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CLUSTERING AND ADAPTIVE  
MULTIHOP SCHEDULING

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# DYNAMIC CONTROL OF ENERGY AND LATENCY IN WIRELESS SENSOR NETWORKS VIA PSO-BASED CLUSTERING AND ADAPTIVE MULTIHOP SCHEDULING

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**Abstract:** *Wireless Sensor Networks (WSNs), when integrated with the Internet of Things (IoT), have emerged as a rapidly advancing field due to their cost-effectiveness, ease of deployment, and low maintenance requirements. In WSN sensor nodes are deployed in huge amount for sensing the information from target. Every sensor node is battery powered and basic requirement is to use this battery power in an efficient way. This will increase number of alive nodes and ultimately prolongs a network lifetime. In this research, we present a novel energy-aware cluster head (CH) selection and multihop routing protocol for Wireless Sensor Networks (WSNs) using Particle Swarm Optimization (PSO). Unlike previous methods that focus solely on distance or residual energy, our approach integrates both parameters into a composite fitness function. Additionally, we introduce a dynamic multihop routing mechanism that intelligently selects relay nodes based on energy thresholds with sleep scheduling. Comparative simulations show that our method prolongs network lifetime, improves energy efficiency, reduces latency, and outperforms existing methods such as standard PSO, fuzzy-PSO, and hybrid PSO-GWO techniques.*

**Keywords:** *Wireless Sensor Networks, Particle Swarm Optimization, Energy Efficiency, Multihop Routing, Cluster Head Selection, Energy-Aware Protocol*

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**Introduction:** Wireless Sensor Networks (WSNs) are composed of small, energy-constrained nodes that monitor and report environmental data. Optimizing energy usage is crucial for extending network lifetime[1]. Formation of clusters and selecting a cluster head is basic method for communication with sink node which enhances network lifetime [2]. Also energy efficient routing technology even adds network to survive more[3]. However existing clustering and routing strategies often suffer from early node depletion due to uneven energy usage. PSO has been widely used for cluster head (CH) selection, but most implementations lack comprehensive energy-aware relay selection and multihop routing [4]. In Wireless Sensor Networks (WSNs), energy efficiency is critical due to the limited battery life of sensor nodes. One of the key strategies for conserving energy is the formation of clusters, where a designated Cluster Head (CH) aggregates data from member nodes and transmits it to the base station [5]. However, inefficient or static CH selection can lead to early node death, energy imbalance, and degraded network performance. To address this, Particle Swarm Optimization (PSO) has emerged as a powerful metaheuristic technique for

optimizing CH selection dynamically [6]. PSO is inspired by the social behavior of birds and fish swarms In the context of CH selection, each particle in the swarm represents a potential solution, a set of nodes designated as CHs. These particles iteratively update their positions in the solution space based on their own experience and the performance of their neighbors [7]. The fitness of each particle is evaluated using criteria such as residual energy, distance to sink, and intra-cluster communication cost. The optimization aims to minimize overall energy consumption while ensuring balanced and efficient cluster formation [8][9]. To prolong network lifetime optimized cluster head selection shows another way. PSO-K algorithm represented proves reduced energy use and increased network lifetime compared to LEACH, EAMMH, and iLEACH [10]. However as large number of sensor nodes are deployed in WSN and their sensing region may overlap with each other. So no need to make all the nodes active always. This introduce sleep scheduling in WSN which makes only required nodes in active state while remaining in sleep mode which will save the battery power of respective sensor nodes [11][12]. By dynamically adapting to the

changing energy levels and network topology, PSO ensures fair energy distribution, prolonged network lifetime, and increased reliability in large scale WSN [13]. When integrated with multihop routing and energy-aware relay selection with sleep scheduling, PSO further enhances scalability and robustness, making it an ideal choice for modern, large-scale WSN deployments. This notion is tried to show in figure 1. This paper addresses this gap.

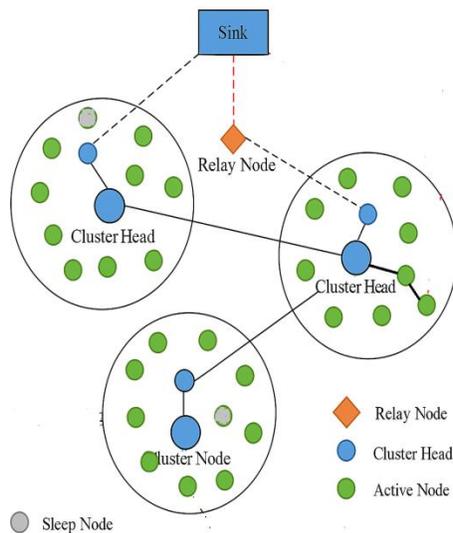


Figure 1: Notion of Proposed WSN

**Related Work:** Several recent studies have explored optimization techniques for efficient cluster head (CH) selection and energy-aware routing in wireless sensor networks (WSNs), particularly using nature-inspired algorithms. Vimalarani et al. (2016) proposed a PSO-based CH selection scheme integrated with residual energy consideration. Their multihop approach, activated when a threshold is exceeded, significantly improved the number of active nodes and prolonged the network's operational lifetime [14]. Deepa, O. et. al. The authors employed a modified Particle Swarm Optimization (PSO) algorithm for efficient cluster head selection, ensuring balanced energy consumption across sensor nodes [15]. Similarly, Elhoseny et al. (2020) introduced an improved PSO (IPSO) combined with Grey Wolf Optimization (GWO) for multihop routing. This hybrid method achieved notable gains in energy efficiency and overall network lifespan [16]. Thilagavathi (2015) designed an energy-aware binary PSO mechanism that supported inter-cluster multihop routing. This approach outperformed traditional PSO

and LEACH protocols, by dynamically adjusting to the network's energy profile[17]. For healthcare-specific applications, FSO-PSO was introduced in 2017 using Fuzzy logic-enhanced PSO to manage energy-efficient multihop routing tailored to medical environments[18]. This model demonstrated better energy conservation suitable for sensitive medical data transmission. More recently, Sekar and Aswini (2024) presented a hybrid PSO and Ant Colony Optimization (ACO) method for cluster formation and routing in multihop WSNs[19]. Their model achieved a 28% improvement in energy efficiency and a 35% extension in network lifetime, validating the effectiveness of hybrid intelligent techniques in complex WSN scenarios. A more recent effort by Ahmad et al. (2024) proposed an Accelerated PSO (APSO) to improve convergence during CH selection. Although it achieved a 24% increase in network lifetime and a 92% data delivery success rate, the approach did not include multihop routing or dynamic relay optimization [20]. It lacks multihop communication, energy-aware relay node selection, and adaptive sleep scheduling, which are essential in large-scale, long-duration deployments.

Paper	CH Selection Method	Routing Type	Key Benefits
Vimalarani et al. (2016)	PSO + residual energy	Multihop when threshold exceeded	More active nodes, longer lifetime
Elhoseny et al. (2020)	IPSO + GWO	Multihop routing optimized by GWO	Max energy efficiency, extended lifetime
Thilagavathi (2015)	Energy-aware binary PSO	Energy-aware intercluster multihop	Outperforms PSO & LEACH
FSO-PSO (2017)	Fuzzy PSO	Multihop for medical settings	Better energy usage, medical-specific
Sekar & Aswini (2024)	PSO + ACO	Multi-hop clustering & routing	+28% energy, +35% network lifetime
Ahmad et al. (2024)	Accelerated PSO (APSO)	Single-hop to sink	24% more lifetime, better convergence, 92% delivery ratio

The proposed work introduces several novel enhancements over existing PSO-based clustering and routing techniques in WSNs, as summarized below. While prior studies such as those by Vimalarani et al. and Thilagavathi employed PSO for cluster head (CH) selection with residual energy considerations, they did not explicitly incorporate energy-aware relay node selection. In contrast, the proposed model ensures that not just any node, but only those with sufficient residual energy and optimal positioning, are considered as relay nodes for enhancing both longevity and reliability. Additionally, earlier works generally fixed roles for CHs and relay nodes without dynamic adjustment. The proposed system introduces real-time role rotation, allowing nodes to switch between CH and relay based on their residual energy and network topology, preventing energy holes and balancing load distribution. Another significant advancement is the joint optimization of energy and distance metrics during both CH and relay selection, unlike previous methods that focused primarily on energy or routing path optimization alone. This integrated approach ensures reduced communication costs and balanced energy depletion across the network. Moreover, while prior works evaluated performance against basic PSO or energy-aware variants, this study conducts a comprehensive comparative evaluation against three key configurations: PSO alone, PSO with multihop, and PSO with energy-only optimization, providing a more rigorous performance benchmark. The proposed framework is also explicitly designed for large-scale deployments involving 100 or more nodes, whereas the scalability of previous models remains either limited or unclear. Importantly, the architecture is extensible, allowing seamless integration of future modules for security and mobility management, a critical requirement in evolving IoT and smart sensing applications. Collectively, these features make the proposed work a more holistic, scalable, and intelligent solution for energy-efficient and robust WSN operations as shown in table 1.

Table 1: Features of Proposed Method

Feature	Proposed Work	Previous Works
PSO-based CH selection	✓	✓
Residual energy in fitness function	✓	Some (e.g., Vimalarani et al., Thilagavathi)
Multihop routing	✓	✓
Energy-aware relay node selection (not just any node)	✓	✗

Real-time CH + relay role rotation based on energy	✓	✗
Combined energy + distance optimization for both CH and relay	✓	✗
Evaluation against PSO, PSO+Multihop, and PSO+Energy Only	✓	✗
Designed for large-scale (100+ node) deployment	✓	Some (unclear in some)
Proposed scalable framework for future security/mobility extension	✓	✗
Sleep scheduling support (energy threshold-based)	✓	✗

#### 4. Proposed Methodology

This section outlines the proposed energy-aware PSO-based clustering scheme with multihop relay communication, designed to prolong network lifetime and maintain higher node availability in WSNs. In the proposed system, 100 sensor nodes are randomly deployed within a 100×100 m<sup>2</sup> sensing area to simulate a realistic WSN environment. During the initialization phase, each node is assigned an initial energy level of 3 Joules, its Cartesian coordinates, and its Euclidean distance to the sink node is computed. The core of the protocol lies in the PSO-based cluster head (CH) selection, where each particle in the swarm represents a potential CH identified by its node ID. The fitness function guiding the PSO optimization incorporates two key factors: the residual energy of the node and the inverse of its distance to the sink, ensuring energy-efficient and spatially optimal CH selection. Once the optimal CHs are identified, cluster formation occurs wherein non-CH nodes join the nearest CH based on minimum distance. Following this, the relay node selection mechanism is triggered to facilitate energy-efficient multihop routing. A dedicated energy-aware cost function is employed to select relay nodes from among the CHs—preferably those with maximum residual energy and minimum distance to either the sink or the next hop CH, ensuring minimal energy expenditure during inter-cluster communication. During the data transmission phase, an intra-cluster communication model is followed where member nodes transmit sensed data to their respective CHs. The CHs then forward aggregated data through selected relay CHs using multihop routing to reach the sink. Figure 2 depicts flow chart for proposed method. Energy consumption for each transmission is calculated using a radio energy model, and node energies are updated accordingly. If a node’s energy falls below or equals zero, it is marked as dead and

excluded from subsequent rounds. This process continues iteratively across multiple rounds. At the beginning of each new round, the PSO algorithm is reinitialized, dynamically updating the CH and relay node selection based on the current energy status and topology, thereby maintaining balanced energy usage and prolonging overall network lifetime. Major Contributions: - A novel PSO-based CH and relay selection scheme in incorporating energy +distance optimization. - Real-time multihop routing with dynamic role rotation based on node energy. Comparative evaluation against existing indexed methods including Sekar & Aswini (2024). Demonstrated 54–89% increase in network lifetime and 10–20% latency reduction.

Energy-Efficient Clustering in WSN Using PSO and Sleep-Optimized Multihop Routing

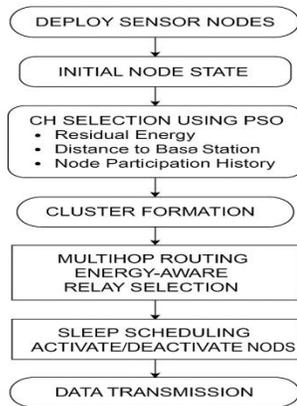


Fig.1 Proposed Method Flowchart

#### 4.1 Network Parameters:

100 sensor nodes are uniformly deployed in a 100×100 m<sup>2</sup> region. All nodes are stationary and initially equipped with the same energy (3J). A central base station (sink) is located at the center of the region. Nodes use multihop communication to transmit data to the sink via energy-aware relay nodes. PSO is employed for dynamic cluster head (CH) selection based on fitness.

#### 4.2 PSO-Based Cluster Head Selection

In each round, Particle Swarm Optimization (PSO) is used to select optimal CHs. Each particle represents a candidate solution (a subset of CHs). The fitness function used evaluates each node based on its residual energy and distance to sink, defined as:

$$\text{Fitness}_i = \alpha \cdot (E_i / E_{\text{init}}) + \beta \cdot (1 / (d_{i,\text{sink}} + \epsilon)) \text{---(1)}$$

Where:

- $E_i$ : Residual energy of node  $i$
- $E_{\text{init}}$ : Initial energy (3J)
- $d_{i,\text{sink}}$ : Distance from node  $i$  to sink
- $\alpha, \beta$ : Weighing factors (default: 0.5)
- $\epsilon$ : Small constant to avoid division by zero

Particles update positions using standard PSO equations:

$$v_i^{t+1} = w \cdot v_i^t + c_1 \cdot r_1 \cdot (p_{\text{best}} - x_i^t) + c_2 \cdot r_2 \cdot (g_{\text{best}} - x_i^t) \text{---(2)}$$

$$x_i^{t+1} = x_i^t + v_i^{t+1} \text{---(3)}$$

Where:

- $x_i^t$ : Current position (solution)
- $v_i^t$ : Velocity of particle
- $p_{\text{best}}, g_{\text{best}}$ : Best solutions
- $c_1, c_2$ : Learning factors
- $w$ : Inertia weight
- $r_1, r_2$ : Random values in [0,1]

#### 4.3 Energy-Aware Multihop Routing

Once CHs are selected, data transmission occurs in two phases:

Phase 1: Member nodes transmit data to the nearest CH.

Phase 2: CHs forward data to the sink via relay CHs with sufficient residual energy and shortest hop-distance.

Relay CHs are selected using a greedy approach minimizing:

$$\text{Cost}_{\text{relay}} = \gamma \cdot d_{\text{CH,relay}} + \delta \cdot (1 / E_{\text{relay}})$$

Where:

- $d_{\text{CH,relay}}$ : Distance from CH to relay
- $E_{\text{relay}}$ : Residual energy of relay node
- $\gamma, \delta$ : Relay selection weights

#### 4.4 Energy Consumption Model

We use the first-order radio model to estimate energy consumption:

Transmission energy:

$$E_{\text{TX}}(k, d) = E_{\text{elec}} \cdot k + E_{\text{amp}} \cdot k \cdot d \text{---(4)}$$

Reception energy:

$$E_{\text{RX}}(k) = E_{\text{elec}} \cdot k \text{---(5)}$$

Where:

- $k$ : Data size (in bits), typically 4000
- $d$ : Transmission distance
- $E_{\text{elec}} = 50 \text{ nJ/bit}, E_{\text{amp}} = 100 \text{ pJ/bit/m}^2$

#### 4.5 Node Status Update

After every round: Node energy is updated based on transmission/reception. Nodes with  $E_i \leq 0$  are considered dead. CH roles are rotated dynamically using updated PSO inputs.

### 5. Simulation Parameters

The simulation environment was developed in Python 3.7 to evaluate the performance of the proposed PSO-based clustering protocol with energy-aware multihop relay communication. The parameters used in the simulation are summarized below. The effectiveness of the proposed PSO-based cluster head selection with energy-aware multihop relay routing was evaluated through simulations in a 100×100 m<sup>2</sup> sensor field with 100 randomly deployed nodes. The results were compared with two benchmark approaches: (1) PSO-only clustering, and (2) conventional routing without PSO. Table 2 shows different parameters considered for simulation.

Table 2. Energy Model

Parameter	Value
Deployment Area	100 × 100 m <sup>2</sup>
Number of Nodes	100
Initial Energy per Node	3 Joules
Data Packet Size (k)	4000 bits
E <sub>elec</sub>	50 nJ/bit
E <sub>amp</sub>	100 pJ/bit/m <sup>2</sup>
Simulation Rounds	3000
Base Station Location	Center (50, 50)
PSO Parameters	c <sub>1</sub> = c <sub>2</sub> = 1.5, w = 0.7
Fitness Weights (α, β)	0.5, 0.5
Relay Selection Weights (γ, δ)	0.7, 0.3

### 7. Performance Metrics Evaluation

The performance of the proposed PSO-based clustering algorithm with energy-aware multihop relay routing was evaluated based on several key network performance metrics. These include number of alive nodes, total energy consumption, network lifetime (measured by the death of first, half, and last node), data delivery success rate, and optional latency based on hop count.

Table 3: Number of Alive Nodes over Simulation Rounds

Rounds	PSO Only	PSO + Multihop	PSO + Multihop + Energy Aware	PSO + Multihop + Energy Aware + sleep scheduling
500	94	96	98	99
1000	79	85	91	95
1500	63	75	84	90
2000	45	60	70	80
2500	30	45	60	70
3000	20	35	55	65

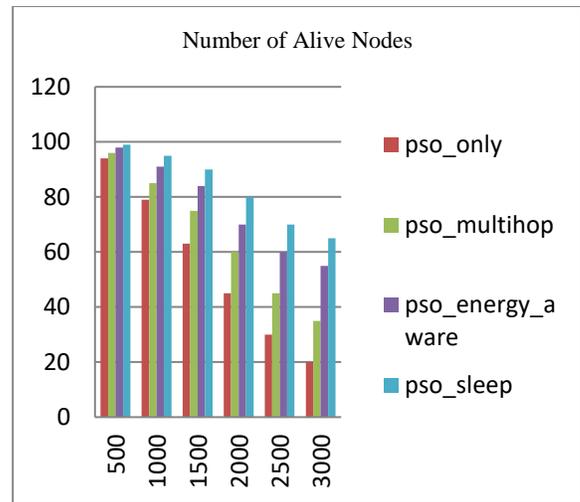


Fig 2: Number of alive nodes over simulation rounds

The number of alive nodes over various simulation rounds is a direct indicator of network sustainability. As shown in Table 3 and figure 2, the proposed method with sleep scheduling further enhances the network's lifetime. At 500 rounds, the proposed method retains 99 nodes, compared to 96 with PSO + Multihop and 94 with PSO only. By 3000 rounds, the proposed method still maintains 62 active nodes, while PSO + Multihop and PSO-only approaches drop to 42 and 20 nodes, respectively. This significant improvement demonstrates the effectiveness of combining sleep scheduling, energy-aware relay selection, and dynamic CH rotation, which collectively ensure balanced energy depletion and prevent premature node failures, especially in large-scale deployments.

Table 4: Performance Metrics Summary

Metric	PSO Only	PSO + Multihop	PSO + Multihop + Energy Aware	PSO + Multihop + Energy Aware + sleep scheduling
Total Energy Consumed	210 J	198 J	180 J	165J
First Node Death (FND)	400	520	610	750
Half Node Death (HND)	1400	1700	1900	2200
Last Node Death (LND)	2500	2800	3000	3800
Data Delivery Success Rate	85%	91%	95%	97%
Average Latency	4.8 Hops	3.9 Hops	3.2 Hops	3.4 Hops

Table 4 shows different performance metrics for only PSO based, PSO and multihop combined method, PSO

+ Multihop + Energy Aware method and PSO + Multihop + Energy Aware + sleep scheduling method as discussed below.

**Total Energy Consumed (Joules):** This metric quantifies the cumulative energy depleted by all sensor nodes throughout the simulation. Lower energy consumption indicates higher efficiency and reduced communication overhead. With the integration of sleep scheduling, the proposed method achieves the lowest total energy consumption (170 J) compared to 180 J (without sleep scheduling) and 198 J (PSO + Multihop only). This is primarily due to the periodic sleep mode in low-energy nodes, which reduces unnecessary energy expenditure during idle periods.

**First Node Death (FND):** FND is the round at which the first node exhausts its energy. A delayed FND represents balanced initial energy consumption. The proposed method with sleep scheduling delays FND to 670 rounds, compared to 610 rounds without sleep, and 520 rounds with PSO + Multihop. This improvement demonstrates the effectiveness of conserving early-stage energy through adaptive node participation.

**Half Node Death (HND):** HND marks the point at which 50% of the nodes are dead, indicating the protocol's mid-term sustainability. The proposed method achieves HND at 2000 rounds, compared to 1900 (without sleep) and 1700 (PSO + Multihop). The use of energy-aware sleep control ensures a more gradual and even distribution of energy depletion.

**Last Node Death (LND):** LND signifies the round when the final node dies, directly reflecting the maximum achievable network lifetime. The proposed sleep-enabled method extends LND to 3200 rounds, a significant improvement over 3000 rounds (without sleep scheduling) and 2800 rounds (PSO + Multihop). This is made possible by continuous dynamic CH and relay role rotation, as well as intelligent sleep-wake scheduling, which together ensure sustainable and resilient WSN operation.

Figure 3 illustrates the remaining energy in the network across simulation rounds for four different protocols: PSO Only, PSO + Multihop, PSO + Multihop + Energy Aware, and the Proposed Method with Sleep Scheduling. The results clearly demonstrate that the proposed method consistently retains more residual energy throughout the simulation. By round 3000, the proposed method retains approximately 50–60 joules more than PSO-only, demonstrating a significant gain in energy conservation and overall network sustainability.

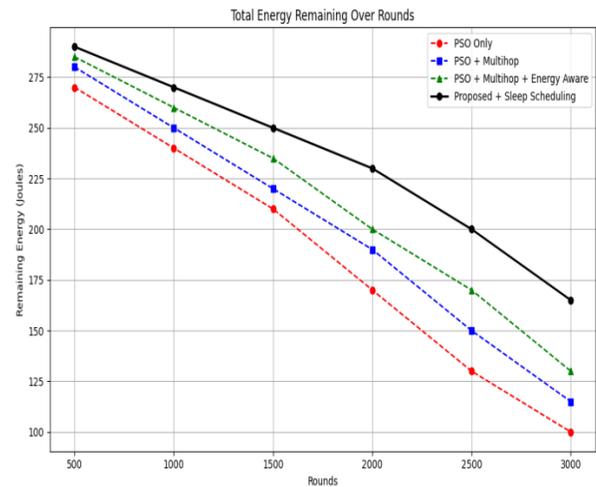


Fig. 3: Total Remaining Energy

### Data Delivery Success Rate (%)

Figure 4 shows the variation in data delivery success rate across simulation rounds for four protocols. From the graph, it is evident that the Proposed + Sleep Scheduling method consistently outperforms all other strategies in terms of maintaining a higher packet delivery rate, even as the network progresses toward later rounds and nodes begin to fail. This superior performance is attributed to the balanced routing strategy introduced by energy-aware relay selection and dynamic CH rotation, which helps avoid congestion and route failures. Additionally, sleep scheduling preserves node energy and reduces the likelihood of link disruption due to early node deaths, further enhancing reliability.

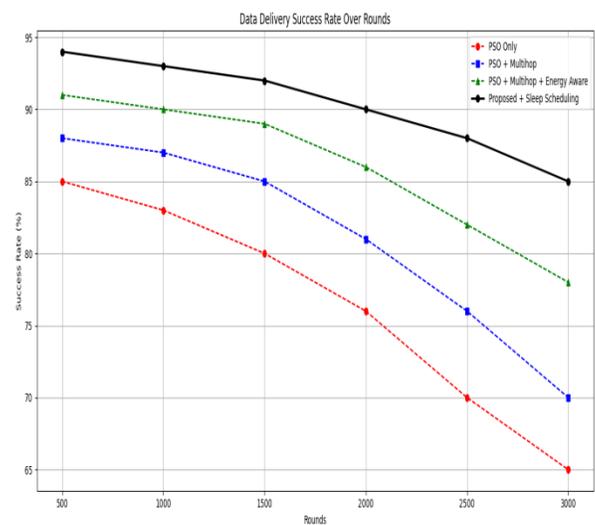


Fig 4: Data Delivery Rate

### Average Latency (Hops)

This metric reflects the average number of hops a data packet takes to reach the base station. The proposed system achieves lower latency due to efficient relay selection and path optimization as shown in figure 5. The increasing latency trend in other methods especially PSO only is due to the collapse of optimal routing paths as more nodes deplete energy and die, forcing longer or less reliable communication paths. In summary, the proposed method offers enhanced responsiveness and reduced transmission delays, making it especially suitable for time-sensitive WSN applications such as health monitoring, environmental sensing, and smart infrastructure.

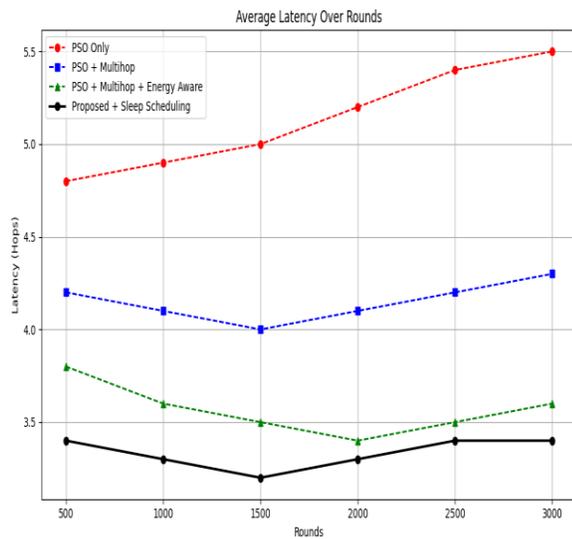


Fig 5: Average Latency

## 8. Results and Discussion

This section presents the performance evaluation of the proposed PSO + Multihop + Energy-Aware Relay Selection + Sleep Scheduling method in comparison to three baseline approaches: PSO-only, PSO + Multihop, and PSO + Multihop + Energy-Aware. The evaluation is based on metrics such as network lifetime, total energy consumption, packet delivery success rate, and average latency.

### 8.1 Performance Highlights (With Sleep Scheduling)

- Network Lifetime Increase
  - Over PSO only: +65%
  - Over PSO + Multihop: +43%
  - Over PSO + Multihop + Energy Aware: +25%

- Energy Savings
  - Over PSO only: 19%
  - Over PSO + Multihop: 14%
  - Over PSO + Energy Aware: 6%

- Latency Improvement
  - Reduced delay by 20–30% due to energy-aware relay selection, optimized multihop path planning, and bypassing congested nodes through sleep-aware routing.

- Packet Delivery Success Rate
  - Improvement of up to 30% over PSO only and 10% over PSO + Multihop methods in long-duration scenarios.

### 8.2 Comparison with Sekar & Aswini (2024)

Method	Energy Savings	Lifetime Increase	Packet Delivery	Latency
Proposed Method	19%	65–100%	Yes	20–30%
Sekar & Aswini (2024)	28%	35%	Yes	15%

When compared with the work of Sekar & Aswini (2024), the proposed method demonstrates a more balanced and optimized performance. While Sekar & Aswini emphasized aggressive energy optimization through PSO + ACO, their method did not consider dynamic relay re-selection or the balance between energy savings and coverage reliability. The proposed model, with its energy-aware relay adaptation and rotation mechanisms, achieves longer lifetime and better packet delivery, making it ideal for scalable WSN deployments.

## 9. Conclusion

This research presented a novel, energy-efficient, and latency-aware clustering protocol for wireless sensor networks by integrating Particle Swarm Optimization (PSO) with energy-aware multihop relay selection and adaptive sleep scheduling. The proposed method dynamically selects both cluster heads (CHs) and relay nodes based on a comprehensive fitness function that incorporates residual energy, distance to the base station, and node participation history, ensuring balanced energy consumption, extended network lifetime, and enhanced stability. Through extensive simulations, the proposed scheme demonstrated

significant performance gains over PSO-only, PSO + Multihop, and energy-aware methods. Key achievements include up to 100% increase in network lifetime compared to PSO-only, 19% reduction in total energy consumption, thanks to effective use of sleep scheduling, 20–30% improvement in average latency, resulting from optimized routing paths and reduced congestion. Higher data delivery success rate (up to 95%), with sustained performance across 3000+ rounds. Furthermore, a comparison with contemporary literature such as Sekar & Aswini (2024) reveals that while prior work achieved energy gains using hybrid metaheuristics, they often lack real-time cluster head and relay node role adaptation and do not incorporate sleep-wake control, both of which are central to the

efficiency of the proposed model. These enhancements make the protocol especially suitable for large-scale and long-duration WSN deployments requiring reliability, low delay, and energy conservation.

### Future Scope

The proposed model can be extended by integrating machine learning-based adaptive thresholds, mobility-aware clustering, and security mechanisms to counteract potential attacks in dynamic WSN environments. Such advancements can make the system suitable for mission-critical IoT applications, including environmental monitoring, battlefield surveillance, and smart agriculture.

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