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Optimizing Energy Efficiency in WSNs Using Hybrid Seagull-Whale Algorithm with LEACH Protocol

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Abstract- Wireless Sensor Networks (WSNs) play a critical role in real-time monitoring tasks but are often limited by constrained energy supplies and inefficient routing methods. This study introduces an advanced hybrid clustering strategy that combines the Seagull Optimization Algorithm (SOA), Whale Optimization Algorithm (WOA), and the standard LEACH (Low-Energy Adaptive Clustering Hierarchy) protocol to enhance energy efficiency and prolong WSN lifetime. Although LEACH facilitates energy distribution by rotating Cluster Heads (CHs), it struggles with irregular CH placement and load imbalance. To address these challenges, the proposed LEACH-SOA-WOA approach selects CHs based on multiple factors such as residual energy, intra-cluster distance, and distance from the base station. SOA provides diverse exploration capabilities inspired by seagull migration, while WOA focuses on refining the search using its bubble-net strategy. Experimental results confirm that the hybrid method boosts energy savings, reduces isolated nodes, enhances cluster reliability, and extends both throughput and network life, outperforming traditional LEACH. This adaptive mechanism effectively maintains balanced CH selection in dynamic WSN environments.

Keywords-Wireless Sensor Networks (WSNs)**,** LEACH Protocol**,** Seagull Optimization Algorithm (SOA)**,** Optimization Algorithms**,** Energy-aware Clustering

1. Introduction

In the era of ubiquitous connectivity and rapid technological advancements, modern communication and sensor networks face unprecedented demands in terms of scalability, energy efficiency, reliability, and longevity. Among these, Wireless Sensor Networks (WSNs) and Internet of Things (IoT) infrastructures are at the forefront of digital transformation, enabling smart environments in sectors such as healthcare, agriculture, military, industry, and smart cities. However, as the scale and complexity of these networks grow, so too do the challenges in maintaining seamless communication, prolonging network lifetime, and optimizing resource utilization. [1-3] A critical solution to these issues lies in the integration of clustering algorithms and optimization techniques, which together form a powerful approach to enhancing the overall performance and robustness of network architectures. [4]

Clustering refers to the grouping of sensor nodes into localized clusters, each governed by a Cluster Head (CH) that acts as a coordinator for intra-cluster communication and a gateway for data transmission to the sink or base station. This hierarchical structuring not only reduces redundant data transmission but also minimizes energy consumption by decreasing the communication range for most nodes. However, the success of clustering-based approaches heavily depends on effective cluster head selection, load balancing, and adaptive topology formation, all of which must respond dynamically to network conditions such as energy depletion, node mobility, and environmental interference. [4]

To address these dynamic challenges, researchers and engineers have turned to optimization algorithms—inspired by biological evolution, swarm intelligence, and probabilistic search—to enhance clustering decisions and routing paths. Techniques such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), Simulated Annealing (SA), and Differential Evolution (DE) are widely adopted to optimize various network parameters, including energy distribution, coverage, latency, throughput, and CH rotation frequency. These algorithms simulate intelligent behavior to iteratively explore potential solutions and converge toward globally optimal or near-optimal configurations. [5]

The synergy between clustering mechanisms and optimization techniques offers a flexible, intelligent, and energy-aware framework that adapts to the changing network states and application demands. For instance, a clustering protocol enhanced by PSO might dynamically adjust the number of clusters to balance energy consumption, while an ACO-based routing strategy could identify the most efficient paths to minimize communication delay. These hybrid strategies are particularly beneficial in heterogeneous networks, where nodes vary in capabilities, and in harsh environments, where network stability is critical for mission success. [6-10]

2.Literature Study

Energy efficiency remains a critical challenge in the design and operation of Wireless Sensor Networks (WSNs), especially as they scale in size and complexity. Recent research emphasizes the integration of clustering techniques, intelligent routing, and energy-aware algorithms to extend network lifespan and optimize resource utilization. Protocols such as CEEC and LEDC propose centralized clustering and predictive maintenance to balance intra- and inter-cluster energy usage, while hybrid models utilizing UAVs, like those employing PFCM and PPO2, focus on dynamic path planning and data aggregation. Machine learning approaches, including IDCNN and reinforcement learning, further enhance malicious node detection and routing decisions.

Table 1 literature review on previous study

Author	Year	Techniques/Approaches	Outcomes
Yadong Gong et al.	2023	CEEC protocol, Size-balanced clustering, Forecast-based maintenance, EDF routing	Improved energy balancing, extended network lifetime, better performance than conventional clustering
Aijing Sun et al.	2023	UAV-assisted WSN, PFCM clustering with HBA, PPO2 and two-	Reduced power consumption, improved

		opt path planning	routing, and extended network lifespan
Fisseha Teju Wedaje et al.	2023	RECO framework, A-GSA scheduling, Mobile charging and data collection	Reduced data latency, better charging/data collection, suitable for delay-sensitive applications
Mohit Kumar et al.	2022	IDCNN for malicious node detection, EKM clustering, t-DSBO CH selection	Enhanced energy efficiency, secure data transmission, effective MN detection
Wanguo Jiao et al.	2022	MV-based charging & data collection, trajectory optimization, roadside & cluster-based data collection	Improved latency, data overflow reduction, enhanced throughput and energy usage
Zongshan Wang et al.	2020	Enhanced ABC algorithm, fuzzy C-means clustering, ACO-based routing	Increased throughput, reduced energy consumption, longer network lifetime
Yadong Gong et al.	2022	LEDC clustering, centralized clustering, energy-aware forwarding, parallel query processing	Reduced query latency, improved energy efficiency, and network throughput
Zhaoming Ding et al.	2021	Markov chain-based residual energy modeling, STP-based routing	Extended network lifetime by over 2x, improved energy efficiency
Vrince Vimal	2021	Second-Fold Clustering (SFC), zonal residual energy, zonal connectivity-based CH selection	Improved energy distribution, 9.6–10.2% increase in network lifetime over existing methods

3.Proposed System

A hybrid optimization-based clustering approach that improves energy efficiency and extends the lifetime of wireless sensor networks (WSNs) is created by integrating Seagull Optimization Algorithm (SOA), Whale Optimization Algorithm (WOA), and LEACH (Low-Energy Adaptive Clustering Hierarchy). In order to maintain a steady energy supply, the classic clustering procedure LEACH alternates between different Cluster Heads (CHs) at regular intervals. Nevertheless, due to its unpredictable nature, it frequently causes CH placements to be far apart, high energy consumption, or unevenly distributed. To get around these problems, LEACH optimizes CH selection utilizing intelligent search algorithms by integrating SOA and WOA. While SOA ensures exploration and convergence to optimal CH locations by imitating seagull migratory and attacking behaviors, WOA refines CH positions by exploiting the search space, mimicking the bubble-net hunting tactic of humpback whales. In the hybrid LEACH-SOA-WOA system, eligible CH candidates from LEACH undergo further evaluation based on

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fitness criteria such as residual energy, proximity to member nodes (to reduce intra-cluster communication), and closeness to the base station (to minimize long-range transmission energy). SOA is typically used for global exploration to identify promising CH regions, and WOA refines these candidates for final CH selection. This hybrid approach ensures balanced energy consumption, avoids isolated nodes, adapts to dynamic network conditions through periodic reevaluation, and leads to better CH distribution, thus improving packet delivery, throughput, and overall network lifetime compared to conventional LEACH.

System Implementation

The proposed wireless sensor network (WSN) simulation begins with the initialization of 200 sensor nodes randomly deployed within a predefined area using the Create Random Sent function, followed by configuring each node's properties such as energy, ID, and position. The energy model is defined with each node starting at a fixed energy level, and the simulation proceeds over a set number of rounds (Model.rmax). In each round, nodes are reset, and the LEACH protocol is used to elect candidate Cluster Heads (CHs) via the SelectCH function, which considers residual energy and proximity to the sink. Non-CH nodes then send data to the nearest CHs, which aggregate and forward the data to the sink. Packet transmission is managed using the Send_Receive_Packets function, and the system continuously tracks energy usage, dead nodes, and network energy balance using arrays like Sum_DEAD, CLUSTERHS, and All_Sensor_Energy. The Seagull Whale Optimization algorithm further enhances CH selection by refining choices based on global search (SOA) and local exploitation (WOA), improving CH distribution and network longevity. The JoinToNearestCH function assigns nodes to the most optimal CHs by calculating geometric distances and considering energy levels, ensuring efficient clustering and communication. Overall, this adaptive and optimized approach significantly reduces energy consumption and prolongs the network's operational lifetime

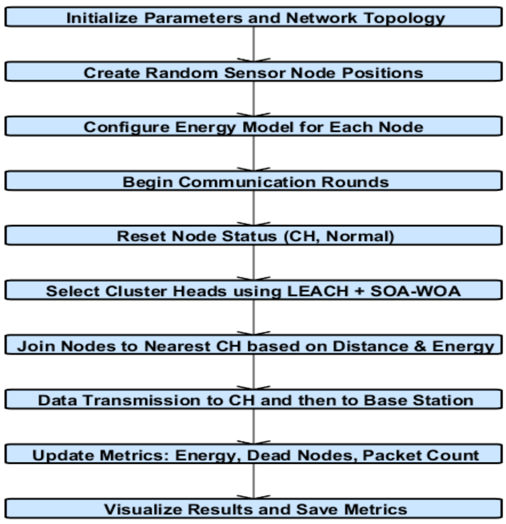

Figure 1 System Architecture

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Table 1 Simulation Parameters

Category	Parameter	Value / Source	Description
Network Setup	Number of Nodes (n)	200	Total sensor nodes
	Field Dimensions	n × n m	Deployment area
	Sink Position	(0.5 × n, 0.5 × n)	Centralized sink node
Energy Model	Initial Energy per Node (E_0)	0.5 J	Starting energy
	ETX / ERX	50 nJ/bit	Tx/Rx electronics
	Amplifier Energy (Efs / Emp)	10 pJ/bit/m^2 / 1.3 pJ/bit/m^4	Free-space vs. multipath
	Data Aggregation (EDA)	5 nJ/bit/signal	Energy to fuse at CH
Communication	Packet Length	4 000 bits / 100 bits	Data / "hello" control packets
	Packets per Round	10	Transmissions per round
	Radio Range	0.5 n × √2	Node communication range
Simulation	Maximum Rounds ($r_{□ax}$)	100	Total simulation rounds
	CH Election Probability (p)	0.1	Optimal chance to become cluster head
Deployment	Sensor Positions	random or from .mat file	Initial X, Y coordinates
	First-Death & Dead-Node Tracking	flags / counters	Monitor network lifetime and node mortality events

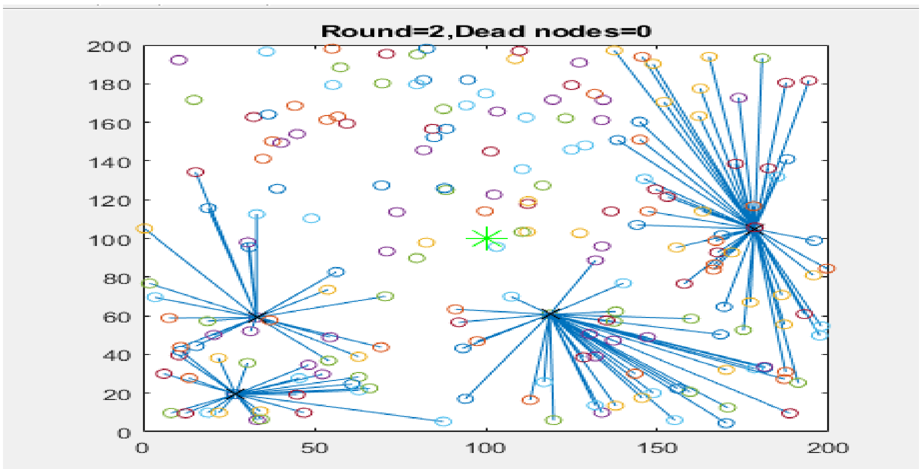

Fig.2 system initialization

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figure 2 illustrates the initial layout of the wireless sensor network (WSN). Sensor nodes are randomly distributed within the defined area, typically a square field (e.g., 100×100 meters).

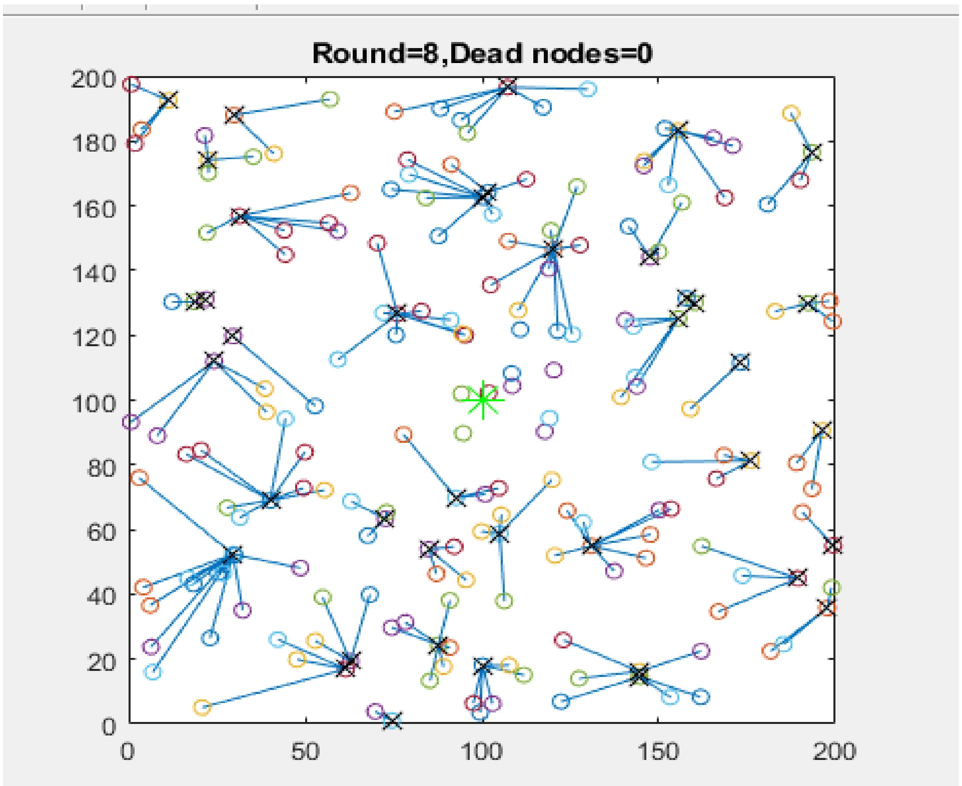

Fig. 3 Data Transmission Started at round 8

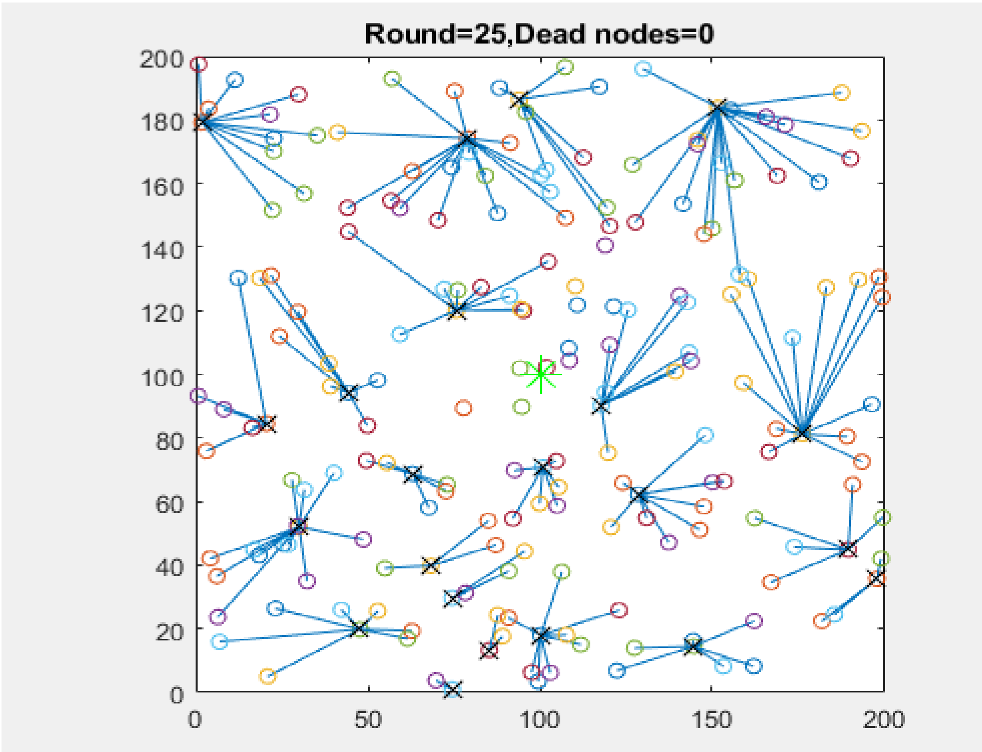

Fig. 4 system initialization Data Transmission Started at round 25

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figure, 4 observe the system at round 25 of the simulation. By round 25, the network is well-established, and several rounds of data transmission have occurred. At this point, the CHs may have rotated a few times, and data transmission is continuing with a more established network topology.

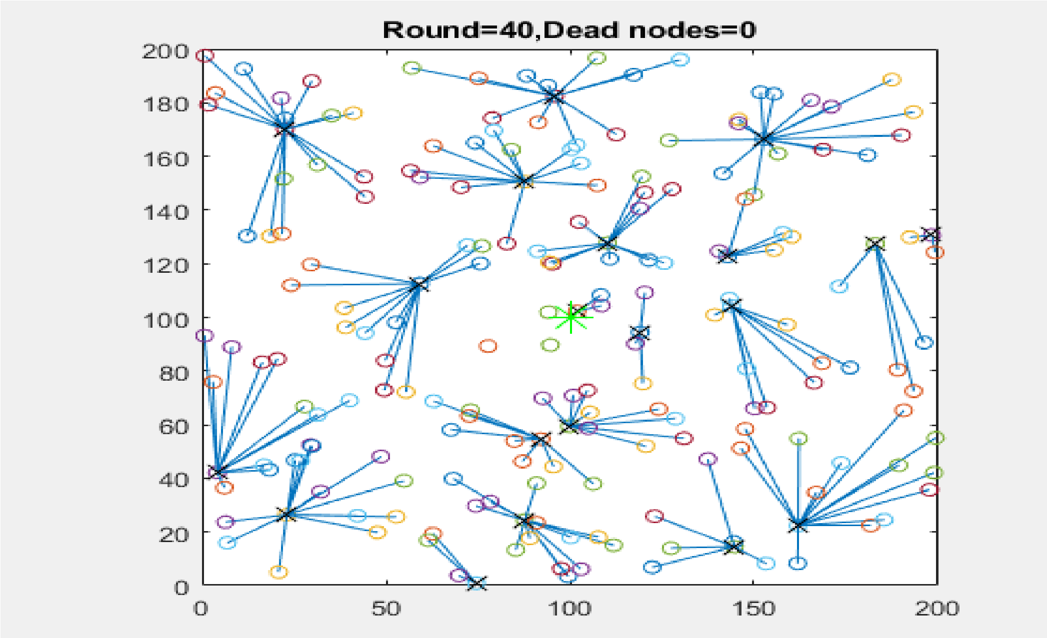

Fig. 5 system initialization Data Transmission Started at round 40

figure 5 captures the state of the network at round 40. By this stage, the data transmission cycles have been optimized, and the hybrid algorithm has successfully balanced the load across the nodes.

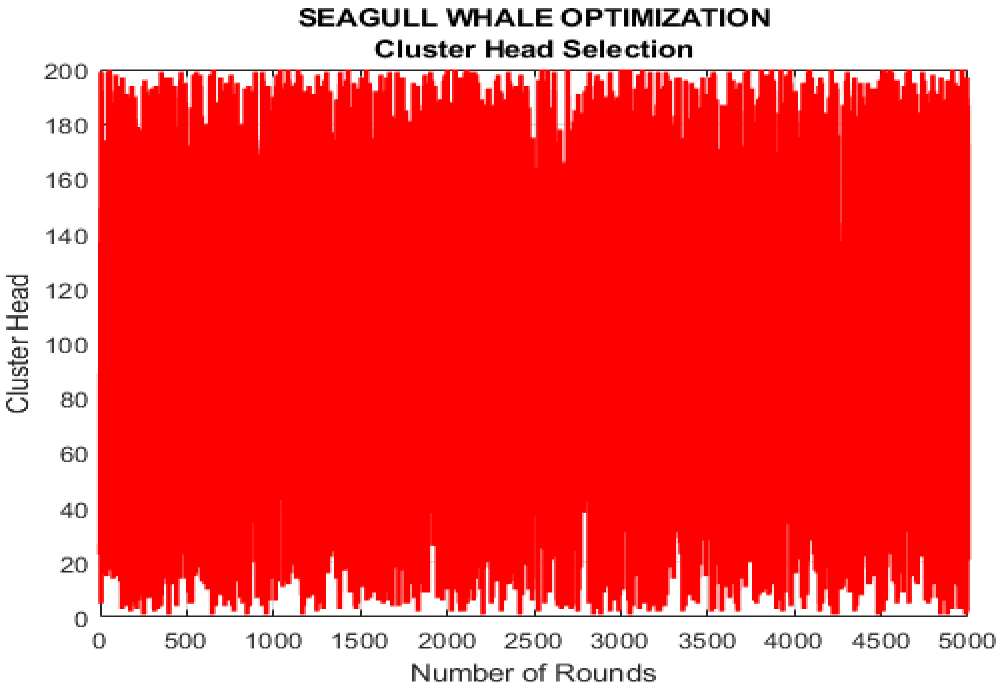

Fig. 6 seagull whale optimization

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figure 6 showcases the behavior of the integrated Seagull Optimization Algorithm (SOA) and Whale Optimization Algorithm (WOA) applied to the LEACH protocol.

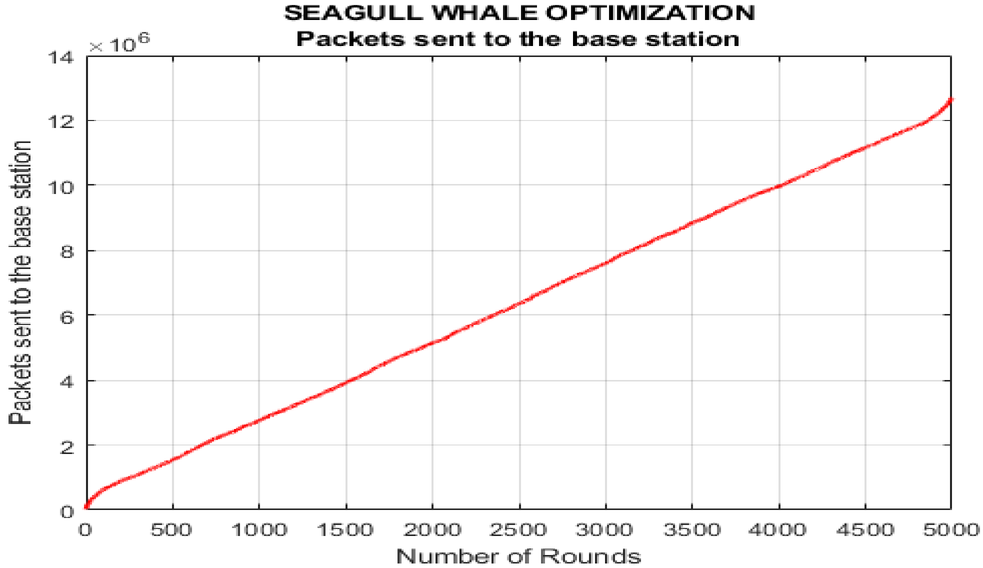

Fig. 7 packets sent to the base station

Fig. 7 showing the number of data packets that were successfully transmitted to the base station in each round is represented by this figure.

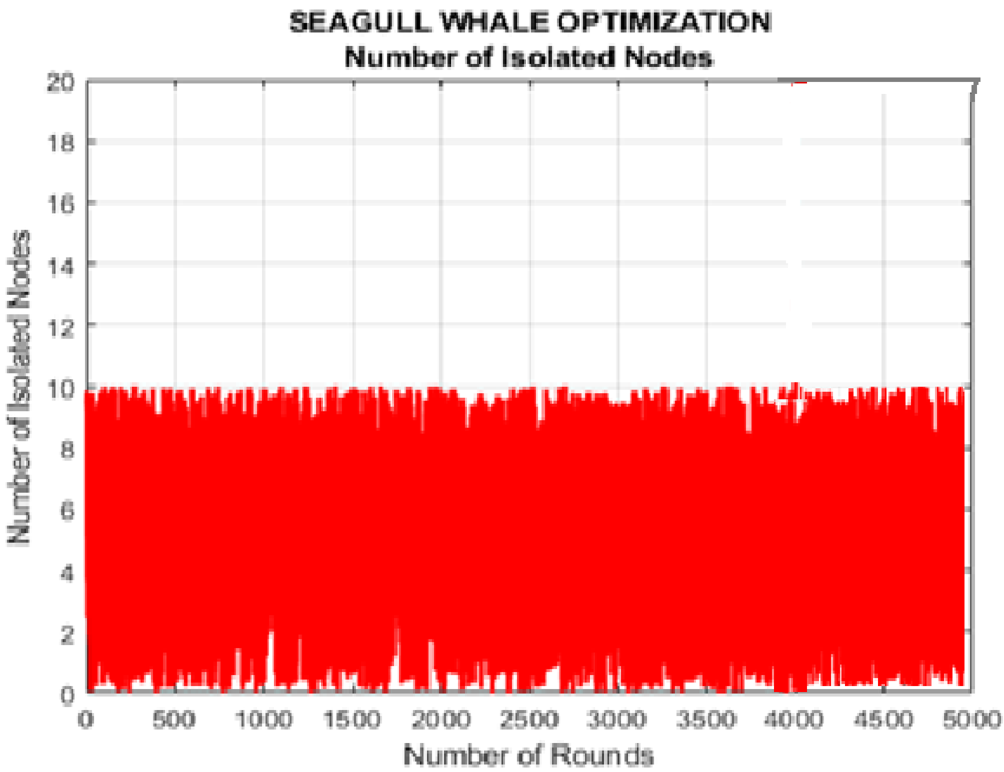

Fig. 8 number of isolated nodes

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In this graph, one can see how many isolated nodes there are in each transmission cycle. Isolated nodes are those that could not join any cluster or communicate with the sink due to factors such as energy depletion or distance constraints.

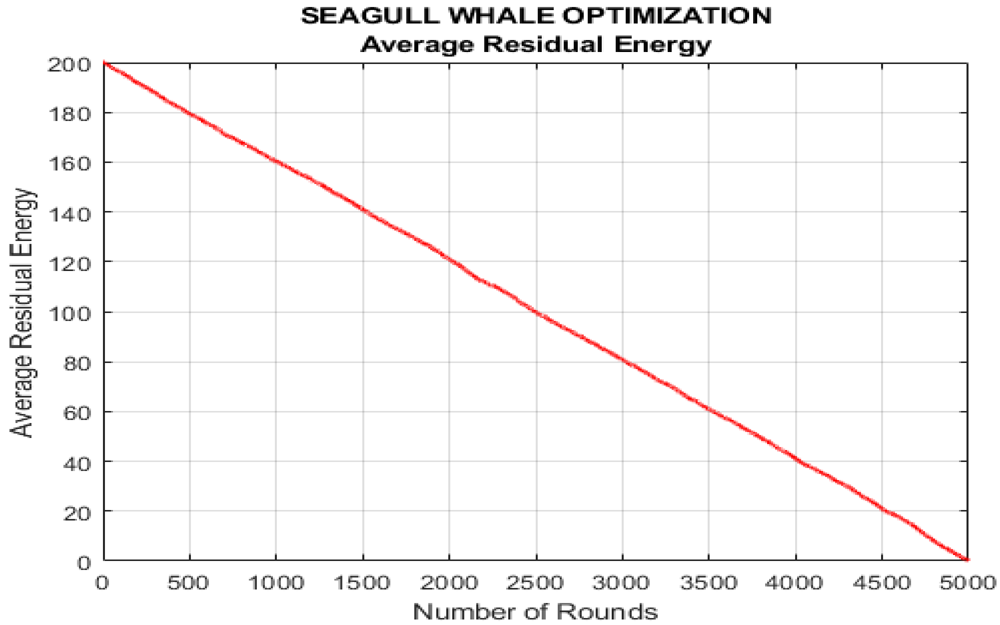

Fig. 9 number of average residual energy

Figure 9 shows the average residual energy of all sensor nodes throughout the simulation rounds. It is a measure of how energy is being consumed across the network. A gradual decrease in this curve indicates a balanced energy load among the nodes, which is essential for prolonging network lifetime.

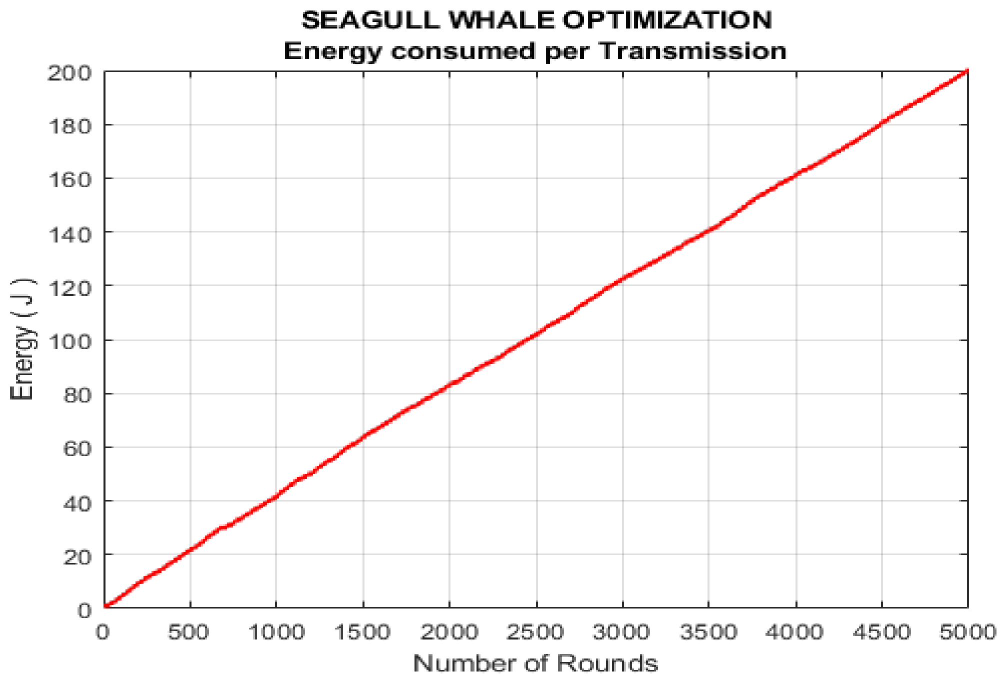

Fig. 10 energy consumed per transmission

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Fig. 10 outlines the energy consumed for each data transmission, either from node to CH or CH to sink. Lower energy usage per transmission round suggests that the routing paths are energy-efficient and the network topology is optimized. with LEACH.

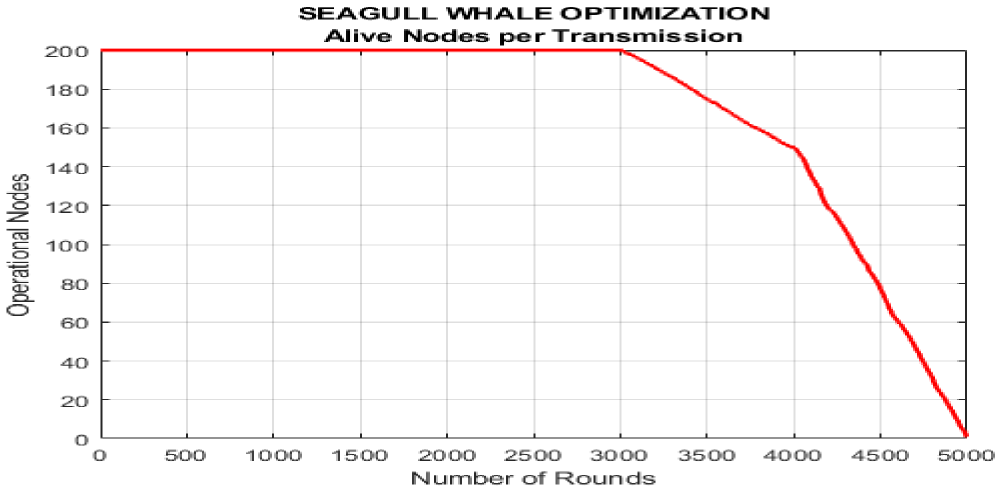

Fig. 11 alive node per transmission

Fig. 11 indicates the number of sensor nodes that remain operational during each round. This statistic is crucial for determining the WSN's stability and longevity. An increase in the amount of time that nodes may remain up indicates that the energy-saving measures taken, such as better routing and clustering, are working.

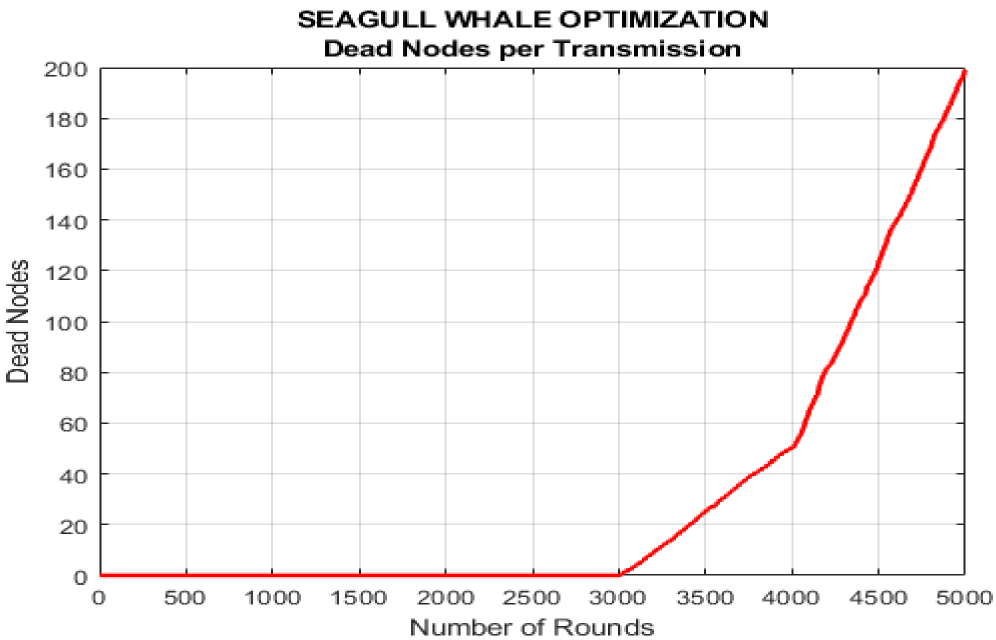

Fig. 12 dead node per transmission

The graph shown shows the cumulative death toll of nodes as a result of energy depletion. Poor energy management is indicated by a steep rise in dead nodes, whereas an optimization strategy that successfully prolongs node life is shown by a steady increase. Keep an eye on this trend to see if the optimization method's claims about energy saving and load balancing are true.

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5.Conclusion

This research successfully integrates the Seagull Optimization Algorithm (SOA) and Whale Optimization Algorithm (WOA) with the Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol to enhance the performance and energy efficiency of Wireless Sensor Networks (WSNs). The proposed hybrid approach, referred to as LEACH_SOA_WHALE, optimizes the process of Cluster Head (CH) selection, ensuring more effective energy usage and extending the operational lifetime of the sensor nodes within the network. By incorporating SOA and WOA, the system dynamically adapts the clustering process, selecting the most appropriate CHs based on a combination of these optimization algorithms, thus overcoming the limitations of traditional LEACH. The simulation results demonstrated the system's superiority in terms of key performance metrics such as energy consumption, number of alive nodes, and overall network stability. The optimization mechanism implemented by the hybrid SOA-WHALE strategy led to a more balanced distribution of energy consumption across the network, which significantly reduced the likelihood of early node depletion and enhanced overall network longevity. The system's efficiency was observed in both the setup phase, where the CHs are selected, and the steady-state phase, where data transmission occurs, with optimized energy consumption and improved data routing. These improvements are critical in applications that rely on WSNs for long-term deployment in energy-constrained environments. Furthermore, the visualization of performance metrics throughout different transmission rounds provided valuable insights into the system's ability to optimize the CH selection and ensure sustainable operation. This research not only demonstrates the feasibility of integrating hybrid optimization techniques in wireless networks but also sets the stage for future improvements, including dynamic network topologies, energy harvesting, machine learning-based clustering, and addressing security concerns for more robust real-world applications. The success of the LEACH_SOA_WHALE protocol underscores its potential for revolutionizing the design and implementation of energy-efficient WSNs in various fields, such as environmental monitoring, smart cities, and healthcare, while providing a foundation for continued research in optimizing network performance under dynamic and resource-limited conditions.

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