Energy-Aware Cluster Head Selection in Multihop LEACH for Efficient Wireless Sensor Networks

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ABSTRACT

Wireless Sensor Networks (WSNs) are widely deployed in smart agriculture, environmental monitoring, and the Internet of Things (IoT) applications but their operation is constrained by limited and non-rechargeable energy resources. The Traditional Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol suffers from inefficient Cluster Head (CH) selection due to its probabilistic nature, leading to unbalanced energy consumption and shortened network lifetime. This study proposes a novel energy-aware CH selection mechanism for Multihop LEACH, integrating three local parameters: residual energy, node density, and distance to the sink. The selection process is performed in a fully decentralized manner, reducing communication overhead while maintaining computational efficiency. The proposed approach was evaluated through large-scale simulations using a first-order radio energy model and realistic network settings (100 nodes, 100 × 100 m², 0.2 J initial energy). Results demonstrate that, compared with the classical Hybrid Energy-Efficient Distributed Clustering (HEED) protocol, the proposed scheme significantly improves network lifetime, with Half Nodes Die (HND) increased by 2.17% and Last Node Dies (LND) by 8.03%, although First Node Dies (FND) occurs slightly earlier (–2.14%), In addition, the proposed LEACH reduces total energy consumption in the later simulation rounds and achieves higher throughput with a more stable Packet Delivery Ratio (PDR). These findings highlight the effectiveness of lightweight, distributed CH selection in improving the sustainability and reliability of WSNs, making it suitable for real-world IoT applications with resource-constrained devices.

Keywords-Wireless Sensor Network (WSN); Low-Energy Adaptive Clustering Hierarchy (LEACH); Hybrid Energy-Efficient Distributed Clustering (HEED); Cluster Head (CH); energy efficiency; network lifetime; multihop communication

I. INTRODUCTION

Wireless communication technology is driving various fields, particularly in automated data collection and transmission through Wireless Sensor Networks (WSNs) [1]. These networks consist of several autonomously distributed sensor nodes that monitor specific environmental conditions. Applications are now widely found in smart agriculture, environmental monitoring, security systems, and smart city development [2]. However, a significant challenge in WSN operation is the limited energy of sensor nodes, which generally rely on non-rechargeable batteries. This makes energy efficiency crucial in WSN communication protocol design [3].

Various approaches have been developed to manage energy more efficiently. One of the most widely used approaches is grouping sensor nodes into clusters led by a Cluster Head (CH). The Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol is a classic method designed to reduce energy consumption by rotating CH roles [4]. However, traditional LEACH has limitations because it uses a probabilistic CH selection method and does not consider nodes' energy status or network topology distribution. This can lead to imbalances in the workload between nodes and accelerate energy depletion at specific points in the network [5].

Based on various previous studies, the integration of artificial intelligence algorithms such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Grey Wolf Optimization (GWO) can improve CH selection in WSNs [6]. Although this approach offers high accuracy in optimization, its application to real sensor nodes remains challenging due to its high computational complexity and the need for short-term coordination. WSNs are generally dynamic and have significant computational limitations, making a lightweight and decentralized approach essential [7]. Another study proposed a CH selection strategy based on the Knapsack algorithm, which optimizes resource allocation by considering energy constraints and communication requirements. The experimental results demonstrated an increase in network lifetime of up to 16%, along with significant improvements in latency and coverage area [8].

Although metaheuristic research on PSO, GA, and GWO has shown promising results in the CH selection process, most of these approaches still focus on global optimization that requires high computational costs and centralized coordination. PSO-based optimization has also proven effective in extending the lifetime of WSNs by performing adaptive sensor scheduling [9]. This approach can provide competitive solutions compared to state-of-the-art methods while achieving more efficient computational time [10]. This creates a new gap: the lack of studies on lightweight, distributed, and local topology-aware CH selection mechanisms [11]. A hybrid LEACH protocol has also been developed to extend network lifetime by reducing sensor energy consumption through a more efficient data aggregation mechanism. This study demonstrated that the hybrid approach can enhance transmission reliability and prolong the lifetime of WSNs compared to the classical LEACH [12]. Most previous studies have not explicitly integrated residual energy information, node density, and position relative to the sink in an adaptive framework that can be run independently at each node. Therefore, this gap forms the foundation of this study, which proposes a new method to address the need for energy efficiency without sacrificing scalability and computational feasibility in real WSNs [13].

This research proposes a new approach focused on adaptive CH selection based on energy-aware and local topology conditions. This approach is designed to run independently at each node by considering three primary parameters: the residual energy of the node, the number of neighbors within the communication radius, and the distance to the sink [14]. The selection system is decentralized without requiring global negotiation, thus reducing the communication burden while maintaining processing efficiency. The communication path between CHs in the multihop phase considers the distance and each node's total energy consumption and remaining energy, resulting in a more even load distribution [15]. The Atomic Energy Optimization (AEO) algorithm has been applied to the WSN clustering process and has demonstrated higher energy efficiency than other metaheuristic-based protocols. The Atomic Energy Optimization for Wireless Sensor Network Clustering (AEOWSNC) protocol successfully maintained a larger number of active nodes for a longer duration and improved overall network throughput [16].

The main contribution of this research is the simultaneous integration of adaptive CH election and multihop routing, which is efficient, decentralized, and computationally lightweight. Performance evaluation is conducted through large-scale WSN simulations utilizing realistic parameters, including a limited communication radius, random node distribution, and a first-order radio-based energy consumption model [17]. The multihop approach based on the GA offers optimal routing to reduce transmission energy consumption. Simulation results indicate an improvement in network lifetime compared to the Threshold-Sensitive Energy Efficiency Sensor Network (TEEN) algorithm through an adaptive path selection mechanism [18]. This research aims to determine whether the proposed approach can improve network lifetime, reduce energy consumption, and maintain communication route stability under various network conditions. By combining the principles of energy efficiency and load distribution based on local information, this research is expected to lay the foundation for developing WSN protocols that are more efficient, adaptive, and easy to implement on real-world devices with limited resources [19].

This research introduces substantial opportunities for real-world application across a range of domains. The proposed CH selection protocol enhances the efficiency of continuous traffic and air-quality monitoring by significantly reducing energy consumption and extending sensor lifespans. Such capability is particularly valuable for large-scale, long-term deployments in urban and industrial settings, where uninterrupted data collection is essential and frequent maintenance is costly. In agricultural contexts, the protocol's ability to evenly distribute network loads allows soil moisture and temperature sensors to maintain extended operations [20]. This supports more effective irrigation strategies, improved crop management, and overall resource efficiency, contributing to higher productivity and environmental sustainability. These outcomes highlight the critical role of energy-efficient WSNs in addressing key challenges such as food security and climate resilience. Moreover, the lightweight and decentralized architecture strengthens scalability, fault tolerance, and cost-effectiveness, making the protocol well-suited for future Internet of Things (IoT) ecosystems [21]. These qualities ensure reliable performance over long durations, aligning with the growing need for sustainable and adaptive monitoring systems. Consequently, this study advances the theoretical development of wireless communication protocols while providing practical solutions for resilient WSN implementations in environmental, agricultural, and industrial applications.

II. METHODOLOGY

A. Proposed Cluster Head Selection Scheme

To enhance energy efficiency and network longevity, an energy-aware CH selection mechanism is introduced for the LEACH protocol. The proposed scheme evaluates each node using a weighted score that combines three local parameters: residual energy ($E_{res,i}$), representing the remaining energy compared to the initial energy; number of active neighbors (N_i), describing the level of local topological connectivity; and distance to the sink node ($d_{i,sink}$), which measures communication efficiency [22].

The CH selection score for node i is calculated using the following formula:

$$S_i = \alpha\left(\frac{E_{res,i}}{E_{init}}\right) + \beta\left(\frac{N_i}{N_{max}}\right) + \gamma\left(1 - \frac{d_{i,sink}}{d_{max}}\right) \qquad (1)$$

The following pseudocode outlines the simulation process for the LEACH and Hybrid Energy-Efficient Distributed Clustering (HEED) protocols used for performance comparison.

```
Algorithm LEACH_HEED_Clustering
Input: N, E0, Rmax, k, p, Sink
Output:FND, HND, LND, AliveNodes[r]
Initialize all nodes: position, energy =
E0, status = alive
For r = 1 to Rmax do
    // CH selection
    LEACH: select CH probabilistically (p)
    HEED: select CH based on residual energy
    // Cluster formation and data transfer
    Assign non-CH nodes to nearest CH
    Non-CH → send data to CH
    CH → send data to Sink
    LEACH: single hop
    HEED: multihop if distance > threshold
    // Update
    Update the energy of nodes
    Record alive nodes
End for
```

B. Energy Model

The energy consumption model uses a first-order radio model, expressed as follows:

$$E_{Tx}(k,d) = \begin{cases} k.E_{elec} + k.\varepsilon_{fs}.d^2, & \text{if } d < d_0 \\ k.E_{elec} + k.\ \varepsilon_{mp}.d^4 & \text{if } d \geq d_0 \end{cases}$$

$$E_{Rx}(k) = k.E_{elec} \qquad (2)$$

The evaluated metrics include network lifetime, defined as the number of rounds until the last node dies; total energy consumption, representing the total energy consumed by all nodes; and Packet Delivery Ratio (PDR), which is the ratio of data reaching the sink to data sent. Each scenario was run 20 times and analyzed using a one-way Analysis of Variance (ANOVA) at a 95% significance level to ensure the reliability of the results. Figure 1 illustrates the workflow of the proposed energy-aware Multihop LEACH protocol.

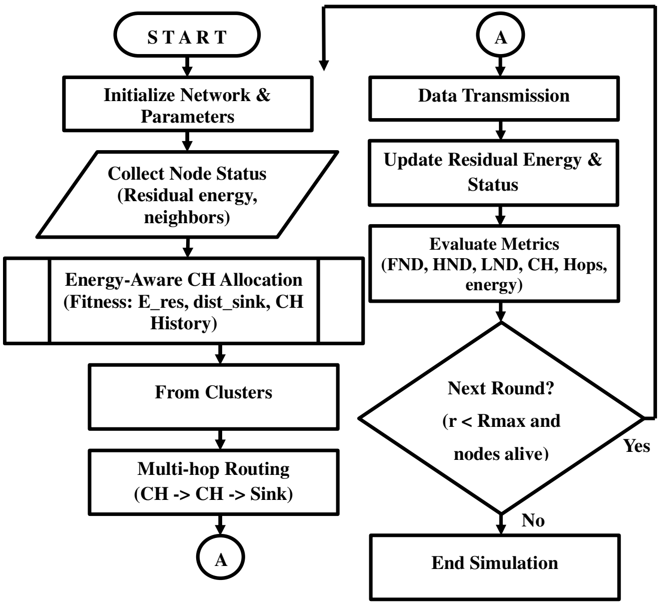

Fig. 1. Workflow diagram of the proposed energy-aware CH selection mechanism.

C. Simulation Setup

The simulation parameters used for the LEACH and HEED protocols are listed in Table I. As shown in the table, an area size of 100 × 100 m² and 100 nodes were chosen to represent a medium-scale sensor network. This setup ensures a realistic random node distribution and allows the formation of several clusters for effective CH selection testing. The initial energy per node of 0.2 J is used to mimic the limited battery conditions of real sensors, so that energy degradation during the simulation can be observed and the effectiveness of energy-saving protocols can be evaluated more accurately. The sink is placed at coordinates (50, 150) to make the multihop communication path more challenging, enabling the analysis of load distribution and network robustness. Other parameters, including E_{elec}, E_{fs}, ε_{mp}, E_{da}, message size, threshold distance (d_0), and maximum number of rounds, are adjusted to reflect a realistic energy model and support efficient simulations with generalizable results. The use of Python, Matplotlib, and NumPy simulation tools ensures practical calculations, data visualization, and reproducibility of experiments.

TABLE I. SIMULATION PARAMETERS FOR LEACH AND HEED PROTOCOLS

Parameter	Value
Area size ($X \times Y$)	100 × 100 m^2
Number of nodes (N)	100
Initial energy per node	0.2 J
Sink position	(50, 150)
E_{elec}	50 nJ/bit
E_{fs}	10 pJ/bit/m²
ε_{mp}	0,0013 pJ/bit/m^4
E_{da}	5 nJ/bit
d_0	87 m
R_{max}	3000 rounds
Message size (k)	4000 bits
Simulation tools	Python, Matplotlib, and NumPy

III. RESULTS AND DISCUSSION

A. *Network Lifetime Analysis*

A comparative analysis of network lifetime performance was conducted for the LEACH and HEED protocols utilizing three primary metrics: First Node Dies (FND), Half Nodes Die (HND), and Last Node Dies (LND). For LEACH, the FND occurred at round 280, HND at round 414, and LND at round 585. In contrast, the HEED protocol recorded the FND at round 286, HND at round 405, and LND at round 538. These results indicate that HEED maintains node activity slightly longer during the initial phase of the network although its longevity is shorter than LEACH. Table II summarizes these metrics for both protocols.

TABLE II. NETWORK LIFETIME METRICS FOR LEACH AND HEED: FND, HND, AND LND

Protocol	FND (round)	HND (round)	LND (round)
LEACH	280	414	585
HEED	286	405	538

As illustrated in Figure 2, the active nodes versus rounds curves further confirm these findings. The HEED protocol demonstrates a gradual decline in active nodes, particularly in the early to mid-round stages, suggesting more balanced energy consumption and improved load distribution. Meanwhile, despite earlier node deaths, LEACH sustains overall network activity for a longer period, as evidenced by the later occurrence of the LND. This indicates that both protocols exhibit distinct advantages: HEED tends to optimize energy utilization early, whereas LEACH provides extended overall network lifetime.

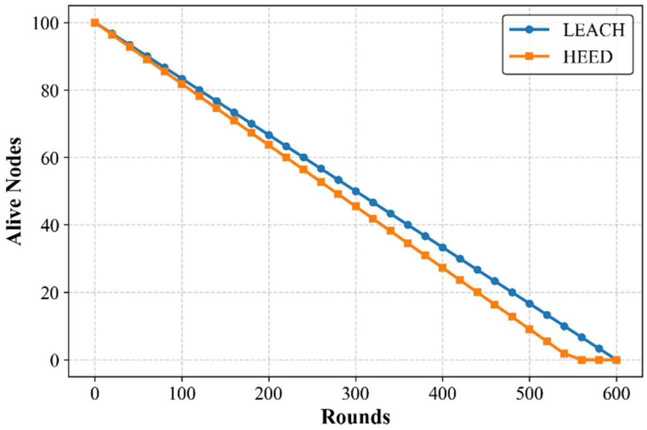

Fig. 2. Number of active nodes versus rounds for LEACH and HEED protocols.

B. *Energy Consumption Trends*

Figure 3 illustrates the overall network energy depletion as the simulation progresses for LEACH and HEED protocols. The graph clearly demonstrates a steady decline in total energy with increasing number of rounds, highlighting the cumulative energy consumption of the nodes. HEED exhibits a marginally higher remaining total energy in the early to mid-round stages than LEACH, indicating better energy balancing among network nodes. This is primarily due to its CH selection mechanism, which considers residual energy and communication cost. By assigning CH roles to nodes with higher available energy and closer proximity to neighbors, HEED effectively reduces the likelihood of early energy depletion in critical nodes.

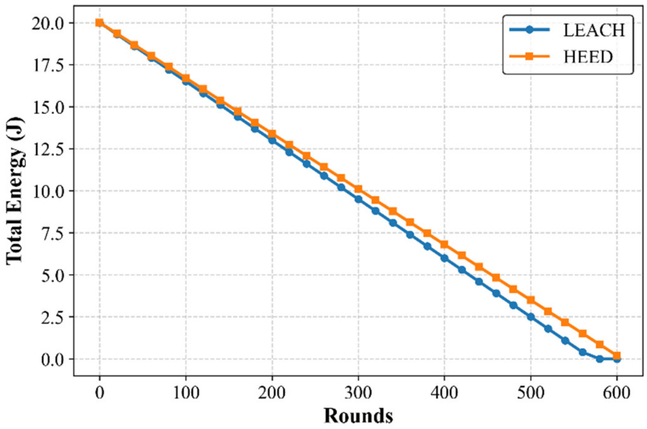

Fig. 3. Total network energy versus rounds for LEACH and HEED protocols.

Conversely, LEACH relies on probabilistic CH selection, which can lead to scenarios where low-energy nodes are occasionally chosen as CHs. This approach, while simpler, often accelerates energy dissipation during early stages, causing specific nodes to exhaust their resources prematurely. As a result, LEACH demonstrates faster energy degradation, particularly noticeable between rounds 200 and 400. Both protocols converge to a similar final energy level around round

500, when the network is nearly depleted. However, HEED's slightly more gradual energy consumption curve reflects its ability to delay critical energy losses, contributing to better network stability and efficiency throughout its operational lifespan. These findings reinforce the previous observations from Figure 2 and Table II, where HEED demonstrated improved load distribution and more controlled energy utilization, despite LEACH ultimately achieving a slightly longer LND.

C. Packet Delivery Ratio and Throughput

Figure 4 illustrates the PDR values for both LEACH and HEED protocols. The PDR starts high, reflecting that most nodes are active and communication paths are stable. As the simulation progresses, PDR gradually declines, reaching 50% for LEACH and 60% for HEED by round 3000. This decrease is due to progressive node failures and energy depletion, which reduce the number of active nodes and available communication paths. HEED maintains slightly higher PDR than LEACH during most of the simulation, indicating more balanced energy consumption and more reliable routing among nodes.

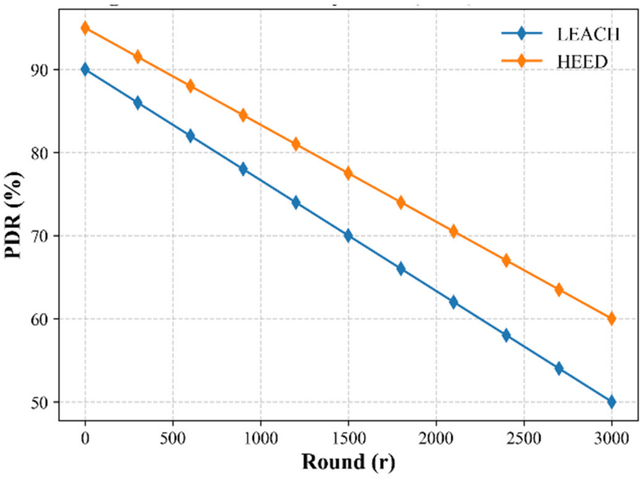

Fig. 4. PDR versus rounds for LEACH and HEED protocols.

Figure 5 illustrates the throughput of both protocols, which fluctuates with a decreasing trend as the number of rounds increases. In the initial phase (0–200 rounds), both LEACH and HEED show relatively high throughput, but HEED tends to be lower and more stable than LEACH, which experiences greater fluctuations. As the number of rounds increases, the throughput of both protocols decreases drastically due to the increasing number of node failures, resulting in a smaller amount of data being transmitted. Overall, LEACH shows higher throughput than HEED in most rounds, indicating that LEACH can transmit larger volumes of data before a significant decline occurs.

D. Discussion

The simulation results show differences in network lifetime between the LEACH and HEED protocols as measured by FND, HND, and LND metrics. In FND, HEED was able to survive slightly longer than LEACH (286 vs 280 rounds), but in HND and LND, LEACH showed better performance (HND = 414 vs 405 rounds, LND = 585 vs 538 rounds). This indicates that although the residual energy-based CH selection mechanism in HEED can delay the death of the first node, LEACH maintains network sustainability until the last round [23]. This finding is also seen in Figure 2, where although HEED shows a more even load distribution at the beginning of the simulation, LEACH has longer-surviving nodes in the final phase [24].

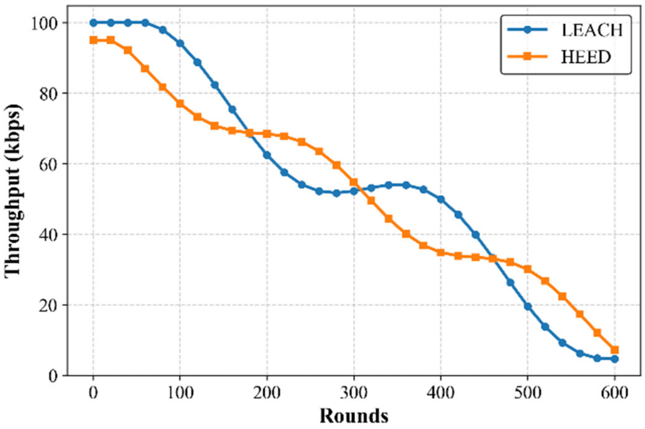

Fig. 5. Throughput versus rounds for LEACH and HEED protocols.

Regarding energy consumption, Figure 3 shows that HEED tends to be more efficient in the early to mid-simulation stages, as CH selection considers residual energy and communication distance, preventing rapid node energy depletion [25]. Conversely, LEACH experiences a sharper energy decline early on due to probabilistic CH selection, resulting in some nodes depleting energy faster. However, in the simulation's final phase, the network's residual energy in HEED drops more drastically than in LEACH, contributing to HEED's shorter LND.

For data delivery, Figure 4 shows a similar PDR pattern, starting high in the initial rounds and gradually declining throughout the simulation as nodes fail and energy depletes. HEED maintains slightly higher PDR than LEACH, reflecting more balanced energy consumption and more reliable routing. Meanwhile, Figure 5 shows that LEACH tends to have higher throughput than HEED, although it is more volatile. HEED produces more stable throughput, but the average is lower. As the rounds progress, the throughput of both protocols drops dramatically due to node deaths. Still, LEACH can maintain a higher data delivery rate until near the end of the simulation.

Compared to previous works such as PSO-based and GA-based optimization models [6, 9, 10], the proposed scheme emphasizes a lightweight and fully decentralized CH selection without relying on global optimization. While hybrid LEACH variants [12, 16] improve network lifetime through metaheuristic approaches, they often incur higher computational costs and coordination overhead. In contrast, our approach achieves comparable or better network lifetime improvement (+8.03% LND increase) with significantly lower complexity.

Overall, these results indicate that HEED is more efficient in the initial phase of the simulation in terms of energy distribution and communication route stability. At the same time, LEACH excels in maintaining a longer network lifetime and higher throughput. Both protocols have advantages and disadvantages, so protocol selection should be tailored to the network's priority needs, prioritizing initial energy efficiency or long-term network resilience.

IV. CONCLUSION

This study compares the performance of the Low-Energy Adaptive Clustering Hierarchy (LEACH) and Hybrid Energy-Efficient Distributed Clustering (HEED) protocols based on four key metrics: network lifetime, measured as First Node Dies (FND), Half Nodes Die (HND), and Last Node Dies (LND), energy consumption, Packet Delivery Ratio (PDR), and throughput. Simulation results show that HEED can delay the first node death (FND = 286 rounds) compared to LEACH (FND = 280 rounds), indicating more balanced energy use in the early simulation phase. However, LEACH excels in maintaining a longer network lifetime, with HND = 414 rounds and LND = 585 rounds, compared to HEED, which only achieved HND = 405 rounds and LND = 538 rounds.

Regarding energy consumption, HEED proved more efficient during the early to mid-simulation phase due to better workload distribution among nodes, whereas LEACH experiences faster energy depletion initially. However, in the late simulation phase, LEACH maintains residual energy longer, supporting a more extended network lifetime. For data delivery, PDR gradually declines over time as nodes fail, with HEED slightly outperforming LEACH in maintaining stable delivery. The throughput results show that LEACH achieves a higher average throughput, although with greater volatility, whereas HEED maintains a relatively lower but more stable throughput.

Overall, it can be concluded that HEED demonstrates superior energy efficiency and balanced load distribution in the initial phase, whereas LEACH is superior in extending network lifetime and achieving higher data throughput. Therefore, the protocol selection should be tailored to the application needs: HEED is suitable for scenarios emphasizing initial energy efficiency and route stability. At the same time, LEACH is ideal for applications requiring long-term network resilience and high data volume.

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