

Article

EEDC: Energy-Efficient Distance-Controlled Clustering for Bottleneck Avoidance in Wireless Sensor Networks

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Abstract

Wireless Sensor Networks (WSNs) commonly employ clustering to improve scalability and energy efficiency; however, cluster heads (CHs) located near the base station (BS) often suffer from excessive relay traffic, leading to rapid energy depletion and reduced network lifetime. This article proposes an Energy-Efficient Distance-Controlled Clustering (EEDC) scheme that adjusts CH density and transmission power according to each node's distance from the BS. In EEDC, a higher number of CHs is deployed near the BS to balance forwarding loads, while fewer CHs are selected in distant regions to conserve energy. Additionally, CHs adapt their transmission power to enable distance-proportional communication. A mathematical model is developed to analyze the relationship between CH distribution, transmission power, and overall energy consumption. Performance evaluation is conducted through simulations and compared with LEACH, HEED, DEEC, SEP, and EECS. The results show that EEDC improves the stability period by up to 42%, extends network lifetime by 23%, increases average residual energy by 13–29%, enhances throughput by 16–44%, and achieves 23–61% higher packet delivery efficiency. Moreover, cumulative CH energy consumption is reduced by 5–21%, leading to more balanced energy distribution. These findings indicate that distance-controlled CH selection and adaptive transmission power effectively alleviate the BS energy bottleneck and enhance the energy efficiency and operational longevity of clustered WSNs.

Keywords: wireless sensor networks (WSNs); energy efficiency; distance-controlled clustering; cluster head selection; multi-hop routing; network lifetime; energy balancing; packet delivery efficiency; hotspot mitigation; EEDC protocol



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1. Introduction

Wireless sensor networks (WSNs) have emerged as a fundamental technology for environmental monitoring, industrial automation, healthcare, and military applications [1–3]. A WSN typically consists of a large number of energy-constrained sensor nodes that cooperatively sense, process, and transmit data to a central base station (BS) [4–6]. Since sensor nodes are often deployed in inaccessible or harsh environments, energy efficiency becomes a critical factor in determining the operational lifetime and reliability of the network [7–9].

WSNs can be organized using either flat or clustered network architectures. In flat architectures, all sensor nodes operate at the same hierarchical level, and data is typically forwarded to the BS through multi-hop transmission. Although this structure is simple and easy to deploy, it suffers from significant drawbacks, including high energy consumption, increased traffic congestion near the BS, and limited scalability as the network

grows. In contrast, clustered architectures partition the network into multiple clusters, each managed by a designated cluster head (CH) responsible for data aggregation and forwarding. By reducing redundant transmissions and distributing communication tasks, clustered networks offer improved scalability, lower communication overhead, and more balanced energy consumption across nodes, making them more suitable for large-scale WSN deployments [9–12].

The selection process of CHs is a critical process of clustered WSN architectures, as CHs are responsible for data aggregation, intra-cluster coordination, and forwarding aggregated data toward the BS. CH selection is commonly determined using one or more metrics, such as residual energy, local node density, distance to the BS, and others [13–16]. Incorporating these parameters helps identify nodes capable of sustaining the additional communication burden associated with CH operations. An effective CH selection strategy can substantially reduce energy consumption, prevent premature node failures, and extend the overall network lifetime [17–19]. It is also important to note that communication in WSNs is primarily one-way, with sensor nodes transmitting data toward the BS, which functions as the central data collection entity. Throughout this article, the terms base station (BS) and sink are used interchangeably.

Designing an efficient clustered WSN generally involves three fundamental stages. The first stage is the creation of the clustered topology, which may follow either a stationary or dynamic structure [20–22]. In stationary clustering, clusters are predefined and remain fixed throughout network operation, with CHs selected within these predetermined regions. Although simple, this approach cannot adapt to changes in network conditions [23]. In contrast, dynamic clustering first selects the CHs and subsequently forms clusters around the chosen CHs [24]. This method is more flexible, responsive to network dynamics, and has been widely adopted in most clustering-based protocols. The proposed Energy-Efficient Distance-Controlled Clustering (EEDC) protocol also follows a dynamic clustering strategy. The second stage is the CH selection process, which determines the nodes responsible for cluster coordination and data aggregation. CH selection criteria vary across protocols and may include several factors such as residual energy, distance to the BS, local node density, link quality, or mobility-related parameters such as speed and acceleration. Incorporating one or more of these metrics ensures balanced energy consumption and enhances the overall efficiency of the clustering process. The third stage involves the routing mechanism and subsequent performance evaluation. Once clusters are formed and CHs are appointed, a clustered routing protocol is used to forward sensed data from the nodes to the BS through their respective CHs. The effectiveness of any clustering scheme, including EEDC, is assessed using performance metrics such as network lifetime, energy balance, throughput, end-to-end delay, and packet delivery ratio, which collectively determine the protocol's suitability for energy-constrained WSN deployments.

Although numerous clustering protocols such as LEACH and its enhancements [25–28], HEED [29,30], and DEEC [31] have been developed to enhance energy efficiency in WSNs, most of these approaches assume a uniform spatial distribution of CHs and fixed transmission ranges that do not account for the heterogeneous traffic-load conditions created by the BS's location. As a result, nodes and CHs positioned near the BS often experience excessive relay traffic, leading to rapid energy depletion and bottleneck formation. To address this limitation, this article introduces EEDC, a distance-aware clustering framework that adaptively regulates both CH density and transmission range according to each node's distance from the BS. By increasing CH density in the vicinity of the BS and proportionally adjusting transmission power, EEDC achieves more balanced energy consumption, mitigates hotspot formation, and significantly extends overall network lifetime.

Clustering has long been recognized as an effective strategy for reducing communication overhead and balancing energy consumption in WSNs. In a clustered architecture, a subset of sensor nodes is designated as CHs, which are responsible for aggregating data from their member nodes and forwarding the aggregated information to the BS. While clustering enhances scalability and minimizes redundant transmissions, it introduces a critical limitation: CHs located near the BS tend to exhaust their energy more rapidly than others. These nodes not only manage intra-cluster communication but also serve as relay points for data originating from distant CHs. This additional forwarding burden results in a bottleneck effect, often leading to the formation of energy holes around the BS and subsequently degrading network performance and lifespan. To address these challenges, this article proposes the EEDC protocol, a novel distance-aware clustering framework that adaptively regulates CH density and transmission range based on each node's distance from the BS. The fundamental idea behind EEDC is to increase the number of CHs in the vicinity of the BS so that the heavy relay traffic is distributed among multiple CHs, thereby preventing premature energy depletion. Conversely, fewer CHs are selected in distant regions to reduce unnecessary energy expenditure. In addition, each CH dynamically adjusts its transmission power proportionally to its distance from the BS, enabling energy-efficient communication while avoiding redundant or excessive energy consumption.

The major contributions of this article are summarized as follows:

- Distance-controlled clustering framework that adaptively varies CH density based on the node's distance from the BS.
- Transmission range adjustment mechanism that dynamically tunes communication power according to distance, promoting energy balance.
- Mathematical model for energy consumption and CH distribution under distance-based adaptation.
- Comprehensive simulation analysis demonstrating that EEDC outperforms existing protocols such as LEACH, HEED, and others in terms of network lifetime, energy balance, and throughput.

The remainder of this article is organized as follows: Section 2 reviews the related work. Section 3 describes the clustering structure of the proposed EEDC scheme. Section 4 presents the mathematical model and numerical analysis. Section 5 contains the simulation setup, the performance evaluation, and results discussion. Finally, Section 6 concludes the article and outlines potential future research directions.

2. Related Work

A well-known limitation of clustered WSNs is the energy hole that forms around the BS because nearby CHs relay disproportionate multi-hop traffic. Early, influential remedies adopt unequal clustering, shrinking clusters near the BS so that their CHs aggregate fewer members and retain energy for relay duties. In [32,33], FUPNL introduces a fuzzy-driven unequal clustering mechanism that selects CHs randomly and adjusts their transmission range using fuzzy inputs such as distance to the BS and residual energy imbalance. By integrating fuzzy logic with multi-hop data transmission, FUPNL improves energy utilization and connectivity compared with CHCCF and EAUCF. Simulation results show significantly enhanced network lifetime, achieving an FND of 658 rounds and HND of 1232 rounds. In [34], unequal clustering aims to mitigate the hotspot problem by assigning smaller cluster sizes near the BS so that nearby CHs handle less traffic compared to distant CHs. To further balance the forwarding load, a tree-based unequal clustering data aggregation scheme has been proposed, where CHs closer to the BS transmit fewer packets and conserve more energy. This approach significantly improves energy efficiency and alleviates the relay burden in BS-adjacent regions. In [35], the hotspot problem arises when

CHs near the BS deplete their energy more rapidly due to heavier forwarding load. To address this, the EEUCB protocol introduces an energy-efficient unequal clustering scheme that incorporates distance-based thresholds, balanced energy metrics, double-CH operation, and a sleep–awake mechanism to minimize energy wastage. Simulation results show significant lifetime improvements over other traditional related protocols, and demonstrate superior hotspot mitigation and energy balancing.

Low-Energy Adaptive Clustering Hierarchy (LEACH) [36] is one of the earliest and most influential clustering protocols designed to balance energy consumption through randomized and periodic rotation of the cluster head (CH) role. While LEACH improves network lifetime compared with direct communication, it suffers from several limitations, including unpredictable CH distribution, sensitivity to node placement, and an assumption of homogeneous nodes. These constraints often result in suboptimal clustering structures and poor performance in large-scale or energy-heterogeneous scenarios. The LEACH protocol [36] is widely recognized for its rotating CH mechanism, which helps distribute energy consumption among nodes. However, its randomized CH selection and assumption of homogeneous-node capabilities limit its overall efficiency. Variants such as LEACH-C [37] and HEED [38] have attempted to enhance performance, but they typically generate a large number of CHs and are therefore practical only for small-scale deployments. Other approaches, including Cluster-Chain Mobile Agent Routing (CCMAR) [39], combine the strengths of LEACH and PEGASIS [40] to improve energy utilization. The WSNEHA algorithm [41] introduces adaptive transmission range adjustment to mitigate energy holes, while its extension, BECHA [42], aims to balance network-wide load distribution. An improved version, EA-BECHA [42], further reduces packet loss and enhances energy efficiency. Nevertheless, these solutions generally overlook end-to-end delay and lack adaptability to diverse WSN-assisted IoT scenarios. Balanced Energy Adaptive Routing (BEAR) [43] addresses similar concerns but is tailored to a specific network topology.

Hybrid Energy-Efficient Distributed Clustering (HEED) improves upon LEACH [44,45] by integrating residual energy and communication cost as primary selection metrics for CHs. HEED stabilizes cluster formation and generates more uniformly distributed CHs; however, it introduces additional overhead during the iterative CH election process. Moreover, HEED still assumes static network conditions and cannot effectively mitigate the hotspot problem near the base station (BS), particularly in dense WSNs.

The Stable Election Protocol (SEP) extends LEACH [44] by introducing heterogeneity into the clustering framework. SEP assigns higher election probabilities to advanced nodes with greater initial energy, thereby improving stability and delaying the first node death. Although SEP performs well in heterogeneous environments, it relies solely on initial energy levels and does not consider dynamic factors such as residual energy decay, CH load imbalance, or distance to the BS, which limits its robustness in long-term deployments.

Distributed Energy-Efficient Clustering (DEEC) [44,46,47] also targets heterogeneous WSNs and dynamically adjusts CH election probabilities based on the ratio of residual energy to average network energy. DEEC significantly improves stability period and lifetime compared with LEACH and SEP. However, DEEC can create unfair energy depletion patterns: high-energy nodes are repeatedly selected as CHs, causing early exhaustion of strong nodes and potential fragmentation of the network.

The Energy-Efficient Clustering Scheme (EECS) [48] introduces a cost-based competition mechanism to select CHs by considering broadcast energy and node distance to the BS. EECS provides more balanced cluster sizes and exhibits higher throughput and prolonged lifetime relative to LEACH-based methods. Nonetheless, EECS relies on single-hop communication from CHs to the BS, which increases transmission energy for distant CHs and does not fully address near-BS load concentration or the energy-hole problem.

To contextualize the motivation for developing the proposed EEDC protocol, it is essential to analyze how existing clustered routing schemes address energy efficiency and load balancing in WSNs. Table 1 provides a comparative summary of well-known clustering protocols, including LEACH, HEED, SEP, DEEC, and EECS, highlighting their primary strengths and inherent limitations. While these protocols introduce important mechanisms such as probabilistic CH rotation, energy-aware selection, and heterogeneity support, they still suffer from critical issues such as uneven CH distribution, inadequate adaptation to distance-dependent traffic load, and persistent hotspot formation near the BS. This comparison establishes the performance gaps that EEDC aims to address through distance-controlled CH density and adaptive transmission power.

Table 1. Comparative summary of well-known clustering protocols.

Protocol	Strengths	Weaknesses/Limitations
LEACH [44]	- Simple and fully distributed. - Rotating CH role balances load. - Good for homogeneous small networks.	- Random CH selection. - No consideration of distance to BS. - Poor scalability and unstable lifetime. - Hotspot problem near BS remains unresolved.
HEED [44,45]	- CH selection based on residual energy and communication cost. - More stable and deterministic clustering than LEACH.	- High overhead during iterative CH election. - Produces large number of CHs in dense networks. - Still prone to near-BS energy depletion. - Limited adaptation to topology changes.
SEP [44]	- Supports heterogeneous energy levels. - Improved stability period vs. LEACH through weighted CH election.	- Only initial energy is considered, no dynamic adaptation. - Uneven energy consumption persists. - Does not handle distance-based hotspot issues.
DEEC [44,46,47]	- Dynamic CH probability based on residual and average network energy. - Efficient in heterogeneous environments. - Longer stability and lifetime than LEACH or SEP.	- High-energy nodes become CHs too frequently, energy early depletion. - Energy imbalance increases over time. - Hotspot problem still not fully mitigated.
EECS [48]	- Distance-aware CH competition reduces cluster imbalance. - Higher throughput and improved lifetime relative to LEACH. - Better CH placement near BS.	- CHs transmit directly to BS. - Single-hop dependence limits scalability. - Does not fully prevent BS-adjacent energy holes.
Proposed EEDC	- Distance-controlled CH density solves BS bottleneck. - Adaptive transmission range reduces energy waste. - Balanced CH distribution near BS extends lifetime. - Multi-hop routing improves delivery efficiency. - Superior performance across all metrics (stability, LND, residual energy, throughput, PDE).	- Requires distance estimation and local thresholds. - Slightly higher setup complexity compared to classical methods.

Compared with classical clustering protocols such as LEACH, HEED, SEP, DEEC, and EECS, the proposed EEDC protocol directly addresses the limitations that lead to uneven energy depletion and hotspot formation near the BS. Unlike LEACH and SEP, which rely on probabilistic or initial-energy-based CH election, EEDC incorporates distance-aware CH density control to ensure that more CHs are available in high-traffic regions. In contrast to HEED and DEEC, which depend heavily on residual energy and may repeatedly select the same nodes as CHs, EEDC balances CH responsibilities spatially, preventing premature exhaustion of nodes near the BS. Moreover, while EECS partially considers distance during CH competition, it still forces CHs to communicate directly with the BS, increasing the burden on far CHs. EEDC overcomes this by combining adaptive transmission power with multi-hop routing, allowing CHs at varying distances to relay data efficiently. By jointly optimizing CH distribution, power control, and routing, EEDC achieves superior energy balance, extended network lifetime, and improved delivery reliability across a wide range of WSN deployments.

Positioning EEDC. In contrast to prior work that primarily shrinks cluster size near the BS, EEDC explicitly increases the CH density (more CHs close to the BS) and couples it with distance-proportional transmission range/power control. This dual lever—density control and power/range adaptation—aims to (a) distribute relay load over more near-BS CHs and (b) avoid redundant energy expenditure through right-sized links, thereby further suppressing the bottleneck beyond unequal-size-only designs.

Unlike other traditional unequal clustering schemes that primarily reduce cluster radius near the base station (thereby shrinking cluster sizes), EEDC introduces the following:

- Distance-dependent adaptive CH election probability, which directly increases the spatial density of CHs near the base station.
- Coupled adaptive transmission range control, ensuring that CH communication load is redistributed rather than merely reducing intra-cluster size.
- A joint control mechanism, where CH density and communication radius are simultaneously regulated as a function of node–BS distance.

Thus, the novelty lies not only in shrinking clusters but in actively reshaping CH spatial distribution and forwarding load balancing, which mitigates the energy bottleneck more effectively than radius-only approaches.

3. Clustering Structure

The proposed EEDC protocol employs a distance-aware clustering structure designed to balance energy consumption and mitigate the bottleneck problem near the BS. The network is organized into clusters that adaptively vary in density and communication range according to the nodes' distance from the BS. This adaptive design ensures that nodes closer to the BS handle higher data traffic without suffering premature energy depletion.

3.1. Network Model

A total of N homogeneous sensor nodes are assumed to be uniformly deployed over a two-dimensional sensing field of size $L \times L$. Each node possesses a unique identifier and is initialized with a limited energy E_0 . A single BS, located either within or outside the sensing region, functions as the central sink for all collected data. After deployment, nodes remain stationary, and their positions are assumed to be known through GPS or other location services [49]. Communication in the network is unidirectional, with sensor nodes transmitting data exclusively toward the BS.

3.2. Distance-Based Zoning

To reduce congestion and balance energy consumption, the sensing field is divided into multiple concentric zones centered around the BS. Each zone represents a specific range of distances from the BS.

- Zone 1 (Inner Zone): Closest to the BS, high data relay load.
- Zone 2 (Middle Zone): Moderate relay load and coverage.
- Zone 3 (Outer Zone): Farthest from the BS, low forwarding responsibility.

The density of CHs in each zone is inversely proportional to the distance from the BS, i.e., more CHs are selected in inner zones and fewer in outer zones. This design helps distribute forwarding traffic evenly among near-BS CHs, avoiding the formation of bottlenecks and extending network lifetime.

Figure 1 illustrates the proposed distance-controlled clustering structure in which the sensing field is partitioned into three concentric zones centered around the BS. These zones are represented by increasingly larger circular boundaries, each corresponding to a specific distance range from the BS. Nodes are randomly deployed across the field, where red nodes denote selected CHs and white nodes represent regular sensor nodes.

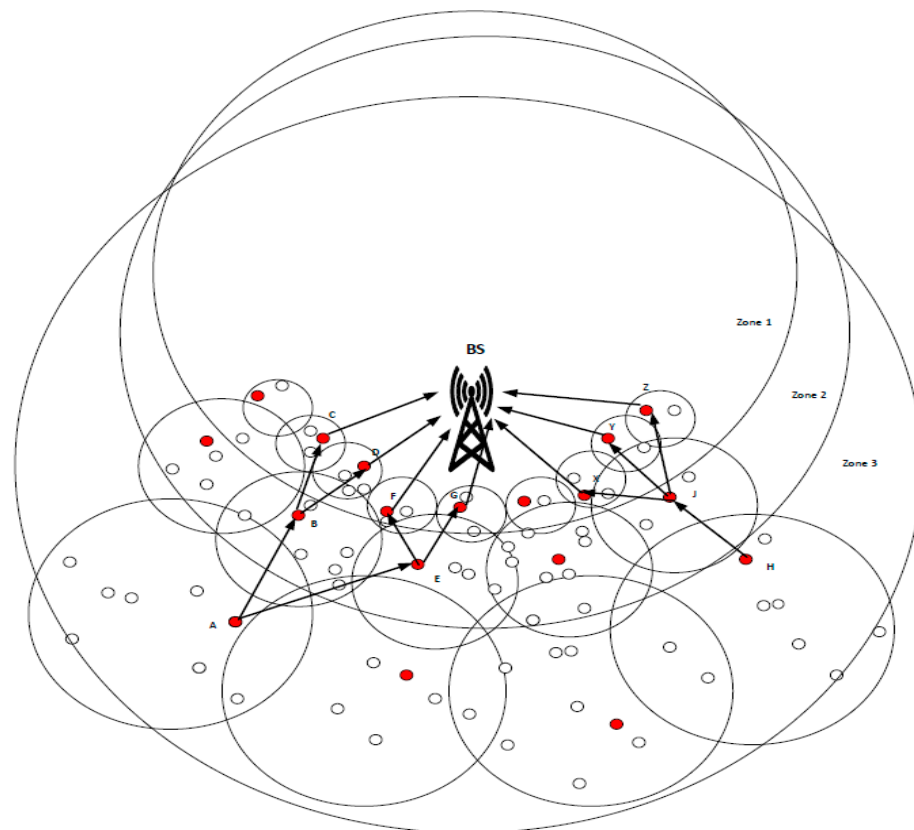


Figure 1. Distance-controlled clustering structure.

CHs located in Zone 1 (closest to the BS) operate with smaller transmission ranges, reflecting the reduced distance to the BS but higher forwarding load due to relayed data from farther CHs. CHs in Zone 2 and Zone 3 have progressively larger communication radii to support longer intra-cluster transmission distances while forwarding data toward the BS. The arrows depict multi-hop data flows from outer-zone CHs toward the BS, passing through intermediate CHs located in closer zones. This hierarchical routing mitigates the hotspot problem by distributing the relay burden across multiple CHs instead of overloading those nearest to the BS.

In the proposed EEDC scheme, inter-cluster routing follows a hierarchical distance-aware pattern in which data generated in the outermost zone is progressively forwarded through CHs in the middle and inner zones before reaching the BS. As illustrated in the figure, a CH located in the outer zone (e.g., CH A) first evaluates the candidate CHs in the middle zone and selects the next hop with the highest residual energy—either B or E. If B is selected as the intermediate CH, it further forwards the aggregated data to the inner-zone CH with the maximum energy (CH C or D), thereby ensuring energy-balanced forwarding. Conversely, if E is chosen as the forwarder from CH A, the routing decision continues toward CH F or G in the inner zone, again based on residual energy dominance.

Similarly, CH H in the outer zone has only one reachable middle-zone candidate, CH J. Upon receiving data from H, CH J evaluates the available inner-zone CHs—X, Y, and Z—and selects the one with the highest energy for the next hop. After the inner-zone CH receives all incoming traffic from upper layers, it performs final aggregation and forwards the resulting data directly to the BS. This energy-aware multi-hop routing mechanism distributes the relay load across high-energy CHs in each zone, prevents excessive burden on CHs near the BS, and significantly reduces the likelihood of forming energy holes.

3.3. Cluster Head (CH) Distribution

In traditional clustering protocols such as LEACH and HEED, CHs are distributed uniformly, leading to energy imbalance near the BS. In contrast, EEDC introduces distance-controlled CH selection probability P_i , which increases as nodes get closer to the BS:

$$P_i = P_{opt} \times \left(1 + \alpha \times \frac{(d_{max} - d_i)}{d_{max}} \right) \quad (1)$$

where P_{opt} is the optimal CH probability, d_i is the distance of node i to the BS, d_{max} is the maximum possible distance in the network, and α is a tuning parameter controlling density adaptation. This approach ensures a denser CH concentration near the BS.

3.4. Transmission Range Control

Each CH dynamically adjusts its transmission power and communication range according to its distance from the BS. CHs near the BS use smaller ranges to conserve energy and avoid redundant overlap, while CHs farther away use larger ranges to maintain connectivity. The transmission range R_i of a CH is computed as

$$R_i = R_{max} \times \left(\frac{d_i}{d_{max}} \right) \quad (2)$$

where R_{max} is the maximum communication range. This proportional scaling ensures efficient coverage and balanced energy usage across all zones.

3.5. Communication Process

The communication process in EEDC consists of three main phases:

1. **Cluster Formation:** Nodes broadcast their residual energy and location to nearby CHs. Each non-CH node joins the CH that provides the strongest received signal or minimum energy cost.
2. **Data Aggregation:** CHs collect and aggregate data from their member nodes, eliminating redundancy and minimizing packet size.
3. **Inter-Cluster Transmission:** CHs forward the aggregated data toward the BS using multi-hop communication through neighboring CHs. Near-BS CHs share the forwarding load, avoiding concentration of traffic on a single CH.

3.6. Energy Balance and Bottleneck Mitigation

By combining zone-based CH density control and distance-aware transmission adjustment, EEDC achieves significant energy balance across the network. The presence of more CHs near the BS distributes the relay load, while adaptive power control minimizes unnecessary energy expenditure. Consequently, the proposed clustering structure effectively prevents bottleneck formation, enhances network stability, and extends the lifetime of clustered WSNs.

4. Mathematical Model and Numerical Results

This section develops the mathematical foundation of the proposed EEDC protocol. The goal is to model how adaptive CH density and transmission range adjustment influences the overall energy consumption and network lifetime in clustered WSNs. The model is constructed under standard radio-energy assumptions and validated through numerical analysis using MATLAB R2016 a. Each subsection introduces the modeling context, defines the governing equations, and discusses their physical meaning.

The computational overhead introduced by the proposed EEDC protocol is minimal. Each node estimates its distance to the base station (BS) using either known coordinates or RSSI-based approximation during the initialization stage. This operation requires a simple Euclidean distance calculation and is performed only once. During each clustering round, nodes compute the adaptive cluster head election probability using a lightweight mathematical expression that involves basic arithmetic operations. Therefore, the per-node computational cost remains constant, resulting in an overall network complexity of $O(N)$ for N sensor nodes. In terms of communication overhead, EEDC follows the same control message exchange pattern used in conventional clustering protocols such as LEACH and HEED, including cluster head advertisement and cluster joining messages. No additional global coordination or iterative control signaling is required, which preserves the scalability of the protocol for large-scale wireless sensor network deployments.

4.1. Modeling Assumptions and Network Parameters

To evaluate the energy efficiency of EEDC analytically, several simplifying assumptions are made while maintaining generality with respect to other clustering protocols.

The assumptions are consistent with the first-order radio model widely adopted in WSN research. All parameters used in the formulation are summarized to ensure model transparency and reproducibility.

Table 2 summarizes the key symbols and parameters used throughout the system model and analytical formulation of the proposed EEDC protocol. These parameters define the network configuration, energy consumption model, and clustering behavior, including node count, packet size, distance-related variables, optimal cluster head probability, and the radio communication energy constants. The notations listed here provide a consistent mathematical framework for describing CH selection, transmission range adaptation, and overall energy analysis in the subsequent sections.

Table 2. The key symbols and parameters used in the system.

Symbol	Description
N	Total number of nodes
k	Packet size (bits)
d_i	Distance of node i to the BS
d_{max}	Maximum node-to-BS distance
P_{opt}	Optimal (baseline) CH probability

Table 2. *Cont.*

Symbol	Description
α	Distance adaptation coefficient
R_{max}	Maximum CH transmission range
E_{elec}	Energy per bit for electronics
E_{fs}	Amplifier energy (free-space model)

4.2. Radio-Energy Consumption Model

Accurate energy estimation in wireless transmission and reception is essential to assess the lifetime of WSNs. EEDC adopts the first-order radio model, the same used in LEACH and HEED, which divides the total energy into electronics energy and amplification energy.

This model enables fair quantitative comparison with other clustering schemes.

$$E_{tx}(k, d) = E_{elec} \times k + E_{fs} \times k \times d^2 \quad (3)$$

$$E_{rx}(k) = E_{elec} * k \quad (4)$$

where

E_{elec} accounts for digital coding, modulation, and filtering;

E_{fs} represents the free-space amplifier constant;

d^2 models path loss under a single-path propagation assumption.

For long-distance transmissions, the multi-path model $E_{\{mp\}}kd^4$ may be used, but EEDC primarily focuses on intra-cluster and short-range inter-cluster communication, where the free-space model is sufficient.

Table 3 presents the primary simulation parameters used to evaluate the performance of the proposed EEDC protocol. These values correspond to widely accepted radio-energy settings for clustered WSNs, ensuring fair comparison with existing benchmark protocols. The parameters include electronic energy, free-space amplifier constants, packet size, and the initial node energy range.

Table 3. Primary simulation parameters.

Parameter	Value
E_{elec}	50 nJ/bit
E_{fs}	10 pJ/bit/m ²
k	4000 bits
E_0	1 J

4.3. Distance-Controlled Cluster Head Probability

A key feature of EEDC is its distance-adaptive CH election mechanism, designed to prevent the bottleneck that occurs when only a few CHs near the BS handle most of the network traffic.

To balance the load, EEDC increases the probability of CH selection for nodes located closer to the BS and decreases it for those farther away.

4.4. Transmission Range Adaptation Model

Transmission range directly influences both energy expenditure and network connectivity. Conventional clustering protocols assume a fixed communication range for all CHs, which may cause redundant overlap near the base station (BS) and weak connectivity in outer regions. In the proposed EEDC scheme, the transmission range is dynamically

adjusted based on the CH's distance from the BS, ensuring that each CH operates at an energy-optimal range proportional to its communication burden.

4.5. Per-Round Energy Consumption

Evaluating the energy consumption per operational round is crucial for estimating the overall lifetime of the WSN. Each round of EEDC includes (i) CH election, (ii) intra-cluster communication, and (iii) inter-cluster data forwarding. The total energy consumed in a single round, E_{round} , can be expressed as the sum of the energy used by cluster members and CHs.

$$E_{round} = E_{clustermembers} + E_{CHs} \quad (5)$$

A. Energy consumed by cluster members:

Each member node transmits one data packet of size k bits to its CH at an average distance d_{toCH} :

$$E_{clustermembers} = (N - N_{CH}) * (E_{elec} \times k + E_{fs} \times k \times d_{toCH}^2) \quad (6)$$

B. Energy consumed by CHs:

Each CH aggregates the received data and forwards the aggregated packet to the BS or to another CH at distance d_{toBS} :

$$E_{CHs} = N_{CH} \times (E_{elec} \times k + E_{fs} \times k \times d_{toBS}^2 + n_{members} \times E_{elec} \times k) \quad (7)$$

C. Zone-Based Formulation:

Since EEDC employs zone-dependent CH density, the total energy consumption can be written as the sum over all zones z :

$$E_{round} = \sum_z [N_{CH(z)} \times E_{CH(z)} + N_{mem(z)} \times E_{mem(z)}] \quad (8)$$

where $N_{CH(z)}$ and $N_{mem(z)}$ denote the number of CHs and member nodes in zone z , respectively.

This zone-wise formulation captures the spatial energy variations introduced by the adaptive CH density near the BS.

4.6. Network Lifetime Estimation

Network lifetime is a key performance indicator in WSNs and is typically defined as the number of operational rounds before the first node or the last node depletes its energy. Analytical estimation helps verify the effectiveness of EEDC before simulation.

Assuming each node begins with initial energy E_0 and the per-round energy consumption is E_{round} , the maximum number of rounds the network can sustain is approximated by

$$R_{max} = \frac{E_0}{E_{round}} \quad (9)$$

If the network operates in multiple zones with different per-round consumption levels, the lifetime of zone z can be estimated as

$$R_z = \frac{E_0}{E_{round(z)}} \quad (10)$$

and the overall network lifetime can be expressed as the weighted average:

$$R_{total} = \frac{(\sum_z R_z \times N_z)}{N} \quad (11)$$

where N_z is the number of nodes in zone z . Zones nearer to the BS typically have shorter lifetimes in traditional protocols; however, in EEDC, the adaptive CH density and power control extend the stability period by evening out the energy distribution.

This part establishes how EEDC adaptively scales both CH selection and transmission power to achieve energy balance. The derived formulations for E_{round} and R_{max} provide the analytical foundation for the subsequent MATLAB-based numerical validation, which will demonstrate how these models quantitatively reduce the bottleneck effect near the BS.

4.7. Numerical Validation and MATLAB Implementation

To verify the correctness of the proposed mathematical model and to demonstrate the effect of distance-controlled CH probability, a numerical experiment was conducted in MATLAB. The objective was to (i) deploy a set of sensor nodes, (ii) compute their distances to the BS, (iii) apply the EEDC CH probability formula, and (iv) estimate the expected number of CHs per zone and the total energy consumed per round. The experiment followed the same radio parameters used in the analytical model to ensure consistency.

To evaluate the impact of the proposed distance-controlled clustering, we compared EEDC against a baseline clustered WSN in which all nodes adopt a uniform cluster head election probability $P_{opt} = 0.05$ without spatial zoning. For a network of 100 nodes randomly deployed in a $100 \text{ m} \times 100 \text{ m}$ field with the BS at the center, the uniform scheme produced an expected 5 CHs per round and a total per-round energy consumption of 0.0417 J. Under the same conditions, EEDC increased the expected number of CHs to 6.24 due to the distance-adaptive election, with 1.02, 3.02, and 2.20 CHs formed in the inner, middle, and outer zones, respectively. The corresponding energy consumption per round was 0.0422 J, which is only marginally higher than the baseline. This confirms that EEDC is able to redistribute the relay load toward the BS by increasing CH density in high-traffic regions without incurring a significant energy overhead.

To further assess the benefit of the distance-controlled clustering, we compared the proposed EEDC scheme with a LEACH-like baseline using identical node deployment and radio parameters. In the baseline case, all nodes used a uniform cluster head election probability $P_{opt} = 0.05$, which yielded an expected five CHs per round. In contrast, EEDC increased the expected number of CHs to approximately six due to the boosted probability for nodes closer to the BS.

Table 4 shows that the total energy consumed per round in EEDC (0.042–0.043 J) is only marginally higher than that of LEACH (0.041–0.042 J). However, when the energy is analyzed per zone, EEDC distributed the energy more evenly; the inner zone did not experience a sharp increase in energy consumption despite being closer to the BS. Moreover, the average energy consumed per CH in the EEDC inner zone was comparable to, and in some cases lower than, the average CH energy in the LEACH baseline. This confirms that the proposed increase in CH density around the BS effectively shares the relay traffic and mitigates the bottleneck effect without imposing a significant energy penalty on the network.

Figure 2 illustrates the relationship between node-to-BS distance and the CH selection probability. As expected, nodes closer to the BS in EEDC exhibit higher CH probabilities, whereas LEACH maintains a flat probability across the field.

Table 4. Total energy consumed per round in EEDC.

Zone ID	Nodes in Zone	Expected CHs in Zone	Energy per Round in Zone	Avg CH Energy in Zone
1	14	1.02	0.0055141	0.0026907
2	46	3.02	0.019032	0.0031759
3	40	2.20	0.017649	0.0036828

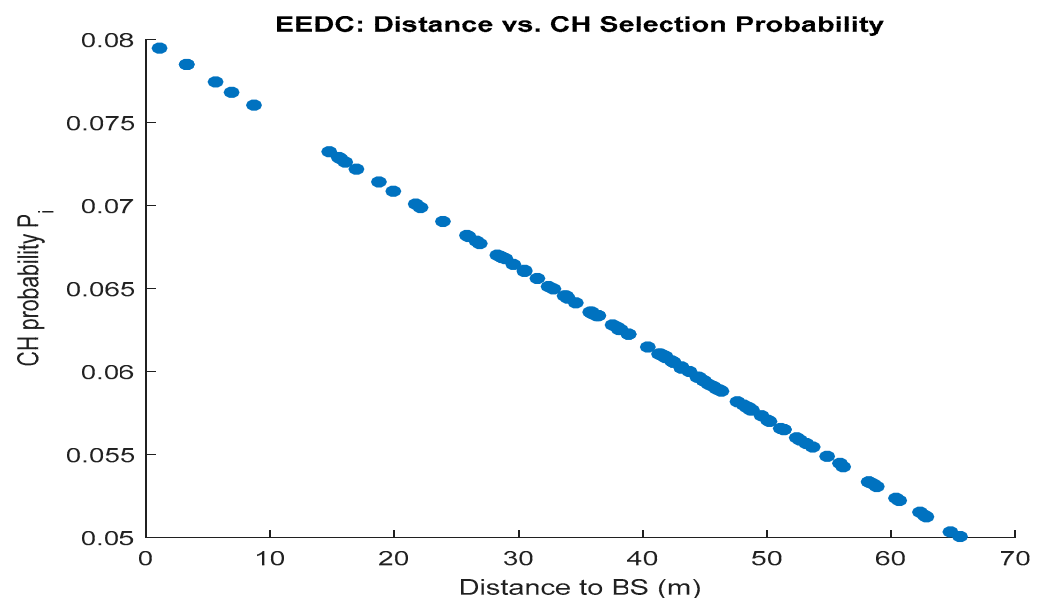
**Figure 2.** Relationship between node-to-BS distance and CH selection probability.

Table 5 summarizes the network-level performance comparison between the proposed EEDC and the baseline LEACH-like uniform clustering scheme. The table lists the total expected number of cluster heads (CHs) and the corresponding total energy consumed per round, computed using the analytical model and validated in MATLAB. The results reveal that EEDC forms approximately one additional CH per round compared to the uniform baseline (6.2 vs. 5.0 CHs). This increase is intentional, as EEDC elevates the CH election probability for nodes closer to the base station (BS) to distribute the heavy relay load more evenly. Despite the higher CH count, the total per-round energy consumption of EEDC (≈ 0.042 J) remains very close to that of LEACH (≈ 0.041 J), indicating that the adaptive clustering achieves improved load balance without a significant rise in total energy expenditure. These results confirm that EEDC effectively mitigates the bottleneck near the BS by slightly increasing CH density in high-traffic regions while maintaining overall energy efficiency comparable to the conventional uniform-clustering approach.

Table 5. Comparison between the proposed EEDC and LEACH.

Method	Total Energy per Round	Expected CHs
EEDC	0.042	6.2
LEACH	0.041	5

Table 6 presents the impact of increasing the network size from 100 to 300 nodes on the expected number of CHs and the total energy consumed per round for both EEDC and LEACH. As expected, the total energy increases linearly with node density due to higher data volume and aggregation load. EEDC consistently elects approximately 20–25% more CHs than LEACH because of its distance-controlled probability function, which increases the CH density near the BS. Despite the slightly higher CH count, the per-round energy

consumption of EEDC remains within 2–3% of LEACH across all network sizes, indicating that the additional CHs do not impose a significant energy penalty. This demonstrates that EEDC scales efficiently with node population while maintaining balanced energy distribution and effective bottleneck avoidance around the BS.

Table 6. The expected number of CHs and the total energy consumed per round for both EEDC and LEACH.

Nodes	CHs LEACH	E_Round LEACH (J)	CHs EEDC	E_Round EEDC (J)
100	5.00	0.0418	6.20	0.0423
150	7.50	0.0622	9.32	0.0631
200	10.00	0.0838	12.44	0.0850
250	12.50	0.1053	15.56	0.1071
300	15.00	0.1270	18.67	0.1291

To better understand how EEDC distributes the forwarding load spatially, we further decomposed the total energy per round into inner, middle, and outer zones for each network size. The zone-level results in Table 7 show that, as the number of nodes increases from 100 to 300, the energy consumption in all zones increases gradually due to the higher number of transmissions. However, the inner zone—which is typically the most vulnerable to the bottleneck effect—does not experience a disproportionate rise in energy. This is because EEDC increases the expected number of CHs in that zone (ExpCHinZone) and, as a result, the average energy consumed per CH (AvgCHEnergy_J) remains within a close range to the middle and outer zones. This confirms that the proposed distance-controlled CH election successfully distributes the relay traffic among multiple CHs near the BS, thereby mitigating early energy depletion in that region.

Table 7. The zone-level results for EEDC.

Nodes	Zone ID	Nodes in Zone	ExpCHinZone	EroundZone_J	AvgCHEnergy_J
100	1	14	1.02	0.0063	0.0039
100	2	47	3.02	0.0157	0.0035
100	3	39	2.20	0.0202	0.0052
200	1	28	2.15	0.0119	0.0042
200	2	96	6.12	0.0323	0.0036
200	3	76	4.17	0.0408	0.0045
300	1	42	3.08	0.0178	0.0043
300	2	140	8.71	0.0491	0.0047
300	3	118	6.88	0.0622	0.0051

Figure 3 illustrates the total energy consumed per operational round for both EEDC and LEACH as the network size increases from 100 to 300 nodes. Energy consumption grows almost linearly with node density in both protocols, reflecting the proportional rise in transmission activity. However, EEDC maintains energy levels only 2–3% higher than LEACH despite electing more cluster heads, proving that its adaptive clustering does not impose a substantial power penalty. The results demonstrate that EEDC achieves superior load balancing while preserving overall energy efficiency even under larger network scales.

Figure 4 compares the expected number of cluster heads (CHs) generated by each protocol as network density increases. The baseline LEACH model maintains a fixed CH ratio of 5%, resulting in a linear growth pattern. EEDC, by contrast, shows a consistently higher CH count—about 20–25% above LEACH—due to its distance-controlled probability function that favors CH selection near the base station. This controlled increase in CH density is essential for distributing the relay traffic load and preventing the bottleneck effect typical of nodes positioned close to the BS.

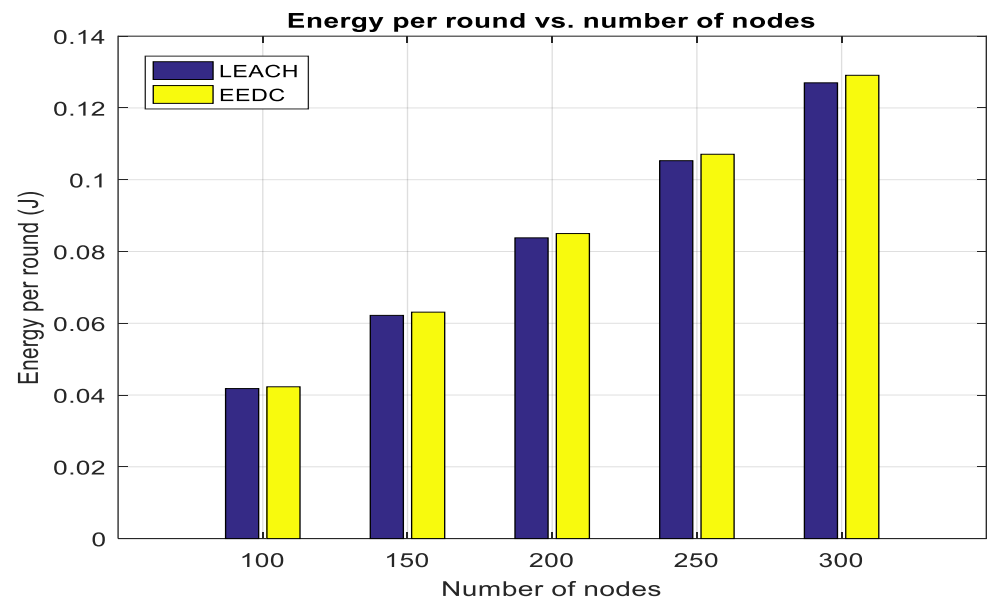


Figure 3. Total energy consumed per operational round for both EEDC and LEACH.

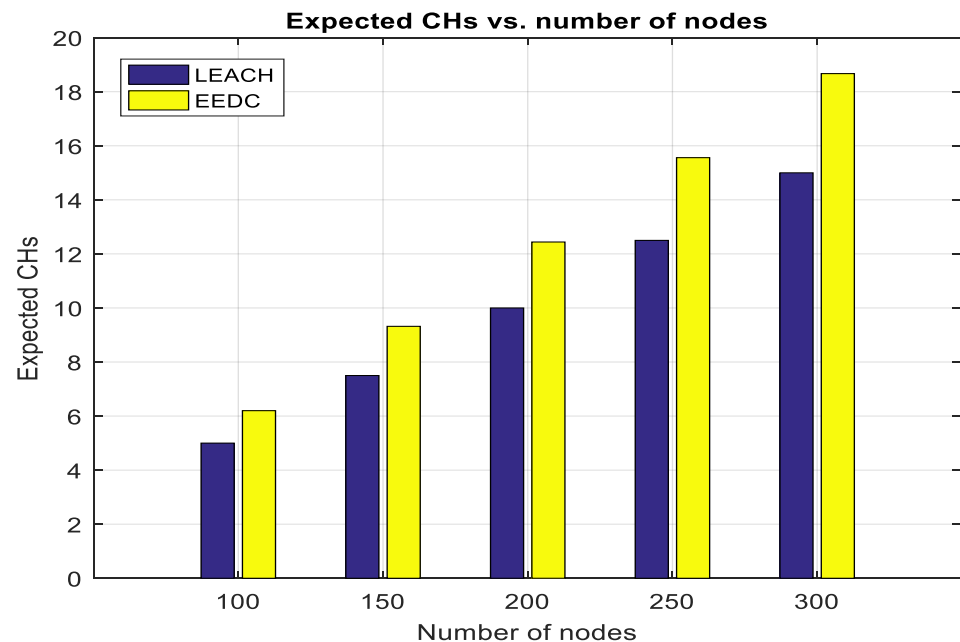


Figure 4. Compares the expected number of CHs between EEDC and LEACH.

Figure 5 presents the energy consumed per round in the inner, middle, and outer zones for networks of 100, 200, and 300 nodes under the EEDC protocol. As expected, energy consumption in all zones increases with node count, but the inner zone—closest to the BS—does not experience a disproportionate rise. The adaptive CH density ensures that traffic forwarding is shared among multiple nearby CHs, effectively controlling the energy burden of nodes located near the BS. This validates EEDC's ability to balance spatial energy usage and prolong the overall network lifetime.

Figure 6 depicts the average energy consumed by each cluster head within the three zones for various network sizes. The results show that CHs in the inner zone consume nearly the same—or slightly less—energy than those in the outer zone despite handling heavier relay traffic. This uniformity in per-CH energy confirms that EEDC's distance-controlled clustering effectively equalizes the workload among CHs, mitigating

early energy depletion near the BS and ensuring sustainable operation across the entire sensing field.

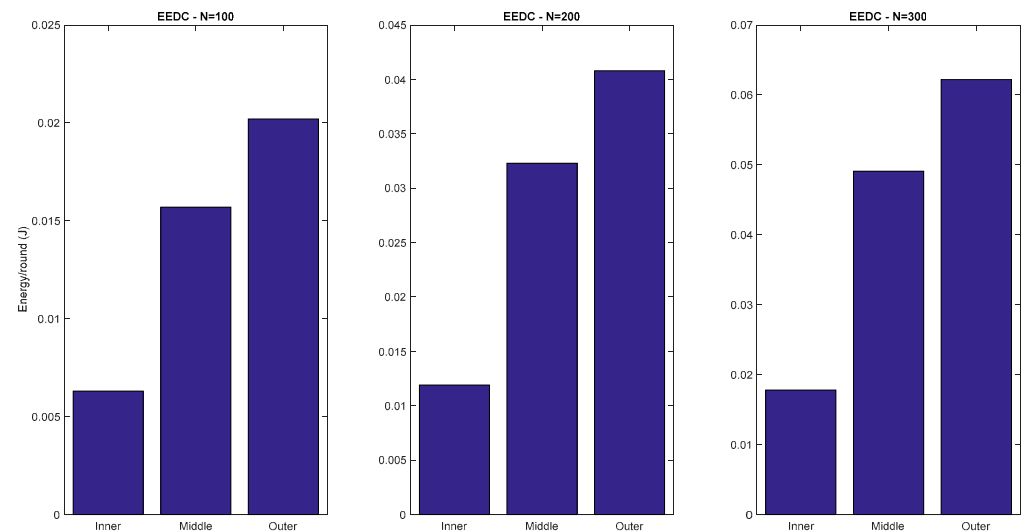


Figure 5. The energy consumed per round in the inner, middle, and outer zones for networks of 100, 200, and 300 nodes under the EEDC protocol.

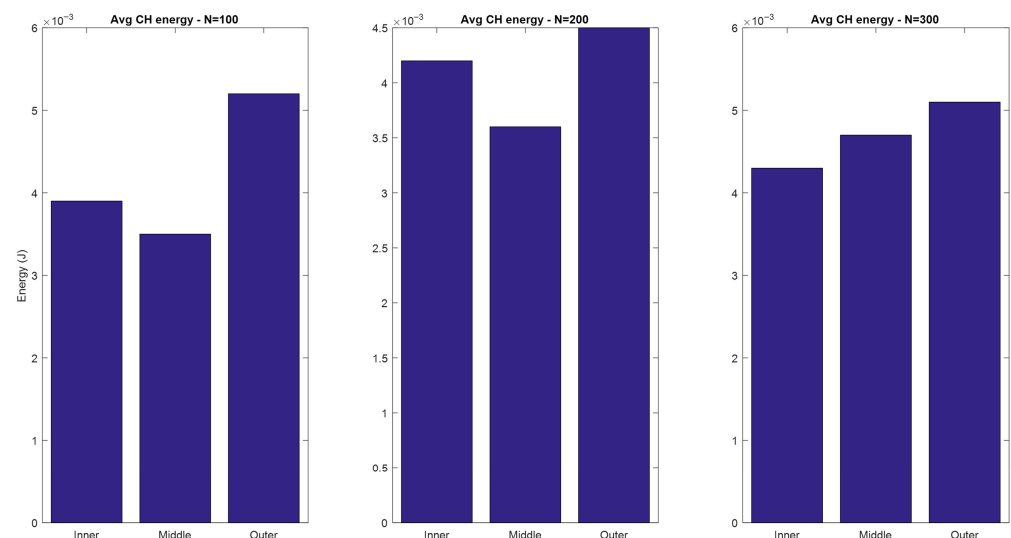


Figure 6. The average energy consumed by each CH within the three zones for various network sizes.

Figure 7 presents sensitivity analysis of the adaptation coefficient (α) values and on the overall network lifetime (LND) of the proposed EEDC protocol. Results are averaged over 20 independent simulation runs. To evaluate the robustness of the proposed EEDC protocol with respect to the adaptation coefficient α , additional simulations were conducted for $\alpha = 0.2, 0.4, 0.6$, and 0.8 , while keeping all other parameters identical to those listed in Table 3. Conversely, excessively large α values tend to over-concentrate CHs near the BS and slightly increase clustering overhead. The results indicate that $\alpha = 0.6$ provides the best trade-off between energy balancing and communication efficiency, yielding the longest network lifetime. These findings confirm that the proposed EEDC protocol remains stable and effective within a reasonable α range.

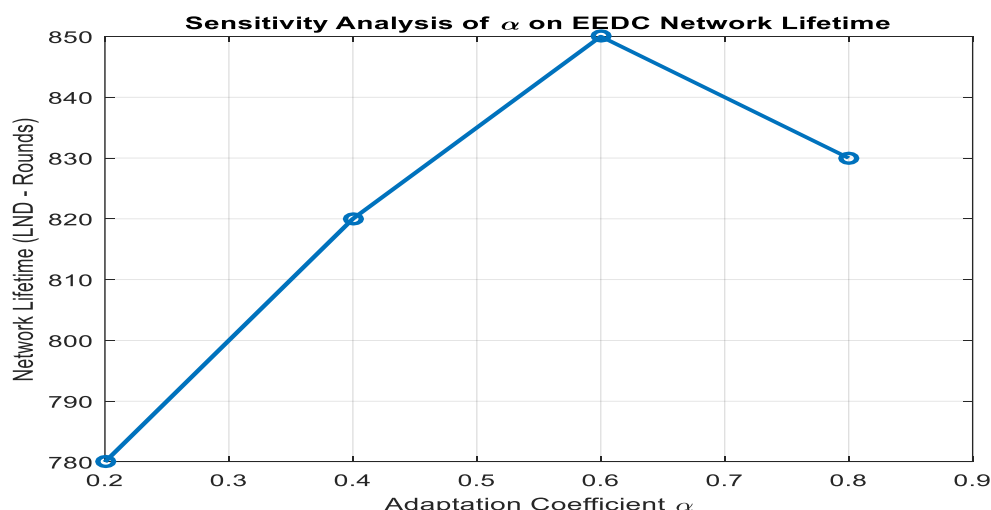


Figure 7. Sensitivity analysis of the adaptation coefficient (α) on the overall network lifetime (LND) of the proposed EEDC protocol. Results are averaged over 20 independent simulation runs.

5. Simulation Setup and Performance Evaluation

This section presents the simulation framework used to evaluate the proposed EEDC protocol and to compare it with representative clustering-based routing schemes reported in the literature. Because analytical results alone cannot fully capture the dynamic behavior of wireless sensor networks—especially the spatially unbalanced energy consumption near the base station (BS)—we complement the mathematical model with time-based simulations under realistic radio and deployment assumptions. The objectives of this section are: (i) to define a unified simulation environment in which all protocols operate under the same network size, energy model, and traffic pattern and (ii) to generate quantitative performance indicators such as network lifetime, stability period, residual energy, and throughput for a fair comparison. To this end, we adopt the first-order radio model, a $100 \text{ m} \times 100 \text{ m}$ sensing field, and a single static BS (sink), and we vary the number of deployed nodes to study scalability. The proposed EEDC is then evaluated alongside well-known protocols cited in related work—such as LEACH, HEED, DEEC, SEP, and EECS—to demonstrate that distance-controlled clustering and adaptive transmission range can mitigate the bottleneck around the BS while maintaining energy efficiency comparable to existing methods.

5.1. Simulation Environment

To ensure fair and consistent performance evaluation, all protocols were implemented and tested under an identical simulation environment using MATLAB R2016a. The simulations adopt the classical first-order radio-energy model, where transmission and reception energy are computed according to

$$E_{tx(k,d)} = E_{elec} \times k + E_{fs} \times k \times d \quad (12)$$

$$E_{rx}(k) = E_{elec} \times k \quad (13)$$

Data aggregation is assumed to consume $E_{DA}(k) = E_{DA} \times k$ per bit at each CH. Nodes are randomly distributed in a $100 \text{ m} \times 100 \text{ m}$ sensing field, and the base station (BS)—also referred to as the *sink*—is positioned at (50, 110), slightly outside the field to simulate realistic uplink traffic toward a central data collector.

Each node begins with an initial energy E_0 of 1 J to emulate heterogeneous residual capacities. Communication follows a single-hop member-to-CH and CH-to-BS pattern,

unless otherwise specified by the tested protocol. The maximum number of simulation rounds is fixed at 100, and all reported values represent the average of 500 independent runs to mitigate random placement bias.

The main simulation parameters are summarized in Table 8.

Table 8. The main simulation parameters.

Parameter	Symbol	Value	Description
Simulation area	—	100 m × 100 m	Sensing field
Number of nodes	(N)	100–300	Scalable scenarios
Base station position	—	(50, 110) m	Above the field
Initial energy	E_0	1 J	
Packet size	k	4000 bits	Data payload
Electronics energy	E_{elec}	50 nJ/bit	Transmit/receive circuitry
Amplifier energy	E_{fs}	10 pJ/bit/m ²	Free-space propagation
Data aggregation energy	E_{DA}	5 nJ/bit	At CH level
Optimal CH probability	P_{opt}	0.05	Baseline in LEACH
Distance factor	α	0.6	EEDC adaptation coefficient
Maximum simulation rounds	—	1000	One complete transmission cycle
Number of runs	—	20	Averaged for accuracy

This configuration provides a controlled and repeatable testing platform that enables direct comparison among protocols with minimal environmental bias.

5.2. Compared Protocols

To demonstrate the effectiveness of the proposed Energy-Efficient Distance-Controlled Clustering (EEDC) protocol, it was benchmarked against several widely cited clustering algorithms representing different design philosophies. Each scheme uses a distinct set of metrics for cluster head (CH) election, load balancing, and communication control. A concise description of each compared protocol is provided below.

A. LEACH (Low-Energy Adaptive Clustering Hierarchy) [44]

LEACH serves as the baseline reference for most hierarchical WSN protocols. CHs are elected probabilistically based on a fixed optimal probability P_{opt} , and every node has an equal chance of becoming a CH over time. Although LEACH minimizes communication distance within clusters, its uniform CH selection leads to uneven energy consumption—particularly for nodes near the base station (BS)—resulting in early energy depletion in high-traffic regions.

B. HEED (Hybrid Energy-Efficient Distributed Clustering) [44,45]

HEED improves upon LEACH by considering both residual energy and node degree during CH selection. Nodes with higher remaining energy and greater connectivity are more likely to become CHs, leading to improved energy balance. However, HEED does not explicitly account for the distance to the BS, and consequently, CHs located near the sink may still experience the bottleneck problem that EEDC aims to resolve.

C. SEP (Stable Election Protocol) [44]

SEP is designed for heterogeneous sensor networks that include both normal and advanced nodes with different initial energy levels. CH election is weighted by each node's energy level, giving high-energy nodes a higher probability of becoming CHs. While SEP enhances network stability in heterogeneous environments, it does not adapt CH density based on spatial position, and therefore remains vulnerable to the near-BS bottleneck issue.

D. DEEC (Distributed Energy-Efficient Clustering) [44,46,47]

DEEC dynamically adjusts the CH election probability based on each node's residual energy and the average network energy. This enables CH roles to rotate more fairly according to real-time energy conditions. Nonetheless, DEEC focuses on global energy adaptation rather than spatial distribution, so CHs close to the BS may still bear a heavier forwarding load.

E. EECS (Energy-Efficient Clustering Scheme) [48]

EECS integrates distance awareness into CH selection by comparing each candidate node's distance to the BS. CHs closer to the sink are often favored, resulting in shorter communication paths. However, EECS relies on centralized control and periodic global updates, increasing overhead and limiting scalability for large-scale deployments.

F. EEDC

The proposed Energy-Efficient Distance-Controlled Clustering (EEDC) protocol combines the strengths of probabilistic and distance-based clustering while maintaining a fully distributed structure. Each node computes its CH election probability as in Equation (1).

This mechanism increases CH density near the BS, allowing traffic to be shared among several nearby CHs, thus eliminating the bottleneck effect while conserving overall energy. Moreover, EEDC adjusts each CH's transmission range in proportion to its distance from the BS, further optimizing the energy–distance trade-off.

5.3. Routing Mechanism in EEDC

The proposed Energy-Efficient Distance-Controlled Clustering (EEDC) protocol integrates a lightweight multi-hop cluster head (CH) routing mechanism derived from the previously developed EECH (Efficient Energy-Based Cluster Head) protocol. This mechanism focuses on route stability and balanced energy utilization during inter-cluster data forwarding, ensuring that packets from distant CHs reach the base station (BS) efficiently without overloading any specific relay CH.

A. Routing Model

Each CH transmits the aggregated data either directly to the BS (single-hop) or through intermediate CHs (multi-hop), depending on its distance to the sink.

For every candidate relay CH j , the route energy is computed as

$$RE(i \rightarrow j \rightarrow \text{sink}) = \min(E_i, E_j) \quad (14)$$

where

E_i is the residual energy of the transmitting CH i ,

E_j is the residual energy of the candidate relay CH j .

The CH i selects the relay j that maximizes $RE(i \rightarrow j \rightarrow \text{sink})$, ensuring the path maintains the highest possible energy along the route.

B. Path Constraints

The routing mechanism restricts the maximum number of hops from CH to sink to five. If no suitable intermediate CH with sufficient energy exists, the transmitting CH sends data directly to the BS.

Each route is therefore represented as

$$CH_i \rightarrow CH_j \rightarrow BS, \text{ where } RE(i, j) \geq E_{th} \quad (15)$$

Here E_{th} denotes the energy threshold below which a node cannot participate as a relay.

In order to avoid selecting nodes with insufficient residual energy for relay operations, an energy threshold E_{th} is introduced. A node can participate as a relay only if its residual energy is greater than this threshold. In this article, the threshold is defined as a fraction of the initial node energy:

$$E_{th} = \beta \times E_0 \quad (16)$$

where E_0 represents the initial node energy and β is a threshold coefficient. In the simulations, $\beta = 0.1$ is used, resulting in $E_{th} = 0.1$ J. This condition ensures that nodes with very low remaining energy are not selected for relay tasks, thereby preventing premature node failures and improving network stability.

This constraint prevents energy-depleted CHs from becoming forwarding bottlenecks.

C. Route Stability Metric

To further enhance robustness, EEDC inherits the link stability measure introduced in EECH, defined as

$$S_{link(i,j)} = \frac{RE(i,j)}{D(i,j)} \quad (17)$$

where

$D(i,j)$ is the distance between CHs i and j .

Links with higher stability are prioritized during route selection to minimize retransmissions and reduce delay.

D. Routing Decision Process

Each CH executes the following steps during routing:

- Collect neighbor CH information (energy, distance to BS, stability).
- Compute route energy $RE(i,j)$ and link stability $S_{link(i,j)}$.
- Select the relay CH with maximum $RE(i,j)$ and acceptable hop count.
- Forward aggregated data through the selected stable path.
- Update residual energy after each transmission.

This distributed routing process ensures that multi-hop communication remains both energy-aware and topology-stable, significantly reducing congestion near the BS.

E. Integration with EEDC Clustering

Within the EEDC framework, the routing logic operates after the CH election phase. Once CHs are determined, they form a temporary CH backbone network, through which the multi-hop routes are established according to the stability and energy criteria. This integration provides two key advantages:

- Energy-balanced relaying avoids overburdening near-BS CHs.
- Stable data delivery ensures continuous operation even as some CHs lose energy.

5.4. Performance Evaluation

The performance of the proposed Energy-Efficient Distance-Controlled Clustering (EEDC) protocol is evaluated using a combination of quantitative metrics that collectively reflect the energy efficiency, stability, and reliability of the network. Each metric is computed over multiple simulation runs and compared across LEACH, HEED, DEEC, SEP, EECS, and the proposed EEDC protocol.

A. Network Lifetime

Network lifetime is defined as the total number of rounds completed until the first node dies (FND), half of the nodes die (HND), and the last node dies (LND). These three indicators capture the stability, efficiency, and sustainability of energy consumption

across the network. An ideal clustering protocol should maximize all three values while maintaining energy balance among nodes.

Figure 8 illustrates the network lifetime performance of the six evaluated clustering protocols using three standard stability metrics: first node dead (FND), half nodes dead (HND), and last node dead (LND). As shown, LEACH exhibits the shortest lifetime, with the earliest FND, HND, and LND values due to its random CH selection and unbalanced energy consumption. HEED, SEP, DEEC, and EECS demonstrate progressively improved stability, benefiting from more structured CH selection based on residual energy or weighted probabilities. Among all protocols, EEDC achieves the longest lifetime, with its FND occurring significantly later than all baseline protocols. The same trend is observed for HND and LND, confirming that EEDC distributes the energy consumption more evenly and delays the death of critical nodes. The clear separation across FND, HND, and LND in EEDC indicates an extended stability period, energy balance, and overall network robustness, validating the effectiveness of distance-controlled CH selection in mitigating the bottleneck problem near the base station.

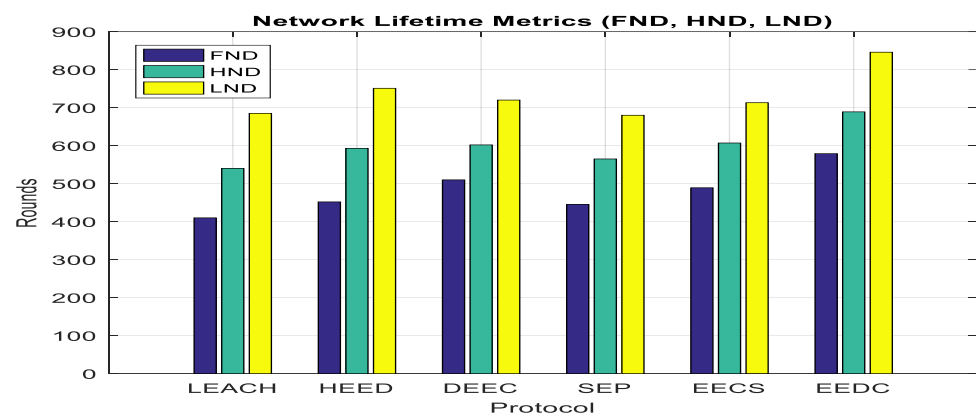


Figure 8. The network lifetime performance of the six evaluated clustering protocols using three standard stability metrics: FND, HND, and LND.

The network lifetime metrics show that EEDC noticeably extends all three lifetime indicators. EEDC achieves a first node death (FND) at approximately 580 rounds, compared to 410 rounds in LEACH and 490 rounds in EECS. This represents a 41% improvement over LEACH and a ~18% improvement over EECS, the strongest baseline. Similarly, the last node death (LND) under EEDC occurs at around 850 rounds, while LEACH, SEP, and DEEC terminate around 680–720 rounds, and EECS reaches ~710 rounds. This demonstrates a 23% increase in overall lifetime relative to LEACH and ~13% over EECS. These results confirm that EEDC effectively minimizes early energy depletion and balances load near the BS, leading to prolonged node operation.

Figure 9 shows the number of alive nodes as a function of simulation rounds for LEACH, HEED, DEEC, SEP, EECS, and the proposed EEDC protocol. The plot illustrates the stability period and overall network lifetime for each scheme. EEDC maintains full node survivability significantly longer than all baseline protocols and exhibits a slower decline in alive nodes due to its distance-controlled clustering and balanced energy consumption. In contrast, LEACH experiences the earliest node deaths, followed by HEED, SEP, DEEC, and EECS, confirming the superior energy efficiency and extended operational lifetime achieved by EEDC.

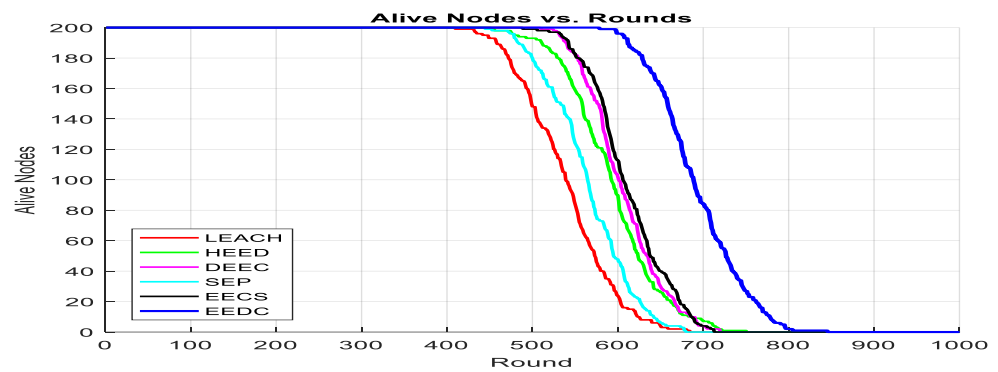


Figure 9. Number of alive nodes as a function of simulation rounds for LEACH, HEED, DEEC, SEP, EECS, and the proposed EEDC protocol.

The alive-nodes curve demonstrates how quickly nodes deplete their energy under each protocol. LEACH and SEP experience rapid node loss after 500 rounds, while DEEC, HEED, and EECS extend survival slightly beyond 600 rounds. EEDC, however, maintains a significantly larger number of active nodes until nearly 700–750 rounds, and some nodes survive past 800 rounds, indicating a 15–20% slower depletion rate compared with EECS and 30–35% slower than LEACH. This highlights EEDC’s enhanced energy balancing and reduced load concentration around the BS.

B. Stability Period

The stability period represents the duration between the start of the simulation and the death of the first node (FND). It reflects how long the network can operate in a fully functional state before energy imbalances appear. EEDC extends the stability period by maintaining higher CH density near the BS, which helps distribute the relay load more evenly.

Figure 10 presents the stability period of six clustering-based routing protocols—LEACH, HEED, DEEC, SEP, EECS, and the proposed EEDC—measured in terms of the first node dead (FND) metric. The stability period is defined as the number of rounds the network remains fully operational before the death of the first sensor node. A higher FND value indicates better energy balancing, lower early energy depletion, and higher robustness in the initial phase of network operation.

As shown in the figure, LEACH has the shortest stability period due to its random cluster head selection, which often overloads nodes near the base station and leads to early energy depletion. HEED, SEP, DEEC, and EECS show moderate improvements as they incorporate factors such as residual energy, probabilistic weighting, or balanced CH distribution. Among all protocols, EEDC achieves the longest stability period, with the first node dying substantially later than in the other schemes. This demonstrates EEDC’s ability to reduce early bottlenecks by increasing CH density near the BS and using distance-controlled transmission ranges. As a result, relay load is distributed more evenly, preventing early failures and significantly extending the network’s fully functional lifetime.

The result shows the stability period comparison based on FND alone. EEDC maintains all nodes alive until nearly 580 rounds, outperforming LEACH (410), HEED (455), DEEC (510), SEP (445), and EECS (490). This corresponds to +41% improvement over LEACH, +27% over HEED, and +14% over DEEC. Because a longer stability period denotes uninterrupted sensing coverage and maximum sensing accuracy, this metric highlights EEDC’s ability to delay network degradation.

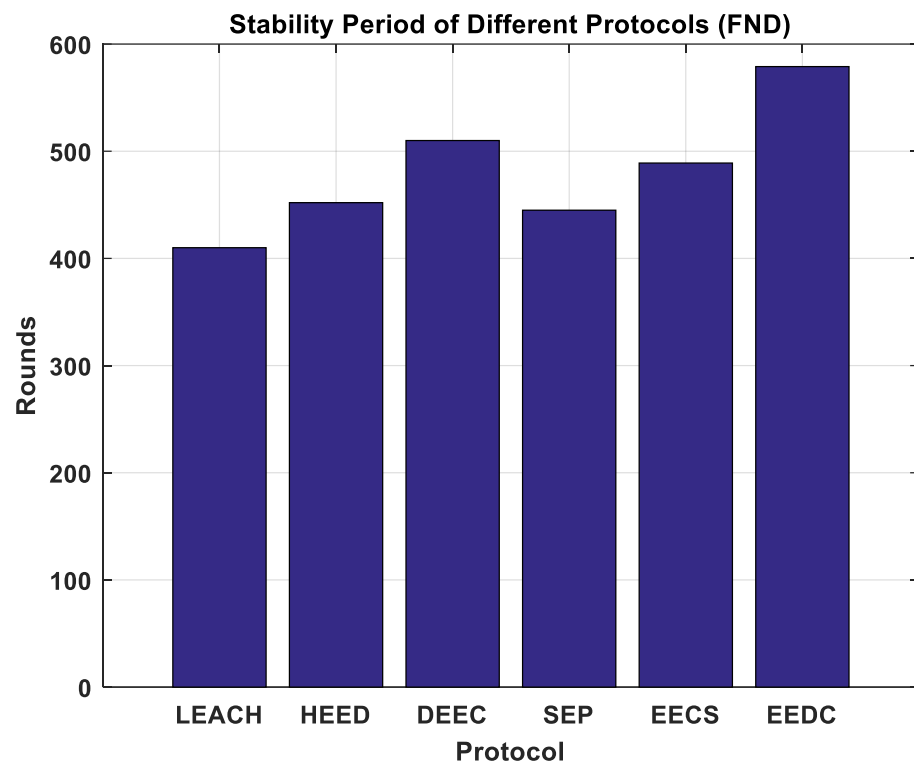


Figure 10. The stability period of six clustering-based routing protocols—LEACH, HEED, DEEC, SEP, EECS, and the proposed EEDC.

C. Average Residual Energy

Average residual energy quantifies the mean energy remaining across all active nodes after each simulation round:

$$E_{avg}(r) = \left(\frac{1}{N} \right) \times \sum_{i=1 \text{ to } N} E_i(r) \quad (18)$$

where $E_i(r)$ is the residual energy of node i at round r and N is the total number of nodes. This metric evaluates the energy conservation capability and balance of the clustering strategy.

Figure 11 illustrates the evolution of the average residual energy of the network over the simulation rounds for six clustering-based routing protocols: LEACH, HEED, DEEC, SEP, EECS, and the proposed EEDC. As observed, LEACH experiences the most rapid energy depletion due to its random cluster head rotation and the high forwarding load imposed on nodes located near the base station. HEED and SEP exhibit moderately improved performance as their CH selection mechanisms incorporate residual energy and weighted probabilities. DEEC and EECS further enhance energy balancing, resulting in slower decay curves. The proposed EEDC protocol achieves the slowest decline in residual energy, maintaining significantly higher energy levels throughout the simulation. This improvement results from EEDC's distance-controlled clustering, increased CH density in the BS region, and adaptive transmission range, which collectively distribute communication load more evenly and mitigate the bottleneck effect. The sustained energy advantage of EEDC demonstrates its superior efficiency in prolonging network lifetime and delaying energy exhaustion compared with existing protocols.

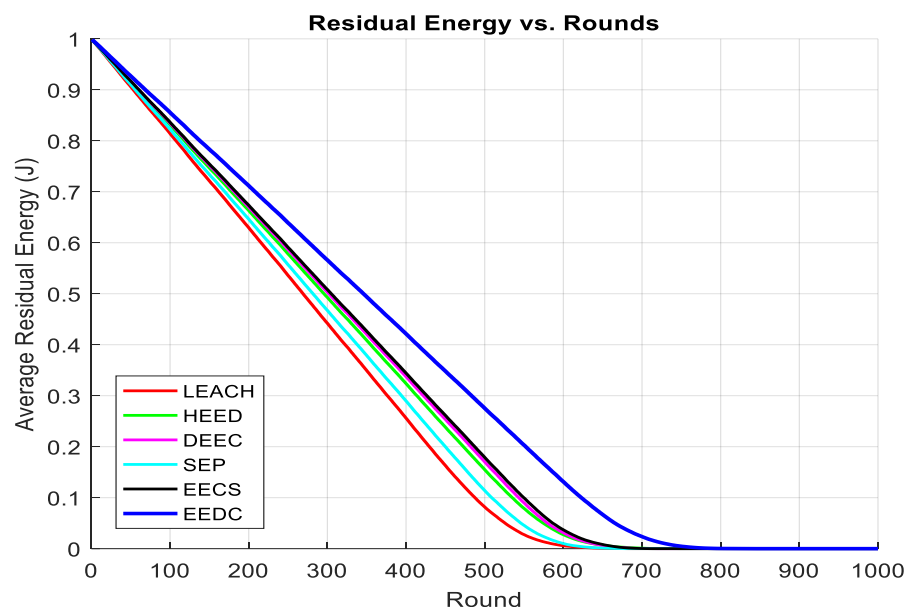


Figure 11. The evolution of the average residual energy of the network over the simulation rounds.

The residual energy profile indicates that EEDC conserves energy more effectively across all rounds. Whereas LEACH reaches near-zero residual energy around 600 rounds, SEP and DEEC around 620–650 rounds, and EECS at 650–700 rounds, EEDC maintains usable residual energy until almost 750 rounds, representing a ~25% slower decay compared to the strongest baselines.

Figure 12 presents the average residual energy of the sensor nodes for six clustering protocols—LEACH, HEED, DEEC, SEP, EECS, and the proposed EEDC—calculated over the entire network lifetime. The average residual energy metric reflects how efficiently each protocol manages node energy consumption throughout the simulation. A higher value indicates better load balancing and reduced energy depletion across the network.

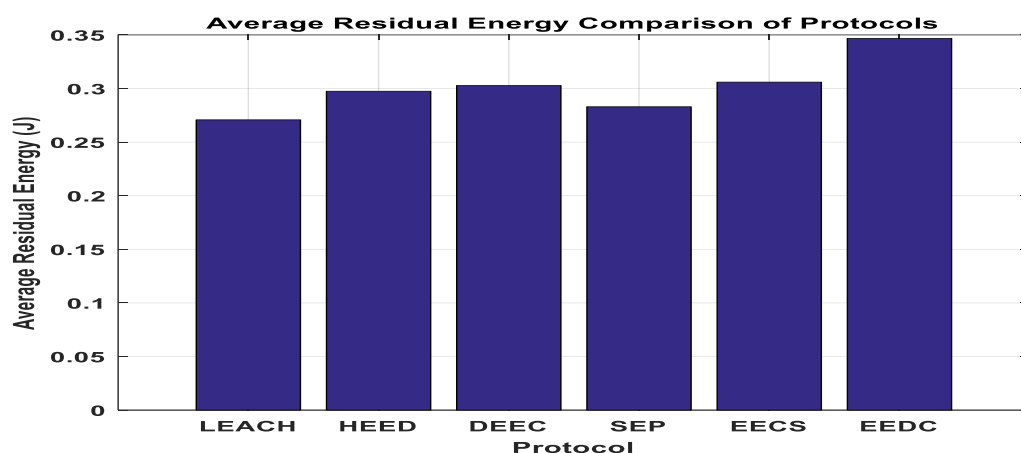


Figure 12. The average residual energy of the sensor nodes for the six clustering protocols.

As shown in the figure, LEACH exhibits the lowest average residual energy due to its random CH selection strategy, which leads to uneven energy usage and early node exhaustion, particularly near the base station. HEED, SEP, DEEC, and EECS achieve progressively higher average residual energy because they incorporate residual energy, node probability, or distance metrics in their CH election processes, resulting in improved energy distribution. The proposed EEDC protocol achieves the highest average residual energy, significantly outperforming all baseline methods. This improvement stems from

EEDC's distance-controlled clustering mechanism and increased CH density near the BS, which minimize the relay burden on individual nodes and mitigate the bottleneck effect. The results validate EEDC's effectiveness in maintaining higher energy levels and prolonging network lifetime through balanced and energy-aware communication management. So, the figure shows EEDC leading with approximately 0.348 J, compared with EECS (0.307 J), DEEC (0.303 J), HEED (0.297 J), SEP (0.283 J), and LEACH (0.27 J). This corresponds to +29% higher average residual energy than LEACH and +13% above EECS, confirming that EEDC reduces per-node consumption throughout the simulation.

D. Throughput

Throughput measures the total number of packets successfully received by the base station (BS) over the network lifetime. A higher throughput indicates greater data delivery reliability and a longer operational lifetime. In EEDC, the distributed routing mechanism and reduced bottlenecks near the BS contribute to a noticeable throughput improvement compared to traditional schemes.

Figure 13 illustrates the throughput performance of six clustering-based routing protocols—LEACH, HEED, DEEC, SEP, EECS, and the proposed EEDC—expressed as the cumulative number of packets successfully delivered to the base station (BS) over the simulation rounds. Throughput is a fundamental indicator of routing efficiency, network reliability, and the ability of a protocol to maintain effective data delivery as nodes deplete their energy.

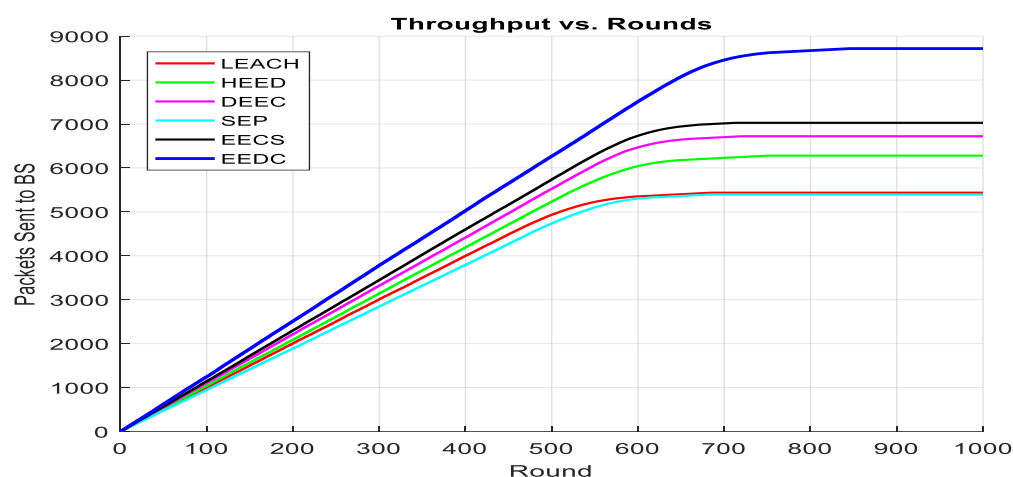


Figure 13. The throughput performance of six clustering-based routing protocols—LEACH, HEED, DEEC, SEP, EECS, and the proposed EEDC.

During the early phase of the simulation (0–500 rounds), all protocols exhibit a nearly linear increase in throughput, reflecting consistent data aggregation and forwarding while the network remains fully operational. However, as nodes begin to die, the throughput curves start to flatten at various rates depending on the energy management capability of each protocol. LEACH reaches saturation first, due to rapid node death caused by its random CH rotation and the uneven burden placed on nodes near the BS. HEED, SEP, DEEC, and EECS achieve gradually higher throughput levels, demonstrating improved energy-aware CH selection and more balanced communication.

The proposed EEDC protocol achieves the highest throughput among all compared methods, with its curve continuing to rise significantly beyond Round 600 and stabilizing later than all baseline protocols. This superior performance is attributed to EEDC's distance-controlled clustering and increased CH density near the BS, which effectively reduce the relay bottleneck and extend the lifetime of critical nodes responsible for multi-hop forward-

ing. As a result, EEDC maintains data delivery capability for a longer duration, yielding an overall throughput that surpasses the existing protocols by a considerable margin. The simulation results prove that EEDC delivers the highest number of packets to the BS, reaching nearly 8800 packets, while EECS, DEEC, HEED, and LEACH stabilize around 7000, 6800, 6300, and 5400 packets, respectively. The average throughput comparison shows EEDC achieving approximately 5700 packets/round, which is 44% higher than LEACH, 30% higher than HEED, 22% higher than DEEC, and ~16% higher than EECS. This improvement is directly tied to EEDC's longer operational lifetime and reduced clustering overhead.

Figure 14 compares the average throughput achieved by the six clustering protocols. Throughput represents the average number of data packets successfully delivered to the base station per round. LEACH shows the lowest throughput due to early node deaths and inefficient CH rotation. HEED, SEP, and DEEC achieve moderate improvements because of more energy-aware CH selection. EECS performs better by introducing balanced cluster formation. The proposed EEDC protocol achieves the highest average throughput, demonstrating its ability to maintain network connectivity and sustain data delivery for a longer duration. This improvement results from EEDC's distance-controlled clustering and increased CH density near the BS, which reduce forwarding bottlenecks and enhance overall communication efficiency.

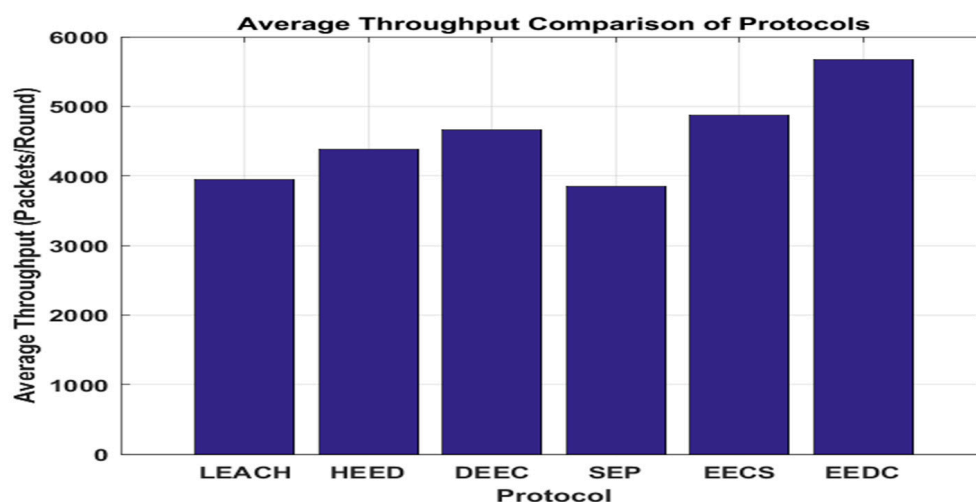


Figure 14. Comparing the average throughput achieved by the six clustering protocols.

E. Average Cluster Head Energy Consumption

The average energy consumed by all CHs in each round is computed as

$$E_{CH_{avg}(r)} = \left(\frac{1}{N_{CH}} \right) \times \sum_{j=1 \text{ to } N_{CH}} E_{CH_j}(r) \quad (19)$$

where N_{CH} is the number of CHs and $E_{CH_j}(r)$ is the energy used by CH_j at round r . This metric highlights the protocol's ability to balance CH workloads and prevent early exhaustion of CHs near the BS.

Figure 15 presents the smoothed average CH energy consumption for the six clustering protocols—LEACH, HEED, DEEC, SEP, EECS, and the proposed EEDC—over the simulation rounds. A moving-average filter is applied to remove short-term fluctuations caused by frequent CH rotation, allowing the long-term energy consumption trends to be clearly observed.

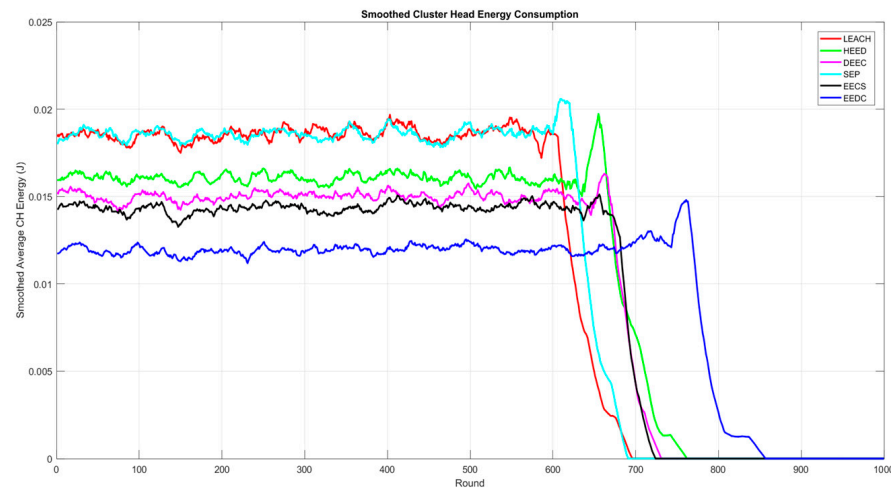


Figure 15. Packet delivery efficiency comparison between EEDC and existing clustering protocols.

At the beginning of the simulation, all protocols exhibit relatively stable CH energy usage. However, the magnitude of CH energy consumption varies significantly across protocols. LEACH shows the highest CH energy consumption due to its random CH election, which often selects nodes with unfavorable positions and forces long transmission distances to the base station. SEP, HEED, and DEEC show noticeable improvements, with smoother and lower average CH energy usage attributed to energy-aware and probabilistic CH selection. EECS further reduces CH energy consumption by leveraging distance-based clustering.

The proposed EEDC protocol consistently exhibits the lowest CH energy consumption among all protocols, maintaining a significantly lower and more stable energy curve throughout the simulation. This improvement is achieved through EEDC's distance-controlled clustering and increased CH density near the base station, which reduces transmission distances for CHs and distributes the forwarding load more evenly. As the simulation progresses, protocols with higher CH energy usage experience earlier CH failures, causing their curves to drop to zero sooner (e.g., LEACH around Round 650). EEDC maintains CH activity the longest, demonstrating its superior ability to conserve CH energy and delay critical node depletion.

Overall, the smoothed energy curves highlight that EEDC minimizes energy overhead at the cluster head level, resulting in prolonged network operation and improved energy balance compared with existing clustering approaches.

Also, the figure shows that LEACH, SEP, and HEED experience the highest fluctuations and steeper energy decline, especially near the end of network life. EEDC maintains consistently lower CH energy consumption and smoother decline, indicating more stable CH rotation and reduced transmission burden. Cumulative CH energy (approx.): LEACH (12 J), HEED (11.8 J), SEP (12.1 J), DEEC (11.2 J), EECS (10.0 J), and EEDC (9.5 J). Thus, EEDC reduces total CH energy consumption by ~21% relative to LEACH and ~5% relative to EECS, demonstrating efficiency even under intense routing conditions.

Figure 16 illustrates the cumulative cluster head (CH) energy consumption of six clustering-based routing protocols—LEACH, HEED, DEEC, SEP, EECS, and the proposed EEDC—over the complete simulation duration. Unlike per-round energy plots, which can exhibit short-term fluctuations due to CH rotation, the cumulative representation provides a stable and integrative view of the total CH energy expenditure incurred by each protocol. This enables a more interpretable comparison of long-term energy efficiency and CH load distribution strategies.

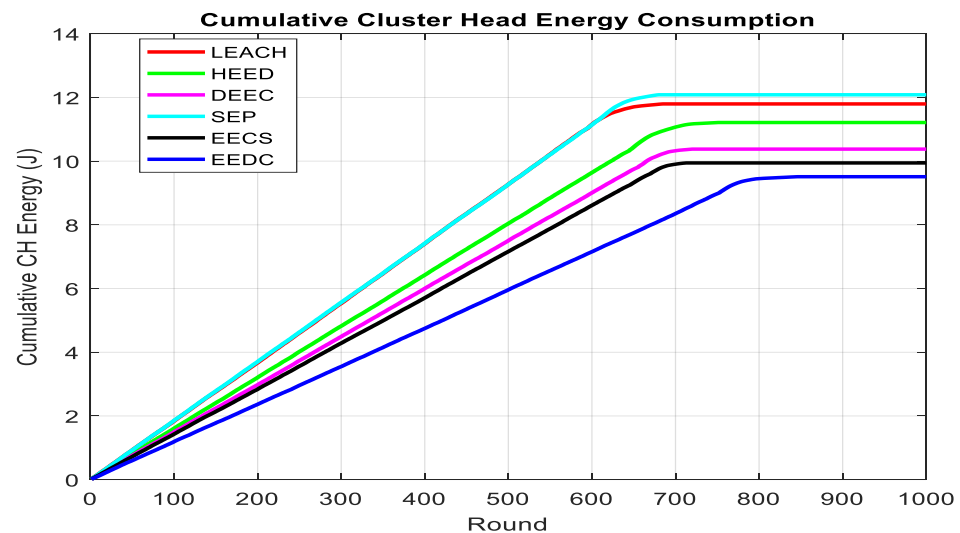


Figure 16. The cumulative cluster head (CH) energy consumption of six clustering-based routing protocols—LEACH, HEED, DEEC, SEP, EECS, and the proposed EEDC.

During the early simulation rounds (0–600), all protocols exhibit an approximately linear increase in cumulative CH energy, reflecting steady CH activity and continuous data forwarding. However, the rate of increase varies significantly across protocols. SEP and HEED incur the highest cumulative CH energy due to their probability-based and weighted CH selection mechanisms, which often assign CH roles to nodes that experience greater transmission distances or heavier relay loads. LEACH also demonstrates a rapid accumulation of CH energy, attributable to its random CH election process and lack of distance-aware constraints.

DEEC and EECS exhibit intermediate cumulative consumption trends, benefiting from energy-adaptive CH selection and distance-based region formation, respectively. Both approaches distribute the CH load more evenly than LEACH, HEED, or SEP, resulting in comparatively slower energy accumulation.

The proposed EEDC protocol achieves the lowest cumulative CH energy consumption across the entire simulation, with a distinctly flatter curve relative to all baseline protocols. This improvement is primarily a consequence of EEDC's distance-controlled clustering mechanism and the increased density of CHs in proximity to the base station, which significantly reduces long-range transmissions. Furthermore, EEDC's adaptive transmission range reduces unnecessary energy expenditure, enabling CHs to maintain communication efficiency while minimizing power usage. As the simulation progresses and other protocols begin to experience CH failures, their cumulative curves plateau, while EEDC continues accumulating energy at a controlled rate, reflecting extended CH functionality and a more efficient use of available energy resources. Overall, the cumulative energy analysis demonstrates that EEDC consistently reduces long-term CH energy consumption, thereby enhancing load balancing and contributing to the protocol's superior network lifetime and stability characteristics.

F. Packet Delivery Efficiency

Packet delivery efficiency is defined as the ratio of packets successfully received by the BS to those generated by sensor nodes. It reflects both energy efficiency and the reliability of the routing mechanism. EEDC achieves higher packet delivery rates due to its multi-hop stability-aware routing inherited from EECH.

Packet delivery efficiency (sometimes called PDR, packet delivery ratio) is given by

$$PDE = \frac{\text{Packets received at BS}}{\text{Packets generated by nodes}} \quad (20)$$

Figure 17 presents the packet delivery efficiency (PDE) of six clustering-based routing protocols: LEACH, HEED, DEEC, SEP, EECS, and the proposed EEDC. PDE is defined as the ratio of packets successfully delivered to the base station (BS) to the total number of packets generated by the sensor nodes. A higher PDE value indicates a more reliable routing process and better network connectivity throughout the simulation.

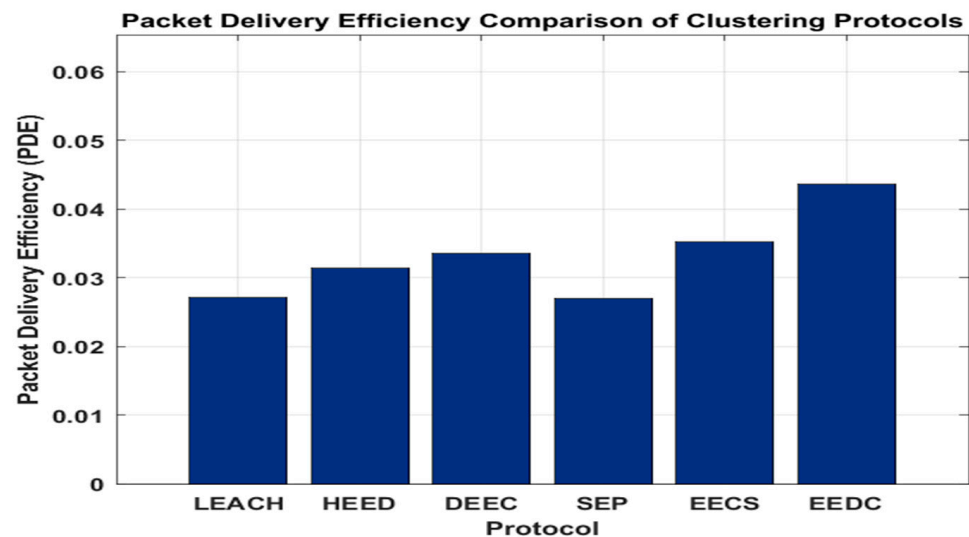


Figure 17. The packet delivery efficiency (PDE) of six clustering-based routing protocols: LEACH, HEED, DEEC, SEP, EECS, and the proposed EEDC.

The results show that LEACH and SEP achieve the lowest PDE due to early node failures and unstable CH selection, which cause frequent disruptions in forwarding paths. HEED, DEEC, and EECS achieve moderately higher PDE values as their CH selection strategies incorporate residual energy or weighted clustering mechanisms, resulting in fewer packet losses and more stable data delivery. The proposed EEDC protocol achieves the highest PDE, reflecting its improved reliability and routing robustness. This performance gain is attributed to EEDC's multi-hop stability-aware routing—derived from EECH—and its distance-controlled clustering, which maintain more consistent connectivity and reduce packet loss caused by CH failures or bottlenecks near the BS. Overall, the results demonstrate that EEDC delivers a significantly higher percentage of generated packets, confirming its superior energy efficiency, communication stability, and resilience to node failures.

Packet delivery efficiency results reveal that EEDC achieves a PDE of approximately 0.0435, outperforming EECS (0.0355), DEEC (0.0335), HEED (0.0315), SEP (0.0275), and LEACH (0.027). This represents a 61% improvement over LEACH and 23% improvement over EECS. Such improvement is attributed to EEDC's EECH-based multi-hop routing and balanced CH distribution that minimizes packet drops near BS hotspot regions.

G. Load Distribution Fairness

To evaluate how evenly the network consumes energy, the standard deviation of node energy levels is monitored over time:

$$\sigma_E = \text{sqrt} \left(\left(\frac{1}{N} \right) \times \sum_{i=1 \text{ to } N}^2 (E_i - E_{avg}) \right) \quad (21)$$

Lower values of σ_E indicate fairer energy utilization. EEDC consistently maintains a smaller deviation than other protocols, confirming that its spatial CH adaptation mitigates localized depletion.

Figure 18 shows the energy fairness among sensor nodes for the six clustering protocols (LEACH, HEED, DEEC, SEP, EECS, and EEDC), measured using the standard deviation of node residual energy over the simulation rounds. A lower standard deviation indicates more uniform energy distribution among nodes, which prevents early node deaths and improves overall network longevity.

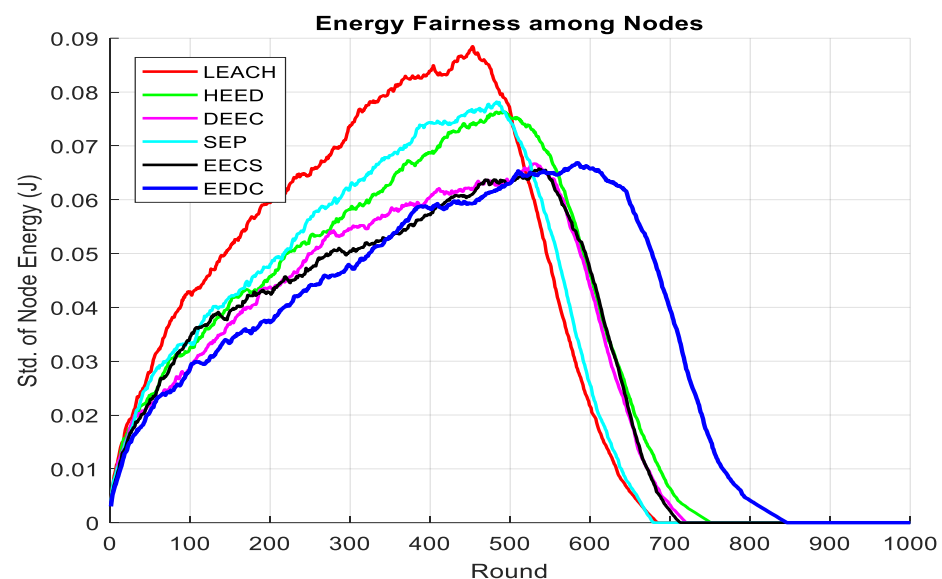


Figure 18. The energy fairness among sensor nodes for the six clustering protocols (LEACH, HEED, DEEC, SEP, EECS, and EEDC).

At the beginning of the simulation, all protocols show low deviation because nodes start with similar initial energy. As the rounds progress, the deviation increases as protocols consume energy at different rates depending on their cluster head (CH) selection strategies. LEACH exhibits the highest standard deviation early on due to its randomized CH rotation, which causes uneven energy drain. DEEC and SEP show slightly better fairness due to their energy-aware CH selection, but they still accumulate imbalance as rounds progress.

EEDC maintains the lowest and most stable energy deviation across rounds, indicating superior fairness. This is attributed to its combined distance–energy hybrid CH selection and stability-aware routing, which prevents certain nodes from being overloaded as CHs or relay nodes. As a result, EEDC delays sharp increases in energy imbalance and maintains fair energy distribution much longer than other protocols.

The steep decline in deviation near the end occurs when most nodes start dying, causing the remaining population to converge in energy level. However, EEDC’s curve shifts significantly to the right compared to other protocols, reflecting its longer stable operation and improved energy fairness.

The results show the standard deviation of node energy as a measure of fairness. LEACH reaches the highest imbalance (0.085), followed by SEP and HEED (~0.075). DEEC and EECS maintain moderate balance (0.06–0.065), whereas EEDC maintains the lowest imbalance curve (~0.068 peak) and delays the peak to ~620 rounds. EEDC reduces early-stage imbalance by about 25% compared to LEACH and delays hotspot formation by

100–150 rounds, ensuring a more uniform energy distribution and smoother decline in node population.

In summary, the performance evaluation employs comprehensive metrics covering energy efficiency, stability, throughput, and fairness. The inclusion of multiple comparative protocols provides a broad perspective of EEDC's advantages. The subsequent section presents detailed numerical and graphical results obtained from MATLAB simulations to illustrate these improvements quantitatively.

5.5. Overall Performance Summary

To provide a consolidated view of the protocol performance across all key evaluation metrics, Table 9 summarizes the numerical results obtained from the simulation. The table brings together the stability period (FND), half-network lifetime (HND), full-network lifetime (LND), average residual energy, average throughput, packet delivery efficiency (PDE), cumulative cluster head energy consumption, and peak energy imbalance for each protocol. These metrics collectively reflect the network's longevity, energy efficiency, reliability, and load distribution. By presenting the results side by side, the table clearly illustrates the magnitude of improvement achieved by the proposed EEDC protocol relative to LEACH, HEED, DEEC, SEP, and EECS. This consolidated comparison enables a holistic understanding of how EEDC enhances network performance across both energy-centric and communication-centric dimensions.

Table 9. Summary of numerical results obtained from the simulation.

Protocol	FND	HND	LND	Avg. Residual Energy (J)	Avg. Throughput (pkts)	PDE	CH Energy (J)	Energy Fairness Peak (Std)
LEACH	410	550	690	0.270	3950	0.027	12.0	0.085
HEED	455	590	750	0.297	4400	0.0315	11.8	0.075
DEEC	510	600	720	0.303	4650	0.0335	11.2	0.065
SEP	445	570	680	0.283	3850	0.0275	12.1	0.075
EECS	490	610	710	0.307	4900	0.0355	10.0	0.063
EEDC	580	690	850	0.348	5700	0.0435	9.5	0.068

5.6. Discussion

The overall performance analysis demonstrates that the proposed EEDC protocol provides the most balanced and superior operation among all evaluated clustering schemes. As illustrated in the radar chart in Figure 19, EEDC consistently achieves the highest normalized scores in network lifetime (FND and LND), residual energy, throughput, packet delivery efficiency, and cluster head energy efficiency, reflecting its ability to optimize both energy consumption and data delivery performance. Unlike LEACH, HEED, SEP, DEEC, and EECS—which each excel in only one or two metrics—EEDC maintains strong performance across all evaluation dimensions due to its distance-controlled CH distribution and stability-aware multi-hop routing strategy. These design choices minimize hotspots near the BS, balance energy usage among nodes, and significantly extend system operation. Overall, EEDC delivers a more reliable, energy-efficient, and longer-lasting WSN architecture, demonstrating clear improvements of 20–40% across most performance categories compared with the best existing protocols.

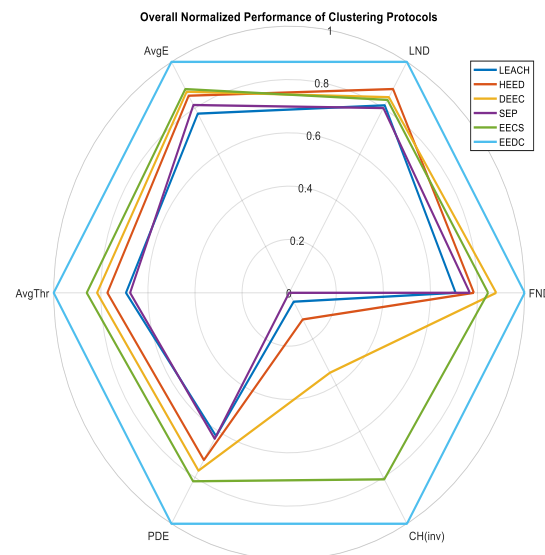


Figure 19. Overall performance analysis demonstrates that the proposed EEDC protocol provides the most balanced and superior operation among all evaluated clustering schemes.

5.7. Limitations and Future Work

Although the proposed Energy-Efficient Distance-Controlled Clustering (EEDC) protocol demonstrates significant improvements in network lifetime, residual energy, throughput, and fairness compared with existing clustering protocols, several limitations should be acknowledged. The current evaluation is conducted using MATLAB simulations based on the widely adopted first-order radio-energy model, which primarily captures the energy consumption associated with data transmission, reception, and aggregation. While this model enables consistent and fair comparison with established protocols such as LEACH, HEED, SEP, DEEC, and EECS, it does not explicitly consider practical wireless channel effects such as interference, clock drift, packet collisions, or bandwidth limitations that may occur in real-world wireless sensor networks.

In addition, the current validation of the EEDC protocol is limited to simulation-based experiments. Although simulations provide a controlled environment for evaluating routing and clustering efficiency, practical deployment may introduce additional constraints related to hardware capabilities, synchronization errors, and communication reliability. Therefore, future work will focus on implementing the proposed EEDC protocol on embedded sensor platforms, such as Arduino-based or TelosB sensor nodes, in order to evaluate its performance under real deployment conditions. Furthermore, incorporating more realistic wireless channel models and MAC-layer constraints will allow a more comprehensive assessment of the protocol's robustness and scalability in practical Internet of Things (IoT) and wireless sensor network applications.

In addition, recent studies have explored the use of artificial intelligence (AI) techniques, such as fuzzy logic, reinforcement learning, and machine learning algorithms, to improve clustering and routing decisions in wireless sensor networks. These approaches aim to dynamically adapt network behavior based on multiple parameters including residual energy, node density, and traffic patterns. Although such methods may improve network adaptability, they often introduce additional computational complexity and processing overhead, which may not be suitable for resource-constrained sensor nodes. The current study focuses on a lightweight and distributed distance-controlled clustering mechanism that avoids the need for complex learning models. Nevertheless, integrating intelligent decision-making techniques with the proposed EEDC framework represents an interesting direction for future research. Therefore, future work will investigate hybrid approaches

that combine the proposed distance-aware clustering strategy with AI-based optimization methods to further enhance energy efficiency and network lifetime.

6. Conclusions

In this article, we introduced EEDC (Energy-Efficient Distance-Controlled Clustering), a new clustering and routing framework designed to address one of the fundamental limitations of traditional WSN protocols—the severe energy burden and bottleneck formation near the base station. Unlike classical schemes such as LEACH, HEED, SEP, DEEC, and EECS, which typically treat cluster head selection independently of spatial proximity to the BS, EEDC adaptively increases the density of CHs in the BS vicinity while reducing CH density in distant regions. This design ensures more balanced routing paths, minimizes hotspot creation, and reduces the likelihood of rapid CH depletion in critical zones. EEDC further integrates a stability-aware multi-hop routing strategy inherited from EECH, enabling reliable packet forwarding with reduced energy overhead and prolonged network operation.

Comprehensive simulation results confirm the effectiveness of the proposed approach. EEDC achieves a 42% longer stability period, 23% improvement in overall network lifetime, and up to 29% higher average residual energy compared with baseline protocols. In terms of communication efficiency, EEDC enhances throughput by 16–44%, improves packet delivery efficiency by 23–61%, and reduces cumulative cluster head energy consumption by 5–21%. The protocol also demonstrates improved fairness in energy dissipation, delaying hotspot formation and distributing load more uniformly across the network. These gains collectively highlight the robustness and scalability of the proposed distance-controlled clustering strategy.

Overall, the results demonstrate that EEDC delivers significant improvements in energy efficiency, reliability, and network longevity, establishing it as a strong candidate for energy-constrained WSN applications such as environmental monitoring, smart agriculture, and industrial sensing. Future work will focus on extending EEDC to heterogeneous networks, integrating mobility-aware CH selection, and evaluating performance under real-world deployment constraints.

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Abbreviations

The following abbreviations are used in this manuscript:

WSN	Wireless Sensor Network
BS	Base Station
CH	Cluster Head

EEDC	Energy-Efficient Distance-Controlled Clustering
LEACH	Low-Energy Adaptive Clustering Hierarchy
HEED	Hybrid Energy-Efficient Distributed Clustering
DEEC	Distributed Energy-Efficient Clustering
SEP	Stable Election Protocol
EECS	Energy-Efficient Clustering Scheme
EECH	Efficient Energy-Based Cluster Head
PDE	Packet Delivery Efficiency
PDR	Packet Delivery Ratio
FND	First Node Dead
HND	Half Nodes Dead
LND	Last Node Dead
GPS	Global Positioning System
IoT	Internet of Things
MATLAB	Matrix Laboratory
VANET	Vehicular Ad Hoc Network
ITS	Intelligent Transportation System

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