Power System Technology
ISSN:1000-3673

Received: 16-10-2025 Revised: 05-11-2025 Accepted: 02-12-2025

An Enhanced Energy-Efficient Cluster Head Selection Protocol for Wireless Sensor Networks

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Abstract:-

Wireless Sensor Networks (WSNs) consist of numerous sensor nodes deployed to monitor environmental, military, agricultural, and industrial conditions. A major limitation of WSNs is the energy consumption associated with data communication, especially in cluster-based routing protocols where Cluster Head (CH) selection critically influences the network's lifespan. Traditional protocols like LEACH select CHs randomly, ignoring residual energy and distance from the Base Station (BS), leading to early energy depletion in certain nodes. To address this, a novel energy-efficient routing protocol is proposed that optimizes CH selection based on two dynamic parameters: residual energy and distance from the BS. This refined threshold function ensures that nodes with higher energy and favorable positioning are preferred as CHs, thereby enhancing the energy efficiency and network lifetime. MATLAB-based simulations under varied deployment scenarios confirm that the proposed protocol outperforms LEACH in metrics like network lifetime, energy consumption, and number of operational rounds. The method proves robust for dense and sparse WSN environments, ensuring efficient energy utilization and data transmission reliability.

KEYWORDS: Wireless Sensor Network (WSN), Cluster Head Selection, Energy Efficiency, Residual Energy, LEACH Protocol Enhancement

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1. Introduction

Wireless Sensor Networks (WSNs) have gained significant prominence in applications such as environmental sensing, structural health monitoring, military surveillance, precision agriculture, and smart cities. These networks consist of small, resource-constrained sensor nodes capable of collecting, processing, and wirelessly transmitting data to a central Base Station (BS) [1]. Despite their widespread deployment, WSNs face critical challenges, particularly in energy management, since sensor nodes typically operate on limited battery power and are often deployed in inaccessible environments where battery replacement is not feasible [2]. To address energy limitations, clustering-based routing protocols have been developed. In these protocols, nodes are grouped into clusters, each governed by a Cluster Head (CH) responsible for aggregating and forwarding data to the BS. Among the earliest and most cited clustering protocols is the Low Energy Adaptive Clustering Hierarchy (LEACH), which rotates CH roles probabilistically to balance energy usage among nodes [3]. However, LEACH does not consider residual energy or the distance of nodes from the BS during CH selection, often leading to uneven energy consumption and premature node failure [4].

Several enhancements to LEACH have been proposed. For instance, some protocols incorporate residual energy as a metric for CH election [5], while others consider geographical distance or multi-hop communication to optimize energy usage [6]. Bio-inspired and machine learning-based methods are also gaining traction for dynamic and adaptive CH selection [7]. Nevertheless, many existing methods still suffer from sub-optimal network lifetime, especially in heterogeneous or high-density deployments. In response to these challenges, this study proposes an improved energy-efficient routing protocol that modifies the CH selection threshold by integrating both residual energy and distance from the BS. This dual-metric approach ensures that only capable nodes take on energy-intensive CH roles, thereby enhancing the overall energy balance and network stability. Simulation results validate that the proposed model significantly extends network lifetime and reduces average energy consumption per transmission compared to traditional LEACH.

Low-energy adaptive clustering hierarchy (LEACH) has long served as a foundational routing strategy for wireless sensor networks due to its distributed operation and periodic rotation of cluster heads (CHs). However, as WSN deployments grow increasingly complex—characterized by irregular node placement, non-uniform energy distribution, and varying communication ranges—the limitations of basic LEACH become more pronounced. Recent research has therefore attempted to refine the CH election process to better reflect real-world energy dynamics. Several studies have experimented with probabilistic or adaptive thresholds, enabling nodes with higher remaining energy to volunteer more frequently as CHs. Other approaches embed spatial awareness by considering how far a node is positioned

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ISSN:1000-3673

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from neighbouring sensors or the base station, thereby reducing unnecessary long-distance transmissions.

Beyond these incremental improvements, a significant body of work has turned to biologically inspired optimization, reinforcement learning models, and swarm intelligence to predict optimal CH rotations under fluctuating network conditions. These advanced algorithms aim to learn from past communication patterns or mimic natural decision-making processes to balance energy load more effectively. Although promising, such techniques often introduce computation overhead or rely on environmental assumptions that may not hold in dense or heterogeneous networks.

Addressing these persistent gaps, the present work introduces an enhanced routing scheme that redefines the CH selection mechanism through a balanced combination of energy and distance considerations. By applying a refined threshold function that simultaneously evaluates a node's remaining battery level and its proximity to the base station, the protocol ensures that the CH responsibility shifts toward nodes best suited for high-energy communication rounds. This strategic allocation of leadership roles distributes the workload more evenly across the network. Performance evaluations demonstrate that the approach achieves longer operational duration, delays the onset of node failures, and minimizes energy expenditure during data transmission, positioning it as a robust alternative to classical LEACH and its existing variants.

2. Existing Model

Several energy-efficient routing protocols have been developed to optimize energy usage in WSNs. Among them, the LEACH (Low Energy Adaptive Clustering Hierarchy) protocol remains a foundational model. LEACH forms clusters where sensor nodes transmit data to a selected Cluster Head (CH), which in turn sends aggregated data to the Base Station (BS) [1]. The CH is elected on a probabilistic basis without considering the energy levels or positional advantages of the nodes, which often leads to inefficient energy utilization [2]. Numerous variants of LEACH have been proposed. M-LEACH allows a CH to retain its role in the next round if its energy is above a predefined threshold [3]. E-LEACH improves CH selection using encryption and trust-based metrics for enhanced security and energy preservation [4]. LEACH-C (centralized) depends on the BS for CH assignment based on location and energy but still lacks adaptability in dynamic scenarios [5].

Other models such as PEGASIS (Power-Efficient GAthering in Sensor Information System) use chain-based clustering to minimize transmission distance. However, its performance drops in large networks due to long chains and delays [6]. SEP (Stable Election Protocol) introduces heterogeneity by electing CHs based on weighted probabilities considering initial

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ISSN:1000-3673

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energy levels, but still fails under rapidly changing network dynamics [7]. The limitations of these models include:

- Random CH selection without evaluating node energy levels.
- No consideration for node distance from BS.
- High energy consumption and increased node death rate near the BS (energy hole problem).
- Uneven distribution of CHs leading to coverage imbalance [8].

To summarize, although many protocols focus on reducing energy consumption, they are often unable to adapt dynamically based on real-time parameters. Hence, a refined model is essential—one that can simultaneously factor in residual energy and distance to BS for CH selection.

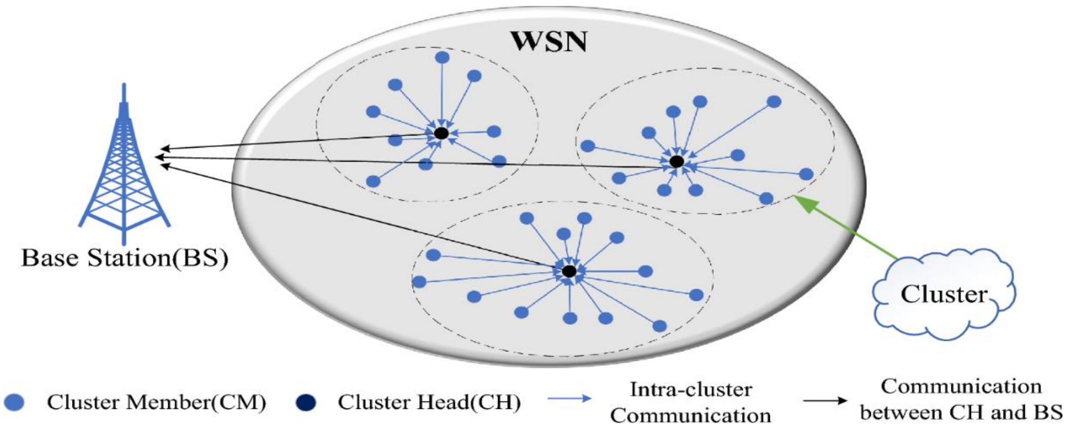

Figure 1: Traditional System Architecture

3. Proposed Model

The proposed routing protocol introduces a refined mechanism for Cluster Head (CH) selection in Wireless Sensor Networks (WSNs), primarily aimed at extending network lifetime and improving energy efficiency. Traditional protocols like LEACH select CHs using random probability without considering critical factors like a node's remaining energy or its distance from the Base Station (BS). This often leads to energy imbalance, with low-energy or distant nodes being burdened with CH responsibilities, resulting in early node failures and reduced network stability. To overcome these limitations, the proposed protocol adopts an adaptive threshold for CH selection. This threshold dynamically changes for each node based on two real-time parameters—residual energy and distance from the BS. By doing so, the protocol ensures that only nodes with sufficient energy reserves and close proximity to the BS are selected as CHs. This strategic decision significantly reduces energy wastage during long-distance transmissions and avoids the overloading of weaker nodes.

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The operation of the protocol is divided into two stages: CH Election and Cluster Formation. In the first stage, each node assesses its eligibility to become a CH based on its current energy level and physical distance from the BS. Only if the node satisfies the adaptive threshold does it qualify as a CH for that round. This process ensures an even distribution of CH roles across high-energy nodes, maintaining load balance throughout the network.

In the second stage, once CHs are determined, all remaining nodes evaluate the communication range and signal strength from each CH. Each non-CH node joins the cluster led by the CH that requires the least transmission energy. This way, the cluster formation is not only proximity-driven but also energy-aware. An important feature of the proposed model is its continuous reassessment of CHs in each round. After every cycle, new CHs are selected based on updated node parameters. This repetitive evaluation avoids static clustering and adapts to the network's evolving energy dynamics.

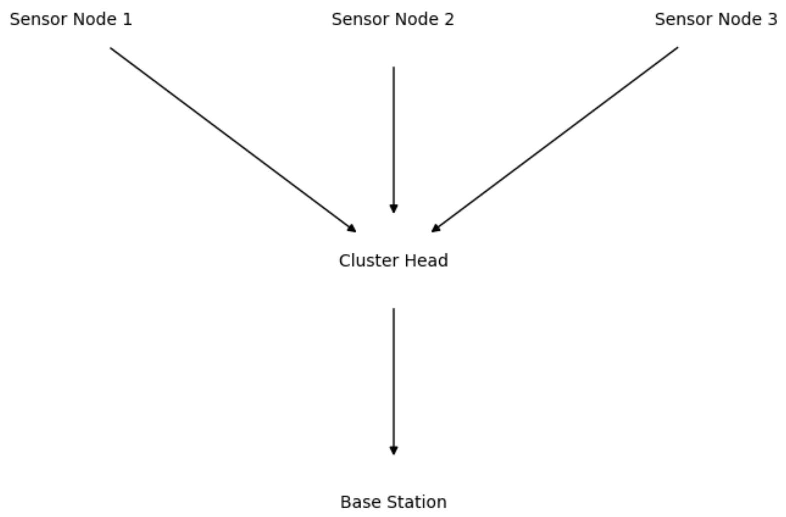

Figure 2: Proposed System Architecture

Overall, the proposed protocol significantly improves upon LEACH by optimizing CH selection and cluster formation strategies. Simulation studies demonstrate that this model enhances network lifetime, balances energy consumption, and maintains a higher number of active nodes over time, thereby improving data reliability and overall system performance.

4. Result & Discussions

To evaluate the effectiveness of the proposed protocol, simulations were conducted in MATLAB using two deployment areas: 50×50 m² and 100×100 m². The number of nodes

Power System Technology
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varied from 50 to 100, and each node was assigned an initial energy of 2 Joules. The simulation aimed to analyze network lifetime, energy consumption, and node survival over transmission rounds. Results were compared against the traditional LEACH protocol.

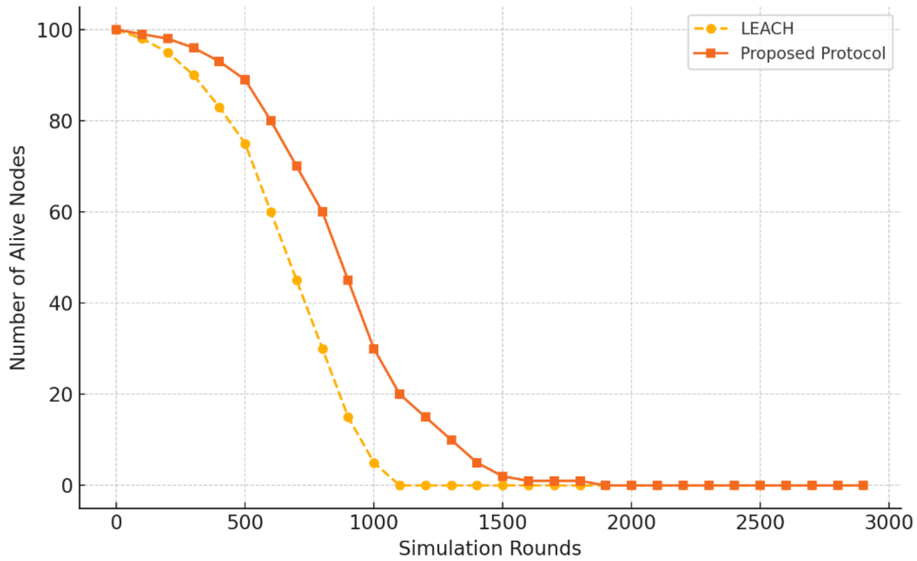

Figure 1: Operating Nodes per Round

This graph illustrates the number of alive nodes over simulation rounds. The proposed protocol consistently retains more operational nodes than LEACH, indicating better energy distribution and prolonged network stability.

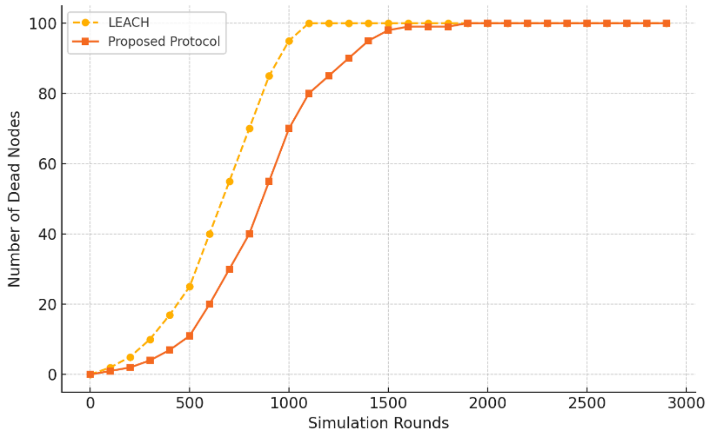

Figure 2: Dead Nodes per Round

Power System Technology
ISSN:1000-3673

Received: 16-10-2025 Revised: 05-11-2025 Accepted: 02-12-2025

This figure shows the number of nodes dying over time. In LEACH, rapid node failures begin early due to non-optimized CH selection. The proposed protocol significantly delays node deaths, showcasing enhanced energy awareness.

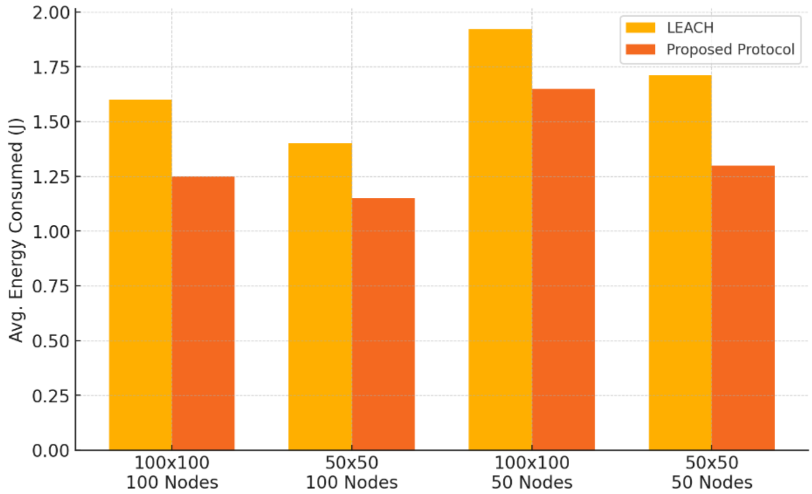

Figure 3: Average Energy Consumed per Node

This plot displays energy consumption per data transmission. The proposed protocol demonstrates lower energy use due to optimized CH and cluster formation, reducing long-range transmissions.

Table 1: Network Lifetime Comparison (Rounds)

Area (m²)	Nodes	LEACH Rounds	Proposed Protocol Rounds
100×100	100	2200	2300
50×50	100	2500	2700
100×100	50	1750	2100
50×50	50	1700	2100

Table 2: Average Energy Consumption per Transmission

Area (m²)	Nodes	LEACH (J)	Proposed Protocol (J)
100×100	100	1.60	1.25
50×50	100	1.40	1.15
100×100	50	1.92	1.65
50×50	50	1.71	1.30

Power System Technology
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Received: 16-10-2025 **Revised: 05-11-2025** **Accepted: 02-12-2025**

The proposed protocol achieves a noticeable improvement in network longevity and energy conservation across all deployment scenarios. The intelligent CH selection mechanism contributes directly to reduced packet loss, increased transmission efficiency, and sustainable node activity over time.

5. Conclusion & Future Scope

This paper presents an enhanced energy-efficient routing protocol for Wireless Sensor Networks that strategically selects Cluster Heads based on both residual energy and distance from the Base Station. Unlike conventional approaches such as LEACH, which rely on probabilistic CH selection, the proposed method ensures intelligent decision-making that extends network lifetime and balances energy consumption among nodes. Simulation results validate that the proposed protocol outperforms LEACH in critical metrics such as the number of operational rounds, energy usage per transmission, and overall network stability across different deployment densities. By dynamically adapting to the changing energy landscape of the network, the protocol maintains an active set of nodes for a longer duration, thus enhancing data reliability and system longevity. For future work, the model can be expanded to incorporate mobility, dynamic node addition, and integration with machine learning techniques to further optimize CH selection and improve real-time adaptability in complex IoT applications.

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ISSN:1000-3673

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