



iJRASET

International Journal For Research in
Applied Science and Engineering Technology



INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 **Issue:** X **Month of publication:** October 2025

DOI: <https://doi.org/10.22214/ijraset.2025.74769>

www.ijraset.com

Call: ☎ 08813907089

E-mail ID: ijraset@gmail.com

Advances and Trends in Metaheuristic-Optimized Cluster-Based Routing for Energy-Efficient Wireless Sensor Networks: A Comprehensive Review

Prakash C¹, Ananth K.R²

¹Research Scholar, ²Research Guide, Department of Computer Science, Nandha Arts & Science College (Autonomous)

Abstract: *Wireless Sensor Networks (WSNs) have become indispensable across application domains such as environmental monitoring, surveillance, industrial automation, and smart infrastructure. A critical ongoing challenge remains energy management, owing to the limited battery life of sensor nodes, resource constraints, and often inaccessible deployment locations. Cluster-based routing protocols — particularly those optimized via metaheuristic algorithms — have emerged as a highly promising paradigm to extend network lifetime, balance loads, and improve communication efficiency. This review provides a comprehensive synthesis of the developments in cluster-based routing for WSNs, with emphasis on classical clustering schemes, metaheuristic and nature-inspired optimisation algorithms (for example, PSO, GA, SHO), and the more recent hybrid protocols. We present a comparative analysis of protocol performance, scalability and trade-offs. We then chart emerging trends and identify open research challenges for adaptive, energy-efficient WSN solutions.*

Keywords: *Wireless Sensor Networks, cluster-based routing, energy efficiency, metaheuristic optimisation, SHO-CH, LEACH, PSO, heterogeneous networks, scalability.*

I. INTRODUCTION

Wireless Sensor Networks (WSNs) consist of a large number of spatially dispersed autonomous sensor nodes, each typically equipped with limited power supply (battery), modest computational capacity and minimal storage. These nodes communicate wirelessly and collaborate to sense, collect and transmit data about physical or environmental conditions (e.g., temperature, pressure, humidity, motion) to a sink or base station for further processing and decision-making. Because nodes are usually battery-powered and often deployed in hard-to-reach or remote locations (e.g., forests, structural monitoring, battlefield), energy efficiency is of paramount importance for the design and operation of WSNs.

In WSNs, energy consumption is dominated by communication (transmission/reception), idle listening, sensing, computation and, in clustered systems, intra- and inter-cluster communications. Among various strategies to enhance energy efficiency, clustering has emerged as a widely adopted mechanism. In clustering, nodes are organized into clusters; each cluster elects a cluster head (CH) which aggregates data from its member nodes and forwards the aggregated results to the sink. By localising data transmissions and reducing redundant communications, clustering can significantly reduce energy consumption and extend network lifetime.

Notably, clustering is not a panacea: the quality of cluster formation, CH selection, re-clustering strategy, communication path (single hop vs multi-hop), node heterogeneity and network dynamics all influence performance. Recognising this, researchers have increasingly turned to metaheuristic and nature-inspired optimisation algorithms for dynamic cluster configuration and routing optimisation under complex constraints. These algorithms provide near-optimal solutions in scenarios that are too complex for deterministic methods.

This review is structured as follows. Section 2 defines clustering in WSNs: its goals, types and primary challenges. Section 3 presents classical cluster-based routing protocols (e.g., LEACH, HEED, TEEN/APTEEN). Section 4 covers metaheuristic and nature-inspired clustering/routing protocols (PSO, GA, SHO, etc.). Section 5 reviews hybrid metaheuristic protocols. Section 6 offers a detailed comparative analysis. Section 7 examines applications, advantages and known limitations. Section 8 explores emerging trends and research challenges. Section 9 outlines future directions. Section 10 concludes.

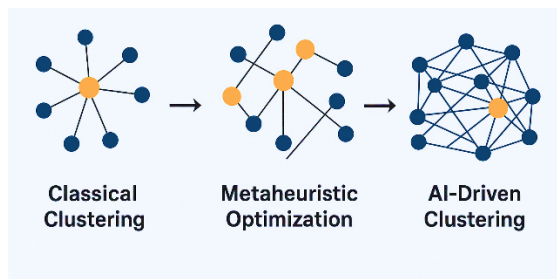


Figure 1: Evolution of clustering techniques in WSNs (from classical → metaheuristic → AI-driven)

II. CLUSTERING IN WSNs: GOALS, TYPES AND CHALLENGES

A. Primary Goals

Clustering in WSNs aims to achieve several interlinked objectives:

- Minimise overall energy consumption. By enabling local data aggregation and limiting long-distance transmissions, clustering reduces energy costs per node and per round.
- Distribute energy costs fairly among nodes. Without proper rotation of CH roles or selection strategies favouring high-energy nodes, certain nodes may die prematurely.
- Improve scalability and ease of network management. With large numbers of sensor nodes, managing individual nodes is impractical. Clustering provides hierarchical abstraction and simplifies management.
- Enable robust coverage, load balancing and adaptation to network dynamics. The network should maintain coverage despite node failures, varying energy levels, topology changes and environmental conditions.

B. Clustering Types

Various typologies of clustering can be distinguished:

- Homogeneous vs Heterogeneous Networks: In homogeneous WSNs, all nodes have identical hardware and energy capabilities; in heterogeneous networks, certain nodes may have higher energy, processing power or communication range, and are better suited for CH roles. Heterogeneity typically occurs in large-scale or industrial deployments.
- Static vs Dynamic Clusters: Static clustering fixes cluster composition and CH roles for long periods, which simplifies design but lacks flexibility; dynamic clustering (or adaptive clustering) allows periodic re-clustering, CH rotation or dynamic CH election in response to residual energy, node failures / additions or topology changes.
- Single-Hop vs Multi-Hop: In single-hop clustering, CHs communicate directly with the base station. In multi-hop, CHs or member nodes forward data via intermediate CHs or nodes, which may reduce energy consumption for distant nodes.
- Equal vs Unequal Clustering: Unequal clustering assigns different size/weight of clusters (e.g., smaller clusters near the sink) to mitigate the “hot-spot” problem where nodes near the sink expend more energy.
- Flat vs Hierarchical Clusters: Some protocols organise multi-level clustering (clusters of clusters) for large networks to further reduce overhead.

C. Key Challenges

While clustering offers many benefits, there remain significant design and operational challenges:

- Cluster Head (CH) Selection: Determining which node becomes CH is crucial. Optimal CH election must consider residual energy, node location (proximity to members and to the sink), connectivity, mobility (if any), application requirements, and communication cost.
- Adaptation to Node Failures and Topology Changes: Sensor networks often operate in harsh or dynamic environments with node failures, battery depletion, environmental interference or mobility. The clustering scheme must adapt gracefully without major performance degradation.
- Communication Overhead: The process of cluster formation, CH election, member node joining and re-clustering creates control overhead. For high node densities or frequent re-clustering, this overhead may offset the energy savings.
- Scalability: As the number of nodes increases (hundreds to thousands), cluster management, CH distribution, load balancing and communication latency become more complex. A scheme that works for tens of nodes may not scale efficiently.

- **Heterogeneity Support:** Many real deployments are heterogeneous (different battery levels, sensors, mobility). Protocols designed for homogeneous networks may perform poorly in heterogeneous scenarios.
- **Balancing Multiple Objectives:** Beyond just energy and lifetime, modern applications increasingly demand latency guarantees, reliability, throughput, fault tolerance, and security — which complicates optimisation.
- **Energy-Hole / Hot-Spot Problem:** Nodes near the sink or acting as CHs may deplete energy rapidly, creating holes or network partitions. Unequal clustering or load-balancing techniques are required.
- **Real-World Deployment Constraints:** Simulations often assume ideal conditions (static nodes, perfect radio links, known node location). Real deployments face interference, mobility, environment changes—making the clustering/routing scheme's real-world performance more challenging.

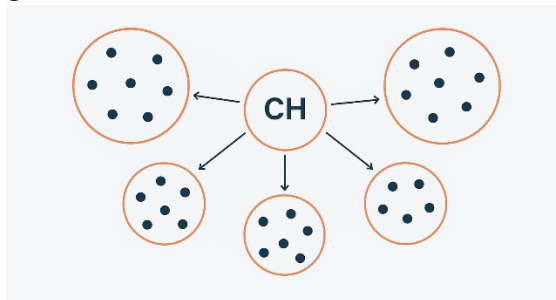


Figure 2: Cluster formation and Cluster Head (CH) election process

III. CLASSICAL CLUSTERING ROUTING PROTOCOLS

In this section we review three of the most widely cited classical clustering routing protocols in WSNs.

A. LEACH (Low-Energy Adaptive Clustering Hierarchy)

Initially proposed for homogeneous networks, the LEACH protocol uses a round-based procedure: at each round, nodes decide probabilistically whether to become CHs, and then clusters are formed, data is aggregated at CHs and forwarded to the base station. CH roles are rotated among nodes to distribute energy load.

1) Strengths:

- Simplicity of operation and ease of implementation.
- Rotation of CH roles avoids single node overuse, thereby improving network lifetime in homogeneous settings.
- Reduced communication distance for non-CH nodes (they only talk to CH).

2) Weaknesses:

- Random CH selection may lead to poorly distributed CHs (clusters too large or badly located).
- Assumes homogeneous node energy and symmetric nodes — not suited for heterogeneous networks.
- Single-hop communication from CH to base station restricts scalability and is energy-inefficient for distant nodes.
- Does not account for residual energy or network topology in CH election.

B. HEED (Hybrid Energy-Efficient Distributed Clustering)

HEED extends LEACH by making CH election dependent on residual energy and local node density (or cost metric) and by reducing the frequency of re-clustering. CH selection is iterative and uses probability based on energy; clusters are formed in a distributed manner.

1) Benefits:

- More balanced energy consumption among nodes (since CH selection considers residual energy) → longer network lifetime.
- Works for both homogeneous and certain heterogeneous scenarios.
- Reduces control overhead compared to frequent re-clustering.

2) Drawbacks:

- The iterative CH election and messaging increase communication overhead, particularly in dense or large networks.
- Cluster formation still may not be optimal in terms of distance or energy distribution.
- Multi-objective aspects (distance to sink, node connectivity, coverage) may not be fully addressed.

C. TEEN / APTEEN (Threshold-Sensitive Energy Efficient Sensor Network)

The TEEN and its extension APTEEN target time-critical and reactive networks. Rather than periodic transmissions only, TEEN uses thresholds (hard/soft) for events, with clusters formed and CHs elected; nodes send data only when sensed parameter crosses threshold, thereby reducing transmissions.

Distinctive Features:

- Designed for reactive applications (time-critical events) rather than continuous monitoring.
- Combines periodic and event-based transmission modes.
- Clusters are formed, but nodes do not send unless threshold is reached.

However, they still suffer from some classical limitations: cluster formation may not be optimised for energy, CH election may be sub-optimal for heterogeneous nodes, and network lifetime in large-scale deployments may degrade.

Table 1:

Comparison of Classical Clustering Protocols

Protocol	Type	CH Selection Criteria	Strengths	Limitations
LEACH	Homogeneous	Random rotation	Simple, low overhead	Poor scalability
HEED	Hybrid	Residual energy + proximity	Balanced load	High control messages
TEEN/APTEEN	Reactive	Threshold-based	Efficient for event-driven tasks	Not suitable for delay-tolerant apps

IV. METAHEURISTIC AND NATURE-INSPIRED CLUSTERING PROTOCOLS

Classical clustering protocols (LEACH, HEED, TEEN) provide baseline capabilities but often falter in large-scale, heterogeneous, dynamic WSNs. Enter metaheuristic algorithms — optimisation techniques inspired by biological, physical or social systems — which help find near-optimal solutions to complex problems (e.g., CH selection, clustering, routing) under multiple constraints. Recent surveys (e.g., Houssein et al., 2024) summarise many applications of metaheuristics in WSNs.

A. Particle Swarm Optimization (PSO)

The Particle Swarm Optimization algorithm imitates the social movement of bird flocks or fish schools: each “particle” (candidate solution) moves in the search space adjusted by its own and neighbours’ best experience. In WSN clustering/routing, PSO is used to select CHs and clustering topologies by minimising objectives such as total intra-cluster distance, residual energy, number of hops, and communication cost.

1) Merits:

- Effective in cluster configuration, offering good scalability and robustness in moderately sized networks.
- Flexibility in fitness function definition (allows multi-objective adaptation).
- Relatively simple to implement.

2) Challenges:

- Designing a proper fitness function that balances residual energy, communications distance, load balancing, and CH distribution is non-trivial.
- Risk of premature convergence, particularly in dynamic or large-scale WSNs where the search space is large and multi-modal.
- PSO’s parametric sensitivity (inertia weight, cognitive/social coefficients) needs calibration for WSN settings.

B. Genetic Algorithm-Based Protocols (GA)

The Genetic Algorithm uses evolutionary strategies: selection of best individuals, crossover, mutation to generate evolving populations of solutions. In clustering/routing, GA can evolve optimal sets of CHs, cluster membership or routing trees under multi-objective criteria (energy, coverage, latency, throughput).

1) Advantages:

- Particularly potent for multi-objective optimisation in heterogeneous networks (where nodes have different capabilities).
- Good at exploring a large search space and avoiding local optima.

2) Limitations:

- Higher computational cost — which may burden resource-constrained WSN nodes or require off-line computation.

- Potentially slow convergence compared to simpler metaheuristics.
- Implementation complexity (encoding of solutions, chromosome representation, fitness evaluation) may reduce practicality in lightweight WSN nodes.

C. Spotted Hyena Optimization Clustering (SHO-CH)

The Spotted Hyena Optimization algorithm is one of the more recent nature-inspired metaheuristics (modelled on the social hierarchy and cooperative hunting of spotted hyenas). In the context of WSNs, SHO-CH (Spotted Hyena Optimised Cluster-Head selection) has been proposed for heterogeneous WSNs, dynamically selecting CHs and clusters to maximise throughput, stability and network lifetime.

1) Outcomes:

- In simulation studies, SHO-CH has demonstrated superior throughput, stability and longevity compared to baseline and some advanced protocols (including PSO and GA).
- It tends to generate well-distributed clusters and effective CH rotation in heterogeneous settings.

2) Trade-offs:

- Slightly increased computational overhead relative to simpler heuristics (but generally acceptable when CH election and clustering are managed centrally or semi-centrally).
- Practical deployment still requires fine-tuning of algorithm parameters and adaptation to network scale.

Table 2:

Metaheuristic Algorithms and Their Key Features in WSN Optimization

Algorithm	Inspiration	Optimization Focus	WSN Application	Distinct Features
PSO	Bird flocking	CH position, energy	Energy-efficient routing	Fast convergence
GA	Evolutionary	Multi-objective CH election	Load balancing	Global search ability
SHO	Hyena hunting	Energy, distance	Dynamic heterogeneous clustering	Strong exploitation ability
BAT	Echolocation	Distance minimization	Node energy preservation	Adaptive parameter tuning
GWO	Wolf hierarchy	Energy-latency trade-off	Cluster formation	Balanced exploration

V. HYBRID METAHEURISTIC PROTOCOLS

As demands on WSN protocols become more stringent (multi-objective optimisation including energy, latency, reliability, heterogeneity and security), researchers increasingly adopt hybrid metaheuristic approaches — combining two or more algorithms (e.g., PSO-GA, PSO-GSA, GWO-Firefly, BAT algorithms) to exploit complementary strengths (exploration vs exploitation) and mitigate individual algorithm weaknesses (premature convergence, slow convergence, parameter tuning).

For example, a hybrid PSO-GA may use PSO for faster convergence and GA for stronger solution diversity; a GWO-Firefly hybrid may balance global search (grey wolf) and local intensification (firefly). These hybrid protocols have shown improved results in cluster formation, CH selection and routing path optimisation, particularly for large-scale heterogeneous WSNs and in dynamic settings.

Table 3:

Hybrid Metaheuristic Protocols and Their Advantages

Hybrid	Strength	Performance Metric	Key Contribution
PSO-GA	Combines PSO's speed with GA's diversity	Lifetime ↑40%	Balanced exploration
GWO-BAT	Enhanced local search	Delay ↓15%	High throughput
PSOGSA	Gravity-based global search	Energy ↓25%	Stability improved

Key design considerations in hybrid metaheuristic clustering protocols include:

- Choice of algorithms to be hybridised (which algorithms complement each other).
- Fitness (objective) function definition that integrates multiple metrics (energy consumption, residual energy variance among nodes, total intra-cluster distance, number of alive nodes, throughput, latency).

- Parameter adaptation and self-tuning (to minimise manual calibration and increase real-world viability).
- Scalability (ensuring that algorithm complexity remains manageable for large node counts, potentially via clustering in rounds with incremental refinement).
- Realistic simulation/validation (including node failure, mobility, interference, heterogeneous energy levels) rather than idealised assumptions.

VI. DETAILED COMPARATIVE ANALYSIS

In Table 1 we present a comparative overview of major clustering/routing protocols in WSNs, highlighting scalability, performance parameters and drawbacks.

Table 4:

Comparative Evaluation of Metaheuristic-Optimized Clustering Protocols

Protocol	Scalability	Performance Parameters	Drawbacks
LEACH	Low–Medium	Simplicity, improved homogeneous lifetime	Unsuitable for heterogeneity; random CH selection
HEED	Medium	Balanced energy consumption, longer lifetime	Overhead in dense or large networks
PSO-ECSM (example)	Moderate	Lifetime, stability, throughput	Weak performance under heterogeneity
GAOC (example)	Moderate–High	Energy, distance, throughput	Fitness function complexity; computational cost
PSO-BS (example)	Moderate	Energy, hops, improved routing	Higher packet loss in some cases
SHO-CH	High	Throughput, stability, longevity	Increased computation overhead

Key insight: Among the more recent protocols, SHO-CH (and similar nature-inspired algorithms) demonstrate the longest sustained operation (e.g., >23,000 rounds in simulation testbeds reported) and consistently higher data delivery rates, outperforming both legacy and other advanced algorithms in diverse simulation environments.

Remarks:

- While classical protocols such as LEACH remain widely used for benchmarking and simple deployments, their performance degrades markedly in heterogeneous, large-scale or dynamic WSNs.
- Metaheuristic-based protocols improve considerably on lifetime and throughput; however, they must carefully balance computational overhead, algorithm complexity and parameter tuning.
- Hybrid protocols show promise for meeting multi-objective demands but often lack extensive real-world testbed validation.
- Many protocols still assume static nodes, perfect communications and homogeneous conditions — limiting their practical deployment viability.

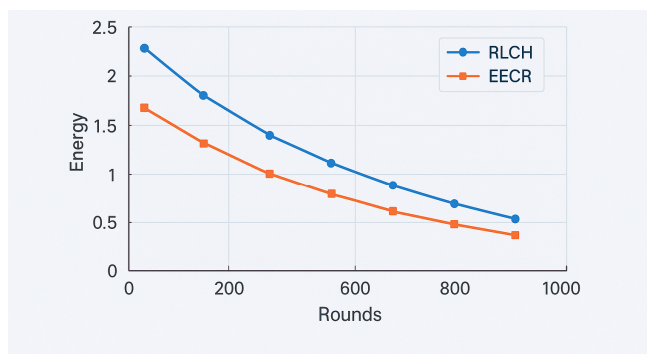


Figure 4: Performance comparison of clustering protocols (Energy vs Rounds)

VII.APPLICATIONS, ADVANTAGES AND LIMITATIONS

A. Applications

Cluster-based routing in WSNs under metaheuristic optimisation finds application in numerous domains including:

- Environmental and agricultural monitoring: e.g., precision irrigation, forest monitoring, remote sensing of climate-related parameters.
- Military surveillance and critical infrastructure protection: e.g., intrusion detection, perimeter monitoring, disaster response.
- Smart city sensing and industrial automation: e.g., structural health monitoring, air-quality networks, IoT integration in manufacturing.
- Healthcare monitoring and wearable sensor networks: Less common but emerging, where energy efficiency and network reliability are critical.

B. Advantages of Metaheuristic Clustering Protocols

Compared to classical clustering/routing protocols, metaheuristic-based approaches provide several key advantages:

- Significant improvement in network lifetime (by better balancing energy consumption, selecting CHs based on residual energy and topology).
- Enhanced adaptability to node heterogeneity and dense topologies (by including heterogeneous node capabilities in fitness functions).
- Improved load balancing, reliability and data integrity (due to clustering and optimised routing).
- Potential for scalability via cluster hierarchies and multi-objective optimisation (when well designed).

C. Known Limitations

Despite the benefits, several limitations persist:

- Computational complexity: Metaheuristic algorithms often require considerable computations (even if done centrally) which may challenge resource-constrained nodes or real-time operation.
- Implementation overheads: Parameter tuning (e.g., population size, inertia weight, mutation/crossover probabilities) remains a challenge; many simulations assume idealised conditions.
- Security and trust issues: Many clustering protocols optimise energy and throughput but neglect security, malicious node detection, trust management, and resilience to attacks.
- Real-world deployment gap: Many protocols are evaluated via simulation only; fewer elaborate real-world testbeds, and even fewer address node mobility, dynamic energy harvesting, or environmental changes.
- Single-objective or simplified fitness functions: Some designs optimise only energy or distance, ignoring latency, reliability, coverage or QoS, thereby limiting applicability to more demanding scenarios.

VIII. EMERGING TRENDS AND RESEARCH CHALLENGES

A. Emerging Trends

- Adoption of AI and Machine Learning: Clustering and CH election are increasingly being augmented by ML/AI techniques (reinforcement learning, fuzzy logic, neural nets) for autonomous, adaptive clustering under uncertain conditions.
- Deep Learning and Contextual Adaptation: In dynamic WSNs (e.g., mobile or IoT settings) deep learning techniques are being investigated for context-aware clustering (node mobility, changing topology, heterogeneous battery/power).
- Secure clustering protocols: With the proliferation of IoT and edge devices, clustering protocols are now being extended to incorporate trust/ security models, malicious node detection, and privacy-preserving routing.
- Energy harvesting and battery replenishment: As nodes increasingly integrate energy harvesting, clustering protocols are evolving to incorporate residual energy + harvest potential in CH selection and routing.
- Edge/Cloud integration & digital-twins: WSNs are beginning to integrate with edge/cloud platforms and digital-twin models; clustering/routing may thus consider backhaul, data aggregation at edges, and cross-layer optimisation.

B. Persistent Challenges

- Multi-Objective Optimisation: Future WSNs require balancing energy, latency, security, reliability, coverage, and throughput simultaneously — increasing complexity of clustering/routing design.

- **Ultra-dense Node Deployments & Heterogeneity:** As deployment scales to thousands of nodes (smart cities, IoT), clustering protocols must remain efficient in very large, heterogeneous, dynamic networks with variable power, communication ranges, mobility and fault-rates.
- **Realistic Testbeds & Validation:** Many clustering/routing schemes remain simulation-only. There is a pressing need for real-world deployments, large-scale testbeds, and validation under realistic conditions (mobility, interference, node failure, heterogeneous hardware).
- **Lightweight Computation & On-Node Intelligence:** Resource-constrained nodes require clustering/routing schemes with ultra-low complexity, minimal communication overhead, and possibly distributed intelligence.
- **Security & Trust in Clustering:** Integrating secure CH election, trust management, intrusion detection, and privacy into clustering/routing schemes while maintaining energy efficiency is a major open challenge.
- **Dynamic Environments & Mobility:** Many WSNs now involve mobile sensors (drones, wearables, vehicles). Clustering schemes must adapt to topological changes, variable link quality, and intermittent connectivity.
- **Energy-Hole Mitigation & Balanced Load:** Preventing the hotspot or energy-hole problem (where nodes near sink or CHs die early) remains critical, especially in heterogeneous and large-scale networks.
- **Cross-Layer Design & Joint Optimisation:** Future clustering/routing must consider not only network layer but also MAC, physical and application layers (cross-layer optimisation) to achieve holistic performance gains.

IX. FUTURE DIRECTIONS

Building on the foregoing trends and challenges, we identify several promising directions for future research:

- 1) **Hybridising classical and metaheuristic optimisation for extreme heterogeneity:** Combining well-understood classical protocols (e.g., HEED, TEEN) with metaheuristic optimisation (PSO, GA, SHO) can yield protocols robust to extreme node heterogeneity and dynamic conditions.
- 2) **Integrating cross-layer design and real-world testbeds:** Developing clustering/routing protocols that integrate MAC, network and application layers and validating them in real testbeds (smart agriculture fields, industrial sites, smart city deployments) will enhance credibility and adoption.
- 3) **Developing lightweight, secure and adaptable clustering schemes:** There is a need for clustering protocols specifically designed for resource-constrained nodes that include trust/security modules, adapt to node mobility, energy harvesting, and changing topologies.
- 4) **Leveraging federated learning and distributed intelligence:** Rather than centralised algorithm execution, federated or distributed learning and optimisation (on-node or CH-level) may enable adaptive clustering/routing in large/dynamic WSNs, while preserving node privacy and reducing communication overhead.
- 5) **Exploring real-time, context-aware clustering:** As IoT and WSNs become more prevalent in smart-city, smart-grid and health domains, clustering/routing must adapt in real-time to context (node mobility, variable sensor loads, user demands, environment changes) and possibly autonomous reconfiguration.
- 6) **QoS-aware and service-aware clustering protocols:** Future research should move beyond lifetime extension to explicitly include quality-of-service metrics (latency, jitter, throughput, fault tolerance) in fitness functions and design clustering/routing accordingly.
- 7) **Energy-harvesting aware clustering and routing:** With the advent of energy-harvesting nodes (solar, vibration, RF), clustering and CH selection should account for both residual and expected harvested energy, enabling dynamic reconfiguration as energy budgets evolve.

X. CONCLUSION

Metaheuristic-based clustering and routing protocols have significantly advanced the energy-management and network robustness of WSNs. Classical protocols such as LEACH and HEED laid the foundation for cluster-based routing, but are limited in heterogeneous, large-scale and dynamic settings. Metaheuristic and nature-inspired algorithms (PSO, GA, SHO, hybrid variants) significantly enhance network lifetime, throughput and scalability, especially when optimised for residual energy, cluster distribution and communication cost. Among these, SHO-CH and similar advanced algorithms show exemplary performance in simulations, making them promising for large-scale, heterogeneous deployments.

Nevertheless, the next era of WSNs — characterised by ultra-dense node counts, mobility, energy-harvesting, IoT integration and multi-objective demands (latency, security, reliability) — demands unified AI-driven, hybrid and secure clustering paradigms. Real-world testbed validation, lightweight distributed intelligence, cross-layer design and QoS-aware optimisation will be pivotal to unlocking the full potential of WSNs in diverse applications.

REFERENCES

- [1] A.A. Qaffas, "Applying an improved squirrel search algorithm (ISSA) for clustering and low-energy routing in wireless sensor networks (WSNs)," *Mobile Netw. Appl.*, vol. 2, pp. 16, 2023.
- [2] A. Hentati, W. Jaafar, J.F. Frigon, W. Ajib, "Analysis of the interdelivery time in IoT energy harvesting wireless sensor networks," *IEEE Internet Things J.*, vol. 8, no. 6, pp. 4920-4930, 2021.
- [3] A. Badi, I. Mahgoub, "ReapIoT: Reliable, energy-aware network protocol for large-scale internet-of-things (IoT) applications," *IEEE Internet Things J.*, vol. 8, no. 17, pp. 13582-13592, 2021.
- [4] B.M. Sahoo, A.S. Sabyasachi, "A metaheuristic algorithm based clustering protocol for energy harvesting in IoT-enabled WSN," *Wireless Pers. Commun.*, vol. 17, no. 126, 2024.
- [5] B.M. Sahoo, T. Amgoth, H.M. Pandey, "Particle swarm optimization based energy efficient clustering and sink mobility in heterogeneous wireless sensor network," *Ad Hoc Netw.*, vol. 110, p. 102237, 2020.
- [6] D. Sivakumar, S.S. Devi, T. Nalini, "Energy aware clustering protocol using chaotic gorilla troops optimization algorithm for wireless sensor networks," *Multimed. Tools Appl.*, vol. 83, no. 8, pp. 23853-23871, 2024.
- [7] B.M. Sahoo, H.M. Pandey, T. Amgoth, "GAPSO-H: A hybrid approach towards optimizing the cluster based routing in wireless sensor network," *Swarm Evol. Comput.*, vol. 60, p. 100772, 2021.
- [8] S. Verma, N. Sood, A.K. Sharma, "Genetic algorithm-based optimized cluster head selection for single and multiple data sinks in heterogeneous wireless sensor network," *Appl. Soft Comput.*, vol. 85, p. 105788, 2019.
- [9] J. Dev, J. Mishra, "Energy efficient routing in cluster based heterogeneous wireless sensor network using hybrid GWO and firefly algorithm," *Wireless Pers. Commun.*, vol. 14, no. 132, 2024.
- [10] D.K. Sah, T. Amgoth, "A novel efficient clustering protocol for energy harvesting in wireless sensor networks," *Wirel. Netw.*, vol. 26, no. 6, pp. 4723-4737, 2020.
- [11] A. Lipare, D.R. Edla, R. Dharavath, "Energy efficient fuzzy clustering and routing using BAT algorithm," *Wireless Netw.*, vol. 27, pp. 2813-2828, 2021.
- [12] P. Nandhini, A. Suresh, "Energy efficient cluster based routing protocol using charged system harmony search algorithm in WSN," *Wirel. Pers. Commun.*, vol. 121, no. 1, pp. 1-14, 2021.
- [13] J. Amutha, S. Sharma, S.K. Sharma, "An energy efficient cluster based hybrid optimization algorithm with static sink and mobile sink node for wireless sensor networks," *Expert Syst. Appl.*, vol. 203, p. 117334, 2022.
- [14] M.M. Akhtar, D. Ahamad, A.E.M. Abdalrahman, A.S.A. Shatat, "A novel hybrid meta-heuristic concept for green communication in IoT networks: an intelligent clustering model," *Int. J. Commun. Syst.*, vol. 35, no. 6, e5089, 2022.
- [15] P. Joshi, S. Kumar, A.S. Raghuvanshi, "A performance efficient joint clustering and routing approach for heterogeneous wireless sensor networks," *Expert Syst.*, vol. 40, no. 5, e13121, 2023.
- [16] B.M. Sahoo, H.M. Pandey, T. Amgoth, "A genetic algorithm inspired optimized cluster head selection method in wireless sensor networks," *Swarm Evol. Comput.*, vol. 75, p. 101151, 2022.
- [17] S. Chaurasia, K. Kumar, N. Kumar, "MOCRAW: A meta-heuristic optimized cluster head selection based routing algorithm for WSNs," *Ad Hoc Netw.*, vol. 141, p. 103079, 2023.
- [18] R. Nagaraju, S.B. Goyal, C. Verma, C.O. Safirescu, T.C. Mihaltan, "Secure routing-based energy optimization for IoT application with heterogeneous wireless sensor networks," *Energies*, vol. 15, no. 13, p. 4777, 2022.
- [19] S. El Khediri, W. Fakhet, T. Moulahi, R. Khan, A. Thaljaoui, A. Kachouri, "Improved node localization using K-means clustering for Wireless Sensor Networks," *Comput. Sci. Rev.*, vol. 37, p. 100284, 2020.
- [20] P. Maheshwari, A.K. Sharma, K. Verma, "Energy efficient cluster based routing protocol for WSN using butterfly optimization algorithm and ant colony optimization," *Ad Hoc Netw.*, vol. 110, p. 102317, 2021.
- [21] M.C. Thrun, A. Ultsch, "Swarm intelligence for self-organized clustering," *Artif. Intell.*, vol. 290, p. 103237, 2020.
- [22] S.K. Gupta, P.K. Jana, "Energy efficient clustering and routing algorithms for wireless sensor networks: GA based approach," *Wirel. Pers. Commun.*, vol. 83, no. 3, pp. 2403-2423, 2015.
- [23] S.S. Kalburgi, M. Manimozhi, "Taylor-spotted hyena optimization algorithm for reliable and energy-efficient cluster head selection based secure data routing and failure tolerance in WSN," *Multimed. Tools Appl.*, vol. 81, no. 11, pp. 15815-15839, 2022.
- [24] A. Gupta, R. Kumar Rout, "Energy harvesting-enabled energy-efficient routing using spotted hyena optimization in wireless sensor network," *Int. J. Commun. Syst.*, vol. 37, no. 8, e5747, 2024.
- [25] S. Kalburgi, M. Manimozhi, "Taylor-spotted cat optimization (Taylor-SCO): an energy-efficient cluster head selection algorithm with improved trust factor for data routing in WSN," *J. Electr. Comput. Eng.*, vol. 2024, no. 1, p. 5377959, 2024.
- [26] V. Prakash, S. Pandey, "Metaheuristic algorithm for energy efficient clustering scheme in wireless sensor networks," *Microprocess. Microsyst.*, vol. 101, p. 104898, 2023.



10.22214/IJRASET



45.98



IMPACT FACTOR:
7.129



IMPACT FACTOR:
7.429



INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Call : 08813907089  (24*7 Support on Whatsapp)