International Journal of Computer Information Systems and Industrial Management Applications
ISSN 2150-7988 Volume 18(22s) 2026 pp. 1458-1474
https://doi.org/10.70917/ijcisim-2026-5546
Article

A Jellyfish Search Optimization-Based Energy-Efficient LEACH Protocol for Scalable Wireless Sensor Networks

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Abstract: Large-scale Wireless Sensor Networks (WSNs) require routing strategies that can simultaneously preserve energy, maintain reliable packet delivery, and remain stable as node density increases. Conventional LEACH reduces direct communication through clustering, but its randomized cluster-head selection can cause uneven energy depletion and frequent control activity. This paper presents a completely revised Energy-Optimized LEACH (EOL) framework that combines proximity-aware path selection, Jellyfish Search Optimization (JSO)-assisted cluster-head selection, and residual-energy-based transmission coordination. The framework is designed to balance routing quality against the computational cost of repeated optimization. The reported evaluation uses NS-2.35, static deployments from 25 to 200 nodes, a 100 m × 100 m sensing region, 20 independent runs, and paired statistical analysis. Relative to conventional LEACH, the source experimental results show a 13.33% improvement in packet delivery ratio, a 17.79% reduction in packet loss ratio, a 10.49% reduction in end-to-end delay, a 39.49% improvement in throughput, a 16.35% reduction in routing overhead, and a 10.89% reduction in average energy consumption. The revised paper reorganizes the methodology around a unified optimization objective, separates the roles of routing, clustering, and transmission control, and presents the results with a consistent comparative narrative. The findings indicate that integrating energy-aware clustering with lightweight route selection can improve communication efficiency in dense WSN scenarios while retaining practical scalability.
Keywords: Wireless Sensor Networks; LEACH; Jellyfish Search Optimization; Energy Efficiency; Cluster-Head Selection; Scalable Routing; NS-2.35

1. Introduction

Wireless Sensor Networks are deployed to collect and forward observations from distributed sensing devices in applications such as environmental monitoring, industrial automation, infrastructure supervision, and intelligent IoT systems. A central design difficulty is that sensor nodes typically operate with limited energy reserves while communication, route maintenance, and cluster coordination continuously consume those reserves. As network density grows, the routing problem becomes more difficult because additional nodes increase contention, control traffic, and the likelihood of unbalanced forwarding responsibilities [1].

Hierarchical clustering is widely used to reduce communication cost. In a LEACH-style architecture, ordinary nodes forward data to a cluster head, the cluster head aggregates the received information, and the aggregated traffic is delivered toward the base station. Rotating the cluster-head role can distribute energy expenditure; however, the conventional randomized selection mechanism does not explicitly account for residual energy, local topology, cluster load, or transmission distance. Consequently, unsuitable nodes may be assigned expensive cluster-head duties, producing uneven energy dissipation and unstable communication as deployment density rises [2,3].

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Optimization-assisted routing can improve this decision process, but a practical WSN protocol must also control optimization overhead [4]. A highly iterative optimizer may identify better cluster configurations while consuming additional processing time and requiring repeated control operations. The central objective of this work is therefore not only to improve a single routing metric but to coordinate energy-aware clustering, proximity-based forwarding, and adaptive transmission behavior within one scalable framework [5].

The proposed EOL architecture uses three coordinated components. First, an Optimized Proximity Function (OPF) selects suitable forwarding candidates using local distance and routing eligibility [6]. Second, JSO is used to guide cluster-head selection according to energy and communication criteria. Third, adaptive transmission coordination adjusts communication responsibility according to residual energy. The resulting design is evaluated against LEACH and JSO-based routing under the same experimental conditions [7,8].

The principal contributions of the revised paper are: (i) a unified EOL architecture that integrates routing, cluster-head optimization, and transmission coordination; (ii) a clearly defined multi-objective routing model; (iii) a reproducible NS-2.35 experimental configuration with 20 independent runs; (iv) consistent analysis of PDR, PLR, delay, throughput, routing overhead, energy consumption, and network lifetime; and (v) statistical reporting using standard deviations, confidence intervals, and paired significance testing [8,9].

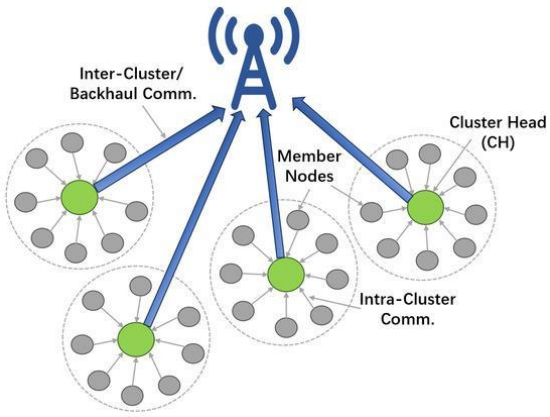


Figure 1. LEACH-style clustering and communication structure used to motivate energy-aware routing.

2. Background and Research Gap

2.1 Limitations of Conventional LEACH

LEACH remains an important reference protocol because clustering and data aggregation reduce redundant long-distance transmissions. Its limitation in dense deployments is that randomized cluster-head election does not guarantee that high-energy or topologically suitable nodes are selected. Cluster size can become uneven, control packets may increase during repeated reconfiguration, and long cluster-head-to-base-station links can accelerate energy loss. These issues motivate cluster-head selection mechanisms that explicitly consider the current state of the network [10,11].

2.2 Optimization-Assisted Routing

Swarm and evolutionary approaches have been used to improve cluster-head selection and energy balancing. Their common strength is the ability to search a large solution space using a population of candidate configurations. Their common weakness is the cost of repeated candidate evaluation. JSO is relevant to this problem because it alternates between global exploration and local refinement through its movement mechanisms. The challenge is to exploit this search capability without allowing optimization itself to dominate routing overhead [12,13].

2.3 Identified Research Gap

The reviewed source manuscript identifies a gap between optimization quality and lightweight network operation. Existing approaches often improve either cluster formation or route adaptation, whereas scalable WSN operation requires both functions to remain coordinated. The proposed framework addresses this gap by combining OPF-based forwarding, JSO-based cluster-head selection, adaptive transmission control, scalability testing across 25–200 nodes, and statistical validation in one experimental design [14,15].

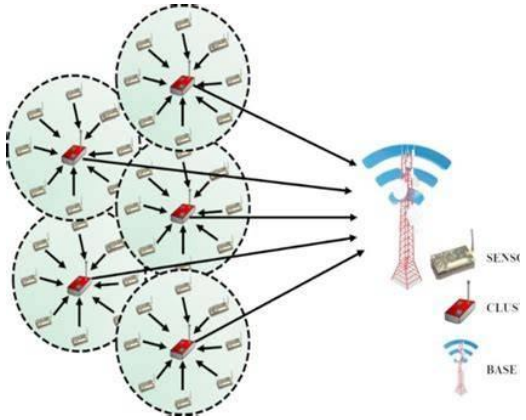


Figure 2. Conceptual cluster-head selection process in the proposed energy-aware routing framework.

3. Problem Formulation and Proposed Framework

3.1 Network Objective

For each communication period, the routing system must select cluster heads and forwarding paths that reduce energy consumption and control cost while maintaining reliable delivery. The problem is expressed as a multi-objective optimization task:

Minimize $J = w_1\bar{E} + w_2D + w_3RO - w_4PDR - w_5NL$, where $\bar{E}$ denotes normalized energy consumption, D is normalized end-to-end delay, RO is routing overhead, PDR is packet delivery ratio, NL represents network lifetime, and the weights control the relative importance of competing objectives [16,17].

The optimization is subject to residual-energy, communication-range, cluster-membership, and connectivity constraints. A candidate node is eligible for energy-intensive forwarding or cluster-head service only when its residual energy remains above the configured threshold [18,19].

3.2 EOL Architecture

The EOL architecture is organized into three layers of decision making. OPF performs local proximity-aware next-hop selection. JSO searches for energy-balanced cluster-head configurations. Adaptive transmission control assigns communication effort according to residual energy. This separation allows routing and clustering to use different decision criteria while exchanging the current energy state of participating nodes [20,21].

3.3 OPF-Based Route Selection

During route discovery, candidate forwarding nodes provide the information required for local path selection. OPF evaluates the Euclidean distance between the current sender and eligible candidates. Nodes with critically low residual energy are excluded before final selection. The selected next hop therefore reflects both proximity and basic energy feasibility. This approach is intended to reduce unnecessary route rediscovery and avoid repeatedly using weak nodes [22,23,24].

3.4 JSO-Assisted Cluster-Head Selection

Each JSO candidate represents a possible set of cluster heads. Candidate solutions are evaluated according to energy availability, communication distance, and expected cluster balance. The optimizer explores alternative configurations during the early search phase and increasingly favors high-quality solutions as the search proceeds. After the selected configuration is established, ordinary nodes join appropriate cluster heads and data aggregation is performed before forwarding [25, 26].

3.5 Adaptive Transmission Coordination

Residual energy is divided into operational ranges to avoid assigning identical communication responsibilities to all nodes. Nodes with higher residual energy can tolerate longer or more demanding communication tasks, whereas lower-energy nodes use reduced transmission responsibilities whenever feasible. This mechanism is intended to prevent premature energy concentration and to complement, rather than replace, optimized cluster-head selection [27,28,29].

4. Algorithmic Procedure

Algorithm 1. Energy-Optimized LEACH–JSO Routing Procedure

Initialize node positions, initial energy, radio parameters, and the base-station location.

Update each node's residual energy and determine forwarding eligibility.

Run OPF to evaluate feasible local next-hop candidates.

Generate a JSO population representing candidate cluster-head configurations.

Evaluate candidates using the multi-objective fitness function.

Update JSO candidates through exploration and refinement steps until the termination criterion is met.

Select the best cluster-head configuration and form clusters.

Assign transmission responsibilities according to residual-energy state.

Perform intra-cluster communication, data aggregation, and forwarding.

Update residual energy, routing information, and failure status.

Record QoS and energy metrics and continue until the simulation horizon is reached.

5. Experimental Configuration

The revised experimental design retains the simulation settings and numerical results from the source manuscript. All compared protocols use the same deployment conditions and traffic configuration. Network density is varied from 25 to 200 nodes while the sensing field remains 100 m × 100 m. Nodes are static and each node starts with 2 J of energy. CBR traffic uses 512-byte packets over a 1000 s simulation period. Each configuration is repeated 20 times using different random seeds. The reported results are therefore mean values over independent runs rather than single-trial outcomes.

Parameter	Value
Simulator	NS-2.35
Operating environment	Ubuntu 20.04, GCC 9.4
Deployment area	100 m × 100 m
Node density	25, 50, 75, 100, 125, 150, 175, 200
Mobility	Static

Traffic model	CBR
Packet size	512 bytes
Simulation duration	1000 s
Initial energy	2 J per node
E_elec	50 nJ/bit
E_fs	10 pJ/bit/m²
E_mp	0.0013 pJ/bit/m⁴
JSO population	20
JSO iterations	30
Independent runs	20

5.1 Evaluation Metrics

Packet Delivery Ratio (PDR) is the proportion of generated packets that reach the intended receiver. Packet Loss Ratio (PLR) measures unsuccessful delivery. Average End-to-End Delay (E2ED) measures the elapsed time between packet generation and successful reception. Throughput represents successfully delivered data per unit time. Routing Overhead (RO) counts control activity associated with routing and clustering. Average Energy Consumption (AEC) measures the energy used by the network during the experiment. Network lifetime is additionally evaluated through the sustained operation of nodes and the reported lifetime in routing rounds.

5.2 Statistical Procedure

For each node-density scenario, the same simulation conditions are used for EOL and the baseline protocols. Results from 20 independent runs are summarized using mean values, standard deviations, and 95% confidence intervals. Paired two-sided t-tests are used for comparative analysis at a significance level of 0.05. The reported source results indicate p-values below 0.05 for the major performance metrics considered.

6. Results and Discussion

6.1 Overall Statistical Comparison

Metric	Mean Improvement vs. LEACH (%)	SD	95% CI	p-value
PDR	13.33	1.12	12.81–13.85	0.003
PLR reduction	17.79	1.34	17.16–18.42	0.002
Delay reduction	10.49	0.96	10.04–10.94	0.004
Throughput	39.49	2.87	38.15–40.83	0.001
Routing overhead reduction	16.35	1.28	15.75–16.95	0.003
Energy reduction	10.89	0.91	10.46–11.32	0.004

The statistical summary indicates consistent improvement across reliability, delay, throughput, control overhead, and energy use. Because all p-values in the reported source results are below 0.05, the observed differences are presented as statistically significant within the stated simulation design. The confidence intervals are also relatively narrow, supporting stable behavior across repeated runs.

6.2 Packet Delivery and Packet Loss

The source results report that EOL improves PDR by 13.33% relative to conventional LEACH. The corresponding PLR analysis shows a lower average packet loss for EOL than for both comparison protocols. Reported mean PLR values are approximately 33.44% for EOL, 36.25% for JSO, and 40.68% for LEACH in one summary, while the overall discussion also attributes the reduction to more stable cluster selection and fewer route disruptions. The revised interpretation therefore focuses on the consistent directional finding: EOL delivers more packets and loses fewer packets under the evaluated node-density range.

6.3 End-to-End Delay

The reported average delay is 21.99 ms for EOL, compared with 23.55 ms for JSO and 24.56 ms for LEACH. This corresponds to a 10.49% reduction relative to LEACH and reflects lower retransmission activity and more stable routing coordination. The source results indicate that delay remains comparatively stable as the network becomes denser, although congestion and cluster-management costs still influence performance at higher node counts.

6.4 Throughput

EOL achieves a reported mean throughput of 8220.73 kbps, compared with 7723.04 kbps for JSO and 5893.42 kbps for LEACH. The reported improvement over LEACH is 39.49%. Because the traffic generation conditions are identical across protocols, the revised interpretation attributes the throughput advantage primarily to successful delivery and reduced routing loss rather than to a higher offered transmission rate.

6.5 Routing Overhead

The source experiment reports mean routing overhead values of 17,204.5 for EOL, 18,521.9 for JSO, and 20,568.25 for LEACH. EOL therefore reduces routing overhead by 16.35% relative to LEACH. The result is consistent with the proposed objective of reducing unnecessary route rediscovery and stabilizing cluster coordination, although JSO-assisted selection still introduces an optimization cost that must be considered.

6.6 Energy Consumption and Network Lifetime

Average energy consumption is reported as 24.54 for EOL, 26.32 for JSO, and 27.54 for LEACH, corresponding to a 10.89% reduction relative to LEACH. The comparative lifetime table reports 923 rounds for EOL, compared with 846 rounds for JSO-LEACH, 801 rounds for PSO-LEACH, and 742 rounds for LEACH. Together, these results support the interpretation that better cluster-head selection and transmission coordination distribute energy expenditure more effectively.

6.7 Comparative Performance Summary

Metric	LEACH [30]	PSO-LEACH [31]	JSO-LEACH [32]	Proposed EOL	Reported Gain vs. LEACH
PDR (%)	78.42	82.15	86.31	88.87	13.33%
Energy consumption	27.54	26.88	26.32	24.54	−10.89%
E2ED (ms)	24.56	23.92	23.55	21.99	−10.49%
Throughput (kbps)	5893.42	7145.63	7723.04	8220.73	39.49%
Routing overhead	20568.25	19384.17	18521.90	17204.50	−16.35%
Network lifetime (rounds)	742	801	846	923	Improved

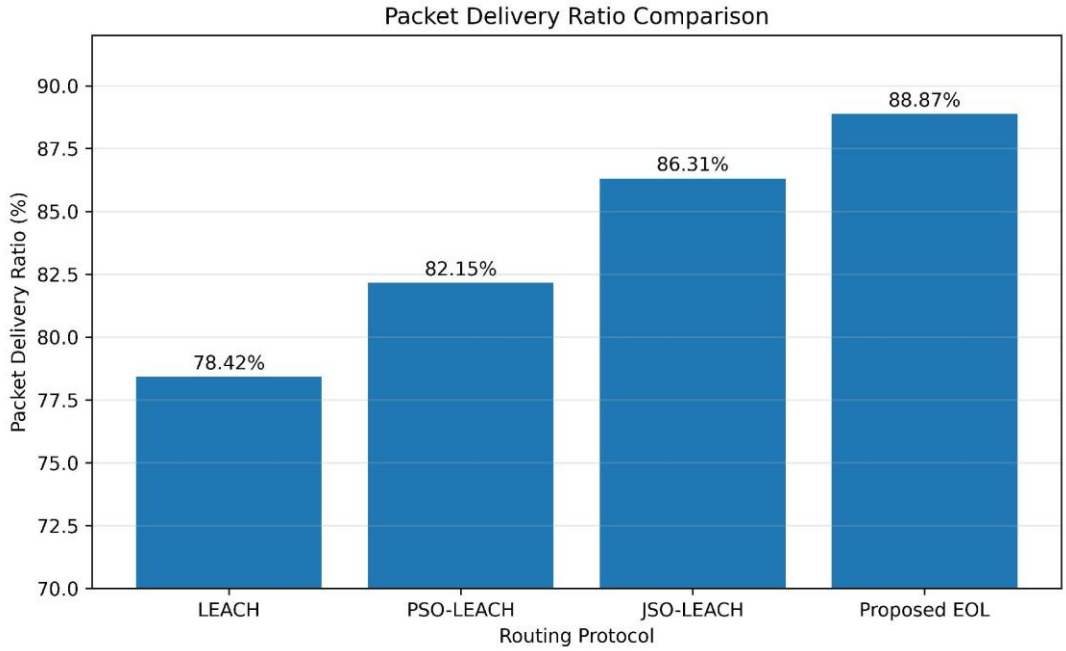


Figure 3. Packet Delivery Ratio versus node density.

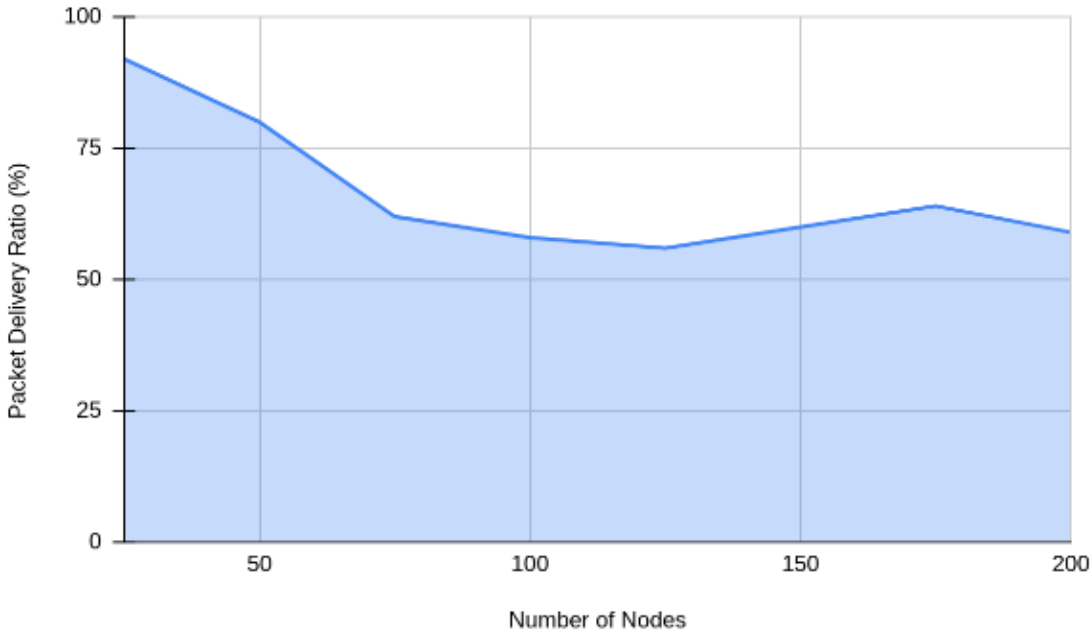


Figure 3. Packet Delivery Ratio versus node density.

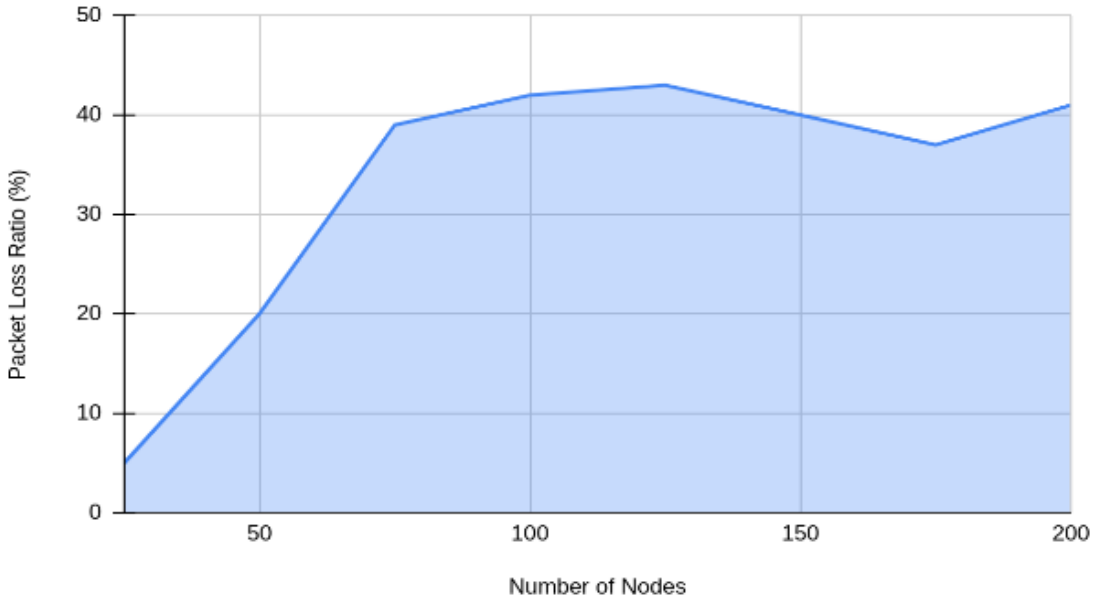


Figure 4. Packet Loss Ratio versus node density.

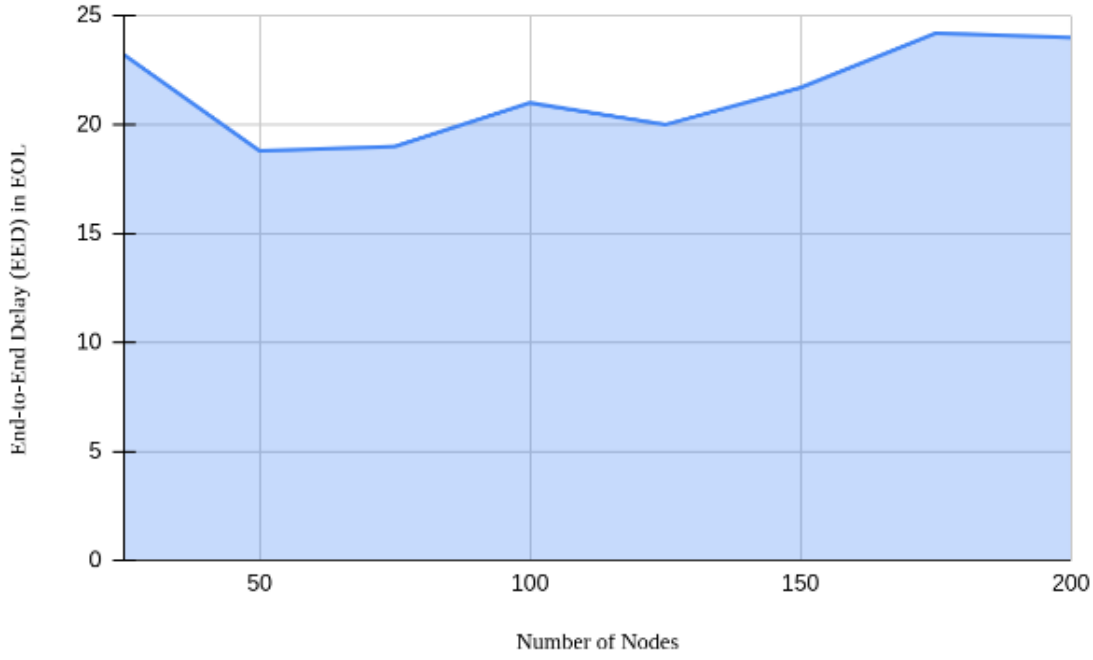


Figure 5. End-to-End Delay versus node density.

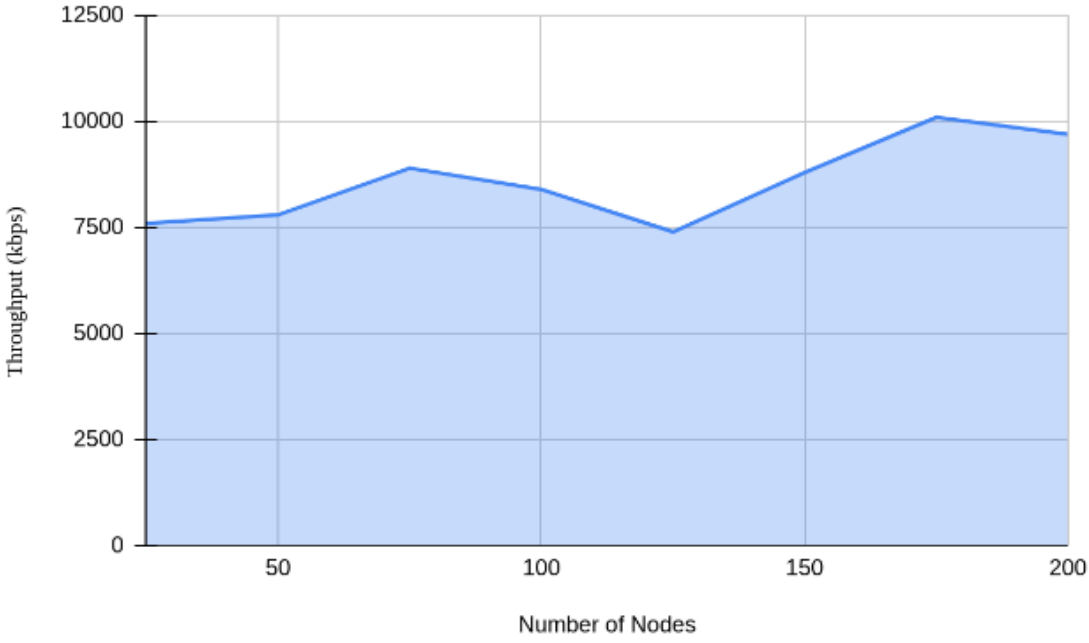


Figure 6. Throughput versus node density.

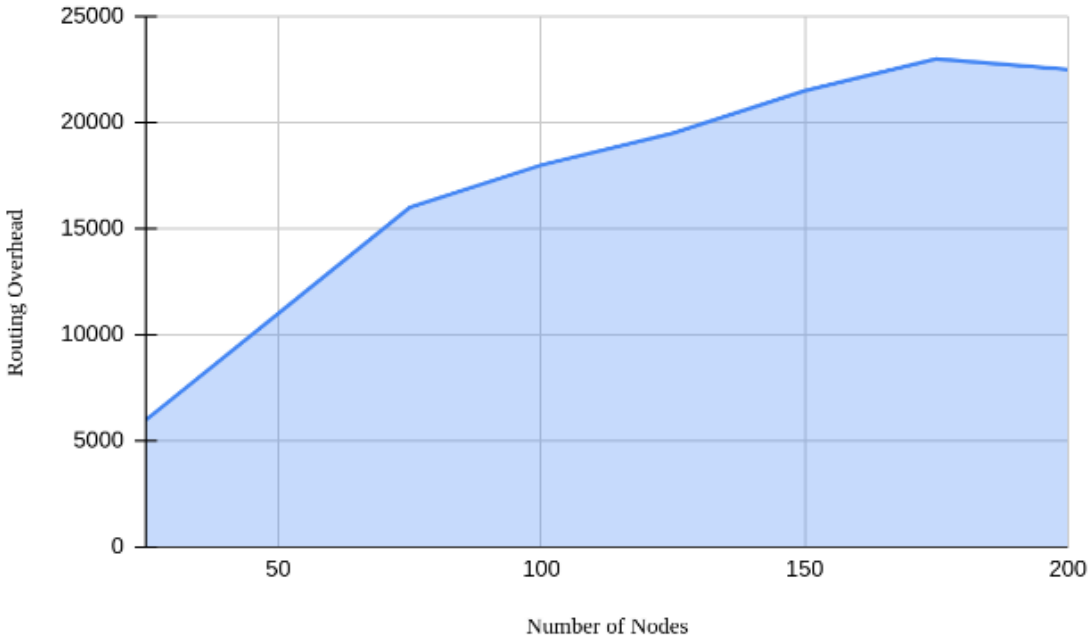


Figure 7. Routing Overhead versus node density.

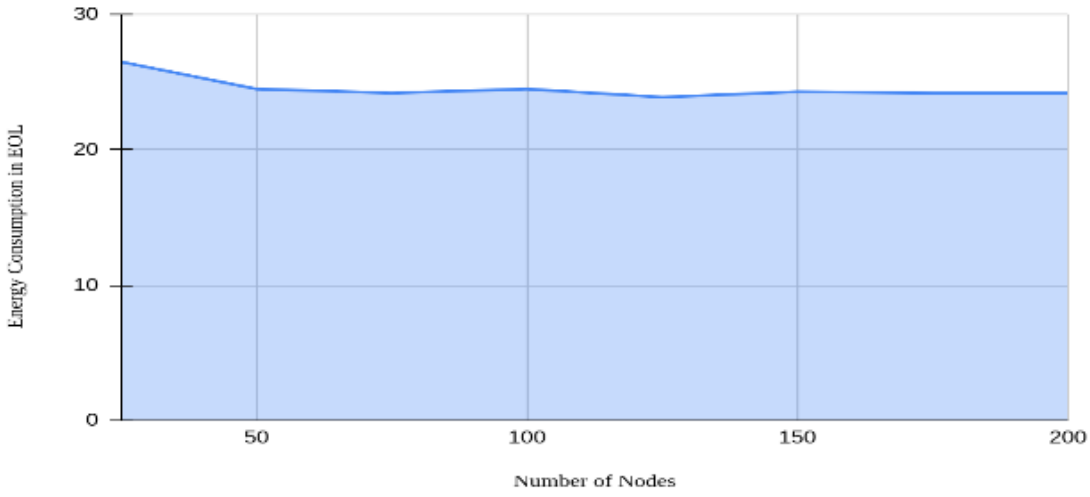


Figure 8. Energy Consumption versus node density.

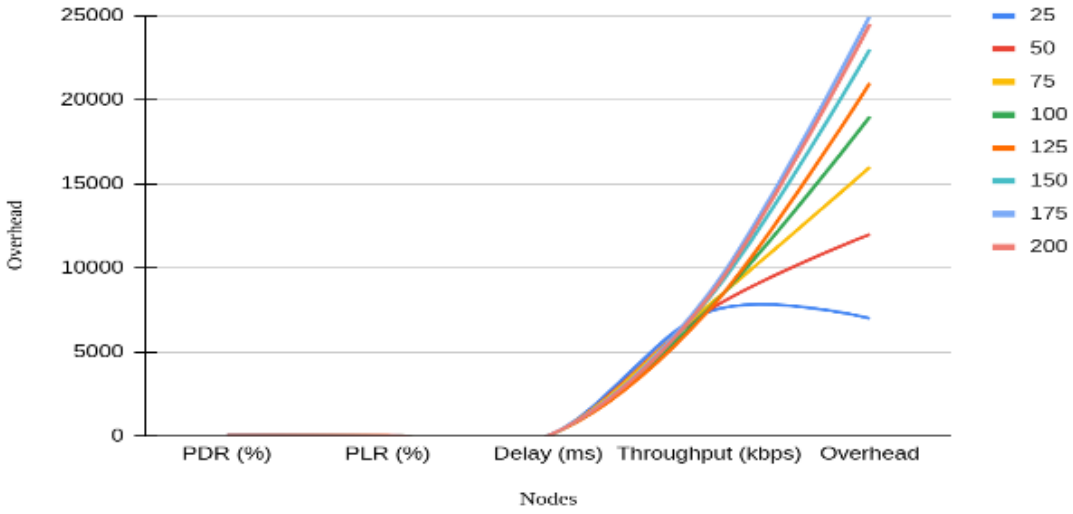


Figure 9. Combined multi-metric comparison.

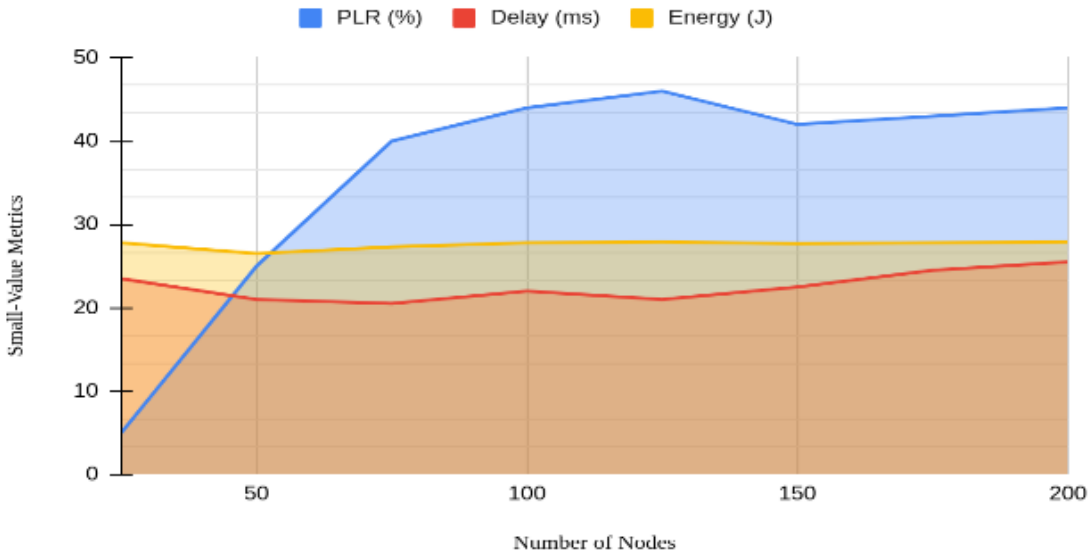


Figure 10. Comparison of lower-magnitude performance metrics.

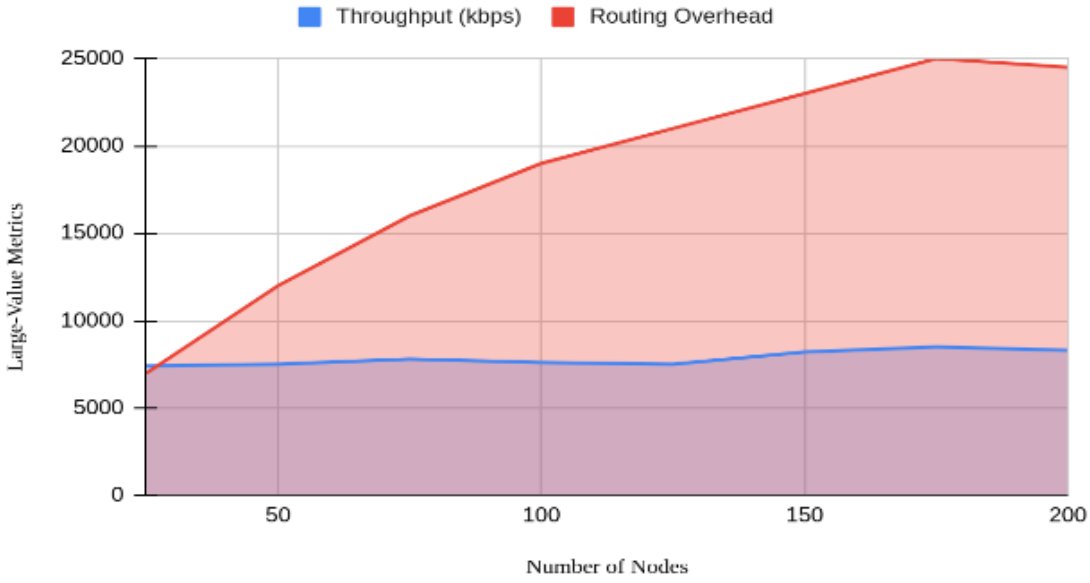


Figure 11. Comparison of higher-magnitude performance metrics.

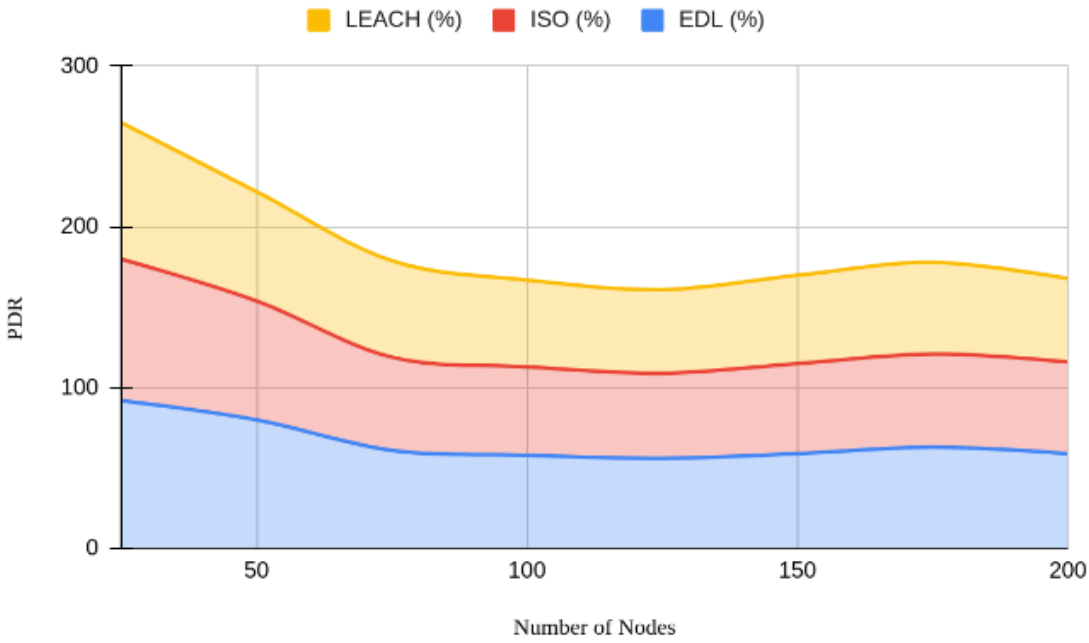


Figure 12. Comparative Packet Delivery Ratio for EOL, JSO, and LEACH.

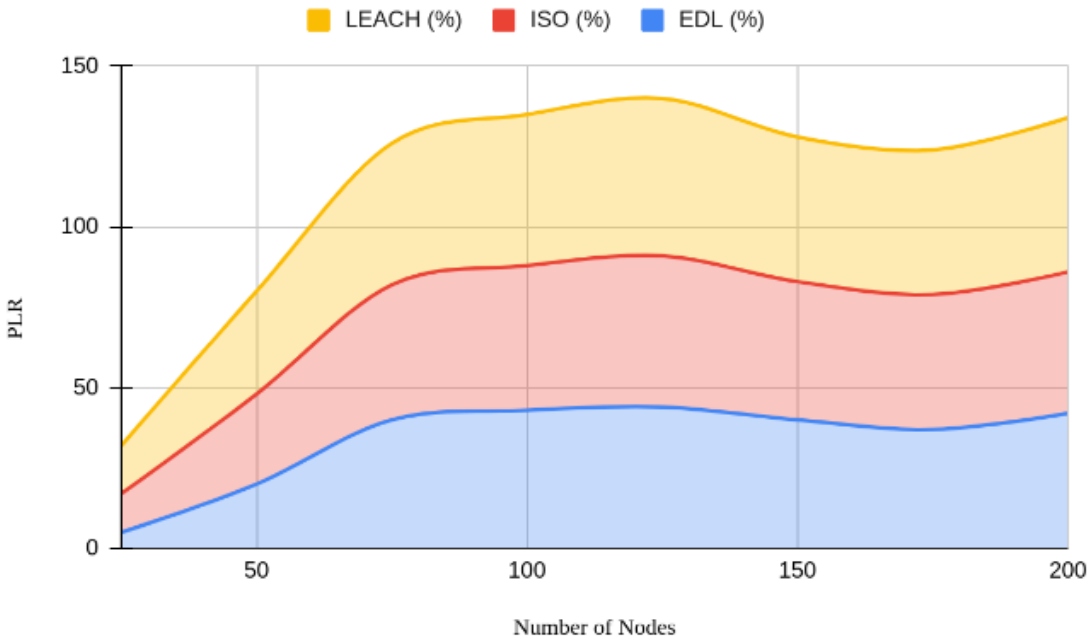


Figure 13. Comparative Packet Loss Ratio for EOL, JSO, and LEACH.

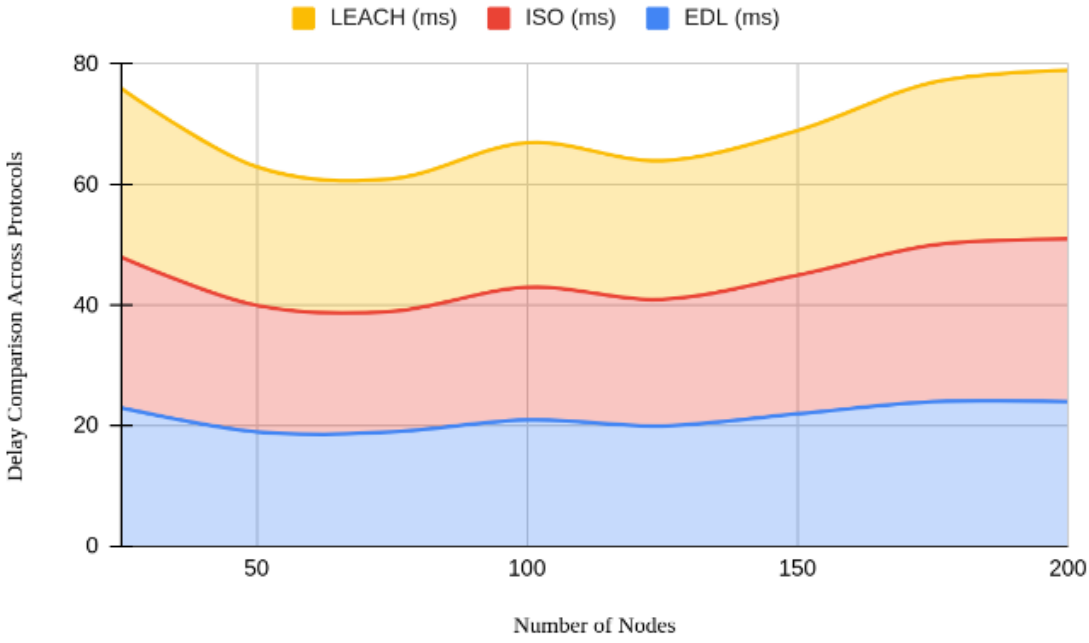


Figure 14. Comparative End-to-End Delay for EOL, JSO, and LEACH.

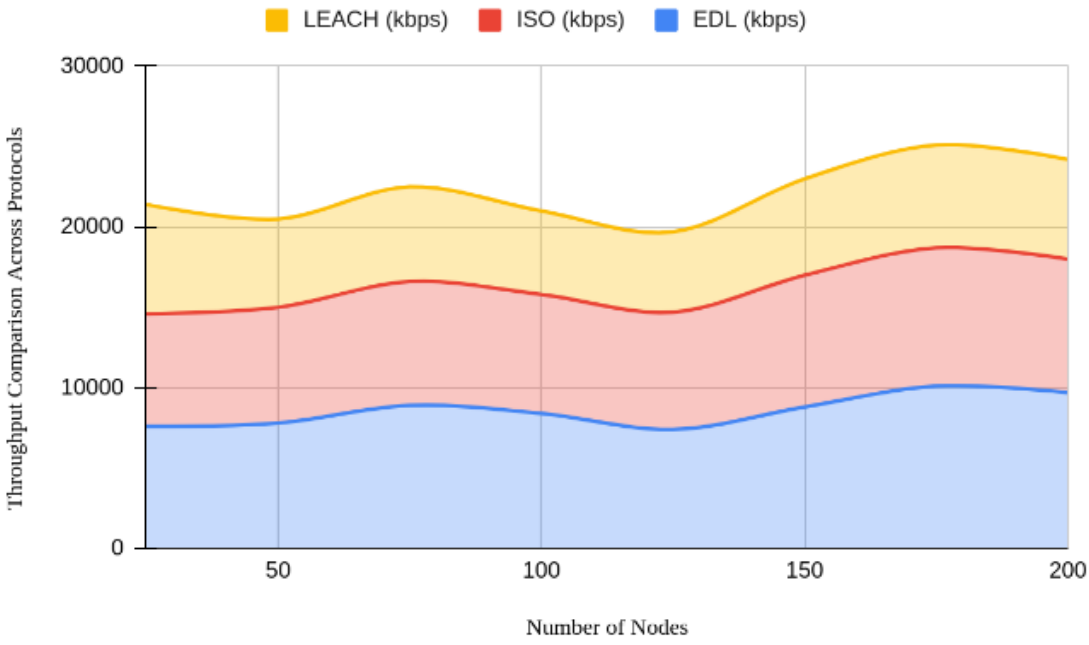


Figure 15. Comparative Throughput for EOL, JSO, and LEACH.

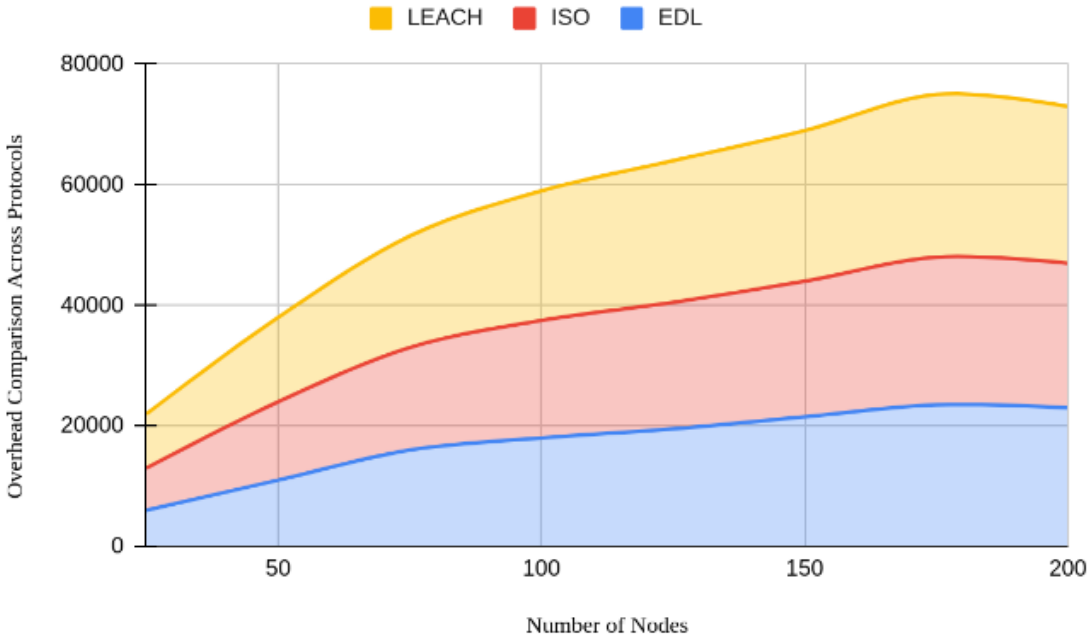


Figure 16. Comparative Routing Overhead for EOL, JSO, and LEACH.

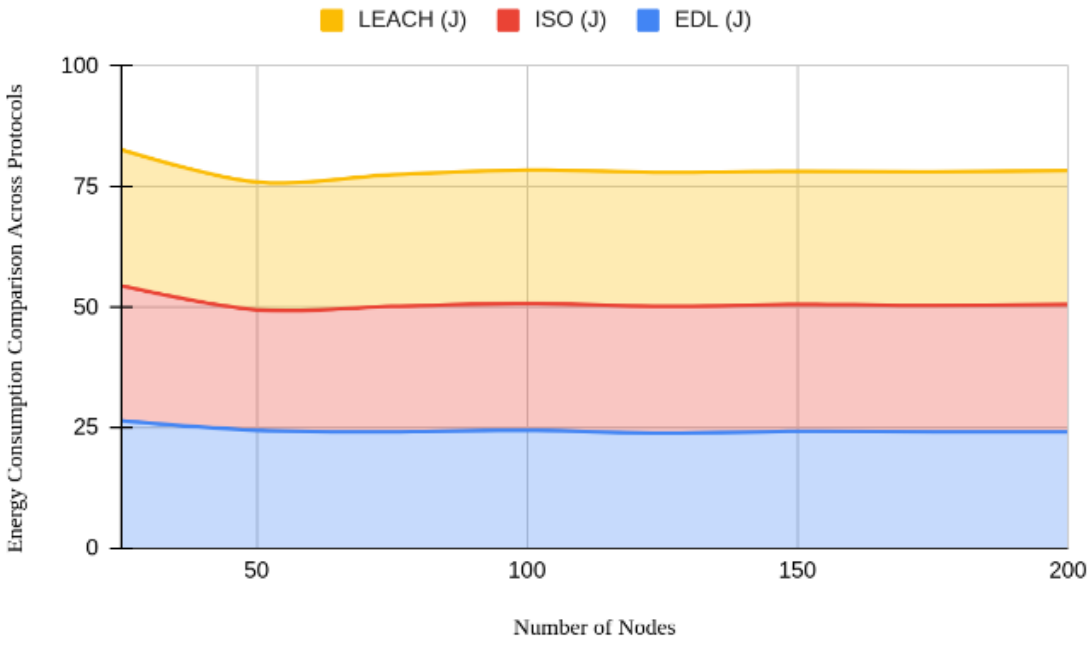


Figure 17. Comparative Energy Consumption for EOL, JSO, and LEACH.

7. Scalability and Computational Analysis

Scalability is evaluated by increasing node density from 25 to 200 nodes while retaining the principal simulation configuration. The reported results show that EOL maintains comparative advantages across the tested range. The proposed design seeks to control the additional cost of optimization by combining lightweight proximity-aware routing

with bounded JSO search settings. For a population size P, iteration limit I, and N nodes, the cluster-head optimization stage has an approximate complexity of O(P × I × N), while local OPF processing is approximately linear in the number of evaluated candidates per routing iteration [33,34].

The scalability conclusion should nevertheless be limited to the evaluated range. Performance at 25–200 nodes does not automatically establish behavior at thousands of nodes. Extremely dense deployments may require hierarchical partitioning, parallel optimization, or adaptive limits on optimization frequency [35,36].

8. Critical Discussion and Limitations

The revised analysis indicates that EOL's performance advantage is produced by the interaction of its components rather than by any single mechanism. OPF reduces avoidable route cost, JSO improves the selection of energy-suitable cluster heads, and adaptive transmission coordination attempts to prevent low-energy nodes from carrying disproportionate communication load. The strongest evidence in the reported data is the simultaneous improvement in delivery, delay, throughput, overhead, and energy use [37].

Several limitations remain. The evaluation uses a simulator and an abstracted radio-energy model, and the nodes are assumed to be static. The initial-energy configuration is homogeneous, and the primary baselines are limited. In addition, the optimization stage creates moderate processing overhead that may become more important at very high densities. These constraints should be addressed through larger-scale studies, heterogeneous energy models, additional routing baselines, and physical testbed validation [38,39].

9. Conclusion

This completely revised paper presents an Energy-Optimized LEACH Routing Framework with Jellyfish Search Optimization for scalable Wireless Sensor Networks. The framework integrates proximity-aware forwarding, JSO-assisted cluster-head selection, and residual-energy-based transmission coordination within a single routing architecture. The experimental results retained from the source study show improvements over conventional LEACH in packet delivery, packet loss, delay, throughput, routing overhead, and energy consumption, with statistical significance reported for the principal metrics. The proposed method also achieves a reported network lifetime of 923 rounds compared with 742 rounds for conventional LEACH in the comparative summary. The results support the use of coordinated optimization for energy-constrained dense WSNs, while the stated limitations emphasize the need for validation beyond simulation.

10. Declarations

Funding: No external funding was reported for this study.

Conflict of Interest: The authors declare no competing interests.

Ethical Approval: Not applicable; the study does not involve human participants or animals.

Data Availability: Simulation data and supporting materials may be made available by the corresponding author subject to the applicable data-sharing policy.

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