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Smart Cluster Head Selection Based on Residual Energy to Enhance Lifetime and Performance in WSN

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ABSTRACT

Efficient cluster head (CH) selection is dominant to optimizing energy usage and prolonging the lifetime of Wireless Sensor Networks (WSNs). Traditional CH rotation approaches, such as LEACH, randomly elects CHs without considering nodes' remaining energy, which often results in early network degradation. To mitigate this, energy-aware schemes have been proposed that incorporate residual energy as primary metric, offering substantial improvements in network longevity and data throughput. The CH selection based on residual energy is a well-established strategy to prolong the lifespan of WSNs and improve data delivery efficiency. This review synthesizes a variety of residual energy-based algorithms from simple LEACH modifications to advanced metaheuristic and fuzzy techniques highlighting their design principles, simulation-based results, practical challenges, and future research directions. This review synthesizes such advancements in CH selection, categorizing them into basic residual-energy threshold methods, multi-criteria/fuzzy decision-making techniques, and optimization-based metaheuristic strategies. We critically analyze algorithmic mechanisms, simulation frameworks, and performance benchmarks, and highlight trade-offs between computational overhead and energy gains.

Finally, we outline determined future research opportunities, such as distributed selection for scalable networks, real-world deployment validation, and security-aware CH election to foster resilient, energy-efficient WSN designs.

Keywords: *Cluster Head (CH), Energy-aware Schemes, Lifetime, Network Degradation, Optimizing Energy, Performance Benchmarks, Residual Energy, Simulation Frameworks, Security-aware CH Election, Wireless Sensor Networks (WSNs).*

1. INTRODUCTION

Wireless Sensor Networks (WSNs) comprise spatially distributed, battery-powered sensor nodes. As communication is energy-intensive, strategic cluster formation is essential to reduce. WSNs have emerged as a critical technology in various applications such as environmental monitoring, military surveillance, smart cities, healthcare, and industrial automation. These networks consist of spatially distributed autonomous sensor nodes that are deployed to monitor physical or environmental conditions and cooperatively transmit the collected data to a central base station [1]. However, one of the major challenges in WSNs is the limited energy supply of sensor nodes, typically powered by non-rechargeable batteries. Therefore, energy-efficient communication protocols play a vital role in enhancing the operational lifetime of WSNs [2].

Clustering is a widely adopted technique to improve the scalability, efficiency, and energy utilization in WSNs. In clustering, sensor nodes are grouped into clusters, each managed by a special node known as the Cluster Head (CH) [3]. The CH aggregates data from its member nodes and transmits the aggregated data to the base station, thereby reducing the number of direct transmissions and conserving energy [4]. However, the selection of an appropriate CH is crucial, as an inefficient CH selection mechanism can lead to early energy depletion of critical nodes, reduced network lifetime, and degraded performance.

Traditional CH selection algorithms like LEACH (Low-Energy Adaptive Clustering Hierarchy) select CHs randomly or in a round-robin manner without adequately considering the residual energy of the nodes [5]. This can result in energy-imbalanced clusters and premature death of CHs, leading to coverage holes and communication failures. To overcome these limitations, smart cluster head selection algorithms based on residual energy and other dynamic parameters such as node degree, distance to the base station, and node mobility have been proposed in recent years [6].

This paper presents a comprehensive review of smart CH selection mechanisms that primarily focus on residual energy as a key metric to prolong the network lifetime and enhance performance. The study covers various algorithms and a technique developed in the past decade, analyzes their methodologies, evaluates their strengths and limitations, and identifies future research directions. By incorporating residual energy awareness in the CH selection process, these approaches aim to achieve load balancing, uniform energy dissipation, and extended network lifespan. To overcome such limitations, energy-aware CH selection algorithms have been proposed. These variants and advanced optimization-based models will be examined in the following sections.

The rest of the paper is organized as follows: Section 2 discusses the Literature review Section 3 will give the basic architecture and clustering mechanism in WSNs; Section 4 provides a taxonomy of cluster head selection algorithms; Section 5 reviews the major residual energy-based CH selection approaches; Section 6 evaluates and compares different techniques based on key performance metrics; and Section 7 concludes the paper with future research perspectives.

2. WSN ARCHITECTURE & CLUSTERING MECHANISM

2.1 Fundamental Components of WSNs

A typical Wireless Sensor Network (WSN) comprises a large number of sensor nodes and one or more base stations (BS). Each sensor node includes:

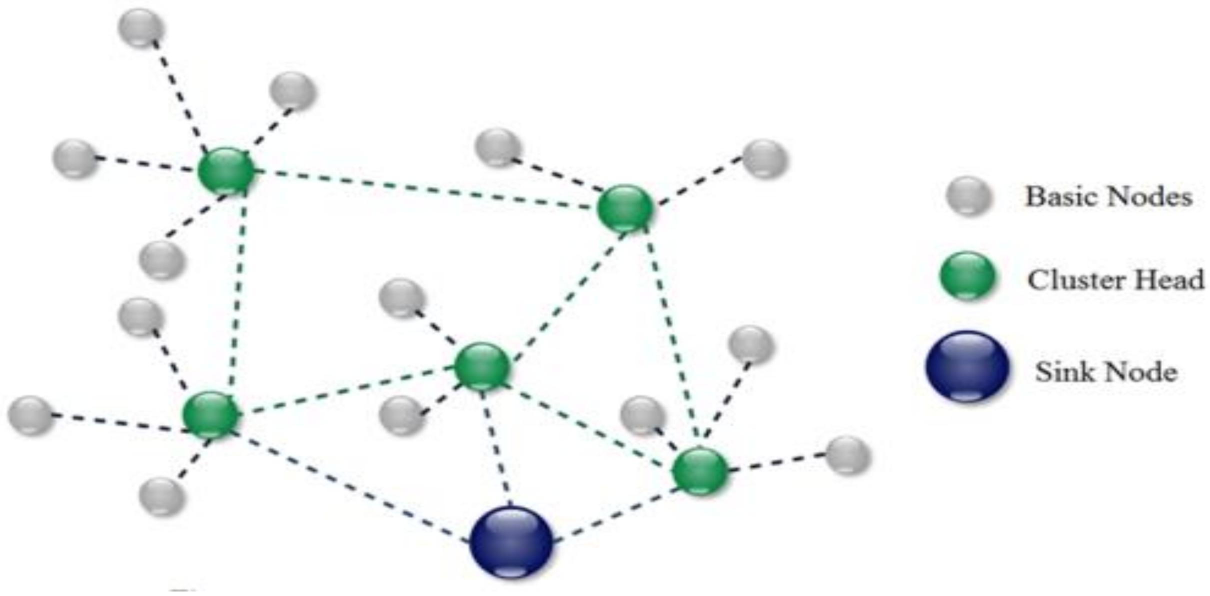

Figure1. Basic Communication Structure of WSN

- A sensing module to capture environmental data.
- A microcontroller for local processing.
- A radio transceiver for wireless communication.
- A power source, typically a limited-life battery.

The base station (or sink) is a more powerful node serving as a gateway that collects data from sensor nodes and often links the WSN to external networks.

2.2 Network Architecture Models

WSNs adopt various architectural models based on application needs:

2.2.1 Flat (or decentralized):

All nodes have equal roles. Data is routed through multiple hops to the BS. While simple, it doesn't scale well and can suffer from uneven energy depletion [7].

2.2.2 Hierarchical (clustered):

The network is organized into clusters, each managed by a Cluster Head (CH). Member nodes send data to the CH, which aggregates and forwards it to the BS. This structure enhances scalability, energy efficiency, and reliability [8].

Many protocols (e.g., HCR) even employ multi-layered clustering to balance load across large sensor networks.

2.3 Clustering Mechanism: Phases & Roles

Clustering in WSNs typically follows two main phases:

2.3.1 Cluster Formation

- CHs are selected dynamically or statically.
  - *Static clustering*: CHs are pre-assigned and remain fixed—simple but fault-prone.
  - *Dynamic clustering*: CHs are re-elected each round based on criteria such as energy, node density, or proximity.
- Each non-CH node chooses and joins the nearest CH.

2.3.2 Data Transmission

- CHs collect and aggregate data from cluster members.
- Member nodes typically use TDMA/CDMA schedules to avoid collisions.
- Aggregated data is sent to the BS, either directly or via multi-hop CH routing.

2.4 Key Advantages of Clustering

Clustering brings several benefits:

- **Scalability**: Nodes manage routes within clusters, reducing routing table size.
- **Energy Efficiency**: Only CHs handle long-range transmission, and data aggregation minimizes redundant communication.
- **Load Balancing & Network Lifetime**: Rotating CH roles distributes energy demands evenly.
- **Collision Avoidance & Latency Reduction**: Scheduled intra-cluster communications reduce interference and improve timeliness.
- **Robustness**: Local failure stays within a cluster; overall network remains operational on other parts.

2.5 Classical Protocol: LEACH

LEACH (Low-Energy Adaptive Clustering Hierarchy) is a seminal hierarchical protocol:

- **Randomized CH rotation**: Nodes decide probabilistically to become CHs, ensuring balanced energy usage.
- **TDMA scheduling**: Avoids collisions within clusters.
- **Data aggregation**: CHs compress member data before forwarding.

Table1. Advanced hierarchical schemes

Sr. No.	Algorithm	Fitness Factors (Energy-based)	Simulation Setup	Results
1.	PSO	Residual energy + hop distance	MATLAB, 100 nodes	Balanced energy; higher throughput
2.	WOA-C	Residual energy & neighbor energy	MATLAB	Higher residual energy and lifetime
3.	GWO (EECHIGWO)	Residual energy + clustering cost	MATLAB, 100 nodes	First node death (FND) at ~5940 rounds; lifetime better by 169–333%
4.	Hybrid GU-WOA	Hybrid WOA + fuzzy logic	MATLAB, 50/100 nodes	Higher throughput and packet delivery than PSO and ACO
5.	PSO + Differential Evolution	Residual energy + throughput	Simulation	Outperforms single heuristics

WSN nodes are comprised of sensing, processing, communication, and power subsystems. Clustering organizes nodes into CH-led groups to improve energy efficiency, scalability, and robustness. Protocols like LEACH pioneered dynamic clustering, though without energy-aware CH selection. Advanced hierarchical schemes refine cluster formation and CH rotation, setting the stage for energy-based enhancements [9].

3. TAXONOMY OF CH SELECTION ALGORITHMS

3.1. Based on Network Architecture

- **Homogeneous**: Identical node capabilities (e.g., LEACH)

- **Heterogeneous**: Nodes with varied resources, like SEP/DEEC.

3.2. Based on CH Selection Criteria

- **Random**: Probabilistic rotation (LEACH)
- **Deterministic**: Based on fixed properties (ID, position).
- **Adaptive/Hybrid**: Uses dynamic metrics (residual energy, degree)—e.g., HEED, TSO-based, Pelican, Sparrow algorithms.

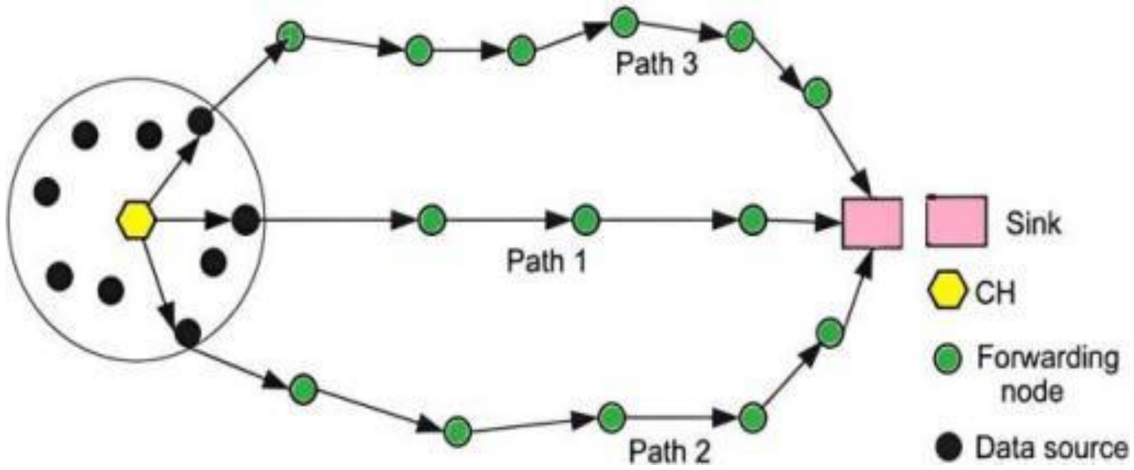

Figure2. Various routing trails in WSN

3.3. Based on Decision-Making Model

- **Centralized**: Sink/BS elects CHs (LEACH-C).
- **Distributed**: Nodes self-elect (HEED, PSO-based, Lion algorithm).

3.4. Based on Optimization Techniques

- **Heuristic**: Residual-energy or energy–distance formulas.
- **Swarm-inspired**: PSO, GA, TSO, Pelican, Sparrow, Lion, etc.
- **Fuzzy logic**: Multi-input fuzzy rules for CH election.
- **Machine learning**: Deep convolutional or other models (e.g., BEA-SSA combined with CNN).

3.5. Based on Clustering Frequency

- **Static**: Long-term or fixed CHs.
- **Dynamic**: CHs rotate each round or adaptively.

3.6. Based on Mobility

- **Mobility-aware**: Designed for networks where nodes move.

3.7. Based on Node Density / Load Balancing

- **Density-aware**: Ensures CHs cover clusters effectively, handles high density.

3.8. Experimental Comparisons

3.8.1. Simulation Parameters

Typical simulation settings:

- **Nodes**: 100 sensor nodes uniformly deployed in $100\times100\ m^2$
- **Energy model**: Eelec=50 nJ/bit,Eamp=100 pJ/bit/m2E_{elec} = 50\text{ nJ/bit}, E_{amp} = 100\text{ pJ/bit/m}^2Eelec=50 nJ/bit,Eamp=100 pJ/bit/m2

- **Initial Energy**: 1–2 J per node

3.8.2. Performance Metrics

- **Network Lifetime**: measured via FND (first node dead), HND (50% dead), and LND (last node dead)
- **Residual Energy**: remaining energy across rounds
- **Throughput**: packets received at Base Station
- **Packet Delivery Ratio (PDR)**

4. MAJOR RESIDUAL ENERGY–BASED CH SELECTION APPROACHES IN WSNS

Here are some major residual energy–based clusters head (CH) selection approaches in Wireless Sensor Networks (WSNs), explained and compared:

4.1. HEED (Hybrid Energy-Efficient Distributed Clustering)

- **Key idea**: Nodes probabilistically elect CHs based on residual energy and intra-cluster communication cost.
- **Strengths**: Balances energy usage across CHs and promotes even spatial distribution of clusters.
- **Widely used**: HEED is a benchmark for residual energy–aware CH design.

4.2. DE-LEACH (Distance & Energy-Aware LEACH)

- **Improvement over LEACH**: Incorporates both distances to sink/neighboring nodes and residual energy into the CH-selection threshold.
- **Benefits**: Reduces energy waste; extends network lifetime; outperforms LEACH in simulations.

4.3. DECSA (Distance Energy Selection Algorithm)

- **Mechanism**: Election probability favors nodes with high residual energy and favorable positioning relative to others and the sink.
- **Impact**: Achieves ~31% longer lifetime than standard LEACH.

4.4. EEHC (Energy-Efficient Heterogeneous Clustering)

- **Heterogeneous-aware**: In networks with nodes of differing initial energy, CH election is weighted by residual energy.
- **Gain**: Demonstrates around 10% network lifetime improvement over LEACH.

4.5. Affinity-Propagation based Double-CH (APDC-M)

The APDC-M uses node residual energy in similarity calculations for clustering centers. It elects two CHs per cluster a fusion CH and a relay CH for better load distribution.

4.6. WOA-Clustering (Whale Optimization Algorithm)

WOA uses whales' social behavior metaphors like encircling prey to select CHs based on a fitness function prioritizing residual energy. It outperforms LEACH in simulations regarding energy consumption, throughput, and stability [10].

4.7. GWO-Based Approaches (Grey Wolf Optimizer):

The Grey Wolf Optimizer use residual energy in fitness evaluation. In this system BS assists by not choosing low-energy nodes as CHs. First node death delayed significantly. Balanced energy consumption; longer stable and total network lifetime [11].

4.8. Other Residual Energy Centric Schemes

4.8.1 RES-EL, DIS-RES-EL:

It favors high-energy nodes for CH roles; extend lifetime compared to LEACH, PEGASIS, and HEED.

4.8.2 PSO-ECHS & ABC-Based CH Selection:

It use PSO or Artificial Bee Colony optimizers to weigh residual energy, intra-cluster and sink distances; demonstrate improved energy efficiency.

The Residual energy awareness is critical for prolonging WSN operation. Simple schemes (HEED, DE-LEACH, DECSA) give good baseline results. Heterogeneous protocols (EEHC) and multi-CH models (APDC-M) further enhance performance. Metaheuristic algorithms (WOA, GWO, PSO, and ABC) offer near-optimal CH placements, boosting energy distribution and extending network stability. Effective schemes often combine residual energy, node distance, and sometimes metaheuristic optimization [12].

5. EVALUATION & COMPARISON

Here's an enhanced evaluation & comparison of key residual-energy-based CH selection techniques in WSNs, structured around critical performance metrics [13]:

5.1 Network Lifetime & Stability

Residual-Energy-Based Schemes vs LEACH: A residual-energy approach notably outperforms standard LEACH showing up to 66% longer lifetime, 64% higher residual energy, and 60% improved throughput in IoT simulations [14].

DEEC and its Variants: The DEEC protocol, considering both individual residual energy and network-wide average, extends lifespan and stability compared to classical LEACH.

EEUCB (Unequal Clustering): Reported lifetime boosts of:

- +57.8% vs LEACH
- +19.6% vs FLEACH
- +14.7% vs EEFUC
- +13.1% vs UDCH.

Table2: Scheme Comparison Table

Algorithm	Key Metric	CH Count	Position-Aware	Optimization Method	Lifetime Gain
HEED	Energy + Comm cost	1	✓	Probabilistic threshold	✓
DE-LEACH	Energy + Distance	1	✓	Threshold-based extension	✓
DECSA	Energy + Distance	1	✓	Similarity-based thresholds	+31%
EEHC	Residual Energy	1	(hetero aware)	Weighted probability	+10%
APDC-M	Energy + Distance	2 per cl.	✓	Affinity propagation	~38% more
WOA-C	Residual Energy	varied	–	Whale optimization	LEACH beaten
GWO variants	Residual Energy	varied	–	GWO metaheuristic	Stability & lifetime boosted
RES-EL/others	Residual Energy	1	–	Probability rules + metaheuristic	Better than LEACH

5.2. Energy Consumption & Residual Energy

- **Metaheuristic & Optimization Approaches**:
  - The Squirrel-Search-based I-SSA incorporates factors like sink distance and intra-cluster distance to maximize residual energy retention.
  - Whale-Optimization (WOA-C) improves network lifetime and residual energy vs. LEACH.
- **Fuzzy Logic with Clustering Criteria**:
  Hybrid methods combining residual energy, node centrality, and node degree ("multi-criteria fuzzy selection") provide more uniform residual energy distribution and reduced drain on CHs.

5.3 Throughput & Delay

- **Residual-Energy CH Selection**: The IoT-focused study reported throughput spikes of about **60%**, and improved energy retention is correlated with sustained data delivery [15].
- **Multi-Criteria & Fuzzy Protocols**: Schemes like FICZP assess both node residual energy and neighbor metrics to optimize data paths, reducing delays & maximizing throughput.

5.4 Load Balancing & Hot-Spot Mitigation

- **Unequal Clustering Designs** (EEUCB, EEUC, UDCH): Smart subdivision of cluster sizes based on distance from BS balances CH load, particularly near the sink, thus avoiding early death of hotspot nodes.
- **Double CH & Sleep–Awake Mechanisms**: EEUCB employs two cluster heads per cluster and synchronized wake-sleep cycles to balance load and reduce energy contention [16].

5.5 Optimization Algorithms: Convergence & Scalability

- **Swarm-based Search Algorithms**: Metaheuristic approaches (e.g., SSA, WOA, Grey-Wolf, and Ant-Colony) provide efficient convergence to near-optimal CH sets. SSA-I has adaptive initialization and dynamic steps to enhance performance [17].

Table 3: Unified Performance Metrics Comparison

Protocol / Method	**Lifetime ↑ (%)**	**Throughput ↑ (%)**	**Energy Retention**	**Load Balancing / Hotspots**	**Scalability & Delay**
Residual-Energy (IoT study)	+66% vs LEACH	+60%	+64% residual	–	–
DEEC / HEED-style protocols	Moderate uplift	Improves stability	Good balance	Basic	Good
EEUCB (Unequal clustering)	+57.8% vs LEACH	Improved	Balanced clusters	☑ Strong	☑ Good
SSA-I & WOA-C (Optimization)	Extended lifetime	Sustained throughput	High residual	Considered	☑ Scalable
CWGO hybrid metrics	Best overall metrics	Best vs comparators	Robust retention	Balanced	☑ Highly scalable

- **Unified Performance Metrics:** Recent studies integrate energy, delay, trust, and distance metrics into a single evaluation function (e.g., Lagrange-interpolation-based), showing that CWGO and similar metaheuristics outperform EECHIGWO, DUCISCA, DE-SEP, and E-CERP across node densities [18].

The Residual energy as a CH selection metric consistently outperforms traditional LEACH in extending network lifetime and throughput. Unequal clustering mechanisms efficiently prevent hotspot depletion near BS and improve fairness across nodes [19]. Optimization-based metaheuristics (e.g., SSA, WOA) adaptively balance multiple parameters, energy, distance, and intracluster metrics for robust CH selection in diverse and larger networks. Incorporating multi-criteria through unified performance measures (energy, delay, distance, and trust) offers a holistic evaluation framework, leading to superior algorithm selection like CWGO [20].

6. CONCLUSION AND FUTURE RESEARCH PERSPECTIVES

6.1 Conclusion:

This paper has reviewed a breadth of residual-energy-aware cluster head (CH) selection strategies designed to enhance network lifetime, throughput, energy efficiency, load balancing, and scalability in Wireless Sensor Networks (WSNs). Key findings include. Residual-energy-based selection mechanisms consistently extend network life and improve throughput over classical protocols like LEACH. Unequal clustering strategies effectively mitigate hotspot issues near base stations by balancing load across nodes. Metaheuristic optimization approaches (e.g., SSA, WOA, and GWO) excel in evolving robust fitness functions that consider energy, distance, intra-cluster cohesion, and more. Hybrid methods combining residual energy with criteria such as node centrality, distance, or transmission probability further enhance performance in large-scale, heterogeneous deployments. These insights affirm that intelligent CH selection based on dynamic metrics is crucial for maintaining WSN performance and longevity in diverse environments.

6.2 Future Research Directions:

Based on gaps identified in the literature, the following promising research directions can be approached.

1. **Maximizing Last Node Lifetime:** Building upon methods that model network lifetime to delay the death of the last active node, such as transmission-probability-driven schemes, future work should explore dynamic CH rotation strategies that prioritize heterogeneous traffic patterns and event-driven sensing.
2. **Hybrid and Mobile-Sink Architectures:** Integrate energy-aware CH selection protocols with **mobile sinks** to offload hotspot clusters and further balance energy usage across the network.
3. **Energy Harvesting–Aware CH Selection:** With deployment of energy-harvesting nodes (e.g., solar-powered), CH algorithms should adapt based on **harvested energy availability**, incorporating unpredictable replenishment into rotation decisions.
4. **Adaptive Hybrid Optimization Protocols:** Design **multi-objective fitness models** that seamlessly integrate residual energy, link quality, latency, trust, and mobility parameters, leveraging hybrid metaheuristics (e.g., ZFO + SHO, water-cycle optimizers) for real-time adaptability.
5. **Security & Trust in CH Selection:** Given the vulnerability of CHs to attacks, embedding **fuzzy-trust mechanisms** and **game theory–based defense** can enhance reliability alongside energy efficiency.

6. **Prototype Deployment & Environmental Validation:** Most studies are simulation-based. Future research should validate schemes using **physical testbeds**, including real-world factors like variable energy consumption and communication delays, as demonstrated in LoRaWAN prototypes.

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