffic Speed	UDP/UBR	-
Transmission Power	1.6	J
Reception Power	1.2	J
Idle Power	0.06	J

Figure 2 shows that as the number of nodes increases, the longevity of the network decreases. The proposed routing system does, however, lead to a longer network lifespan with an increasing number of nodes. Figure 3 shows how the three protocols' End-to-End (E2E) delay is affected by the speed of the nodes. Rapid increases in node speed significantly increase the E2E latency of routing protocols, which in turn increases the risk of a node connection breaking. It is worth noting that SIACOPSO achieves the lowest E2E delay when the node speeds are high.

TABLE II. PERFORMANCE COMPARISON FOR PROTOCOLS WITH VARYING NUMBER OF NODES

Parameters	Protocols	50	80	110	140	170	200
E2E Delay	SIACOPSO	22.71	20.65	18.45	15.98	14.65	11.56
	ACO	27.65	25.65	24.74	21.96	20.12	19.56
	AODV	29.83	28.69	27.96	23.65	21.96	21.41
PDR (%)	SIACOPSO	78.5	84.5	87.32	91.23	93.65	95.65
	ACO	76.22	81.65	83.74	86.74	87.63	89.54
	AODV	75.45	79.68	81.85	83.52	85.35	88.74
EC (J)	SIACOPSO	13.52	15.69	19.63	23.41	24.56	26.36
	ACO	15.68	18.69	20.41	25.36	26.12	28.96
	AODV	17.25	19.36	23.65	26.85	28.96	31.25
Network Lifetime	SIACOPSO	26532	19564	15366	13699	11523	9655
	ACO	21521	15969	11966	8756	6124	4658
	AODV	18896	12875	8963	6522	4145	1965
Throughput (b/s)	SIACOPSO	31590	32570	35698	37522	39633	42966
	ACO	27964	28965	30145	32521	34587	37126
	AODV	27564	29633	30966	33552	35215	38521

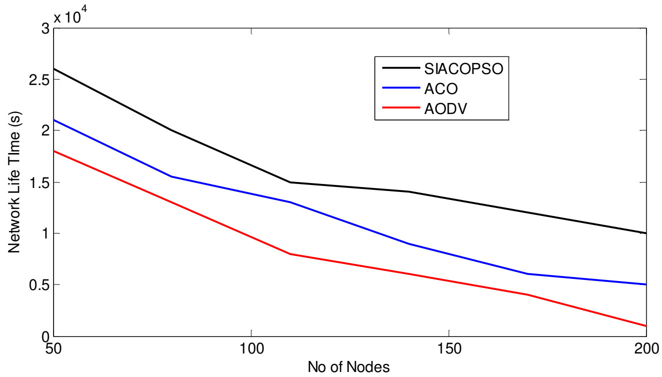

Fig. 2. Network lifetime with different amounts of nodes.

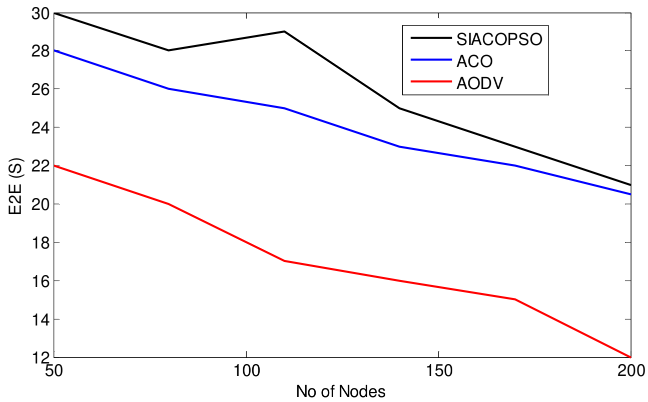

Fig. 3. E2E delay with different amounts of nodes.

Figure 5 shows that SIACOPSO achieves a packet delivery ratio of up to 95.65% for 200 nodes, which is significantly higher than the other routing protocols. PDRs are lower in the ACO system (89.54% vs. 88.74%) and the reactive AODV protocol (88.74%).

These findings highlight the benefits of the SIACOPSO protocol in maintaining optimal energy consumption, increasing lifetime, and enhancing the overall performance of WSNs in different environments.

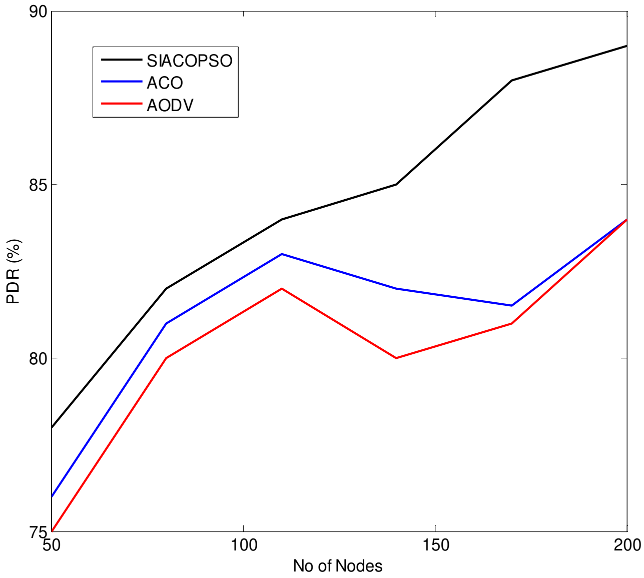

Fig. 4. PDR for different amounts of nodes.

SIACOPSO demonstrated the lowest energy consumption compared to ACO and AODV, indicating better energy management. The extended network lifetime observed in SIACOPSO highlights its effectiveness in balancing energy usage among nodes. SIACOPSO also achieved significantly lower delays, particularly at higher node speeds, making it suitable for dynamic environments. In addition, with a PDR of 95.65% at 200 nodes, SIACOPSO outperformed ACO and AODV, which achieved 89.54% and 88.74%, respectively. Finally, the higher throughput of SIACOPSO reflects its superior data transmission capabilities, even in dense network conditions.

IV. CONCLUSION

This study aimed to contribute to the design of robust, scalable, and energy-efficient WSNs that can operate reliably in diverse and dynamic environments. The SIACOPSO protocol was introduced as an advanced routing solution for WSNs. This approach not only enhances the network lifetime but also provides a foundation for future research on intelligent and adaptive sensor network protocols. The proposed protocol combines the strengths of PSO and ACO to achieve optimal clustering and routing, addressing energy consumption, scalability, and adaptability in WSNs. The key advantages of the proposed protocol are that it minimizes energy consumption by balancing energy loads and updating routing paths and extends lifetime by reducing energy depletion rates. The proposed protocol demonstrated significant improvements in energy efficiency, network lifetime, and overall performance compared to existing protocols such as ACO and AODV. The SIACOPSO method achieved 95.65% PDR, 22.71 E2E delay, and was more energy efficient. The SIACOPSO protocol is suitable for various applications, including environmental monitoring, healthcare, and smart cities. Future work could explore the integration of additional optimization techniques and its application to heterogeneous WSNs with diverse node capabilities.

REFERENCES

[1] P. M. Kumar, K. R. Chythanya, P. Dineshkumar, S. Saravanan, and S. Chakraborty, "Swarm Intelligence-Based Energy-Centric Clustering and Routing in WSN," in *2023 International Conference on Evolutionary Algorithms and Soft Computing Techniques (EASCT)*, Bengaluru, India, Oct. 2023, pp. 1–5, https://doi.org/10.1109/EASCT59475.2023.10392575.

[2] A. B. Gavali, M. V. Kadam, and S. Patil, "Energy optimization using swarm intelligence for IoT-Authorized underwater wireless sensor networks," *Microprocessors and Microsystems*, vol. 93, Sep. 2022, Art. no. 104597, https://doi.org/10.1016/j.micpro.2022.104597.

[3] M. Elhoseny, R. S. Rajan, M. Hammoudeh, K. Shankar, and O. Aldabbas, "Swarm intelligence–based energy efficient clustering with multihop routing protocol for sustainable wireless sensor networks," *International Journal of Distributed Sensor Networks*, vol. 16, no. 9, Sep. 2020, Art. no. 1550147720949133, https://doi.org/10.1177/1550147720949133.

[4] A. Barzin, A. Sadeghieh, H. Khademi Zareh, and M. Honarvar, "Hybrid swarm intelligence-based clustering algorithm for energy management in wireless sensor networks," *Journal of Industrial and Systems Engineering*, vol. 12, no. 3, pp. 78–106, Jul. 2019.

[5] C. Shin and M. Lee, "Swarm-Intelligence-Centric Routing Algorithm for Wireless Sensor Networks," *Sensors*, vol. 20, no. 18, Jan. 2020, Art. no. 5164, https://doi.org/10.3390/s20185164.

[6] F. L. Benmansour and N. Labraoui, "A Comprehensive Review on Swarm Intelligence-Based Routing Protocols in Wireless Multimedia Sensor Networks," *International Journal of Wireless Information Networks*, vol. 28, no. 2, pp. 175–198, Jun. 2021, https://doi.org/10.1007/s10776-021-00508-9.

[7] Q. Tang and F. Nie, "Clustering routing algorithm of wireless sensor network based on swarm intelligence," *Wireless Networks*, vol. 30, no. 9, pp. 7227–7238, Dec. 2024, https://doi.org/10.1007/s11276-023-03584-2.

[8] X. Yang, J. Yan, D. Wang, Y. Xu, and G. Hua, "THSI-RP: A two-tier hybrid swarm intelligence based node clustering and multi-hop routing protocol optimization for wireless sensor networks," *Ad Hoc Networks*, vol. 149, Oct. 2023, Art. no. 103255, https://doi.org/10.1016/j.adhoc.2023.103255.

[9] U. E. Zachariah and L. Kuppusamy, "A hybrid approach to energy efficient clustering and routing in wireless sensor networks," *Evolutionary Intelligence*, vol. 15, no. 1, pp. 593–605, Mar. 2022, https://doi.org/10.1007/s12065-020-00535-0.

[10] A. Barzin, A. Sadegheih, H. K. Zare, and M. Honarvar, "A Hybrid Swarm Intelligence Algorithm for Clustering-Based Routing in Wireless Sensor Networks," *Journal of Circuits, Systems and Computers*, vol. 29, no. 10, Aug. 2020, Art. no. 2050163, https://doi.org/10.1142/S0218126620501637.

[11] G. Devika, D. Ramesh, and A. G. Karegowda, "Swarm Intelligence–Based Energy-Efficient Clustering Algorithms for WSN: Overview of Algorithms, Analysis, and Applications," in *Swarm Intelligence Optimization*, John Wiley & Sons, Ltd, 2020, pp. 207–261.

[12] M. S. Maharajan, T. Abirami, I. V. Pustokhina, D. A. Pustokhin, and K. Shankar, "Hybrid Swarm Intelligence Based QoS Aware Clustering with Routing Protocol for WSN," *Computers, Materials & Continua*, vol. 68, no. 3, pp. 2995–3013, 2021, https://doi.org/10.32604/cmc.2021.016139.

[13] A. S. Balobaid, S. B. Ahamed, S. Shamsudheen, and S. Balamurugan, "Neural Network Clustering and Swarm Intelligence-Based Routing Protocol for Wireless Sensor Networks: A Machine Learning Perspective," *Computational Intelligence and Neuroscience*, vol. 2023, no. 1, 2023, Art. no. 4758852, https://doi.org/10.1155/2023/4758852.

[14] H. Hu, X. Fan, and C. Wang, "Energy efficient clustering and routing protocol based on quantum particle swarm optimization and fuzzy logic for wireless sensor networks," *Scientific Reports*, vol. 14, no. 1, Aug. 2024, Art. no. 18595, https://doi.org/10.1038/s41598-024-69360-0.

[15] S. E. Khediri, A. Selmi, R. U. Khan, T. Moulahi, and P. Lorenz, "Energy efficient cluster routing protocol for wireless sensor networks using hybrid metaheuristic approache's," *Ad Hoc Networks*, vol. 158, Mar. 2024, https://doi.org/10.1016/j.adhoc.2024.103473.

[16] T. Zhang, "An intelligent routing algorithm for energy prediction of 6G-powered wireless sensor networks," *Alexandria Engineering Journal*, vol. 76, pp. 35–49, Aug. 2023, https://doi.org/10.1016/j.aej.2023.06.038.

[17] V. Srividhya and T. Shankar, "An Energy Efficient Distance-Based Spectrum Aware Hybrid Optimization Technique for Cognitive Radio Wireless Sensor Network," *Journal of The Institution of Engineers (India): Series B*, vol. 104, no. 1, pp. 51–60, Feb. 2023, https://doi.org/10.1007/s40031-022-00837-0.

[18] J. Dev and J. Mishra, "Energy Efficient Routing in Cluster Based Heterogeneous Wireless Sensor Network Using Hybrid GWO and Firefly Algorithm," *Wireless Personal Communications*, vol. 137, no. 2, pp. 997–1028, Jul. 2024, https://doi.org/10.1007/s11277-024-11447-y.

[19] V. Prakash and S. Pandey, "Metaheuristic algorithm for energy efficient clustering scheme in wireless sensor networks," *Microprocessors and Microsystems*, vol. 101, Sep. 2023, Art. no. 104898, https://doi.org/10.1016/j.micpro.2023.104898.

[20] Gunjan, A. K. Sharma, and K. Verma, "GA-UCR: Genetic Algorithm Based Unequal Clustering and Routing Protocol for Wireless Sensor Networks," *Wireless Personal Communications*, vol. 128, no. 1, pp. 537–558, Jan. 2023, https://doi.org/10.1007/s11277-022-09966-7.

[21] V. Narayan, A. K. Daniel, and P. Chaturvedi, "E-FEERP: Enhanced fuzzy based energy efficient routing protocol for wireless sensor network," *Wireless Personal Communications*, vol. 131, no. 1, pp. 371–398, 2023.

[22] S. El Khediri, A. Selmi, R. U. Khan, T. Moulahi, and P. Lorenz, "Energy efficient cluster routing protocol for wireless sensor networks using hybrid metaheuristic approache's," *Ad Hoc Networks*, vol. 158, May 2024, Art. no. 103473, https://doi.org/10.1016/j.adhoc.2024.103473.

[23] D. Deepalakshmi and B. Pushpa, "Cognitive Fish Swarm Optimization for Multi-Objective Routing in IoT-based Wireless Sensor Networks utilized in Greenhouse Agriculture," *Engineering, Technology & Applied Science Research*, vol. 15, no. 1, pp. 19472–19477, Feb. 2025, https://doi.org/10.48084/etasr.9203.

[24] S. Kamel, A. A. Qahtani, and A. S. M. Al-Shahrani, "Particle Swarm Optimization for Wireless Sensor Network Lifespan Maximization," *Engineering, Technology & Applied Science Research*, vol. 14, no. 2, pp. 13665–13670, Apr. 2024, https://doi.org/10.48084/etasr.6752.

[25] K. K. Almuzaini *et al.*, "Survelliance monitoring based routing optimization for wireless sensor networks," *Wireless Networks*, vol. 30, no. 6, pp. 6069–6087, Aug. 2024, https://doi.org/10.1007/s11276-023-03381-x.