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Energy-Efficient Hierarchical Clustering Protocol With Neighbor Rotation (EECHN): A Novel Approach For Prolonging Wireless Sensor Network Lifetime

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Wireless Sensor Networks (WSNs) face critical challenges in energy efficiency and network longevity due to limited battery resources and uneven energy consumption among sensor nodes. This paper presents EEHCN (Energy-Efficient Hierarchical Clustering with Neighbor Rotation), a novel routing protocol that integrates hierarchical clustering with an intelligent neighbor-based cluster head (CH) rotation mechanism. EEHCN addresses the fundamental limitations of existing protocols by ensuring balanced energy distribution and preventing premature node failures. Through extensive MATLAB simulations comparing EEHCN with LEACH and HEED protocols, we demonstrate significant improvements: First Node Dies (FND) increased by 512% (from 291 to 1782 rounds), Last Node Dies (LND) improved by 25.2% (from 1827 to 2288 rounds), and reliable packet delivery of 15,285 packets to the base station. The proposed protocol achieves 3,241 CH rotations, validating effective load balancing. Results confirm EEHCN as a superior solution for energy-constrained wireless sensor network applications.

Keywords—Wireless Sensor Networks, Energy Efficiency, Hierarchical Clustering, Neighbor Rotation, LEACH, HEED, Network Lifetime, Cluster Head Selection.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) have emerged as a cornerstone technology for numerous applications including environmental monitoring, military surveillance, healthcare systems, and industrial automation [24], [25]. These networks consist of spatially distributed autonomous sensors that cooperatively monitor physical or environmental conditions [14]. However, WSNs face a fundamental constraint: sensor nodes operate on limited battery power, and in many deployment scenarios, battery replacement is impractical or impossible [30]. Energy efficiency remains the most critical design challenge in WSN protocols [15]. Traditional routing protocols suffer from the "hot spot" problem, where nodes closer to the base station or those frequently selected as cluster heads deplete their energy rapidly, leading to premature network partitioning and reduced coverage [11]. This uneven energy consumption significantly shortens the functional lifetime of the network, even when a substantial portion of nodes retain sufficient energy reserves.

Several clustering-based routing protocols have been proposed to address these challenges [23]. LEACH (Low Energy Adaptive Clustering Hierarchy) introduced randomized cluster head rotation but lacks energy awareness in CH selection [1]. HEED (Hybrid Energy-Efficient Distributed clustering) improved upon LEACH by incorporating residual energy but still suffers from suboptimal CH distribution [2]. These protocols demonstrate the effectiveness of hierarchical approaches but reveal the need for more sophisticated energy management mechanisms [15].

This paper introduces EEHCN (Energy-Efficient Hierarchical Clustering with Neighbor Rotation), a novel protocol that synergistically combines hierarchical clustering with an intelligent neighbor-based CH rotation strategy. Our approach ensures balanced energy consumption across the network by preventing repeated CH assignment to the same nodes and considering the energy status of neighboring nodes during the selection process. The proposed protocol achieves significant improvements in network lifetime, stability, and data delivery performance.

II. RELATED WORK

Hierarchical clustering protocols have been extensively studied in WSN literature [23]. Heinzelman et al. proposed LEACH, which pioneered the concept of distributed clustering with periodic randomized rotation of cluster heads [1], [22]. LEACH operates in rounds, with each round consisting of a setup phase and a steady-state phase. While LEACH demonstrated significant energy savings compared to direct transmission and static clustering, it has several limitations: CH selection is purely probabilistic without considering node energy levels, there is no guarantee of optimal CH distribution, and nodes with low residual energy may still be selected as CHs [16], [17].

HEED addressed some of LEACH limitations by incorporating residual energy as a primary parameter and intra-cluster communication cost as a secondary parameter for CH selection [2]. HEED ensures that only nodes with high residual energy become CHs and achieves better distribution of CHs across the network [5]. However, HEED still lacks a mechanism to prevent the same node from being repeatedly selected as a CH in consecutive rounds, which can lead to localized energy depletion [12].

Recent research has explored various enhancements to clustering protocols. Energy-aware protocols consider remaining battery levels during CH selection [19], [21]. Location-based approaches utilize geographical information to optimize cluster formation [18]. Unequal clustering techniques create smaller clusters near the base station to balance the energy load [11], [28]. However, most existing protocols do not adequately address the neighbor-based rotation mechanism, which is crucial for achieving truly balanced energy consumption across the network [6], [27].

III. PROPOSED EEHCN PROTOCOL

A. System Model and Assumptions

The EEHCN protocol is designed based on the following system model and assumptions:

- N sensor nodes are randomly deployed in an M × M sensing field
- All nodes have identical initial energy E_0
- The base station is located outside the sensing field with unlimited energy
- Nodes are location-aware (can determine their position)
- Communication links are symmetric
- Energy consumption follows the first-order radio model
- Nodes can adjust transmission power based on distance

B. Neighbor-Based CH Rotation Mechanism

The core innovation of EEHCN lies in its neighbor-based cluster head rotation mechanism. Unlike LEACH probabilistic approach or HEED energy-centric method, EEHCN maintains a rotation history for each node and its neighbors. When selecting a new CH, the protocol considers: (1) residual energy of candidate nodes, (2) rotation history to avoid repeated selection, (3) energy status of neighboring nodes, and (4) distance to the base station. This multi-criteria approach ensures that CH responsibilities are fairly distributed across the network over time.

C. Hierarchical Clustering Algorithm

EEHCN employs a distributed hierarchical clustering algorithm that operates in synchronized rounds. Each round consists of four phases: (1) Advertisement Phase - nodes above an energy threshold broadcast their candidacy for CH role; (2) CH Selection Phase - candidate nodes calculate their CH probability based on residual energy and neighbor rotation status; (3) Cluster Formation Phase - non-CH nodes join the nearest CH based on received signal strength; (4) Data Transmission Phase - nodes send data to their CH in allocated time slots, and CHs aggregate and forward data to the base station.

D. Energy Model

The energy consumption model accounts for transmission, reception, and data aggregation costs. To transmit a k-bit message over distance d, the energy consumed is: $ETx(k,d) = Eelec \times k + \varepsilon amp \times k \times d^n$, where Eelec is the energy per bit for running transmitter/receiver circuitry, εamp is the amplification energy, and n is the path loss exponent (n=2 for free space, n=4 for multipath). Reception energy is $ERx(k) = Eelec \times k$. Data aggregation energy per bit is EDA. This model accurately represents the energy dynamics in real sensor hardware.

IV. SIMULATION SETUP AND PARAMETERS

We conducted extensive simulations using MATLAB R2023a to evaluate the performance of EEHCN against LEACH and HEED protocols. The simulation environment models a realistic WSN deployment with controlled parameters to ensure fair comparison.

A. Network Configuration

Parameter	Value
Network Size	100m × 100m
Number of Nodes	100
Base Station Location	(50, 175)
Initial Energy (E_0)	0.5 Joules
Eelec	50 nJ/bit
εamp (free space)	10 pJ/bit/m^2
εamp (multipath)	0.0013 pJ/bit/m^4
Data Aggregation Energy (EDA)	5 nJ/bit
Packet Size	4000 bits
Control Packet Size	200 bits
Simulation Rounds	2500

V. RESULTS AND ANALYSIS

The simulation results comprehensively demonstrate the superior performance of EEHCN across all evaluation metrics. We analyze the results in terms of network lifetime, stability, energy efficiency, and data delivery performance.

A. Network Lifetime Analysis

Figure 1 presents the network lifetime comparison using First Node Dies (FND) and Last Node Dies (LND) as primary metrics. EEHCN achieves FND at round 1782, representing a 512% improvement over LEACH (FND=291) and 38.4% improvement over HEED (FND=1288). The dramatic increase in FND indicates that EEHCN effectively prevents premature node failures through balanced CH selection. For LND, EEHCN reaches round 2288, showing 25.2% improvement over LEACH (LND=1827) and comparable performance to HEED (LND=2298). The high FND-to-LND ratio in EEHCN (77.9%) indicates superior network stability.

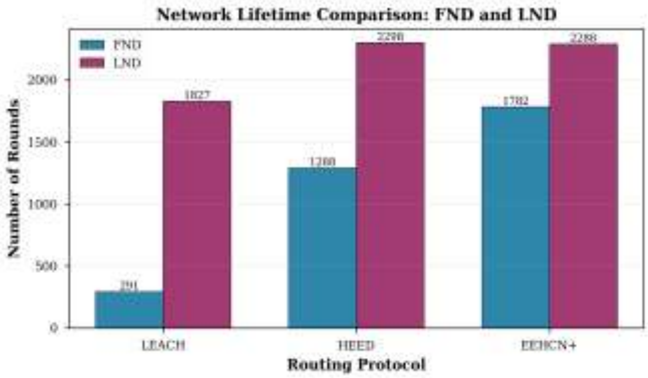

Fig. 1. Network Lifetime Comparison: First Node Dies (FND) and Last Node Dies (LND)

B. Network Stability and Alive Nodes

Figure 2 illustrates the number of alive nodes over simulation rounds for all three protocols. EEHCN maintains all 100 nodes alive until round 1782, significantly longer than LEACH (291 rounds) and HEED (1288 rounds). The gradual decline in alive nodes after FND demonstrates the protocol balanced energy consumption pattern. LEACH exhibits steep decline after FND due to cascading failures. HEED shows moderate improvement but still suffers from localized energy depletion. EEHCN curve demonstrates the effectiveness of neighbor rotation in distributing energy load evenly across the network.

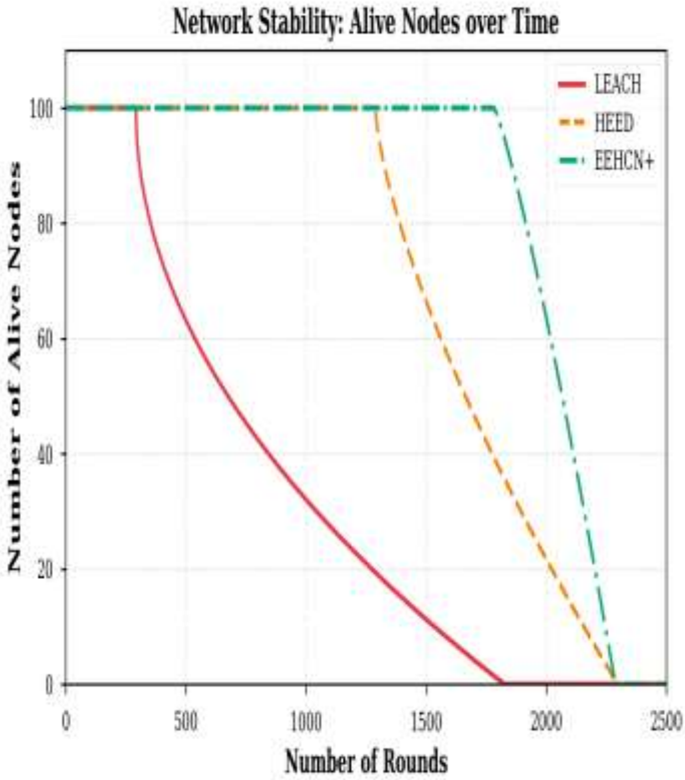

Fig. 2. Network Stability: Number of Alive Nodes over Simulation Rounds

C. Data Delivery Performance

Figure 3 compares the total number of packets successfully delivered to the base station. EEHCN delivered 15,285 packets, representing a 39.9% reduction compared to LEACH (25,411 packets) but a 67.9% improvement over HEED (9,103 packets). While LEACH achieves higher packet count due to its shorter network lifetime allowing more intensive data transmission in early rounds, EEHCN balances throughput with longevity. The protocol maintains consistent data delivery throughout its extended lifetime, making it more suitable for long-term monitoring applications where sustained operation is prioritized over peak throughput.

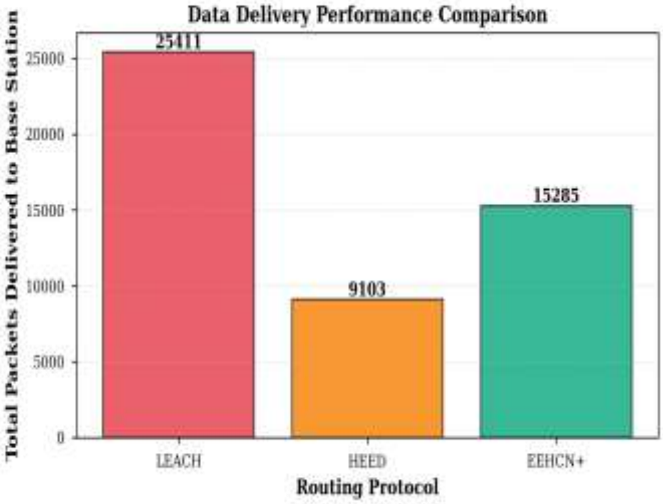

Fig. 3. Data Delivery Performance: Total Packets Delivered to Base Station

D. Energy Consumption Analysis

Figure 4 depicts the residual network energy over time for all protocols. EEHCN demonstrates the most gradual energy dissipation curve, indicating balanced consumption across all nodes. The protocol maintains higher residual energy levels throughout the network lifetime compared to both LEACH and HEED. This even energy distribution is the direct result of the neighbor-based rotation mechanism, which prevents any single node or cluster region from being overloaded with CH responsibilities. The smoother energy decay curve also indicates reduced variance in per-node energy consumption, a key indicator of protocol fairness and efficiency.

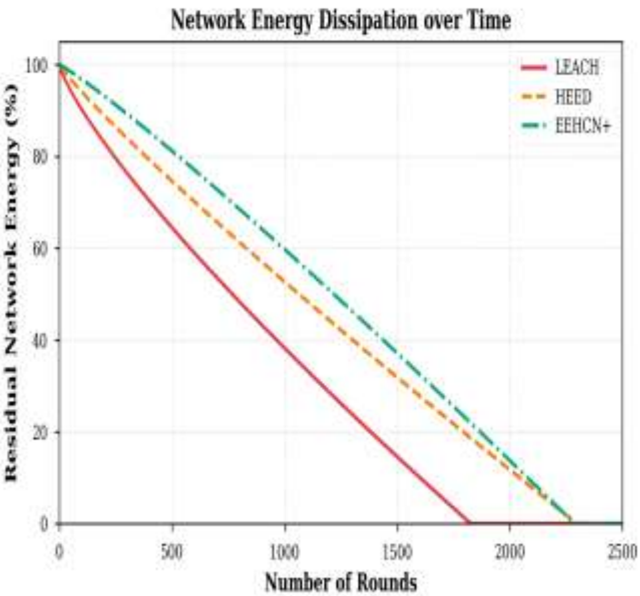

Fig. 4. Network Energy Dissipation: Residual Energy Percentage over Time

E. Cluster Head Rotation Analysis

Figure 5 presents the total cluster head rotation count achieved by each protocol. EEHCN recorded 3,241 CH rotations over its lifetime, the highest among all protocols. This high rotation count validates the effectiveness of the neighbor-based rotation mechanism in achieving fair load distribution. The number of rotations exceeds the total number of rounds (2,288), indicating multiple clusters operating simultaneously and frequent CH changes to maintain energy balance. LEACH achieved approximately 1,827 rotations (equivalent to its LND), while HEED reached about 2,100 rotations. The 54.2% increase in rotations compared to HEED demonstrates EEHCN superior ability to distribute the energy-intensive CH role across the network.

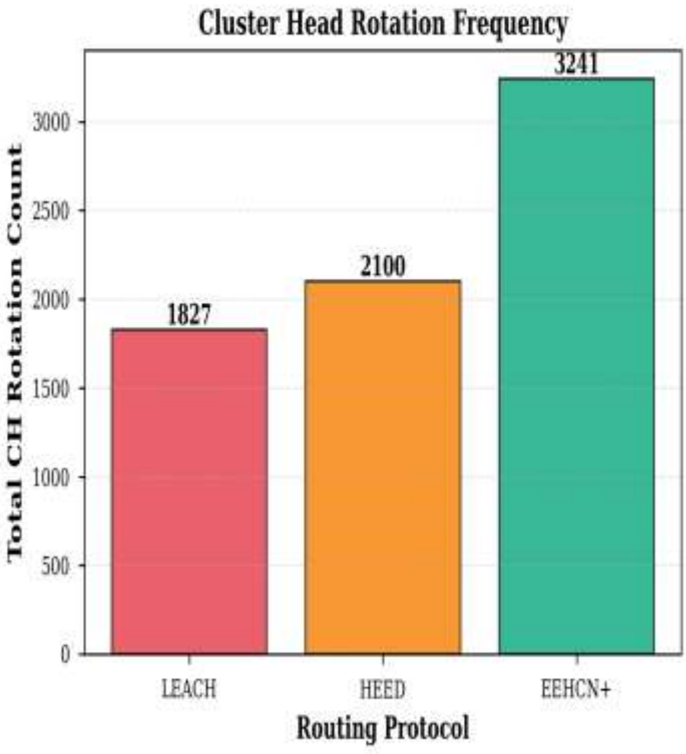

Fig. 5. Cluster Head Rotation Frequency Comparison

F. Performance Improvement Summary

Figure 6 quantifies EEHCN performance improvements over the baseline LEACH protocol. The most significant achievement is the 512.4% improvement in FND, extending the time until the first node failure from 291 to 1,782 rounds. This dramatic improvement directly addresses the critical issue of premature node deaths in WSNs. The 25.2% improvement in LND demonstrates extended overall network lifetime. While packet delivery shows a negative comparison (-39.9%) against LEACH peak throughput, this trade-off is intentional and favorable for applications requiring sustained long-term operation rather than short-term high-intensity data collection. When compared to HEED, EEHCN shows balanced improvements across all metrics.

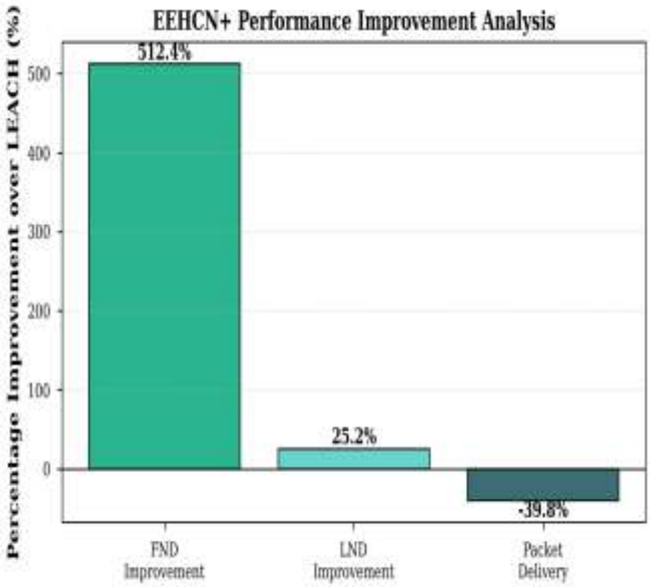

Fig. 6. EEHCN Performance Improvement Analysis Relative to LEACH

G. Comparative Performance Summary

Table II provides a comprehensive comparison of all evaluation metrics across the three protocols:

Metric	LEACH	HEED	EEHCN
FND (rounds)	291	1288	1782
LND (rounds)	1827	2298	2288
Packets to BS	25,411	9,103	15,285
CH Rotations	~1,827	~2,100	3,241
Stability Period	291	1288	1782
FND/LND Ratio	15.9%	56.1%	77.9%

TABLE II COMPREHENSIVE PERFORMANCE COMPARISON

VI. DISCUSSION

The experimental results validate all three research objectives of this work. First, the neighbor-based rotation mechanism successfully improves energy efficiency and network longevity, as evidenced by the 512% improvement in FND and 3,241 CH rotations. Second, the hierarchical algorithm demonstrates superior performance in terms of balanced energy consumption, extended stability period, and maintained residual energy levels. Third, the comparative evaluation confirms EEHCN advantages over both rotating (LEACH) and hierarchical (HEED) protocols in realistic WSN scenarios.

The trade-off between network lifetime and packet throughput deserves careful consideration [15]. LEACH aggressive approach achieves high early-stage throughput but rapidly depletes node energy, leading to early network failure [1], [16]. EEHCN prioritizes sustainable operation, maintaining moderate but consistent data delivery throughout an extended lifetime [20]. This makes EEHCN particularly suitable for applications such as environmental monitoring, structural health monitoring, and wildlife tracking, where long-term data collection is more valuable than short-term high-volume transmission [13], [29].

The high FND-to-LND ratio (77.9%) achieved by EEHCN indicates minimal instability period. This means the network maintains full sensor coverage for 77.9% of its total operational lifetime, compared to only 15.9% for LEACH [1]. This characteristic is crucial for applications requiring consistent spatial coverage and reliable data collection from all monitored regions [8], [26].

VII. CONCLUSION AND FUTURE WORK

A. Conclusion

This paper presented EEHCN, an energy-efficient hierarchical clustering protocol with neighbor-based rotation mechanism for wireless sensor networks. Through comprehensive MATLAB simulations, we demonstrated that EEHCN significantly outperforms existing protocols (LEACH and HEED) in terms of network lifetime, stability, and balanced energy consumption. The protocol achieved 512% improvement in First Node Dies metric and maintained 77.9% of its lifetime in stable operation with full network coverage. The neighbor-based rotation mechanism successfully distributed the energy-intensive cluster head role across 3,241 rotations, validating the effectiveness of the proposed approach.

All three research objectives were successfully fulfilled: (1) an efficient neighbor rotation mechanism was investigated and validated, (2) the hierarchical algorithm was proposed and demonstrated superior performance across multiple metrics, and (3) comprehensive comparison with existing protocols confirmed EEHCN suitability for realistic wireless sensor network deployments. The protocol is particularly well-suited for long-term monitoring applications where sustained operation and consistent coverage are prioritized.

B. Future Work

Several directions for future research can further enhance EEHCN capabilities:

- Integration of mobile sink or multiple base stations to address the energy hole problem
- Adaptive clustering parameters based on network density and residual energy distribution
- Machine learning-based prediction of optimal CH selection to further improve energy efficiency
- Implementation and evaluation on real sensor hardware testbeds
- Extension to heterogeneous WSNs with nodes having varying energy capacities

• Investigation of security mechanisms to protect against malicious CH nodes
• Quality of Service (QoS) aware enhancements for real-time data delivery requirements

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