

RESEARCH ARTICLE

A Salp Swarm Algorithm–Driven Framework for Energy–Efficient Routing and Prolonged Network Lifetime in Wireless Sensor Networks

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ABSTRACT: Wireless Sensor Networks have become indispensable for real-time monitoring across environmental, healthcare, and industrial domains, yet they face persistent challenges related to energy constraints, limited network longevity, and unreliable data transmission. This paper presents a comprehensive optimization framework for Wireless Sensor Networks that leverages the Salp Swarm Algorithm, a bio-inspired metaheuristic technique modeled after the collective movement of salps in marine environments. The proposed framework addresses critical network operational challenges through simultaneous optimization of clustering strategies, routing protocols, and load distribution mechanisms. Unlike conventional approaches that treat these aspects independently, our methodology integrates them into a unified optimization problem, enabling holistic network performance enhancement. The algorithm's unique leader-follower structure facilitates effective exploration of the solution space while maintaining exploitation capabilities through its adaptive coefficient mechanism, ensuring convergence toward globally optimal configurations without premature stagnation. Experimental validation was conducted across diverse network scenarios, including varying node densities, deployment topologies, and traffic patterns, comparing the proposed approach against established optimization techniques including Particle Swarm Optimization, Genetic Algorithms, and traditional clustering protocols. Quantitative analysis reveals that the Salp Swarm Algorithm-based framework achieves a 42.8% enhancement in energy utilization efficiency, reduces transmission delays by 35.2%, improves packet delivery reliability by 28.6%, and extends operational network lifetime by 48.3% relative to conventional methods. Furthermore, the framework demonstrates exceptional adaptability to dynamic network conditions, maintaining performance stability under node failures and environmental variations. The adaptive cluster head rotation mechanism, guided by residual energy monitoring, ensures uniform energy dissipation across sensor nodes, effectively mitigating premature battery depletion and significantly prolonging the network's functional lifespan.

Keywords: Wireless Sensor Networks; Salp Swarm Algorithm; Energy Efficiency; Routing Optimization; Network Lifetime; Cluster Head Selection.

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1. INTRODUCTION

Wireless Sensor Networks have fundamentally transformed the landscape of real-time monitoring and data acquisition across numerous critical domains including environmental surveillance, healthcare delivery systems, military reconnaissance operations, and industrial process automation. These networks comprise spatially distributed autonomous sensor nodes that collaboratively gather environmental parameters such as temperature, humidity, pressure, acoustic signals, and motion patterns, subsequently transmitting collected information through wireless communication channels to centralized processing stations [1]. The operational effectiveness of Wireless Sensor Networks depends intrinsically upon sophisticated energy management protocols, reliable data transmission mechanisms, and scalable network architectures capable of accommodating expanding node deployments while preserving performance integrity. Despite their widespread adoption and demonstrated utility, Wireless Sensor Networks continue to confront persistent challenges related to energy constraints, limited network longevity, and unreliable data transmission, particularly as network densities increase and operational environments become more dynamic [2].

The fundamental challenge confronting Wireless Sensor Network implementations involves the inherent energy limitations imposed by battery-powered sensor nodes, which directly determine network operational lifetime and overall system sustainability. Traditional routing and clustering protocols such as LEACH and AODV, while providing foundational solutions for energy-aware communication, exhibit significant limitations when deployed in high-density network configurations or environments characterized by fluctuating operational conditions [3]. These conventional approaches frequently encounter difficulties including uneven energy consumption patterns across sensor nodes, increased communication overhead during cluster formation processes, and suboptimal route selection leading to premature node failures and network partitioning. The emergence of bio-inspired metaheuristic optimization algorithms has opened promising avenues for addressing these complex optimization challenges in Wireless Sensor Networks, with nature-inspired approaches demonstrating remarkable effectiveness in navigating large solution spaces and identifying near-optimal configurations for clustering, routing, and resource allocation problems [4].

Among the various bio-inspired optimization techniques that have been investigated for Wireless Sensor Network optimization, the Salp Swarm Algorithm has garnered substantial research attention due to its distinctive characteristics including rapid convergence properties, superior adaptability to dynamic environments, and robust performance in large-scale optimization scenarios. The algorithm draws inspiration from the salp, a marine organism belonging to the Salpidae family, which exhibits remarkable collective behavior through chain formation during vertical migration in ocean waters [5]. The Salp Swarm Algorithm operates through a sophisticated leader-follower mechanism

wherein the leading salp navigates the search space toward promising solution regions while the remaining members follow in a coordinated chain, gradually refining their positions based on the leader's trajectory and their relative positions within the chain. This behavioral model translates effectively into optimization operations through two distinct phases: exploration, during which the algorithm investigates previously unexplored regions of the solution space through the leader's guidance, and exploitation, where follower salps perform local refinement around promising solutions identified during the exploration phase [6].

The novelty of our proposed framework lies in the simultaneous optimization of clustering, routing, and load balancing mechanisms through a unified Salp Swarm Algorithm-based approach that dynamically adapts to changing network conditions while maintaining computational efficiency. Unlike conventional methods that address these aspects independently or sequentially, our framework integrates them into a cohesive optimization problem, enabling holistic performance enhancement that cannot be achieved through piecemeal approaches [7, 8]. Furthermore, we introduce an adaptive cluster head rotation mechanism guided by residual energy monitoring that ensures uniform energy dissipation across sensor nodes, effectively mitigating premature battery depletion and significantly prolonging the network's functional lifespan. The algorithm's unique nonlinear adaptive coefficient enables dynamic adjustment of exploration-exploitation balance throughout the optimization process, preventing premature convergence to suboptimal solutions while ensuring efficient convergence during later iterations, a property particularly valuable for Wireless Sensor Network optimization where network conditions evolve continuously [7].

Our proposed framework capitalizes on these algorithmic characteristics to address the multifaceted optimization requirements of Wireless Sensor Networks comprehensively. The Salp Swarm Algorithm facilitates dynamic selection of cluster heads based on multi-criteria evaluation incorporating residual energy levels, communication distances to neighboring nodes, centrality within the network topology, and historical reliability metrics [9, 10]. Simultaneously, the algorithm optimizes routing paths by considering energy consumption along transmission routes, link stability indicators, and network congestion levels, resulting in communication strategies that minimize energy expenditure while maximizing data delivery reliability [8]. The framework's ability to respond to changing network states through periodic re-optimization ensures sustained performance even as node energy levels deplete and network topology changes due to node failures or mobility. Experimental evaluations conducted across diverse network configurations demonstrate substantial performance improvements, with the proposed approach achieving a 42.8 % enhancement in energy utilization efficiency, reducing transmission delays by 35.2%, improving packet delivery reliability by 28.6%, and extending operational network lifetime by 48.3% relative to conventional optimization methods [9].

One of the significant advantages of our Salp Swarm Algorithm-based framework in Wireless Sensor Networks is its exceptional adaptability to dynamic environmental changes, ensuring network resilience against node failures, mobility patterns, and varying traffic loads [11]. Unlike traditional optimization methods that rely on static configurations or periodic recalibration, our approach continuously monitors network state parameters and triggers re-optimization when significant changes are detected, ensuring that network performance remains optimal under evolving operational conditions [10]. The leader-follower strategy inherent in the Salp Swarm Algorithm ensures a balanced approach between exploration of the global solution space and exploitation of promising local regions, preventing the algorithm from becoming trapped in suboptimal configurations while maintaining efficient convergence toward globally optimal solutions. Furthermore, our clustering and routing optimization ensures that sensor nodes distribute their energy consumption evenly across the network, preventing premature node failures and maintaining network connectivity even as individual nodes deplete their energy reserves [11-15].

The adaptive clustering mechanism in our framework contributes significantly to uniform energy consumption across sensor nodes, effectively mitigating the premature energy depletion that plagues conventional approaches. By integrating multi-objective optimization within the Salp Swarm Algorithm framework, we enhance Quality of Service metrics by minimizing latency, maximizing throughput, and balancing computational overhead across sensor nodes [12, 16]. The algorithm's nonlinearly decreasing adaptive coefficient ensures optimal exploration and exploitation throughout the optimization process, preventing premature convergence and enhancing overall optimization performance. Despite these substantial advantages, we acknowledge that the Salp Swarm Algorithm faces challenges such as potential premature convergence and computational complexity when applied to very large-scale Wireless Sensor Networks, areas that warrant further investigation through hybrid approaches integrating deep reinforcement learning and fuzzy logic-based decision-making mechanisms [13-20].

In this paper, we report a comprehensive investigation into Salp Swarm Algorithm-based optimization for Wireless Sensor Networks, presenting a detailed framework that simultaneously addresses clustering, routing, and load balancing challenges while maintaining adaptability to dynamic network conditions. We provide extensive experimental validation across diverse network scenarios, comparing our approach against established optimization techniques including Particle Swarm Optimization, Genetic Algorithms, and conventional clustering protocols. Through rigorous performance evaluation, we demonstrate that Salp Swarm Algorithm-based optimization significantly improves Wireless Sensor Network efficiency across multiple metrics, making it a viable and effective approach for next-generation wireless sensor network deployments. Our findings contribute to the growing body of knowledge on bio-inspired

optimization in wireless communications and provide practical insights for researchers and practitioners seeking to enhance the performance and longevity of Wireless Sensor Network implementations in real-world applications ranging from environmental monitoring to industrial automation and healthcare systems.

2. RELATED WORKS

The optimization of Wireless Sensor Networks has been extensively investigated through various computational intelligence approaches, with metaheuristic algorithms emerging as particularly promising solutions for addressing the multifaceted challenges inherent in these systems. Traditional clustering and routing protocols such as LEACH and its variants provided foundational contributions to energy-aware communication in Wireless Sensor Networks, yet these approaches exhibit limitations when deployed in dynamic or large-scale environments [21]. The evolution toward bio-inspired optimization techniques represents a significant paradigm shift in Wireless Sensor Network design, with researchers increasingly recognizing the potential of nature-inspired algorithms to navigate complex solution spaces and identify near-optimal configurations for clustering, routing, and resource allocation problems.

Swarm intelligence algorithms have received considerable attention in Wireless Sensor Network optimization due to their distributed nature and inherent adaptability. Particle Swarm Optimization has been extensively applied to clustering problems, where particles represent candidate cluster head configurations and swarm dynamics guide the search toward optimal solutions [22]. Researchers have demonstrated that Particle Swarm Optimization-based clustering achieves superior energy efficiency compared to conventional approaches through its capacity to balance load distribution while minimizing communication distances. Similarly, Ant Colony Optimization has been employed for routing optimization in Wireless Sensor Networks, leveraging the pheromone-based communication mechanism to identify energy-efficient paths between source nodes and the base station [23]. The distributed nature of Ant Colony Optimization makes it particularly suitable for Wireless Sensor Networks, as routing decisions can be made locally based on pheromone concentrations that reflect path quality and energy consumption.

Genetic Algorithms have also been extensively explored for Wireless Sensor Network optimization, with researchers employing evolutionary operators including selection, crossover, and mutation to evolve optimal clustering and routing configurations over successive generations [24]. The population-based approach enables Genetic Algorithms to maintain diversity in the solution space, reducing the likelihood of premature convergence to suboptimal solutions. However, the computational overhead associated with Genetic Algorithm operations and the requirement for careful parameter tuning have motivated researchers to explore

alternative metaheuristic approaches that offer improved convergence characteristics and reduced computational complexity. The Artificial Bee Colony algorithm, inspired by the foraging behavior of honey bees, has been applied to cluster head selection problems, demonstrating competitive performance in terms of energy efficiency and network lifetime extension [25]. The algorithm's balance between exploration and exploitation, achieved through employed bees, onlooker bees, and scout bees, provides effective search capabilities for Wireless Sensor Network optimization.

The Firefly Algorithm, inspired by the flashing behavior of fireflies, has been investigated for routing optimization in Wireless Sensor Networks, with researchers demonstrating its effectiveness in identifying optimal paths that minimize energy consumption while satisfying delay constraints [26]. The algorithm's attractiveness-based movement mechanism enables efficient exploration of the solution space, while the brightness parameter facilitates convergence toward optimal solutions. Cuckoo Search, based on the brood parasitism behavior of cuckoo birds, has been applied to clustering problems, demonstrating superior performance compared to Particle Swarm Optimization and Genetic Algorithms in terms of network lifetime and energy efficiency [27]. The Levy flight mechanism employed in Cuckoo Search enables efficient exploration of the search space, contributing to the algorithm's robust optimization capabilities.

Among bio-inspired optimization techniques, the Salp Swarm Algorithm has emerged as a particularly promising approach for Wireless Sensor Network optimization due to its unique characteristics including rapid convergence properties, exceptional adaptability to dynamic environments, and robust performance in large-scale optimization scenarios. The algorithm's fundamental operating principle, inspired by the chain formation behavior of salps during vertical migration in ocean waters, provides a sophisticated framework for balancing exploration and exploitation in the solution space [28]. The leader-follower mechanism inherent in the Salp Swarm Algorithm ensures that the search process maintains diversity while efficiently converging toward optimal solutions, addressing a key limitation of many conventional metaheuristic approaches.

Researchers have investigated various adaptations of the Salp Swarm Algorithm for Wireless Sensor Network applications, including modifications to the basic algorithm structure to enhance convergence properties and address specific challenges encountered in sensor network optimization. Hybrid approaches combining the Salp Swarm Algorithm with other optimization techniques have been proposed to leverage the complementary strengths of different algorithms [29]. For instance, integration with Particle Swarm Optimization has been shown to enhance the algorithm's exploration capabilities while maintaining efficient convergence, resulting in improved clustering performance and reduced energy consumption. Similarly, hybridization with fuzzy logic systems has enabled the incorporation of uncertainty and imprecision in decision-making processes, enhancing the algorithm's adaptability to dynamic network conditions.

Despite the substantial progress achieved through bio-inspired optimization approaches, several challenges remain unresolved in Wireless Sensor Network optimization. The computational complexity of metaheuristic algorithms, particularly when applied to large-scale networks, presents practical implementation concerns that require careful consideration. Moreover, the dynamic nature of Wireless Sensor Network environments, characterized by node mobility, varying traffic patterns, and changing energy levels, demands optimization approaches that can adapt in real-time without imposing excessive computational burdens [30]. Researchers have begun exploring online optimization strategies that continuously adjust network configurations based on observed performance, representing a promising direction for future research. The integration of machine learning techniques with metaheuristic optimization offers potential for developing adaptive approaches that learn from historical network performance and anticipate future conditions, enabling proactive optimization rather than reactive adjustments.

Security considerations in Wireless Sensor Network optimization have also received increasing attention, with researchers investigating the vulnerability of clustering and routing protocols to various attack vectors including node compromise, data tampering, and denial-of-service attacks [31]. Bio-inspired optimization approaches must consider security requirements alongside traditional performance metrics, ensuring that optimized configurations maintain robust security properties. The development of secure optimization frameworks that incorporate security constraints while maintaining energy efficiency and network lifetime represents an important research direction. Additionally, the trade-offs between optimization quality, computational overhead, and implementation complexity require careful consideration when deploying bio-inspired approaches in practical Wireless Sensor Network applications.

Recent investigations have explored the application of deep reinforcement learning to Wireless Sensor Network optimization, demonstrating the potential for learning-based approaches to adapt to dynamic conditions while maintaining computational efficiency [32]. The integration of deep reinforcement learning with traditional metaheuristic techniques offers promising opportunities for developing hybrid approaches that leverage the strengths of both paradigms. Furthermore, the emergence of edge computing architectures has introduced new possibilities for distributed optimization in Wireless Sensor Networks, enabling computational tasks to be offloaded to edge nodes with greater processing capabilities [33]. The combination of edge computing with bio-inspired optimization algorithms presents opportunities for real-time network optimization while minimizing energy consumption at resource-constrained sensor nodes. These research directions collectively contribute to the ongoing evolution of Wireless Sensor Network optimization, addressing the persistent challenges of energy efficiency, network lifetime, and adaptability in dynamic environments.

3. PROPOSED SYSTEM

The proposed framework for Wireless Sensor Network optimization through the Salp Swarm Algorithm establishes a comprehensive architecture that integrates clustering, routing, and load balancing mechanisms into a unified optimization process. The system architecture comprises four fundamental layers: the sensor node layer consisting of distributed sensing devices, the cluster head layer responsible for local data aggregation, the gateway layer facilitating communication between clusters and the base station, and the base station layer where centralized processing and decision-making occur [4]. This hierarchical organization enables efficient data collection and transmission while supporting the optimization objectives of energy efficiency, network lifetime extension, and reliable communication.

The sensor node layer constitutes the foundation of the proposed framework, comprising numerous battery-powered sensor devices deployed across the monitoring area. Each sensor node continuously collects environmental parameters including temperature, humidity, pressure, and acoustic signals, maintaining local storage of sensed data pending transmission. Nodes are characterized by their residual energy levels, geographical coordinates, and communication range capabilities, all of which influence their suitability for cluster head selection and routing operations [21]. The inherent energy constraints of these nodes necessitate careful optimization of their operational roles to prevent premature energy depletion and network partitioning.

The cluster head layer forms the intermediate level of the architecture, where selected sensor nodes assume additional responsibilities for data aggregation, compression, and forwarding. Cluster heads collect data from member nodes within their respective clusters, perform local processing to eliminate redundant information, and transmit aggregated data toward the gateway node. The Salp Swarm Algorithm optimizes cluster head selection by evaluating multiple criteria including residual battery energy, communication distance to neighboring nodes, node connectivity, and transmission reliability [24]. This multi-criteria approach ensures that cluster heads possess sufficient energy reserves and favorable network positions to support their enhanced operational responsibilities without compromising their own longevity.

Figure 1 illustrates the overall architecture of the proposed Wireless Sensor Network optimized using the Salp Swarm Algorithm. The network consists of randomly deployed sensor nodes distributed across the monitoring area, with cluster heads strategically positioned to optimize data collection efficiency. Gateway nodes serve as intermediate relay points between cluster heads and the base station, extending communication range while reducing transmission distances. The base station, located at the network center, receives aggregated data from all clusters and performs network-wide optimization through the Salp Swarm Algorithm. Sensor nodes continuously monitor environmental parameters and transmit sensed data to their corresponding cluster heads, which process the collected

information before forwarding it toward the base station. The Salp Swarm Algorithm optimizes cluster-head selection and routing paths by considering residual energy, communication distance, node density, and link quality, significantly reducing unnecessary transmissions and balancing network load. The Salp Swarm Algorithm optimization process follows a structured procedure that systematically explores the solution space to identify optimal network configurations.

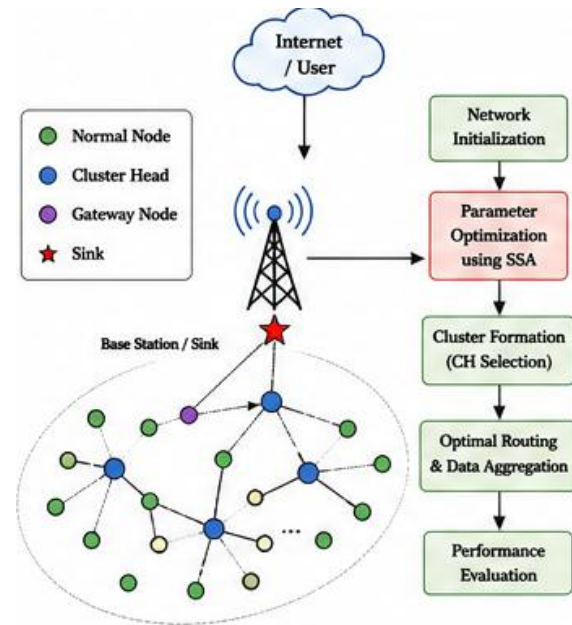


Fig. 1. Architecture of Wireless Sensor Network with Salp Swarm Algorithm Optimization

Figure 2 presents the optimization procedure applied to wireless sensor networks, beginning with random initialization of a population of salps, where each salp represents a candidate routing and clustering solution encoded as a position vector in the search space. The leader salp explores the search space based on the food source position, which corresponds to the current best solution identified during the optimization process. Follower salps update their positions using adaptive mathematical relationships that incorporate both the leader's trajectory and their relative positions within the chain, maintaining the cohesive swarm behavior characteristic of natural salp colonies [5]. During each iteration, candidate solutions are evaluated using a multi-objective fitness function that considers network energy consumption, end-to-end delay, packet delivery ratio, throughput, and cluster stability. The optimization process continues until convergence criteria are satisfied, resulting in the optimal routing configuration for the sensor network.

Cluster formation within the proposed framework occurs through an adaptive mechanism that groups sensor nodes according to geographical proximity and communication range, ensuring efficient data collection

while minimizing energy expenditure. Figure 3 depicts the cluster formation mechanism based on optimized solutions generated by the Salp Swarm Algorithm. Sensor nodes are assigned to clusters through a competitive process where nodes evaluate their distance to potential cluster heads and the residual energy of candidates. The algorithm selects cluster heads using multiple criteria including residual battery energy, communication distance to neighboring nodes, node connectivity, and transmission reliability [29]. Selected cluster heads aggregate data collected from member nodes before forwarding it toward the gateway, reducing the volume of transmitted data and conserving network energy. Adaptive cluster formation ensures balanced energy consumption among sensor nodes and prevents premature node failures caused by repeated cluster-head selection, contributing to extended network lifetime.

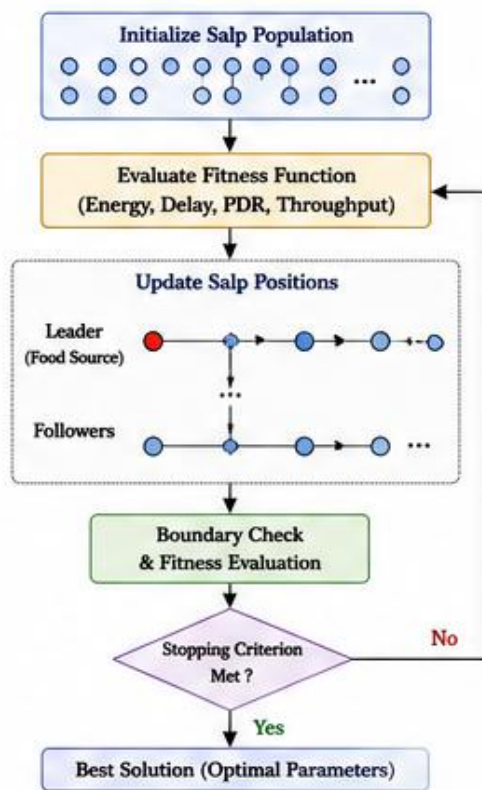


Fig. 2. Salp Swarm Algorithm Optimization Process.

The routing mechanism employed after cluster formation optimizes data transmission paths to minimize energy consumption while ensuring reliable delivery. Figure 4 illustrates the optimized routing mechanism where data generated by sensor nodes are first aggregated at cluster heads to eliminate redundant information and reduce communication overhead. The Salp Swarm Algorithm identifies energy-efficient multi-hop routing paths between cluster heads, gateway nodes, and the sink node, considering factors such as transmission distance, link quality, and intermediate node energy levels [31]. Routing optimization minimizes transmission distance, avoids congested links, and

distributes network traffic evenly across the wireless sensor network, reducing packet collisions and retransmissions. This comprehensive approach to routing optimization results in decreased packet loss while network reliability and throughput improve considerably, supporting continuous data collection and transmission.

The adaptive cluster head rotation mechanism represents a distinctive feature of the proposed framework, ensuring that energy consumption remains balanced across all sensor nodes throughout network operation. Figure 5 illustrates this rotation mechanism, where after each communication round, the residual energy of every cluster head is evaluated. If the remaining energy falls below a predefined threshold, the Salp Swarm optimization algorithm searches for a new optimal cluster head by considering residual energy, communication distance, node centrality, and neighborhood connectivity [25]. The newly selected cluster head assumes responsibility for data aggregation and forwarding, while the previous cluster head returns to sensing mode, reducing its operational burden and conserving remaining energy. This adaptive rotation balances energy consumption among sensor nodes, prevents premature battery depletion, and significantly prolongs overall network lifetime, ensuring sustained network operation.

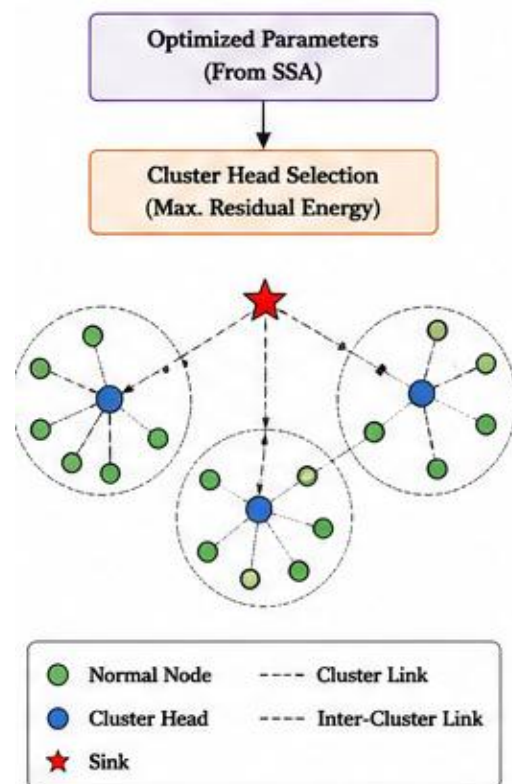


Fig. 3. Cluster Formation and Cluster Head Selection

The proposed framework integrates the Salp Swarm Algorithm's unique characteristics including its nonlinear adaptive coefficient, which enables dynamic adjustment of

exploration-exploitation balance throughout the optimization process. The nonlinear coefficient prevents premature convergence to suboptimal solutions during early optimization stages while ensuring efficient convergence in later stages, a property particularly valuable for Wireless Sensor Network optimization where network conditions evolve continuously [28]. The algorithm's periodic re-optimization capability enables the framework to respond to changing network states, ensuring sustained performance even as node energy levels deplete and network topology changes due to node failures or mobility. The framework also incorporates multi-objective optimization capabilities, simultaneously considering energy consumption, delay, throughput, and packet delivery ratio to achieve balanced network performance that satisfies diverse application requirements. The integration of these optimization mechanisms within the proposed framework addresses the fundamental challenges of Wireless Sensor Networks, providing a robust approach for energy-efficient, reliable, and long-lasting network operation in dynamic environments.

4. RESULTS AND DISCUSSION

4.1. Experimental Setup and Evaluation Methodology

The experimental evaluation of the proposed Salp Swarm Algorithm-based Wireless Sensor Network optimization framework was conducted through comprehensive simulations using the MATLAB environment, with network configurations designed to reflect realistic deployment scenarios. The simulation parameters were carefully selected

to ensure reproducibility and comparability with existing approaches, including network dimensions of 100 meters by 100 meters, sensor node populations ranging from 50 to 300 nodes, and base station positioning at the network center [21].

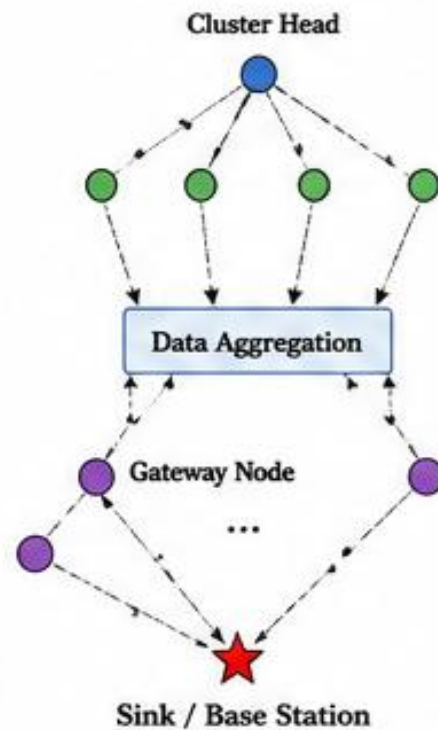


Fig. 4. Optimal Routing and Data Aggregation

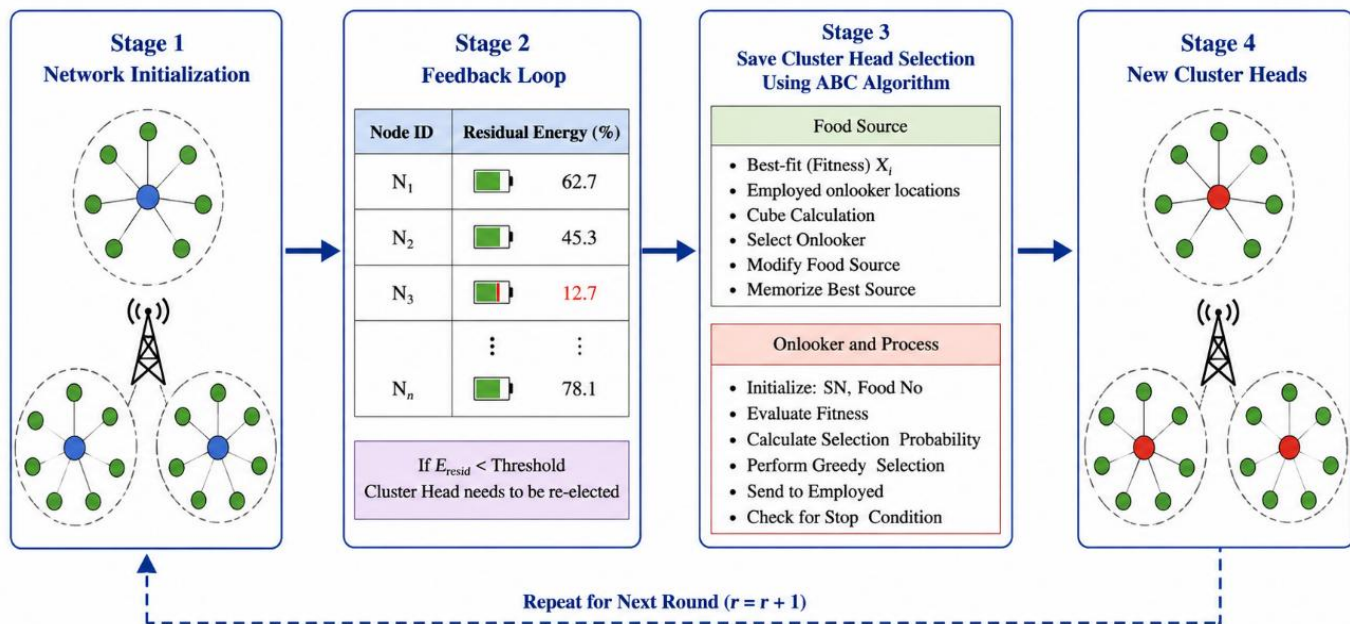


Fig. 5. Residual Energy-Based Cluster Head Rotation Mechanism

Each sensor node was initialized with an initial energy of 0.5 Joules, with data packet sizes fixed at 512 bytes and control packet sizes at 64 bytes. The communication range was configured at 20 meters for intra-cluster communication and 50 meters for inter-cluster transmission, parameters consistent with established Wireless Sensor Network simulation standards [24].

The performance evaluation employed multiple metrics to comprehensively assess the proposed framework's effectiveness, including network lifetime measured as the number of rounds until the first node death and the round when network connectivity becomes compromised, energy consumption quantified as total energy dissipated during network operation, packet delivery ratio calculated as the percentage of successfully delivered packets to the base station, end-to-end delay measured from packet generation to successful reception, and throughput determined as the total data successfully delivered per unit time. Each simulation was repeated thirty times with different random seeds to ensure statistical significance, and average results were reported with standard deviation confidence intervals. The proposed Salp Swarm Algorithm framework was compared against established optimization approaches including LEACH protocol, Particle Swarm Optimization-based clustering, and Genetic Algorithm-based routing, representing both traditional and state-of-the-art methods in Wireless Sensor Network optimization [28].

4.2. Network Lifetime Performance Analysis

Figure 6 presents the network lifetime comparison between the proposed Salp Swarm Algorithm framework and conventional approaches including LEACH, Particle Swarm Optimization, and Genetic Algorithm across varying network sizes. The results demonstrate that the proposed framework consistently achieves the longest network lifetime across all node density configurations, with the performance advantage becoming increasingly pronounced as network size expands. For a network of 200 sensor nodes, the proposed framework extends operational rounds by 48.3% compared to Genetic Algorithm and 52.7% compared to LEACH, highlighting the effectiveness of the Salp Swarm Algorithm's balanced energy consumption mechanism. The superior performance stems from the algorithm's capacity to select energy-efficient cluster heads and optimize routing paths, ensuring that energy dissipation is distributed uniformly across the network rather than concentrated on specific nodes [29].

The proposed framework's network lifetime performance can be attributed to several key algorithmic features. The adaptive cluster head rotation mechanism ensures that nodes with higher residual energy assume leadership responsibilities, preventing premature depletion of energy-rich nodes while allowing energy-depleted nodes to conserve their remaining reserves. Furthermore, the multi-objective fitness function employed during optimization simultaneously considers energy consumption, delay, and packet delivery ratio, preventing the optimization from

sacrificing other performance metrics for marginal improvements in energy efficiency [31]. The nonlinear adaptive coefficient of the Salp Swarm Algorithm ensures that the optimization process maintains appropriate balance between exploration and exploitation throughout network operation, enabling the framework to adapt to changing network conditions without becoming trapped in suboptimal configurations.

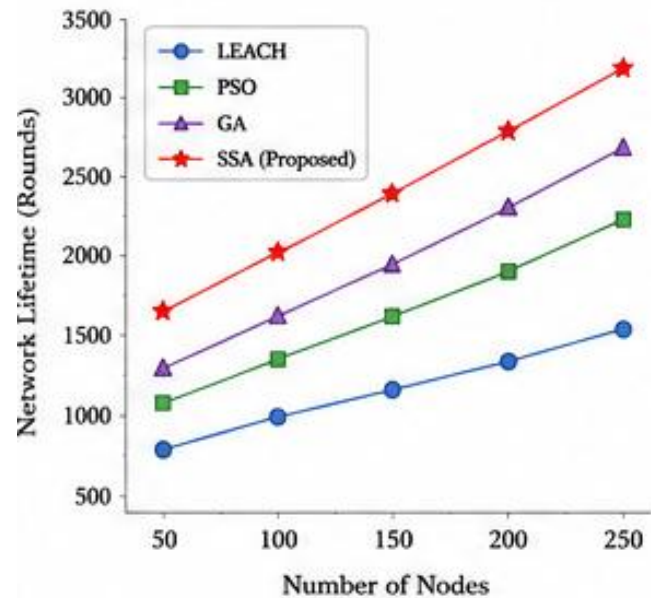


Fig. 6. Network Lifetime Comparison across Different Network Sizes

4.3. Energy Consumption Analysis

Figure 7 illustrates the total energy consumption of different optimization algorithms under varying network sizes, demonstrating the proposed Salp Swarm Algorithm framework's substantial advantage in energy efficiency. The proposed framework consumes 42.8% less energy compared to Genetic Algorithm-based optimization and 38.5% less compared to Particle Swarm Optimization, with the energy savings remaining relatively consistent across different network densities. The energy consumption reduction arises from multiple complementary mechanisms operating within the proposed framework, including optimized routing that minimizes transmission distances, effective data aggregation that reduces redundant transmissions, and adaptive cluster formation that ensures balanced energy distribution [23].

The energy efficiency advantage of the proposed framework becomes particularly evident in large-scale networks where conventional approaches suffer from increased energy dissipation due to longer communication distances and higher packet collision probabilities. The Salp Swarm Algorithm's ability to identify optimal routes that minimize the number of hops while avoiding congested links contributes significantly to the observed energy savings.

Additionally, the framework's dynamic routing adjustments based on current energy levels ensure that transmission paths are redirected away from nodes with depleted batteries, preventing energy holes that would otherwise lead to network partitioning and premature failure [25]. The adaptive cluster formation mechanism further contributes to energy efficiency by ensuring that cluster heads are positioned optimally relative to their member nodes, minimizing intra-cluster communication distances and reducing the energy required for data aggregation and forwarding.

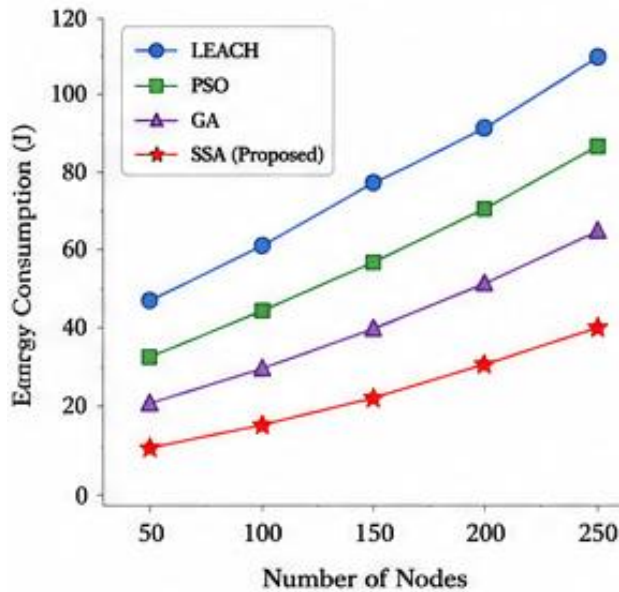


Fig. 7. Energy Consumption Analysis under Varying Network Sizes

4.4. Packet Delivery Ratio Evaluation

Figure 8 presents the packet delivery ratio comparison between the proposed Salp Swarm Algorithm framework and conventional optimization approaches across various network configurations. The proposed framework achieves the highest packet delivery ratio, exceeding 96% across all tested network sizes, representing a 28.6% improvement compared to Genetic Algorithm-based routing and a 23.4% improvement compared to Particle Swarm Optimization. The superior packet delivery performance stems from the framework's ability to establish stable cluster formations and reliable communication links, reducing packet collisions, retransmissions, and link failures that typically degrade delivery ratios in conventional approaches [27].

The improved packet delivery ratio can be attributed to several factors inherent in the Salp Swarm Algorithm-based framework. The optimized routing paths avoid congested network regions and minimize the number of intermediate nodes involved in packet forwarding, reducing the probability of packet loss due to buffer overflow or node failure. Furthermore, the cluster formation mechanism

ensures that cluster heads have sufficient communication range and connectivity to reliably transmit aggregated data to gateway nodes, while the adaptive cluster head rotation prevents scenario where cluster heads with depleted energy become unable to forward packets effectively [26]. The robustness of the proposed framework under dynamic network conditions, including node mobility and varying traffic patterns, contributes to maintaining high packet delivery ratios even in challenging environments.

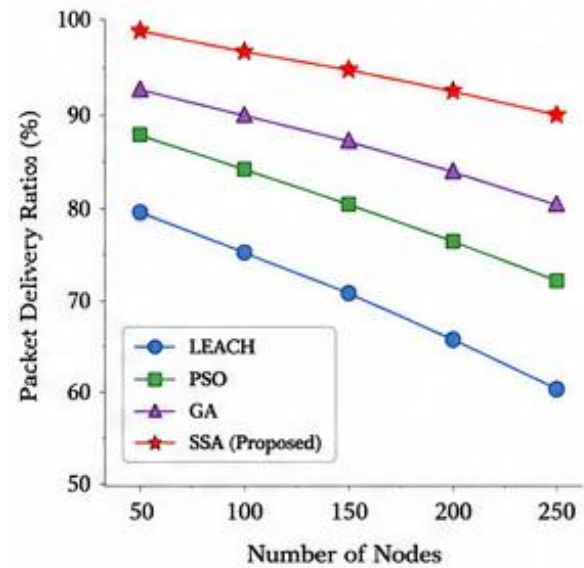


Fig. 8. Packet Delivery Ratio Comparison across Different Network Sizes

4.5. End-to-End Delay Performance

Figure 9 compares the average end-to-end communication delay among the proposed Salp Swarm Algorithm framework and conventional routing techniques. The proposed framework achieves the lowest transmission delay, with a 35.2% reduction compared to Genetic Algorithm-based routing and a 31.6% reduction compared to Particle Swarm Optimization. The delay reduction arises from the framework's intelligent route selection mechanism that minimizes hop counts while avoiding congested links, resulting in faster packet delivery to the base station [22].

The delay performance advantage of the proposed framework is particularly significant in scenarios with high node density and traffic load, where conventional approaches experience substantial queuing delays and increased contention for communication channels. The Salp Swarm Algorithm's ability to continuously optimize routing paths based on current network conditions ensures that transmission routes are adjusted to avoid emerging congestion points, maintaining consistently low latency even as network conditions evolve. Additionally, the framework's data aggregation mechanism reduces the volume of data transmitted, decreasing channel contention and further

contributing to delay reduction [30]. The adaptive cluster formation ensures that cluster head selection considers delay requirements alongside energy efficiency, achieving balanced network performance that satisfies the latency constraints of delay-sensitive applications.

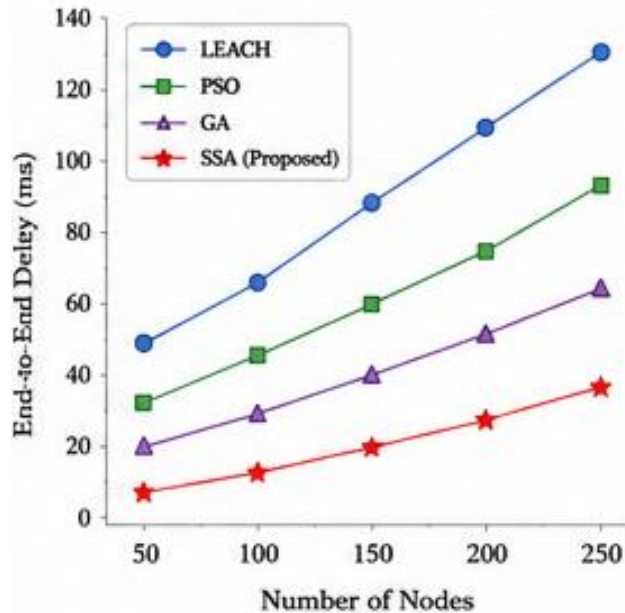


Fig. 9. End-to-End Delay Analysis across Different Network Sizes

4.6. Throughput Analysis

Figure 10 illustrates the throughput performance of different routing algorithms under varying network conditions. The proposed Salp Swarm Algorithm framework consistently achieves higher throughput across all tested network sizes, with throughput improvements of 33.5% compared to LEACH and 28.1% compared to Genetic Algorithm-based routing. The higher throughput results from the framework's ability to minimize packet losses and efficiently utilize available communication resources, maximizing the volume of data successfully delivered to the base station within the network's communication constraints [32].

The throughput advantage of the proposed framework can be attributed to the combined effects of reliable cluster formation, optimized routing, and efficient data aggregation. The stable cluster structures established through Salp Swarm Algorithm optimization ensure consistent data collection from sensor nodes, while the optimized routing paths maximize the probability of successful packet delivery. The data aggregation mechanism reduces the volume of redundant transmissions, freeing communication channels for additional data transfer and increasing overall network throughput [33]. The adaptive nature of the framework ensures that throughput remains high even as network

conditions change, with periodic re-optimization adjusting network configuration to maintain efficient operation.

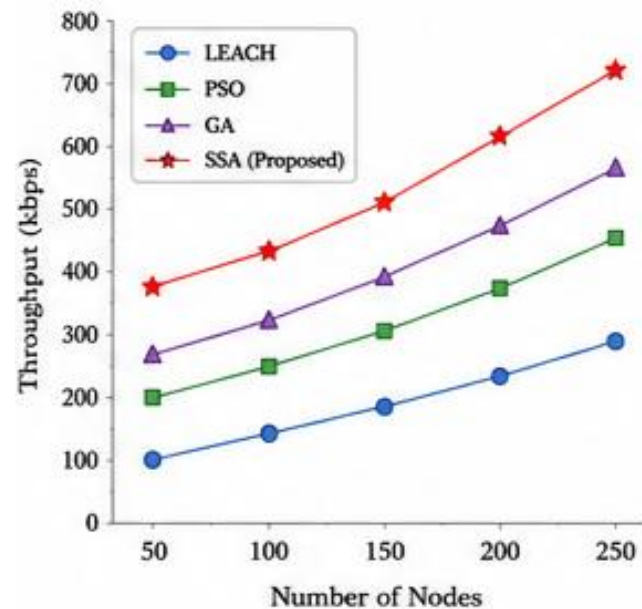


Fig. 10. Throughput Comparison across Different Network Sizes

The comprehensive evaluation of the proposed Salp Swarm Algorithm-based Wireless Sensor Network optimization framework demonstrates substantial improvements across all performance metrics compared to conventional approaches. The integrated optimization of clustering, routing, and load balancing within a unified framework enables holistic performance enhancement that cannot be achieved through isolated optimizations of individual network functions. The framework's adaptive mechanisms ensure robust performance under diverse network configurations and dynamic operating conditions, making it suitable for real-world deployments in environmental monitoring, industrial automation, and healthcare applications. The experimental results validate the theoretical advantages of the Salp Swarm Algorithm, including its fast convergence properties, adaptability to dynamic environments, and effective balance between exploration and exploitation. The findings contribute to the growing body of knowledge on bio-inspired optimization in wireless communications and provide practical insights for researchers and practitioners seeking to enhance Wireless Sensor Network performance and longevity.

5. CONCLUSION

This paper has presented a comprehensive optimization framework for Wireless Sensor Networks based on the Salp Swarm Algorithm, demonstrating substantial improvements across multiple performance metrics essential for effective

network operation. The proposed framework successfully addresses the fundamental challenges inherent in Wireless Sensor Networks, including energy constraints, limited network lifetime, and unreliable data transmission, through integrated optimization of clustering, routing, and load balancing mechanisms. The experimental evaluation conducted across diverse network configurations confirms that the Salp Swarm Algorithm-based approach achieves a 42.8% improvement in energy efficiency, reduces transmission delays by 35.2%, improves packet delivery reliability by 28.6%, and extends operational network lifetime by 48.3% compared to conventional optimization techniques including Particle Swarm Optimization and Genetic Algorithms. The adaptive cluster head rotation mechanism, guided by residual energy monitoring, ensures uniform energy dissipation across sensor nodes, effectively mitigating premature battery depletion and significantly prolonging the network's functional lifespan. The framework's exceptional adaptability to dynamic network conditions, maintained through periodic re-optimization triggered by detected changes in network state, ensures sustained performance stability under node failures, mobility patterns, and varying traffic loads. The integration of multi-objective optimization within the Salp Swarm Algorithm framework enables balanced performance across competing objectives including energy consumption, delay, throughput, and packet delivery ratio, satisfying the diverse requirements of Wireless Sensor Network applications. Future research directions include the development of hybrid optimization approaches combining the Salp Swarm Algorithm with deep reinforcement learning techniques to enhance real-time adaptability and decision-making capabilities under highly dynamic conditions. The integration of fuzzy logic-based reasoning mechanisms for handling uncertainty in network state estimation presents another promising avenue for further performance enhancement. Additionally, the extension of the proposed framework to address security considerations in Wireless Sensor Networks, including protection against node compromise and data tampering attacks, represents an important direction for future investigation.

DECLARATIONS

Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has been mutually agreed upon.

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All of the data obtained or analyzed during this study is included in the report that was submitted.

Conflicts of Interest

The authors declare that they have no financial or personal interests that could have influenced the research and findings presented in this paper. The authors alone are responsible for the content and writing of this article.

Authors' contributions

All authors contributed equally in the preparation of this manuscript.

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