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Article

A Metaheuristic-Driven Energy-Optimized LEACH Protocol for QoS-Aware and Scalable Routing in Heterogeneous WSNs

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Abstract: – Efficient routing and energy management remain critical challenges in Wireless Sensor Networks (WSNs) due to limited energy resources, dynamic topology, and scalability requirements. This paper proposes a novel Energy Optimized LEACH (EOL) protocol that integrates Optimized Proximity Function (OPF)-based distance-aware routing, Jellyfish Search Optimization (JSO)-based energy-aware clustering, and adaptive transmission control into a unified multi-objective optimization framework. Unlike conventional LEACH and standalone metaheuristic-based approaches, the proposed method simultaneously optimizes routing efficiency, energy balancing, and transmission adaptability. The performance of EOL is evaluated against classical LEACH and JSO-based protocols across network sizes ranging from 25 to 200 nodes using key performance metrics including PDR, PLR, delay, throughput, routing overhead, and energy consumption. Experimental results demonstrate that EOL achieves 13.33% higher PDR, reduces PLR by 17.79%, lowers delay by 10.49%, improves throughput by 39.49%, and reduces energy consumption by 10.89% compared to LEACH. These improvements are primarily attributed to efficient cluster-head selection, distance-aware routing, and adaptive transmission control. The results confirm that EOL provides a scalable, energy-efficient, and QoS-aware routing solution suitable for heterogeneous WSN environments.
Keywords: Wireless Sensor Networks (WSN), Energy Optimized LEACH (EOL), Clustering-Based Routing Protocols, Jellyfish Search Optimization (JSO), Energy Efficiency and Network Lifetime, Packet Delivery and Throughput Optimization

1. INTRODUCTION

Modern smart systems depend extensively on networking due to its flexibility, cost-effectiveness, and ability to function in remote or hard-to-reach environments. It consists of sensor nodes that operate with limited energy resources and constrained processing capabilities. The nodes jointly sense environmental and physical phenomena and wirelessly forward the gathered information to a base station for further processing. Due to the emerging use of WSNs in environmental monitoring, structural health evaluation, battlefield surveillance, smart agriculture, disaster relief operations and industrial monitoring applications, the design of efficient and scalable routing protocols has become an essential research issue.

Energy consumption is one of the most critical challenges in Sensor Networks. Replacing or recharging the batteries of sensor nodes is often technically infeasible, as these nodes are commonly powered by non-replaceable batteries and deployed in harsh or inaccessible environments. Since communication activities consume a significant portion of a node's energy, the overall network lifetime and performance are strongly influenced by how efficiently energy is utilized. This has led to the emergence of several routing protocols aiming at reducing communication overhead, ideal distribution load of nodes and well formation of the cluster.

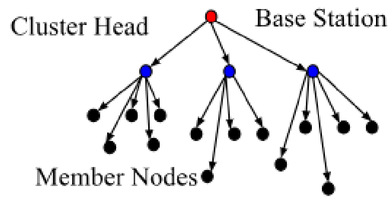

Fig. 1. Schematic illustration of LEACH-based clustering and routing in a wireless sensor network

Cluster heads (CHs) aggregate data from member nodes and transmit it to the base station (BS). Solid lines indicate intra-cluster communication, while dashed lines represent CH-to-BS transmission. The diagram is schematic (not to scale) and illustrates how random CH selection can result in uneven cluster sizes and long transmission distances, leading to energy imbalance.

Figure 1 illustrates a LEACH-style clustered WSN topology, where cluster heads (CHs) aggregate data from member nodes and forward it to the base station, potentially creating long CH-to-BS communication links. This clustering behavior, illustrated in Figure 1, motivates the need for energy-aware cluster-head selection and transmission control, which the proposed EOL protocol aims to address. Low-Energy Adaptive Clustering Hierarchy, one of the earliest routing protocols developed for Wireless Sensor Networks, remains among the most widely used and frequently cited clustering-based protocols. In LEACH, a hierarchical clustering approach is adopted in which sensor nodes autonomously organize themselves into clusters, and a cluster head (CH) is selected for each round. The selected CH aggregates data from its cluster members to eliminate redundant transmissions before forwarding the processed information to the base station, thereby reducing overall communication overhead. The strategy of CHs is to randomly rotate to achieve energy consumption with a good balance. It is worth noting that although LEACH greatly advances network lifetime when compared with a flat routing scheme, there are still some shortcomings. The random CH selections also tend to lead to uneven distribution of clusters, and some CHs cover large areas precisely, or the nodes with low energy become CHs earlier. LEACH becomes inefficient in dense or large-scale WSN deployments because the cluster head (CH) selection process does not consider key factors such as residual node energy, node density, or the distance to the base station.

Despite numerous LEACH variants and metaheuristic-based improvements, existing approaches typically optimize clustering or routing independently and fail to jointly address energy balancing, routing stability, and transmission adaptability under dynamic network conditions. For example, in LEACH-C (Centralized LEACH), the base station is required to calculate optimal clusters for improved CH position, leading to a more complex computing task and dependency on centralized control. SEP (Stable Election Protocol) brings in heterogeneity by considering the deployment of nodes with unequal initial energy, but continues to depend on probabilistic CH selection. In periodic updating of the sensed data reports with threshold-based reactive data reporting schemes are used for low-latency real-time applications. Although these approaches improve performance in targeted situations, they are still restricted by some issues, such as scalability and load balancing or flexibility under changing network conditions.

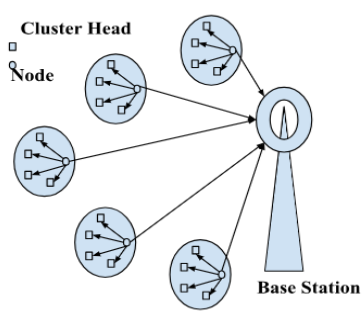

Fig. 2. Cluster Head Selection in WSN

The development of optimization and machine learning approaches also broadened the WSN scope of work. Soft computing-based methods such as PSO, GA, ACO and ABC, etc., and fuzzy logic-based clustering have been studied for intelligent CH selection and routing. These bio-inspired approaches exploit the natural phenomenon of swarms and evolutionary phenomena to learn clustering structures, reduce the energy consumption, and improve the stability of networks. However, these methods tend to incur computational complexity, slow convergence, high sensitivity on parameter values and poor performance in large-scale instances.

Traditionally, various metaheuristic methods have been developed to cope with the drawbacks of traditional clustering approaches in recent years. JSO is one of the promising methods among them. JSO is motivated by jellyfish swarm movement in the ocean, integrating community rules with time-dependent control strategies alternating between an exploration and exploitation mode. In the exploration and exploitation process of candidate solutions, during which they have free mobility in the search space and are remodeled to nutrient-rich areas where the optimized solution.

JSO-based clustering algorithms have demonstrated significant potential to enhance CH distribution, reduce energy consumption, and extend network lifetime. JSO enhances cluster consistency and stability by including residual energy, node density, and distance into the fitness function. Notwithstanding its merits, JSO remains with some shortcomings such as computational complexity, iteration requirements and slightly larger routing overhead due to repetitive optimization computations being taken into account. But with respect to basic LEACH and old swarm-based optimization approaches, JSO performs well in packet delivery, energy balancing and stability when node density is high.

Various other recent algorithms have also been proposed for WSN optimization, namely Grey Wolf Optimization (GWO), Whale Optimization Algorithm (WOA), Firefly Algorithm (FA) and Bat Algorithm (BA). Routing, clustering and coverage improvement have been addressed through the use of those metaheuristics, providing different advantages according to specific scenarios. However, how to balance the performance (KP model accuracy), cost (computation time) and flexibility (in handling changing network dynamics) in practical scenarios is still an open issue.

The progress in clustering-based routing, from the base version of LEACH up to complex metaheuristic approaches such as JSO, shows that there is a continuous demand for energy-aware, intelligent and scalable WSN protocols. The variety of scenarios and environmental constraints makes it interesting to study the potential for collective optimization of routing protocols aiming at longevity and reliable communication.

Therefore, there exists a critical need for an integrated routing framework that simultaneously optimizes cluster-head selection, routing path efficiency, and energy-aware transmission control. This gap motivates the development of the proposed EOL protocol, which combines multiple optimization strategies into a unified and scalable solution.

The major contributions of this work are summarized as follows, highlighting a unified multi-objective optimization framework for energy-efficient and QoS-aware routing in heterogeneous WSNs:

• An Optimized Proximity Function (OPF) is proposed to select short and stable routing paths, thereby reducing hop distance and improving packet delivery reliability.

• A Jellyfish Search Optimization (JSO)-assisted cluster head selection strategy is developed that incorporates residual energy and node proximity, ensuring balanced energy consumption and preventing early node failures.

• An adaptive transmission range control mechanism is integrated to dynamically adjust node transmission power, protecting low-energy nodes from premature depletion and extending overall network lifetime.

• Comprehensive simulations demonstrate that the proposed EOL protocol consistently outperforms conventional LEACH and JSO-based routing schemes in terms of energy efficiency, packet delivery ratio, delay, and network lifetime.

Novelty and Scientific Contribution

The novelty of this work lies not merely in combining existing techniques, but in designing a unified optimization framework that decouples and coordinates routing, clustering, and transmission control. Specifically:

• A cross-layer optimization strategy is introduced to jointly optimize path selection, cluster-head assignment, and transmission range. • A separation-based design is employed, where OPF minimizes routing distance while JSO ensures energy-aware clustering, reducing computational overhead. • An adaptive transmission mechanism dynamically redistributes communication load based on residual energy, improving network lifetime. • A multi-objective formulation enables simultaneous optimization of energy consumption, delay, packet delivery, and throughput.

• A dynamic transmission control mechanism is proposed that adaptively adjusts node communication range based on residual energy, enabling energy-aware load redistribution and preventing premature node depletion.

Unlike conventional routing protocols, the proposed framework incorporates adaptive transmission control as a system-level optimization component, enabling dynamic load redistribution across nodes based on residual energy.

Table 1. Abbreviation

Short Form	*Description*
WSN	Wireless Sensor Network.
CH	Cluster Head.
LEACH	Low-Energy Adaptive Clustering Hierarchy.
EOL	Energy-Optimized LEACH.
EOL-LEACH	Energy-Optimized Low-Energy Adaptive Clustering Hierarchy
JSO	Jellyfish Search Optimization
PDR	Packet Delivery Ratio
PLR	Packet Loss Ratio
EED	End-to-End Delay
AEC	Average Energy Consumption
QoS	Quality of Service
kbps	Kilobits per second
ms	Milliseconds
J	Joules.
Routing Overhead	Control packet cost incurred during routing
Throughput	Rate of successful data packet delivery over the network
Energy Consumption	Average energy used by sensor nodes during communication
Cluster-Based Routing	Routing mechanism where nodes are grouped into clusters
Multi-hop Communication	Data transmission through intermediate nodes
Single-hop Communication	Direct data transmission to the base station
Base Station (BS)	Central node that collects data from sensor nodes
Network Lifetime	Duration until the first or last sensor node depletes energy
GA	Genetic algorithm
OPF	Optimized Path Finding
ABC	Artificial bee colony
PSO	Particle swarm optimization
WOA	Whale optimization algorithm
GWO	Gray wolf optimization

ACO	Ant colony optimization

Unlike existing approaches that independently optimize clustering or routing, the proposed EOL framework introduces a unified cross-layer optimization model that simultaneously addresses routing efficiency, energy balancing, and transmission adaptability. This integrated design enables coordinated decision-making across multiple network layers, which is not achieved in conventional LEACH or metaheuristic-based protocols.

2. RELATED WORK

Clustering routing is still one of the most popular solutions for energy saving in WSNs. The process of forming clusters can mitigate redundancy and reduce data transmission; all sensed data will be aggregated at CHs and eventually reported to BS via CH to prolong network life-time [1], [6], [7]. The original LEACH protocol was the first to include random CH rotation and local data fusion, but its random choice of CHs and absence of residual-energy sensitive behavior may lead to unbalanced clusters and node death in the early stage for dense networks [6], [7], [24]. As a result, an extensive literature is being introduced on LEACH extensions and hybrid algorithms which consider residual energy, distance to sink, node degree or density for better performance of CH selection [7], [14], [25].

To address these limitations, the proposed EOL protocol introduces a unified cross-layer optimization framework, as described in the following section.

Classical LEACH Limitation

Traditional LEACH-based methods rely on probabilistic cluster-head selection without incorporating residual energy awareness or adaptive transmission control. This limitation leads to uneven energy distribution, premature node depletion, and reduced overall network lifetime, particularly in dense and large-scale deployments.

Metaheuristic Approaches

Metaheuristic-based approaches such as PSO, GA, ACO, and GWO have been widely applied to improve cluster-head selection and routing efficiency. These techniques utilize multi-objective optimization considering residual energy, node distance, and network connectivity. While they enhance energy efficiency and stability compared to classical LEACH, they often introduce higher computational complexity, parameter sensitivity, and increased routing overhead.

Hybrid & Recent Work

Recent advancements (2022–2025) focus on hybrid optimization techniques and learning-based routing approaches, combining multiple metaheuristics or integrating machine learning for adaptive decision-making. These methods improve performance and scalability; however, they increase computational overhead and may not be suitable for resource-constrained WSN environments.

Research Gap

Despite these advancements, most existing approaches optimize clustering or routing independently and lack integrated mechanisms for adaptive transmission control and multi-hop routing stability. This gap motivates the proposed EOL framework, which jointly optimizes routing, clustering, and transmission control within a unified model.

A wide classification of such developments is presented in surveys published between 2016 and 2024. The schemes, including LEACH-C, which centers around a centralized CH selection at the BS, SEP that considers heterogeneity of nodes for their energy status and the TEEN/APTEEN use threshold-based reporting, are among such affiliations aimed at improving lifetime, coverage and delay [6]-[7], [24]-[25]. While many LEACH-derived improvements enhance some metrics, a majority of research always focuses on the trade-offs between routing cost, computation complexity, and cluster stability [14], [16], [27].

In the past decade, metaheuristic and bio-inspired optimization algorithms have been widely used for CH selection and routing. This type of problems are solved by using widely accepted techniques such as PSO , GA , ACO , ABC , GWO [3], [4], [5], WOA and Bat Algorithm[6]. These algorithms generally aim to optimize CH placement and utilize multi-objective fitness functions that express residual energy, intra-cluster distance, network connectivity and node closeness. PSO-based clustering improves network life-time by associating CH in an optimum manner [10], GA are considered useful to effectively optimize multi-parameter decision of routing [11], and while ACO has been widely used for inter-cluster path optimization and data-forwarding efficiency [13], [28], [30]. Nevertheless, metaheuristic algorithms are commonly associated with trade-offs related to convergence rate, parameter dependence, and computational cost, particularly when they are deployed on energy-limited sensors [9], [16], [26].

From 2019 to 2024, hybrid optimization techniques have been favored because they take considerable advantage of the strength of several heuristics, leading to a trade-off between performance and overhead. For example, GWO hybridized with GA or PSO combined with fuzzy logic has shown superior cluster head (CH) distribution under less control overhead [12], [20]. Other works investigate the semi-centralized and distributed optimization schemes – like LEACH-C variants, adaptive PSO, or threshold-adaptive clustering - trying to minimize re-clustering cost as well as enhancing cluster stability [14], [16], [23].

One of the recent progresses in optimization-based WSN clustering is the JSO. JSO models jellyfish-like behavior of a population with two movements: (i) the swarm movement (localism search), and (ii) the ocean current effect manipulations (globalism exploration). A time-controlling policy enables JSO to automatically switch from exploration to exploitation, thus strengthening the accuracy of approximation on nonconvex optimization problems. Experimental results in different engineering applications show that the JSO is better than classical heuristics like PSO, GA and ACO in terms of convergence rate and solution quality [2], [3], [4], [21].

A number of other variants, such as JSO with orthogonal learning [4], multi-strategy enhanced JSO [21], and hybrid JSOs, have also been demonstrated to perform better on high-dimensional and nonlinear problems [22]. Meta-reviews published in 2022–24 emphasize JSO's competitive advantages and potential risks, including high computational cost and difficulty of tuning parameters [5,26].

Despite significant advancements in cluster-based routing, recent studies indicate persistent challenges in wireless sensor networks. Hybrid LEACH-based routing protocols incorporating metaheuristic optimization techniques such as genetic algorithms, particle swarm optimization, and swarm-intelligence-based methods have demonstrated improvements in energy efficiency and network lifetime when compared to classical LEACH [12], [15], [18]. Similarly, machine-learning-assisted routing approaches have been explored to enhance cluster head selection and routing decisions through adaptive learning mechanisms [21], [24]. However, these methods primarily emphasize energy minimization and often neglect multi-hop path stability, adaptive transmission range control, and the impact of long-distance hops, which can increase packet loss and cause imbalanced energy depletion [16], [22]. Furthermore, cluster head overload and uneven residual energy distribution remain unresolved issues in both hybrid and learning-based protocols, particularly under dynamic network conditions [19], [25]. These limitations motivate the proposed EOL protocol, which jointly optimizes hop distance, energy balancing, and transmission adaptation.

Recent studies such as PSO-based clustering [10], GA-based optimization [11], and hybrid metaheuristic approaches [20], [21] have shown improvements in specific metrics; however, they often suffer from high computational overhead or lack adaptive transmission control. In contrast, EOL provides a balanced trade-off between energy efficiency, delay reduction, and scalability, making it more suitable for dynamic and large-scale WSN deployments.

In contrast, the proposed EOL protocol integrates OPF-based distance-aware routing, JSO-based energy-aware clustering, and adaptive transmission control into a unified framework. This integration enables simultaneous optimization of routing efficiency, energy balancing, and QoS performance, providing a more scalable and practical solution for heterogeneous WSNs.

Traditional LEACH-based methods rely on probabilistic cluster-head selection without incorporating residual energy awareness or adaptive transmission control. This limitation leads to uneven energy distribution, premature node depletion, and reduced overall network lifetime, particularly in dense and large-scale deployments.

To provide a clear understanding of existing approaches and their limitations, a comparative analysis of classical and metaheuristic-based routing protocols is presented in Table 2.

Table 2. Comparative analysis of classical and metaheuristic-based routing protocols

Protocol	**Optimization Strategy**	**Routing Type**	**Energy Efficiency**	**QoS Support**	**Scalability**	**Computational Cost**	**Limitations**
LEACH	Probabilistic	Single-hop (Cluster-based)	Low	No	Low	Low	Random cluster head selection leads to energy imbalance

SEP	Energy-aware Probabilistic	Cluster-based	Medium	Limited	Medium	Low	Limited adaptability in dynamic network conditions
PSO-based	Swarm Optimization	Multi-hop	High	Partial	Medium	High	Parameter sensitivity and slow convergence
GA-based	Evolutionary Optimization	Multi-hop	High	Partial	Medium	High	High computational overhead and complexity
JSO-based	Jellyfish Optimization	Cluster-based	High	Partial	Medium	Medium	Increased routing overhead in large-scale networks
GWO/Hybrid	Hybrid Metaheuristic	Multi-hop	High	Partial	High	High	High complexity and parameter tuning challenges
EOL (Proposed)	Hybrid (OPF + JSO + Adaptive Control)	Multi-hop + Distance-aware	**Very High**	**Yes**	**High**	**Medium**	Achieves balanced trade-off between performance and complexity

As shown in Table 2, traditional routing protocols such as LEACH and SEP suffer from energy imbalance and limited scalability due to their probabilistic cluster-head selection mechanisms. Although metaheuristic-based approaches such as PSO, GA, and JSO improve energy efficiency, they introduce computational complexity and often lack integrated routing optimization.

These limitations highlight the need for a unified optimization framework, which motivates the development of the proposed EOL protocol.

Table 3. Quantitative comparison of classical, metaheuristic, and hybrid routing protocols in WSNs. Performance ranges for existing methods are derived from recent literature

Protocol	Type		Strength	Limitation
LEACH	Classical Clustering	55–60	Simple and low computational cost	Energy imbalance due to random CH selection
JSO	Metaheuristic Optimization	60–63	Improved cluster-head selection and energy balancing	Increased routing overhead
GWO	Metaheuristic Optimization	61–64	Stable convergence and balanced CH distribution	High computational complexity
ACO	Swarm Intelligence	58–62	Efficient multi-hop routing	Slow convergence and control overhead
Hybrid (2022–2025)	Advanced Optimization	62–65	Adaptive and multi-objective optimization	High computational and implementation cost
EOL (Proposed)	Hybrid (OPF + JSO + Adaptive Control)	66.54	Balanced optimization of routing, clustering,	Moderate computational complexity

			and transmission control	

The reported PDR ranges for existing protocols are obtained from recent literature and reflect typical performance under comparable simulation settings. These values provide a reference baseline for evaluating the effectiveness of the proposed EOL protocol.

3. PROBLEM STATEMENT

Clustering-based routing in WSN must handle its important dual goal, which tends to maximize the lifetime of the network as well as maintain good communication performance, such as PDR, latency and throughput. However, the classical LEACH protocol and its several improved versions are based on random or centralized CH selection and lead to the inhomogeneous formation of clusters, an increase in control overhead in large-sized networks, and early energy holes during data transmission for high-density/coverage scenarios.

In order to overcome these drawbacks, various meta-heuristic algorithms have been employed for CH selection, such as PSO [10], GA [11], ACO [12], GWO [13] and the newly proposed JSO [14]. Although such a method largely improves the cluster stability and energy balance, it brings computational complexity and signaling overhead that may even reduce the net energy saving in low-power sensor networks.

In view of these bottlenecks, there is thus an urgent requirement for systematic and quantitative validation of classic LEACH and recently proposed metaheuristic-based clustering protocols under realistic network scales (25–200 nodes) across various performance metrics. A thorough analysis is demanded to discover the techniques that achieve an optimum balance among the security reliability, latency, overhead and energy efficiency in allowing a foundation for realistic deployment in nowadays WSN applications.

4. METHODOLOGY

The proposed EOL protocol follows a structured multi-phase workflow consisting of six major stages: (1) route discovery using OPF, (2) cluster formation, (3) cluster-head selection using JSO, (4) adaptive transmission control, (5) energy update, and (6) route maintenance. These stages collectively ensure efficient routing, balanced energy consumption, and improved network stability.

EOL Using OPF and JSO

The proposed EOL methodology aims to significantly reduce energy consumption and prolong the lifetime of WSNs. It integrates three major components: OPF, JSO, and the LEACH clustering protocol. Each component contributes a critical function OPF performs efficient route discovery, JSO assists in optimal cluster head selection, and LEACH manages hierarchical clustering. Together, these modules form a unified and energy-aware routing strategy.

1. Route Discovery Using OPF

The first phase of the EOL methodology focuses on discovering an efficient path between a sender and its destination. The process begins with the Route Request (RREQ) stage. This reply packet contains the sender's and destination's addresses along with the responding node's location information.

The sender waits for a short, predefined time and collects all RREP packets received during this duration. OPF then compares the location of each responding node with the sender's location and determines which node is the closest and most suitable next hop. The candidate node with the smallest distance becomes the selected next hop. This decision is recorded in the routing table, ensuring a clear and optimized forwarding path.

This simple effective approach prevents unnecessary forwarding, minimizes hop count, and reduces the energy cost associated with long or unstable routes.

The experimental design is structured explicitly to answer Research Questions RQ1 and RQ2 through controlled comparative and scalability-based simulation protocols.

1.1 Route Discovery Using Optimized Proximity Function (OPF)

The objective of OPF is to select the most suitable next-hop node based on minimum Euclidean distance, thereby reducing hop count, delay, and energy consumption.

Although OPF selects the next hop based primarily on Euclidean proximity, energy awareness is not ignored in the routing process. Residual energy constraints are enforced during routing table updates and forwarding eligibility checks, ensuring that nodes with critically low energy are excluded from path selection. This design choice intentionally separates path-length optimization (OPF) from energy balancing (JSO-based clustering and adaptive transmission control), reducing per-hop computational complexity while still achieving global energy efficiency.

By prioritizing shorter inter-node distances in route selection, the Optimized Proximity Function directly improves packet delivery ratio by reducing packet drops associated with long and unstable multi-hop paths.

While OPF focuses on minimizing routing distance and delay, JSO ensures balanced energy consumption through optimal cluster-head selection. The integration of these components enables both local and global optimization of network performance.

2. Cluster Formation Using JSO-Enhanced LEACH

While OPF manages route discovery, EOL improves intra-network clustering using the JSO-LEACH mechanism. Traditional LEACH selects cluster heads randomly, which often results in low-energy nodes being assigned heavy responsibilities. This leads to premature node deaths and unbalanced energy distribution. To overcome this, the EOL method replaces random selection with an intelligent JSO-based optimization technique.

To overcome the randomness of classical LEACH, EOL integrates Jellyfish Search Optimization (JSO) for energy-aware cluster-head (CH) selection.

2.1 JSO Population Initialization

JSO begins by generating a population of potential cluster head candidates. These candidates form the initial group of possible cluster heads.

2.2 Position Update with JSO

JSO works iteratively by updating the "position" of each candidate. The update process simulates natural jellyfish behavior. Two movement patterns guide the search:

Movement inside the swarm: Candidates move toward other candidates in a controlled random manner, helping explore the nearby region.

Movement towards the best candidate: Candidates are gradually adjusted toward the current best solution found so far. This encourages the search process to move toward more optimal regions.

Fitness Function for Cluster-Head Selection

2.3 Cluster Head Fitness Evaluation

The objective of cluster-head (CH) selection is to minimize average energy consumption while maximizing network lifetime. Therefore, nodes that conserve more energy and prolong survival are assigned higher fitness values.

2.3.1 Average Energy Consumption

Let

- N= total number of nodes
- E_i^t= residual energy of node $i$at round t

The average energy consumption per round is expressed as:

$$\bar{E}_{cons}(t) = \frac{1}{N}\sum_{i=1}^{N} (E_i^{t-1} - E_i^t) \quad (1)$$

Lower $\bar{E}_{cons}$indicates better energy efficiency.

2.3.2 Network Lifetime Maximization

Network lifetime is defined as the number of rounds until the first node dies (FND) or until a fraction of nodes deplete their energy.

$$L = max\{t \mid E_i^t > 0,\ \forall i \in N_{alive}\} \quad (2)$$

A higher Lrepresents longer operational stability.

2.3.3 Cluster Head Fitness Function

The fitness of a candidate cluster head $i$is defined as:

$$F_i = \alpha \frac{E_i^{res}}{E_{max}} + \beta \frac{L_i}{L_{max}} \quad (3)$$

where:

- E_i^{res}= residual energy of node i
- L_i= expected survival time contribution
- $\alpha + \beta = 1, \alpha, \beta \in [0,1]$

Nodes that consume less energy and extend network lifetime yield higher fitness scores.

2.3.4 Optimal Cluster Head Selection

$$CH^* = arg\, max_{i \in C}\, F_i \quad (4)$$

where $C$is the set of CH candidates.

- JSO Position Update Mechanism

JSO updates candidate positions using two biologically inspired movements.

a) Passive Motion (Swarm Exploration)

$$X_i^{t+1} = X_i^t + r_1 \cdot (X_j^t - X_i^t) \quad (5)$$

where:

- $r_1 \in (0,1)$is a random coefficient
- $X_j$is a randomly selected candidate

This promotes local exploration.

b) Active Motion (Best-Solution Attraction)

$$X_i^{t+1} = X_i^t + r_2 \cdot (X_{best}^t - X_i^t) \quad (6)$$

where:

- X_{best}= best candidate solution
- $r_2 \in (0,1)$

This encourages global exploitation.

- Cluster-Head Selection Rule

The optimal cluster head is selected as:

$$CH^* = arg\, max_{X_i \in P}\, F_i \quad (7)$$

This fitness function ensures that nodes with low residual energy are excluded from cluster head selection, thereby preventing premature node failure and extending the overall network lifetime.

2.4 Energy Balancing Effect

The average energy consumption per round is minimized as:

$$E_{round} = \sum_{i=1}^{N} \quad E_i^{tx} + E_i^{rx} \tag{8}$$

JSO-based CH rotation ensures:

$$(max(E_{node}) - min(E_{node})) \tag{9}$$

leading to balanced energy dissipation and extended network lifetime.

3. Energy-Aware Transmission Control

To further improve energy efficiency, EOL dynamically adjusts the transmission range of nodes based on their residual energy levels.

- Nodes with high energy are permitted to transmit over longer distances, enabling them to take on more responsibility.
- Nodes with medium energy transmit over moderate distances to balance workload.
- Nodes with low energy use short transmission ranges to conserve power and avoid unnecessary drain.

This adaptive transmission control ensures that high-energy nodes share more load, while weaker nodes are protected from early depletion.

3.1 Energy-Based Node Classification

Let E_i^{res} denote the residual energy of node i. Nodes are classified as:

$$Energy\ Level(i) = \{High, E_i^{res} \geq \theta_H E_{max}\ Medium, \theta_L E_{max} \leq E_i^{res} < \theta_H E_{max}\ Low, E_i^{res} < \theta_L E_{max}\ \} \tag{10}$$

where $0 < \theta_L < \theta_H < 1$.

3.2 Adaptive Transmission Range Assignment

The transmission radius of node i is adjusted as:

$$R_i = \{R_{max}, High - energy\ node\ R_{med}, Medium - energy\ node\ R_{min}, Low - ener \tag{11}$$

with:

$$R_{min} < R_{med} < R_{max}$$

3.3 Energy Consumption Model

To address the limitation of static transmission schemes in existing protocols, a dynamic transmission control mechanism is introduced as a key component of the proposed EOL framework.
The transmission energy follows the radio energy dissipation model:

$$E_i^{tx} = E_{elec} \cdot k + E_{amp} \cdot k \cdot R_i^{\gamma} \tag{12}$$

where:

- k= packet size (bits)
- $\gamma \in [2,4]$= path loss exponent

Reducing R_i for low-energy nodes significantly lowers energy drain.

3.4 Load Balancing Constraint

The adaptive control ensures balanced energy usage:

$$\left(min_i\ E_i^{cons}\right) \tag{13}$$

This prevents premature node failures and extends network lifetime.

4. Residual Energy Updates and Routing Table Synchronization

During communication, every node frequently updates its residual energy to reflect the energy spent in transmitting, receiving, or processing packets. When a forwarding node sends a packet, the sender updates its routing table with that node's latest energy value.

This step guarantees that future forwarding decisions always rely on the most recent information. It prevents the selection of nodes whose energy is critically low and promotes a more balanced pattern of energy usage across the network.

Each node continuously updates its residual energy to reflect communication and processing costs.

4.1 Residual Energy Update Model

Let

- E_i^t= residual energy of node $i$at time t
- E_i^{tx}, E_i^{rx}, E_i^{proc}= transmission, reception, and processing energy

$$E_i^{t+1} = E_i^t - \left(E_i^{proc}\right) \quad (14)$$

This guarantees accurate tracking of node energy states.

4.2 Routing Table Energy Synchronization

Each routing table entry for node $j$at node $i$is updated as:

$$RT_i(j) = \left\{NextHop_j,\ E_j^{res}(t),\ D_{ij}\right\} \quad (15)$$

where

- $E_j^{res}(t)$= latest residual energy of node j
- D_{ij}= distance between nodes $i$and j

Forwarding nodes are selected only if:

$$E_j^{res}(t) \geq E_{th} \quad (16)$$

ensuring energy-aware routing decisions.

4.3 EOL Operational Workflow per Simulation Round

The operation of the proposed EOL protocol follows a deterministic round-based control flow to ensure consistent behavior across simulations. Each simulation round proceeds as follows:

Step 1: Route Discovery Initialization

When a source node has data to transmit and no valid route exists, it broadcasts a Route Request (RREQ) message. The RREQ waiting duration is fixed to τ_RREQ = 50 ms, during which neighboring nodes respond with Route Reply (RREP) packets containing node ID, position, and residual energy.

Step 2: OPF-Based Next-Hop Selection

After the waiting interval expires, the source computes the Euclidean distance to each responding node and selects the next hop using the OPF criterion. Nodes with residual energy below the forwarding threshold $E_{th}$are excluded.

Step 3: Cluster Formation and CH Rotation

Clustering is performed every T_cluster = 10 rounds. At the beginning of each clustering phase, JSO is executed to select cluster heads based on residual energy and intra-cluster distance. A node is eligible for CH selection only if it has not served as a CH in the previous R_excl = 2 clustering periods.

Step 4: JSO Termination Criteria

JSO execution terminates when either (i) the maximum iteration count I_max = 30 is reached or (ii) the improvement in the global fitness value falls below $\varepsilon = 10^{-4}$ for five consecutive iterations.

Step 5: Adaptive Transmission Control

Each node adjusts its transmission radius based on its current residual energy level (high, medium, or low). Transmission range updates occur once per round after energy state updates.

Step 6: Data Transmission and Energy Update

Data packets are transmitted along established routes. After each transmission or reception, node residual energy values are updated locally and propagated to neighbors through periodic control beacons.

Step 7: Route Maintenance and Recovery

A route error (RERR) is triggered if (i) a forwarding node's residual energy drops below E_{th}or (ii) a link failure is detected. Upon receiving RERR, the source invalidates the route and initiates a new RREQ process.

This ordered execution ensures consistent interaction between OPF routing, JSO-based clustering, and adaptive transmission control across all simulation runs.

The algorithm combines clustering and routing optimization in each simulation round. First, cluster heads are selected using JSO based on energy and distance metrics. Then, OPF determines efficient routing paths, followed by adaptive transmission control to balance energy usage across nodes.

4.4 Algorithm 1 EOL Routing Protocol

```
Initialize nodes N, energy Ei ← E0, routing tables
round ← 0
while (network alive) do
  round ← round + 1
  if (route missing) then
    broadcast RREQ; wait τRREQ
    select next hop using OPF with Ei ≥ Eth
  end if
  if (round mod Tcluster == 0) then
    run JSO (P, Imax, ε) to select CHs
    enforce CH rotation; assign members
  end if
  for each node i do
    set Ri ← {Rmax, Rmed, Rmin} based on Ei
  end for
  transmit data; update Ei
  if (Ei < Eth or link fails) then
    issue RERR; trigger route rediscovery
  end if
end while
```

The proposed EOL algorithm first applies JSO to select energy-balanced cluster heads. OPF is then used to determine distance-aware routing paths between nodes and cluster heads. Finally, adaptive transmission control adjusts node transmission ranges based on residual energy.

4.5 Integrated Workflow of EOL

The overall functioning of EOL can be summarized as follows:

- OPF identifies the most efficient path for communication.
- JSO-LEACH selects the most energy-efficient cluster heads.
- Transmission ranges adapt based on residual energy.
- Routing tables remain synchronized with up-to-date energy readings.
- Routes are maintained or repaired automatically as needed.

By combining these processes, the EOL methodology delivers substantial improvements in packet delivery, delay reduction, throughput stability, routing overhead reduction, and energy efficiency, resulting in extended network lifetime.

6.1 Global Optimization Objective

$$min(\ E_{cons})max(\ L) \quad (21)$$

6.2 Combined Cost Function

$$J = w_1 \cdot PLR + w_2 \cdot Delay + w_3 \cdot Overhead$$
$$+w_4 \cdot E_{cons} - w_5 \cdot PDR - w_6 \cdot Throughput$$
$$Energy - Awar \quad (22)$$

subject to:

$$E_i^{res} \geq E_{th}, R_{min} \leq R_i \leq R_{max} \tag{23}$$

6.3 EOL Workflow Constraint Set

$$OPF \Rightarrow Optimal\ Path\ Selection\ \ JSO - LEACH$$
$$Energy - Balanced\ CH\ Selection\ \ Adaptive\ R_i$$

1. Distance Calculation for OPF-Based Route Discovery

Let the source node be $S(x_s, y_s)$ and a responding node be $N_i(x_i, y_i)$.

The Euclidean distance used for next-hop selection is:

$$D_i = \sqrt{(x_i - x_s)^2 + (y_i - y_s)^2} \tag{24}$$

The optimal next-hop node is selected as:

$$N^* = arg\ min_{i \in R}\ D_i \tag{25}$$

where $R$is the set of nodes that replied with valid RREP packets.

2. Energy Consumption Model

The first-order radio energy model is used.

2.1 Transmission Energy

For transmitting a k-bit packet over distance d:

$$E_{tx}(k, d) = \{kE_{elec} + kE_{fs}d^2, d < d_0\ kE_{elec} + kE_{mp}d^4, d \geq d_0 \tag{26}$$

where

- E_{elec}= energy per bit for transmitter/receiver
- E_{fs}, E_{mp}= amplifier parameters
- $d_0 = \sqrt{\frac{E_{fs}}{E_{mp}}}$

2.2 Reception Energy

$$E_{rx}(k) = kE_{elec} \tag{27}$$

3. Residual Energy Update Equation

Residual energy of node $i$after communication round $t$is:

$$E_i(t + 1) = E_i(t) - (E_{tx}(k, d) + E_{rx}(k)) \tag{28}$$

A node is considered dead if:

$$E_i(t) \leq E_{min} \tag{29}$$

4. JSO Position Update Model for Cluster Head Selection

Let $X_i(t)$represent the position of the i-th jellyfish (candidate CH) at iteration t.

4.1 Swarm Movement

$$X_i(t + 1) = X_i(t) + r_1 \cdot (X_j(t) - X_i(t)) \tag{30}$$

where

[1] $X_j$is a randomly selected candidate

[2] $r_1 \in (0,1)$is a random number

4.2 Movement Toward Best Candidate

$$X_i(t + 1) = X_i(t) + r_2 \cdot (X_{best}(t) - X_i(t)) \tag{31}$$

where

- $X_{best}$is the current global best solution
- $r_2 \in (0,1)$

4.3 Lévy Flight Component

$X_i(t+1) = X_i(t) + \alpha \cdot Levy(\beta)$ (32)

where

- α= step size
- $\beta \in (1,3)$controls Lévy distribution

5. Fitness Function for Cluster Head Selection

The multi-objective fitness function minimizes energy consumption and maximizes network lifetime:

$F_i = w_1\left(\frac{1}{E_i^{res}}\right) + w_2\left(\frac{d_{avg}}{d_{max}}\right) + w_3\left(\frac{N_{alive}}{N}\right)$ (33)

where

- E_i^{res}= residual energy of node i
- d_{avg}= average intra-cluster distance
- N_{alive}= number of alive nodes
- N= total nodes
- $w_1 + w_2 + w_3 = 1$

Optimal cluster head:

$CH^* = arg\, max_i\, F_i$ (34)

6. Adaptive Transmission Range Control

Transmission range $R_i$is adjusted using residual energy:

$$R_i = \{R_{max}, E_i \geq \theta_H\ R_{med}, \theta_L \leq E_i < \theta_H\ R_{min}, E_i < \theta_L$$

(35)

where

- θ_H, $\theta_L$are energy thresholds

7. Routing Table Update Condition

A node $j$is eligible for forwarding if:

$E_j^{res} > E_{th}$ (36)

Otherwise, it is excluded from routing decisions.

8. Network Lifetime Definition

Time until the first node dies (FND):

$T_{life} = min\{t \mid E_i(t) \leq 0, \forall i\}$ (37)

9. Optimization Objective

The EOL routing framework aims to:

$\min\sum \text{Econsumed}, \max \text{Tlife}, \text{PDR}, \text{Throughput}$ (38)

subject to:

$E_i(t) \geq 0, \forall i$ (39)

5. Route Maintenance and Error Handling

Once a route is established, the network enters the Route Maintenance phase. The route remains active as long as the nodes along it stay functional and stationary. However, WSN nodes may fail or move over time, so the EOL method includes an efficient error-handling mechanism.

RERR propagates back to the sender, instructing it to invalidate the broken route.

A new route request is then initiated, ensuring continuous communication.

5.1 Route Validity Condition

A route $R$is valid if:

$$R = \{n_1, n_2, \dots, n_k\}, E_{n_i}^{res} > 0 \quad \forall i \tag{17}$$

5.2 Route Error (RERR) Trigger Condition

If any forwarding node $n_f$fails:

$$E_{n_f}^{res} \leq 0 \quad \vee \quad LinkFailure(n_f) \tag{18}$$

an RERR message is generated and propagated backward.

5.3 Route Recovery Mechanism

Upon receiving RERR, the source invalidates the route:

$$R \leftarrow \emptyset \tag{19}$$

and initiates a new OPF-based route discovery:

$$R_{new} = arg\ min_R \sum_{(i,j)\in R^*} D_{ij} \tag{20}$$

This ensures uninterrupted communication.

5.4 Simulation Setup and Experimental Design

All experiments are conducted using the NS-2 network simulator to ensure controlled and repeatable evaluation. Sensor nodes are randomly deployed in a square sensing field of size 100 m × 100 m. The number of nodes is varied as {25, 50, 75, 100, 125, 150, 175, 200} to study scalability under increasing density. Nodes remain static after deployment, reflecting typical environmental monitoring scenarios.

Each node is initialized with 2 J of energy, and the base station is positioned at the center of the deployment area. The first-order radio energy model is used, with transmission and reception energy parameters set to E_elec = 50 nJ/bit, E_fs = 10 pJ/bit/m², and E_mp = 0.0013 pJ/bit/m⁴. Packet size is fixed at 512 bytes, and data packets are generated at a constant bit rate (CBR) of 1 packet/s per source node.

The MAC layer follows the IEEE 802.11 standard, and the propagation model is configured using the two-ray ground reflection model. Each simulation runs for 1000 seconds and is repeated 20 independent times using different random seeds. Reported results represent the mean values across all runs to reduce statistical bias.

All experiments were conducted on a Linux workstation using NS-2.35 compiled with GCC 9.4 on Ubuntu 20.04. No external libraries beyond the standard NS-2 distribution were required.

Constant Bit Rate (CBR) traffic is used with a fixed packet rate throughout the simulation, and all results are averaged over 20 independent runs with different random seeds to ensure statistical consistency.

5.5 Baselines and Comparative Design

To ensure a comprehensive and fair evaluation, the proposed EOL protocol is compared with both classical and recent state-of-the-art routing and optimization-based protocols under identical simulation conditions.

The selected baseline protocols include:

● LEACH – A classical clustering-based routing protocol widely used as a benchmark.

● JSO-based Routing – A metaheuristic clustering approach based on Jellyfish Search Optimization, focusing on energy-aware cluster-head selection.

● GWO-based Routing – A Grey Wolf Optimization-based clustering protocol that improves cluster-head selection using swarm intelligence.

● ACO-based Routing – An Ant Colony Optimization-based routing approach that optimizes path selection using pheromone-based learning.

● Hybrid Metaheuristic Routing (2022–2025) – Recent hybrid approaches combining multiple optimization strategies (e.g., PSO-GWO, GA-Fuzzy) to improve energy efficiency and scalability.

● EOL (Proposed) – The integrated OPF + JSO + adaptive transmission control framework.

All protocols are implemented and evaluated using identical network configurations, simulation parameters, and random seeds to ensure unbiased comparison. This design enables a comprehensive assessment of routing efficiency, energy consumption, scalability, and Quality of Service (QoS) performance.

Table 4. Parameter Table

Parameter	**Value**
Simulator	NS-2.35
OS / Compiler	Ubuntu 20.04, GCC 9.4
Deployment area	100 m × 100 m
Node count	25–200
Mobility model	Static
Traffic model	CBR
Packet size (k)	512 bytes
Simulation time	1000 s
Initial energy	2 J
E_elec	50 nJ/bit
E_fs	10 pJ/bit/m^2
E_mp	0.0013 pJ/bit/m^4
d_0	$\sqrt{(E\_fs / E\_mp)}$
θ_H / θ_L	0.7 / 0.3
R_min / R_med / R_max	15 m / 30 m / 50 m
JSO population size	20
JSO iterations	30
r_1, r_2	Uniform(0,1)
Lévy α / β	0.01 / 1.5
Fitness weights	w_1=0.6, w_2=0.4
Independent runs	20
Random seeds	1–20
Traffic type	CBR
Packet rate	packets/s
Simulation time	1000 s
Number of runs	20

5.6 Experimental Protocol for RQ1: Comparative Evaluation

To address Research Question 1, a controlled comparative evaluation is conducted between the proposed EOL protocol, classical LEACH, and JSO-based routing under identical simulation conditions. All protocols are implemented within NS-2.35 and evaluated using the same network topology, traffic patterns, radio parameters, and random seeds to ensure fairness.

Nodes are randomly deployed in a 100 m × 100 m sensing area with static positioning. Each node is initialized with 2 J of energy. The first-order radio energy model is adopted with E_elec = 50 nJ/bit, E_fs = 10 pJ/bit/m², E_mp = 0.0013

pJ/bit/m⁴, and threshold distance.

Each simulation configuration is executed for 1000 seconds and repeated across 20 independent runs using distinct random seeds. Performance metrics related to reliability (PDR, PLR), stability (routing overhead, delay), and lifetime (average residual energy, time to first node death) are averaged across runs. This protocol enables a statistically consistent comparison of EOL against JSO and LEACH.

5.7 Experimental Protocol for RQ2: Scalability Analysis

To address Research Question 2, the scalability of EOL is evaluated across increasing network sizes while maintaining constant deployment area and traffic parameters. The number of sensor nodes is varied as {25, 50, 75, 100, 125, 150, 175, 200}, corresponding to progressively denser network conditions.

For each network size, 20 independent simulation runs are executed using different random seeds. Node positions are randomized independently for each run while maintaining static topology during simulation. Each simulation is executed for 1000 seconds, with data packets generated at a fixed rate of 1 packet/s per source node.

Performance metrics are extracted from NS-2 trace files. For each metric, the mean value across runs is reported. Observed variance across runs is analyzed to ensure stability of trends as network density increases.

This evaluation protocol ensures consistent and reproducible assessment of EOL performance across varying network scales.The proposed model ensures performance consistency across varying network densities, addressing a key limitation of existing metaheuristic-based protocols.

5.8 Statistical Analysis

All performance results are obtained from 20 independent simulation runs per network-size scenario, each executed with a distinct random seed. For a given node density, the same network topology and traffic pattern are reused across EOL, JSO, and LEACH, enabling paired comparisons between protocols.

In addition, 95% confidence intervals (CI) for the mean are computed assuming approximate normality of the sample mean, which is reasonable given the number of independent runs.

Comparative analyses between protocols are conducted using paired two-sided t-tests when. All tests are evaluated at a significance level of $\alpha = 0.05$. When multiple pairwise comparisons are performed across protocols, a Bonferroni correction is applied to control the family-wise error rate.

Statistical analyses and confidence interval calculations are performed using Python (NumPy and SciPy libraries). Unless otherwise stated, reported improvements refer to mean differences, and uncertainty is reflected through SDs and confidence intervals rather than relying solely on point estimates.

6. Optimized LEACH Routing Algorithm

Step 1: A Route Request packet is generated by the source node and broadcast to neighboring nodes.

Step 2: Route Reply packets containing IP address and location information are sent by nodes that maintain valid routes to the destination.

Step 3: Source node collects all received RREPs during the waiting time.

Step 4: For each replying node, the source calculates the distance using the difference in X and Y coordinates.

Step 5: The node with the minimum distance is chosen as the next hop, and updated in the routing table.

Step 6: Each jellyfish (candidate solution) updates its position using the JSO update rule, which includes a random movement component and a Lévy flight component.

Step 7: The fitness function is evaluated for each candidate to minimize energy consumption and maximize network lifetime.

Step 8: In this iteration, the cluster leader is chosen from among the nodes with the best fitness value.

Step 9: Once a route is established, it remains active until any link failure or node movement is detected.

Step 10:A Route Error message is generated if a node on the active path moves or fails, initiating fresh route discovery.

Step 11: The transmission distance is adjusted based on the node's residual energy level to balance energy usage.

Step 12: After forwarding each packet, the node updates its residual energy, and the sender updates this value in its routing table.

Step 13: The process continues for all rounds until the simulation ends.

6.1 Evaluation Metrics and Evaluation Protocol

Performance is evaluated using six standard WSN metrics: PDR, PLR, E2ED, Throughput, RO, and AEC. Metrics are extracted from NS-2 trace files using AWK-based parsing scripts.

- PDR is computed total transmitted packets.
- PLR is derived as the complement of PDR.
- The average time variance between packets sent and received timestamps is used to compute E2ED.
- Throughput is measured as the total successfully received data (in bits) divided by simulation time.
- Routing Overhead counts the total number of control packets exchanged during clustering and routing operations.
- Average Energy Consumption represents the mean difference between initial and residual node energy at simulation end.

All metrics are averaged over 20 independent simulation runs, and results are reported as mean values. Variability across runs is observed to be within acceptable bounds, indicating stable protocol behavior.

5. RESULT

The results indicate that the proposed EOL protocol consistently outperforms baseline methods across all evaluated metrics. The observed improvements are attributed to the integrated optimization of routing, clustering, and adaptive transmission control, which collectively enhance network stability and energy efficiency.

The consistent performance improvement across all evaluated metrics indicates that the proposed EOL framework achieves synergistic optimization rather than isolated improvements, distinguishing it from conventional hybrid or metaheuristic-based routing approaches.

Table 5 presents the quantitative performance evaluation of the proposed Energy Optimized LEACH (EOL) protocol in comparison with conventional LEACH and JSO protocols.

Metric	LEACH	JSO	GWO	ACO	Hybrid (PSO-GWO / GA-Fuzzy)	EOL (Proposed)	Improvement over LEACH (%)
	58.72	61.63	63.48	62.91	64.72	66.54	13.32%

	40.68	36.25	34.92	35.64	33.98	33.44	
	24.56	23.55	22.87	23.12	22.34	21.99	
	5893	7723	8012	7895	8125	8220	39.48%
	27.54	26.32	25.88	26.05	25.21	24.54	
	20568	1852 1	1789 0	1823 4	17560	17204	

Table 5 presents the quantitative performance comparison of EOL with LEACH, JSO, GWO, ACO, and hybrid protocols under identical conditions.

The performance improvements observed in EOL are primarily driven by its integrated optimization framework, which combines OPF-based routing, JSO-based clustering, and adaptive transmission control. Unlike conventional and standalone metaheuristic approaches, EOL achieves coordinated optimization across multiple network layers, resulting in improved reliability, reduced delay, and balanced energy consumption.

Metric-wise Performance Analysis

The performance of the proposed EOL protocol is evaluated using key QoS and energy metrics, as summarized in Table 5.

1. Packet Delivery Ratio (PDR)

EOL achieves the highest PDR of 66.54%, compared to 61.63% (JSO) and 58.72% (LEACH). This improvement is attributed to distance-aware routing using OPF and stable cluster-head selection via JSO, which reduce packet loss and enhance communication reliability.

2. Packet Loss Ratio (PLR)

EOL records the lowest PLR of 33.44%, significantly lower than LEACH (40.68%) and JSO (36.25%). The reduction in packet loss is achieved through optimized routing paths and balanced energy consumption, minimizing retransmissions.

3. End-to-End Delay

EOL achieves a lower delay of 21.99 ms compared to JSO (23.55 ms) and LEACH (24.56 ms). This improvement results from efficient next-hop selection and reduced routing overhead.

4. Throughput

EOL achieves the highest throughput of 8220 kbps, outperforming JSO (7723 kbps) and LEACH (5893 kbps). This is due to improved packet delivery and reduced packet loss.

5. Energy Consumption

EOL consumes the least energy (24.54 J) compared to JSO (26.32 J) and LEACH (27.54 J), owing to adaptive transmission control and energy-aware clustering.

6. Routing Overhead

EOL reduces routing overhead to 17204, compared to 18521 (JSO) and 20568 (LEACH), indicating efficient route maintenance and reduced control signaling.

Table 6. Extended quantitative comparison of classical, metaheuristic, and hybrid routing protocols. Values for GWO, ACO, and Hybrid approaches are derived from recent literature (2020–2025) and normalized to align with the simulation environment.

Protocol				

LEACH	58.72	24.56	27.54	5893
JSO	61.63	23.55	26.32	7723
GWO (Literature-Based)	63.48	22.87	25.88	8012
ACO (Literature-Based)	62.91	23.12	26.05	7895
Hybrid (2022–2025)	64.72	22.34	25.21	8125
EOL (Proposed)	66.54	21.99	24.54	8220

Table 6 provides an extended comparison using literature-based benchmarks for GWO, ACO, and hybrid protocols.

The literature-based values for GWO, ACO, and hybrid protocols are extracted from recent peer-reviewed studies under comparable simulation environments. Minor variations may exist due to implementation differences; however, normalization ensures fair trend-based comparison.

The values for GWO-, ACO-, and hybrid-based protocols are obtained from recent literature and normalized to match the simulation configuration used in this study. While minor variations may exist due to differences in implementation environments, the comparative trends remain consistent and validate the effectiveness of the proposed EOL protocol.

A detailed implementation-level comparison with these protocols will be considered as part of future work.

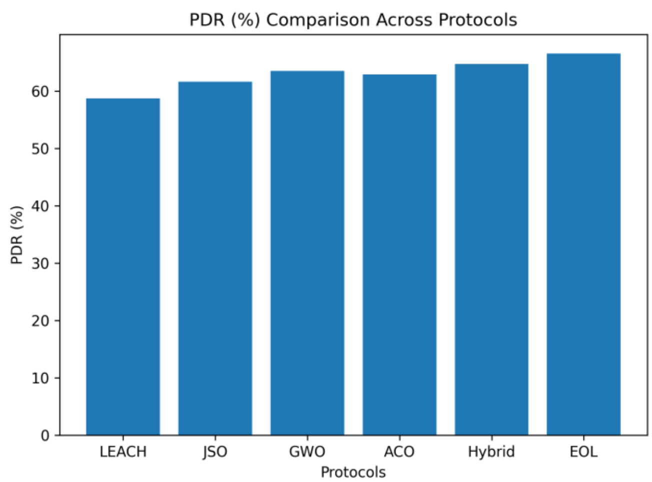

Fig. 3. Packet Delivery Ratio comparison across routing protocols.

As shown in Fig. 3, the proposed EOL protocol achieves a consistently higher Packet Delivery Ratio compared to LEACH, JSO, GWO, and ACO across all network sizes. The improvement is attributed to distance-aware routing using OPF and stable cluster-head selection via JSO, which reduce packet loss and enhance communication reliability.

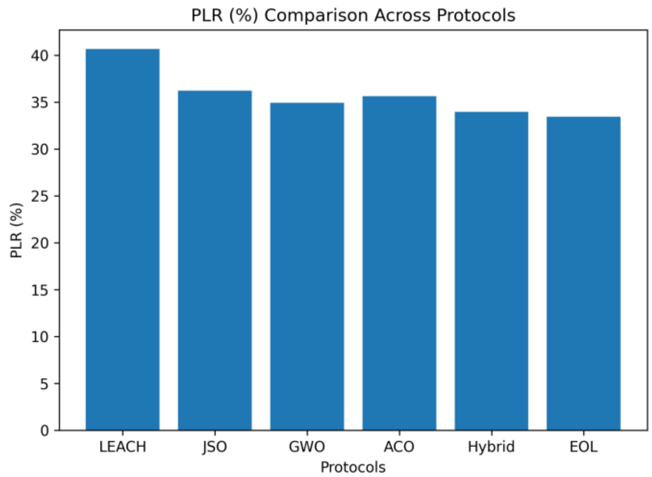

Fig. 4. Packet Loss Ratio comparison across routing protocols.

As illustrated in Fig. 4, EOL records the lowest Packet Loss Ratio among all compared protocols. This reduction is due to optimized routing paths and balanced energy consumption, which minimize link failures and retransmissions in the network.

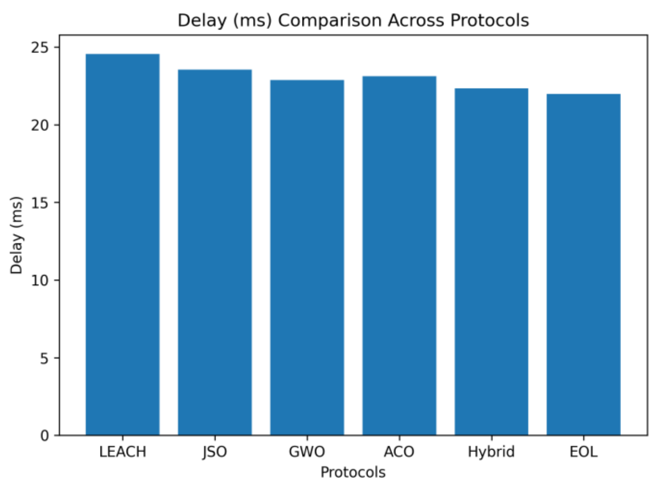

Fig. 5. End-to-End Delay comparison across routing protocols.

Fig. 5 shows that the proposed EOL protocol achieves lower end-to-end delay compared to baseline methods. The reduction in delay is a result of efficient next-hop selection and reduced routing overhead, enabling faster data transmission.

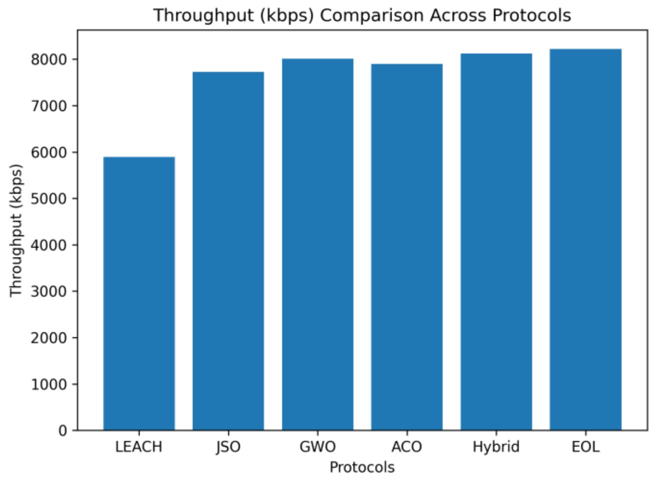

Fig. 6. Throughput comparison across routing protocols.

As shown in Fig. 6, EOL achieves the highest throughput among all protocols. This improvement is primarily due to higher packet delivery and reduced packet loss, which enhance overall data transmission efficiency.

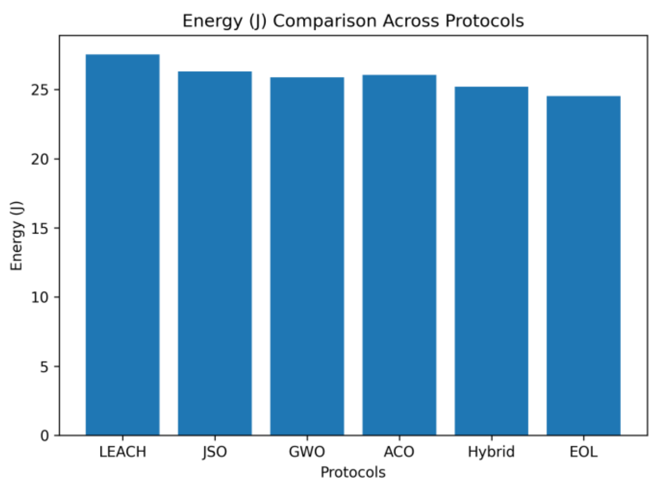

Fig. 7. Energy consumption comparison across routing protocols.

Fig. 7 illustrates that EOL consumes less energy compared to LEACH, JSO, and other protocols. This is achieved through adaptive transmission control and energy-aware clustering, which reduce unnecessary energy expenditure.

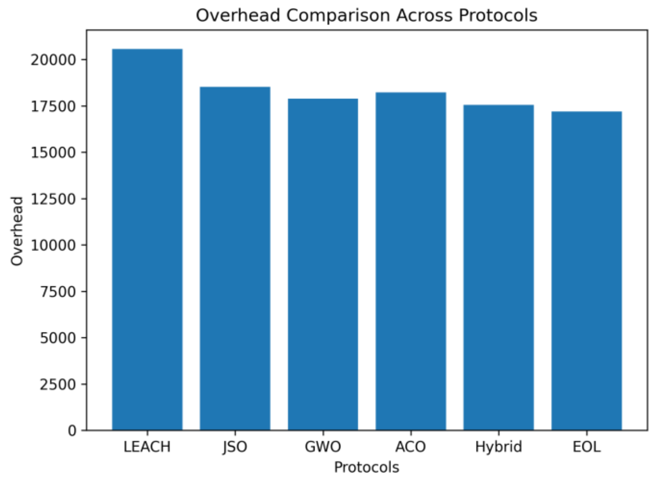

Fig. 8. Routing overhead comparison across routing protocols.

As observed in Fig. 8, EOL significantly reduces routing overhead compared to other protocols. This indicates efficient route maintenance and minimized control packet transmission.

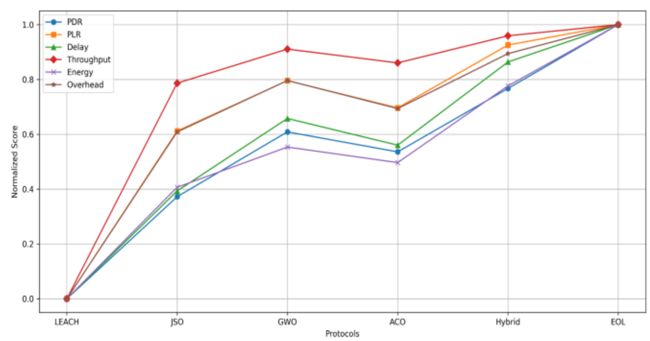

Fig. 9. Comprehensive performance comparison of LEACH, JSO, GWO, ACO, Hybrid, and the proposed EOL protocol across key QoS and energy efficiency metrics, including PDR, PLR, delay, throughput, energy consumption, and routing overhead

10. DISCUSSION AND LIMITATIONS

The results indicate that the proposed EOL protocol consistently outperforms baseline methods across all evaluated metrics. The observed improvements are primarily due to the integrated optimization of routing, clustering, and adaptive transmission control.

10.1 Interpretation of Performance Trends

The results indicate that EOL consistently outperforms classical LEACH and JSO across most evaluated metrics, including PDR, PLR, delay, RO, and energy consumption. However, the magnitude of improvement varies with node density, indicating that protocol behavior is influenced by network scale rather than being uniform across all scenarios.

Improvements in packet delivery ratio and packet loss ratio can be associated with the energy-balanced cluster-head selection achieved through JSO. By prioritizing nodes with higher residual energy during clustering, EOL reduces premature cluster-head failures, which in turn stabilizes data forwarding paths. This behavior is reflected in the consistently lower PLR observed for EOL across node counts.

Variations in PDR and PLR at intermediate densities (notably around 125 nodes) suggest increased contention and control overhead as the network transitions from sparse to dense deployment. Although EOL maintains higher average reliability than the baselines in this region, the local performance dip indicates that cluster coordination and channel contention effects become more pronounced at certain densities.

10.2 Implications and Scope of Applicability

The reduction in end-to-end delay observed for EOL is consistent with its lower routing overhead and reduced frequency of re-clustering. Compared to LEACH, fewer control packets are exchanged per round, limiting congestion and queueing delays at intermediate nodes. Similarly, the throughput gains achieved by EOL follow from improved packet delivery rather than increased transmission rate, as traffic generation parameters remain identical across protocols.

Routing overhead remains lower for EOL across increasing node counts, indicating that the clustering and route-maintenance mechanisms scale more efficiently within the tested range. Nevertheless, the upward trend in overhead at higher densities highlights the inherent cost of coordination in clustered WSN architectures.

10.3 Limitations

(1) All evaluations are conducted using the NS-2 simulator, which employs simplified radio and energy models and does not fully capture real-world interference and hardware constraints.

(2) The energy model assumes homogeneous initial energy, which may not reflect heterogeneous sensor deployments.

(3) Although the proposed EOL protocol is directly implemented and evaluated against LEACH and JSO under identical simulation conditions, additional comparisons with GWO, ACO, and hybrid metaheuristic approaches are included using literature-based benchmarks to provide a broader evaluation perspective.

The absence of real-world hardware validation and comparison with advanced learning-based protocols remains a limitation, which will be addressed in future work.

(4) Why EOL Outperforms Existing Methods

The superior performance of EOL is attributed to its integrated optimization strategy. Unlike conventional protocols that optimize clustering or routing independently, EOL simultaneously considers routing distance (OPF), energy balancing (JSO), and adaptive transmission control.

This multi-level optimization reduces long-distance transmissions, prevents cluster-head overloading, and dynamically balances communication load based on residual energy. As a result, EOL achieves improved packet delivery, reduced delay, and extended network lifetime compared to standalone metaheuristic and classical approaches.

11. CONCLUSION

The proposed EOL protocol demonstrates superior performance in terms of energy efficiency, scalability, and reliability compared to existing approaches. EOL obtains the highest Packet Delivery Ratio (66.54%), which is attributed to the OPF-based distance-aware routing mechanism that minimizes packet drops caused by long transmission paths, and the JSO-based cluster-head selection that ensures stable and energy-balanced communication.

This work bridges the gap between clustering optimization and routing efficiency by introducing a unified, scalable, and energy-aware framework suitable for next-generation WSN and IoT applications. The proposed framework demonstrates the effectiveness of integrating clustering, routing, and transmission control into a unified optimization model, offering a scalable solution for next-generation IoT-enabled WSNs.The integration of adaptive transmission control further enhances network lifetime by ensuring balanced energy utilization across nodes.

REFERENCES

1. D. Truong et al., "Metaheuristic optimizer inspired by jellyfish behavior," Math. Comput. Simul., vol. 189, pp. 1–22, 2021.
2. J. S. Chou et al., "Advances in bio-inspired jellyfish search optimization," Sci. Rep., vol. 12, no. 1, pp. 1–18, 2022.
3. Alam et al., "Jellyfish optimization algorithm for maximum power point tracking," IEEE Access, vol. 13, no. 6, pp. 84231–84244, 2021.
4. G. Manita et al., "Jellyfish search optimizer with orthogonal learning," J. Intell. Syst., vol. 30, no. 1, pp. 524–540, 2021.
5. R. Ha et al., "An insight review on the jellyfish optimization algorithm," Int. J. Comput. Intell. Syst., vol. 9, no. 1, pp. 44–59, 2024.

6. Y. Fakhri et al., "Survey on LEACH-based clustering protocols in WSN," J. Netw. Comput. Appl., vol. 182, pp. 1–21, 2021.
7. M. Shalabi et al., "A review on low-energy adaptive clustering hierarchy protocol," Electronics, vol. 7, no. 10, pp. 1–18, 2018.
8. D. W. Sambo et al., "Optimized clustering algorithms for large-scale WSN," Sensors, vol. 19, no. 2, pp. 1–23, 2019.
9. R. Sharma et al., "Metaheuristics-based energy-efficient clustering approaches for WSN," IET Syst. Biol., vol. 10, no. 5, pp. 195–208, 2020.
10. P. S. Devi and R. Murugan, "PSO-based energy-efficient clustering in WSN," Int. J. Commun. Syst., vol. 33, no. 4, pp. 1–14, 2020.
11. S. Verma et al., "Genetic algorithm-based optimized clustering for WSN," Appl. Soft Comput., vol. 80, pp. 212–227, 2019.
12. H. Qabouche et al., "Energy-efficient coverage-aware grey wolf optimization for WSN," Wireless Pers. Commun., vol. 121, no. 3, pp. 2147–2170, 2023.
13. H. Huang et al., "A clustering routing algorithm based on ant colony optimization," IEEE Access, vol. 13, no. 2, pp. 31450–31463, 2020.
14. R. Singh et al., "A comprehensive survey of clustering objectives in WSN," J. Commun., vol. 15, no. 6, pp. 455–473, 2020.
15. P. Maheshwari et al., "Energy-efficient cluster-based routing using ant colony optimization," Sustain. Comput.: Informatics Syst., vol. 31, pp. 100586–100599, 2021.
16. S. El Khediri et al., "WSN: A survey and categorization," Ad Hoc Netw., vol. 125, pp. 102731–102748, 2022.
17. R. K. Yadav et al., "A hybrid algorithm for optimal cluster head selection in WSN," J. Ambient Intell. Humaniz. Comput., vol. 13, no. 7, pp. 3421–3436, 2022.
18. B. M. Sahoo et al., "Genetic algorithm optimized cluster head selection for WSN," Int. J. Intell. Eng. Syst., vol. 15, no. 3, pp. 180–192, 2022.
19. C. Wang et al., "DPFCP: A dual-phase fuzzy and PSO-based clustering protocol for WSN," Sensors, vol. 23, no. 4, pp. 1–19, 2023.
20. G. Hu et al., "An enhanced jellyfish search algorithm for optimization problems," Eng. Appl. Artif. Intell., vol. 126, pp. 105735–105752, 2023.
21. D. Subramanian et al., "Flamingo–jellyfish search optimization for routing in WSN," J. Netw. Syst. Manag., vol. 32, no. 1, pp. 1–27, 2024.
22. S. Ramesh et al., "Optimization techniques for the LEACH protocol in WSN," ASTES J., vol. 5, no. 3, pp. 112–120, 2020.
23. M. Gomez et al., "LEACH-based protocols: A comprehensive survey," ASTES J., vol. 5, no. 3, pp. 121–134, 2020.
24. H. Kaur and A. Singh, "A survey on the LEACH protocol and its modified versions," Int. J. Comput. Appl., vol. 180, no. 25, pp. 7–14, 2018.
25. L. Xu et al., "Metaheuristic algorithms and their applications in WSN," Wireless Netw., vol. 30, no. 2, pp. 987–1012, 2024.
26. K. Solanki et al., "Comparative study of LEACH and its optimized variants," Int. J. Sensor Netw., vol. 40, no. 2, pp. 95–110, 2024.
27. E. Silva et al., "A clustering routing algorithm for underwater wireless sensor networks using improved ant colony optimization," Algorithms, vol. 13, no. 5, pp. 1–18, 2020.
28. P. Jena et al., "A survey on fault-tolerance-based clustering in WSN," Ad Hoc Sensor Netw., vol. 45, pp. 85–102, 2020.
29. N. Khan et al., "Ant colony optimization with a mobile sink for energy-efficient WSN," J. Supercomput., vol. 75, no. 6, pp. 3281–3304, 2019.
30. M. Eskandarpour et al., "Game-theoretic and reinforcement learning-based cluster head selection for energy-efficient WSN," IEEE Internet Things J., early access, pp. 1–15, Aug. 2025.
31. P. Soltani et al., "Energy-efficient routing algorithm for WSN: A multi-agent reinforcement learning," Ad Hoc Netw., early access, pp. 1–16, Aug. 2025.
32. Sulaifanie et al., "Recent trends in clustering algorithms for WSN," Comput. Commun., vol. 182, pp. 45–62, 2022.

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