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Sector-based midpoint LEACH enhancement for improved energy efficiency and network lifetime

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Abstract

This study proposes a sector-based, midpoint-driven enhancement of the low-energy adaptive clustering hierarchy (LEACH) protocol to address energy imbalance and inconsistent cluster head (CH) placement in wireless sensor networks (WSNs). Conventional LEACH and its variants often rely on random CH selection and produce uneven cluster geometries, accelerating node depletion and shortening network lifetime. The proposed method divides the network into four sectors and applies a midpoint-guided CH selection mechanism that prioritizes nodes near the geometric center of each sector, thereby shortening intra-cluster communication distances and balancing energy consumption. The protocol is evaluated through Python-based simulation using 100 randomly deployed nodes in a 200×200 m^2 monitoring area and is compared with several widely used LEACH-based protocols under identical radio and traffic parameters. Key performance metrics include first node death (FND), half nodes death (HND), all nodes death (AND), residual energy, and throughput. Simulation results show lifetime gains of roughly 30–40 % across standard lifetime metrics relative to the original LEACH, while maintaining higher residual energy and stable throughput. These findings highlight the suitability of the protocol for long-duration IoT and smart monitoring applications where energy efficiency is critical.

Keywords: wireless sensor networks; energy-efficient routing; enhanced LEACH; sector-based clustering; midpoint-driven cluster-head selection.

I. Introduction

Wireless sensor networks (WSNs) have become a fundamental component of modern internet of things (IoT) infrastructures, supporting applications in smart agriculture, environmental monitoring, structural health assessment, and industrial automation [1][2]. These networks consist of numerous low-power sensor nodes that collect and transmit data to a base station, and their operational lifetime strongly depends on efficient energy usage. Since nodes are typically battery-powered and often deployed in locations where maintenance is difficult or impossible, strategies that reduce communication overhead and distribute workload more evenly are essential for sustaining long-term network functionality. Clustering has emerged as one of the most effective mechanisms for improving energy efficiency, and among clustering-based routing schemes, the low-energy adaptive clustering hierarchy (LEACH) remains one of the most widely adopted. LEACH rotates cluster head (CH) roles to balance energy consumption across nodes, but its probabilistic CH selection leads to random CH placement, uneven cluster formation, irregular communication distances,

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and the emergence of energy hotspots, all of which shorten the network's operational lifetime [3][4].

Various LEACH enhancements have been introduced to address these weaknesses. Approaches such as LEACH-KMeans, LEACH-C, TL-LEACH, and S-LEACH attempt to improve CH selection through centralized optimization, geometric partitioning, hybrid clustering, or metric-based adjustments [5][6][7]. These methods reduce some of LEACH's limitations but still struggle to ensure stable and spatially balanced CH placement within regions of the network. In particular, existing sector-based or area-partitioning methods divide the monitoring field but do not explicitly consider the geometric center of each sector when determining CH candidates. As a result, cluster geometry remains inconsistent, average node-to-CH distances vary widely, and intra-sector energy usage becomes imbalanced. To the best of our knowledge, no prior work has incorporated a midpoint-driven CH selection strategy within a sectorized topology, leaving a specific gap in maintaining cluster uniformity and communication stability across network subregions.

To overcome these limitations, this study proposes a sector-based midpoint-driven enhanced LEACH protocol. The method partitions the monitoring area into four sectors and assigns each sector a geometric midpoint that serves as a spatial reference for CH selection. The probability of a node becoming CH is then adapted to prioritize nodes that are closer to the midpoint, thereby reducing intra-cluster communication distances, stabilizing CH placement patterns, and distributing energy consumption more evenly among nodes. This approach provides geometric consistency without requiring computationally intensive optimization techniques, making it well-suited for lightweight WSN deployments.

The objective of this study is to design an energy-efficient clustering mechanism that integrates sector partitioning with midpoint-guided CH selection, evaluate its performance against widely used LEACH variants under identical simulation conditions, and measure improvements in lifetime metrics, remaining energy, and throughput. The contributions of this research include the introduction of a novel midpoint-driven CH selection method embedded within a sector-based topology, the development of a lightweight clustering mechanism that improves energy balance without high computational overhead, and a comprehensive simulation-based evaluation demonstrating substantial improvements over existing LEACH variants. By combining geometric partitioning with distance-aware CH prioritization, the proposed protocol addresses long-standing limitations of LEACH and offers a more stable and energy-efficient clustering solution for long-duration IoT and environmental monitoring applications.

Research on energy-efficient routing in wireless sensor networks (WSNs) has produced numerous clustering-based methods, with LEACH serving as the foundational protocol [8][9]. LEACH introduced probabilistic rotation of cluster head (CH) roles to balance energy consumption, but its reliance on random CH selection and single-hop communication leads to suboptimal cluster distribution and premature node depletion [10][11]. These limitations have motivated the development of several enhanced LEACH variants.

A. Spatially optimized LEACH variants

Approaches such as LEACH-KMeans integrate geometric clustering algorithms to reduce intra-cluster distance by grouping nodes based on spatial proximity [12][13]. While this improvement lowers communication cost, the method does not incorporate residual energy in CH selection, potentially leading to unbalanced energy consumption over time [14]. Recent enhancements, such as MDC-KMeans and Grid-based LEACH, have further improved spatial partitioning, yet still exhibit challenges in dynamic environments where node distribution evolves [15].

B. Centralized LEACH variants

The LEACH-C (Centralized LEACH) protocol addresses random CH distribution by using the sink to compute optimal CH placement based on node location and energy [16]. Although this strategy improves energy balance, it introduces communication overhead due to frequent reporting to the sink and creates a dependency on centralized processing [17]. Studies have shown that centralized schemes perform well in static networks but degrade under topology changes or intermittent communication with the sink [18].

C. Evolutionary and optimization-based LEACH variants

Optimization-based extensions such as LEACH with a genetic algorithm (LEACH-GA), LEACH with particle swarm optimization (PSO-LEACH), LEACH with fuzzy logic (FL-LEACH), and other meta-heuristic-driven clustering algorithms attempt to optimize CH selection using fitness functions that consider energy, distance, or node density [19][20]. These methods generally improve lifetime metrics but demand higher computational resources—making

Table 1.
Simulation parameters.

Parameter	Symbol	Value	Description
Network size	—	200×200 m²	Square deployment area
Number of nodes	n	100	Random uniform distribution
Sink position	(x_{sink}, y_{sink})	(100, 100)	Center of the area
Initial energy	E_0	0.5 J	Per-node battery energy
Max rounds	r	3000	Simulation duration
CH probability	p	0.05	Optimal CH percentage
Packet size	k	4000 bits	Data transmitted per round
Free-space amplifier	ε_{fs}	10^{-12} J/bit/m²	Short-range model
Multi-path amplifier	ε_{mp}	0.0013×10^{-12} J/bit/m⁴	Long-range model
Data aggregation	E_{DA}	5×10^{-9} J/bit	CH aggregation energy
Electronics energy (TX)	$E_{elec\,TX}$	3.3 μJ/bit	Transmission cost
Electronics energy (RX)	$E_{elec\,RX}$	0.7 μJ/bit	Reception cost

them less suitable for real-time and resource-constrained sensor nodes. Additionally, their convergence time may limit responsiveness in dynamic scenarios.

D. Sector-based and partition-based LEACH variants

Several studies propose sectoring or region partitioning to balance node distribution and limit cluster size [21][22]. Protocols such as solar-aware low-energy adaptive clustering hierarchy (S-LEACH) and two-level low-energy adaptive clustering hierarchy with partitioned regions (TL-LEACH-P) introduce partitioned areas to improve cluster stability [23][24]. However, existing sector-based methods typically rely on geometric partitioning alone and do not explicitly optimize CH placement inside each sector, especially in relation to intra-sector distance minimization. As a result, energy imbalance may persist, and the benefits of partitioning remain constrained.

E. Research gap

Existing enhancements to the LEACH protocol address various aspects such as spatial clustering, centralized optimization, evolutionary computation, and geometric partitioning; however, none of these approaches combine sector-based clustering with a midpoint-driven cluster head (CH) selection strategy. The absence of this integration creates a gap in achieving optimal intra-sector communication efficiency, stable localized CH placement, balanced energy distribution, and reduced computational complexity compared to optimization-based methods. To overcome these limitations, this study introduces a sector-based midpoint-driven enhanced LEACH protocol that incorporates sector partitioning with a lightweight midpoint proximity mechanism for CH selection, ultimately providing a more energy-efficient and stable clustering structure for wireless sensor networks (WSNs).

II. Materials and Methods

This section describes the simulation environment, energy model, sector-based clustering mechanism, and midpoint-driven cluster head (CH) selection process used to evaluate the proposed enhanced LEACH protocol. The methodological revision emphasizes reproducibility, clarity, and alignment with the research gap identified earlier.

A. Simulation parameters

To ensure a fair and standardized comparison across all LEACH variants (LEACH original, LEACH-KMeans, LEACH-C, LEACH-GA, and LEACH-proposed), all simulations were conducted using an identical environment with the same radio model and network topology [25]. The simulation parameters are summarized in Table 1.

These simulation parameters were selected to represent a typical medium-scale WSN scenario and to remain comparable with widely used LEACH-based studies [26]. A 200 × 200 m² field with 100 randomly deployed nodes and a centrally located sink ensures a sufficiently dense topology while keeping average communication distances realistic for monitoring applications. The cluster-head selection probability $p = 0.05$ and initial energy $E_0 = 0.5\,J$ per node follow standard LEACH configurations, enabling a fair comparison of network lifetime and energy balance. A data packet size of 4000 bits and a maximum of 3000 rounds allow long-term evaluation under realistic traffic loads. The radio-energy parameters ($E\_elec = 3.3\,\mu J/bit$ for transmission, $0.7\,\mu J/\,bit$ for reception, ε_{fs}, ε_{mp} , and $E_{DA} = 5 \times 10 - 9\,J/bit$) are

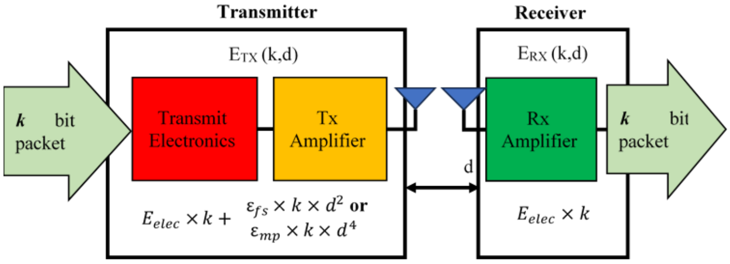

Figure 1. Energy consumption model for data transmission and reception in WSNs.

adopted from the first-order radio model so that performance gains can be attributed to the proposed protocol design rather than artificially favorable hardware settings [26].

All protocols were implemented and simulated in Python (version 3.11) using custom scripts based on the first-order radio model. Each simulation scenario was executed once with a fixed random seed, and the resulting curves represent a single-run outcome for each protocol. As a limitation, the current study does not include statistical averaging or variance analysis; future work will incorporate multiple independent runs and error-bar statistics to assess the robustness of the proposed protocol under varying network conditions.

B. Energy consumption model

In wireless sensor networks (WSNs), energy consumption is a critical factor influencing network performance and lifespan [27]. Each sensor node operates under strict energy constraints, making it essential to understand the energy consumption model that governs data transmission and reception processes [28]. This model comprises several key components, including energy for electronic processing, data transmission, and data reception. Additionally, it accounts for the impact of communication distance between nodes, which significantly affects energy consumption patterns, especially with the presence of a specific distance threshold, denoted as d_0. The threshold is determined using equation (1) [29][30][31].

$$d_o = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} \tag{1}$$

where d_0 represents the communication distance threshold between nodes. Here, ε_{fs} denotes the energy parameter for short-range transmission (free-space), while ε_{mp} represents the energy parameter for long-range transmission (multi-path fading). This threshold differentiates energy consumption based on two communication models: short-range and long-range. Figure 1 provides a visual representation of the energy consumption model used in this study.

The diagram in Figure 1 illustrates the energy flow required to transmit a data packet of size k bits from the transmitting node to the receiving node. The energy components include E_elec for data processing, ε_{fs} for short-range communication, and ε_{mp} for long-range communication. The energy consumption model is used to analyze energy efficiency in the communication process of wireless sensor networks. On the transmitting side (Transmitter), the required energy consists of electronic energy (E_{elec}) for data processing and amplifier energy (ε_{fs} or ε_{mp}) for transmitting data, depending on the communication distance d. The transmission energy is calculated using equation (2) [29][30][31].

$$E_{Tx} = \begin{cases} E_{elec} \times k + \varepsilon_{fs} \times k \times d^2, d < d_0 \\ E_{elec} \times k + \varepsilon_{mp} \times k \times d^4, d \geq d_0 \end{cases} \tag{2}$$

where ε_{fs} is applied for short-range communication ($d < d_0$) using the free-space model, whereas ε_{mp} is utilized for long-range communication ($d \geq d_0$) based on the multi-path fading model. The parameter d_0 serves as the distance threshold that governs the transition between these two models. The formula highlights that energy consumption increases significantly over longer distances due to the greater impact of propagation losses. On the receiving side (receiver), the required energy only involves electronic energy for processing the received data. This energy is computed using equation (3).

$$E_{Rx} = E_{elec} \times k \tag{3}$$

where E_{Rx} represents the energy expended by the receiving node to process the data. The total energy consumed for each communication between nodes is the sum of transmission energy (E_{Tx}) and reception energy (E_{Rx}), which can be seen in equation (4).

$$E_{Tot} = E_{Tx} + E_{Rx} \tag{4}$$

where E_{Tot} is the total energy consumed for each communication event between nodes. This model enables the evaluation of energy efficiency based on data transmission and reception patterns within the network. Moreover, determining the distance threshold d_0 provides crucial insights for optimizing routing protocols, ultimately extending the operational lifespan of wireless sensor networks.

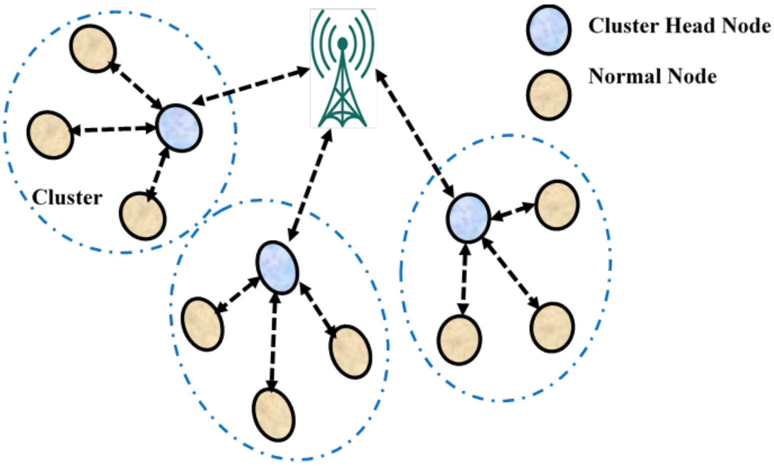

Figure 2. The structure of a wireless sensor network (WSN) under the LEACH protocol.

C. Original LEACH protocol

The low-energy adaptive clustering hierarchy (LEACH) protocol is a foundational clustering mechanism for wireless sensor networks (WSNs), designed to reduce energy consumption during data transmission. LEACH forms clusters and assigns one node as the Cluster Head (CH) within each cluster. The CH aggregates data from its member nodes, compresses it, and transmits it to the sink, thereby minimizing the number of long-range transmissions required from regular nodes.

Figure 2 presents the structure of a LEACH-based WSN, showing the cluster formation, CH placement, and direct communication between CHs and the sink.

Figure 2 illustrates the organization of a Wireless Sensor Network (WSN) under the LEACH protocol. The network is divided into clusters, each managed by a cluster head (CH) communicating directly with the sink node. Normal nodes within a cluster transmit their data to the designated CH, which aggregates the received data before forwarding it to the sink. This hierarchical communication mechanism minimizes energy consumption while improving data transmission efficiency within the network.

1) *Cluster head selection mechanism*

LEACH uses a probabilistic mechanism to rotate the CH role among nodes. Each node independently determines whether it becomes a CH using the threshold function in equation (5) [25][32].

$$T(i) = \begin{cases} \frac{p}{1-p\left[r \times mod\left(\frac{1}{p}\right)\right]} & , \textit{if node } i \in G \\ 0 & , \textit{otherwise} \end{cases} \quad (5)$$

where $T(i)$ is the probability that the node i becomes a CH in round r. The parameter p represents the desired proportion of CHs per round, and G is the set of nodes that have not served as CHs during the current cycle. Nodes generate a random value between 0 and 1 and compare it with $T(i)$; if the value is less than the threshold, the node becomes a CH. Once selected, a node is excluded from the candidate set G until a full cycle of $\frac{1}{p}$ rounds conclude. This mechanism ensures fairness by distributing the CH role among all nodes over time.

The rotation of CH roles prevents excessive energy depletion in any single node, thereby maintaining balanced energy usage across the network. However, the random nature of CH selection can result in uneven spatial placement of CHs, leading to clusters with poor geometry, long intra-cluster distances, and suboptimal energy distribution issues later addressed by various enhanced LEACH-based protocols.

2) *Cluster head re-selection cycle*

Each round in LEACH consists of the setup phase, in which CHs are selected and clusters are formed, and the steady-state phase, during which nodes transmit sensed data to the CH in predefined time slots (TS1–TSN) [33][34]. The CH aggregates the received data and forwards it to the sink. Figure 3 illustrates the CH re-selection cycle, showing how LEACH ensures fairness by allowing all nodes to serve as CHs at least once every full cycle.

The diagram in Figure 3 illustrates the structure of the LEACH protocol's Cluster Head re-selection cycle. Each cycle is divided into two main phases: the Set-up Phase (where clusters are initialized, and CHs are selected) and the Steady-State Phase (during which time slots, labeled TS1 through TSN, are allocated for data transmission). This process ensures that all nodes have the opportunity to serve as CHs over time.

The LEACH protocol process includes clustering and re-clustering mechanisms to evenly distribute energy consumption among sensor nodes. The protocol ensures fairness by cycling Cluster Head roles

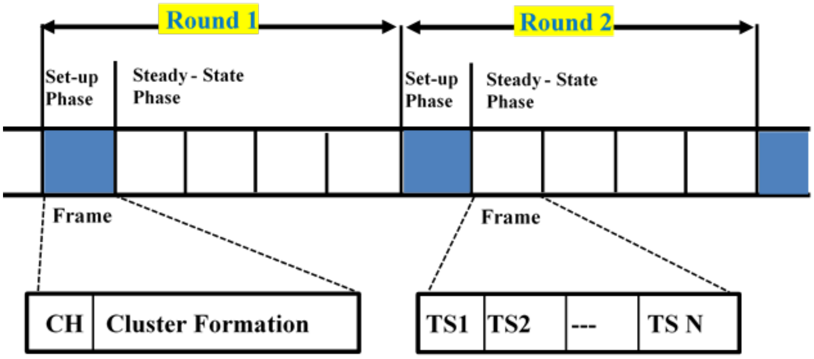

Figure 3. CH re-selection cycle in LEACH, consisting of the setup phase and steady-state phase repeated over multiple rounds.

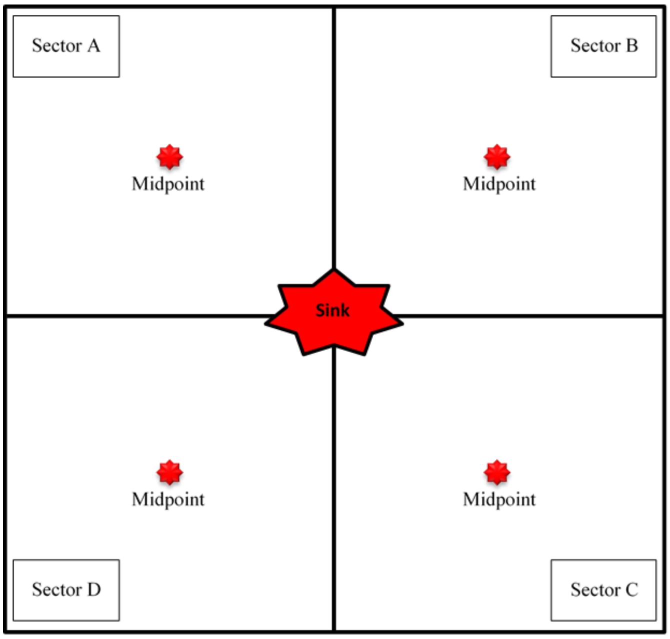

Figure 4. Sector-based topology with four sectors (A–D), each assigned a geometric midpoint to guide CH selection.

across all nodes over multiple rounds, promoting balanced energy usage and enhancing network longevity. After every $\frac{1}{p}$ cycle, the Cluster Head eligibility set G is refreshed to restart the selection process, allowing nodes that were previously excluded to participate again [1][32].

D. Proposed protocol (enhanced LEACH)

The proposed sector-based midpoint-driven enhanced LEACH protocol introduces a geometric clustering mechanism designed to address energy imbalance and load distribution issues in wireless sensor networks (WSNs). The network area is divided into four sectors A, B, C, and D, and each sector is assigned a geometric midpoint that serves as a reference for cluster head (CH) selection. This structure minimizes node-to-CH communication distances, thereby reducing energy consumption and extending network lifetime.

The sink node is positioned at the center of the deployment area to ensure uniform communication distance across all sectors. Acting as the main data collection point, the centrally placed sink also lowers the risk of communication bottlenecks and contributes to balanced energy usage across the network. Figure 4 illustrates the sector-based topology and the midpoint placement within each region. Each midpoint is computed as the geometric center of its respective sector, enabling spatially balanced CH placement and more predictable cluster geometry.

The midpoints minimize the average distance between nodes and their CHs. In this topology, the sink node is positioned at the center of the network, while the midpoints of each sector act as reference points for communication and CH selection. This strategy is designed to reduce communication costs and prolong the network's lifetime.

Within this topology, each sensor node determines its distance to the midpoint of its assigned sector. The

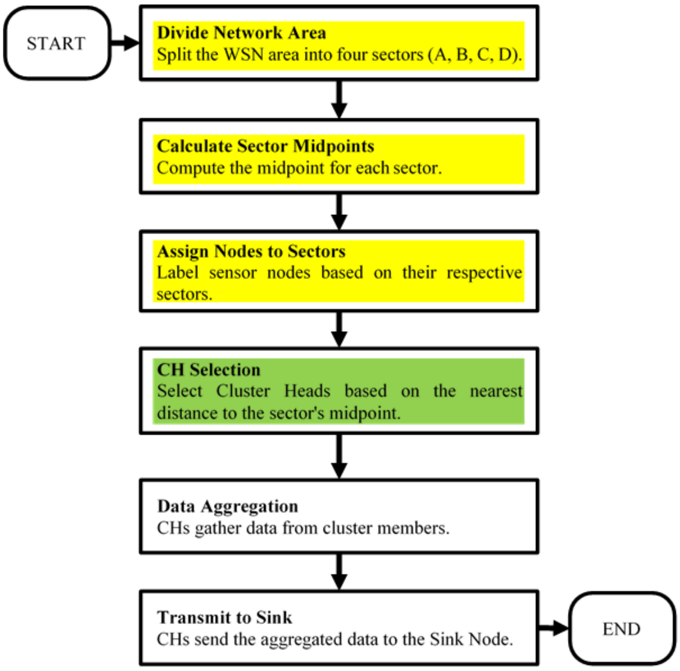

Figure 5. Flowchart of the proposed sector-based, midpoint-driven enhanced LEACH protocol.

distance is calculated using the Euclidean metric in equation (6).

$$d(i) = \sqrt{(x_i - x_m)^2 + (y_i - y_m)^2} \tag{6}$$

where $d(i)$ is the distance between node i and the midpoint (x_m, y_m), while (x_i, y_i) are the coordinates of node i.

This distance value is then incorporated into the threshold probability for CH selection. Nodes closer to the midpoint have a higher probability of being selected as CHs, thereby reducing communication costs and energy consumption. The modified threshold is shown in equation (7).

$$T_{new}(i) = \begin{cases} \frac{p}{1-p\left[r \times mod\left(\frac{1}{p}\right)\right]}, & if\ node\ n \in G \\ 0 & , otherwise \end{cases} \times \frac{1}{d(i)} \tag{7}$$

where, p represents the desired percentage of CHs, r is the current round number, and G is the set of nodes that have not yet been selected as CHs in the current cycle. The term $\frac{1}{d(i)}$ biases the threshold such that nodes nearer to the midpoint obtain higher selection priority. Once a node becomes a CH, it is removed from G until all other nodes in that sector have taken a turn, ensuring fair rotation and preventing repeated CH selection for the same node.

This midpoint-driven approach differs from conventional LEACH and its variants by integrating both geometric constraints and deterministic spatial referencing. The method stabilizes CH placement patterns, reduces the variance in cluster sizes, and decreases the average energy expenditure for intra-cluster communication.

To provide a clear overview of the operational workflow, Figure 5 summarizes the main stages of the proposed sector-based, midpoint-driven Enhanced LEACH protocol, from network partitioning and node labeling to cluster-head selection and data transmission to the sink. The flowchart in Figure 5 shows four main stages: network area initialization and sector partitioning, node labeling based on geographic location, cluster-head selection guided by the distance to each sector's midpoint, and finally, intra-cluster communication and data aggregation toward the sink node. By constraining CH candidates around sector midpoints and aggregating data locally, the protocol reduces average communication distance and balances energy usage across the network.

Algorithm 1 describes the process of dividing the WSN area into four sectors, calculating the midpoints of these sectors, and labeling each sensor node based on its sector. Algorithm 1 divides the WSN area into four quadrants (sectors) and assigns predefined midpoints for each sector. Each node is labeled based on its position in one of these quadrants, facilitating the CH selection process in the next step.

Algorithm 2 calculates the distance of each node in a sector to its midpoint. The node with the maximum adjusted threshold probability T_new (i) is selected as the Cluster Head (CH) for that sector. This strategy ensures efficient CH selection while maintaining a balanced energy load across nodes in the network.

Algorithm 1: Setting up WSN area based on sector and node labeling

Require:

N	: *Number of sensor nodes*
x, y	: *Dimensions of the network area*
(x_{sink}, y_{sink})	: *Coordinates of the Sink Node*
$sectors_{midpoints}$	: *Dictionary containing midpoints for sectors*
$label[i]$	: *Array for storing sector labels for each node*

Ensure:

Define midpoints for each sector:
    $sectors_{midpoints} = \{$
        $'A': \{'x': x\ /\ 4, 'y': 3\ \times\ y\ /\ 4\},$ $\#\ Top - left\ quadrant$
        $'B': \{'x': 3\ \times\ x\ /\ 4, 'y': 3\ \times\ y\ /\ 4\},$ $\#\ Top - right\ quadrant$
        $'C': \{'x': 3\ \times\ x\ /\ 4, 'y': y\ /\ 4\},$ $\#\ Bottom - right\ quadrant$
        $'D': \{'x': x\ /\ 4, 'y': y\ /\ 4\}$ $\#\ Bottom - left\ quadrant$
    $\}$
for each node i = 1 to N do
  if x[i] <= x / 2 and y[i] > y / 2 then
    label[i] ← 'A'   *// Top-left quadrant*
  else if x[i] > x / 2 and y[i] > y / 2 then
    label[i] ← 'B'   *// Top-right quadrant*
  else if x[i] > x / 2 and y[i] <= y / 2 then
    label[i] ← 'C'   *// Bottom-right quadrant*
  else
    label[i] ← 'D'   *// Bottom-left quadrant*
  end if
end for

Algorithm 2: Midpoint-driven cluster head selection in each sector.

Require:

N	: *Number of sensor nodes*
$label[i]$	: *Sector labels of nodes*
$sectors_{midpoints}$	: *Midpoints of sectors*
P	: *Proportion of nodes to be selected as CHs*
G	: *Set of nodes not yet CHs in the current cycle*

Ensure:

// CHs are selected for each sector based on distance to the midpoint.
G ← {All nodes}
for each sector k ∈ {'A', 'B', 'C', 'D'} do
  CH[m] ← None
  for each node i ∈ G with label[i] = k do
    $d(i) \leftarrow \sqrt{(x_i - x_m)^2 + (y_i - y_m)^2}$ $//\ distance((x_i, y_i), midpoint[k])$
    $T_{new}(i).. \leftarrow \begin{cases} \frac{p}{1-p\left[r \times mod\left(\frac{1}{p}\right)\right]} & , if\ node\ n \in G \\ 0 & , otherwise \end{cases} \times \frac{1}{d(i)}$
  end for
  Select node n *with* $max(T_{new}\ (i))$ *in sector k*
  CH[m] ← n
  Remove n from G
end for
Broadcast CH selection
Update G and rotate CHs in subsequent rounds

III. Results and Discussions

This section presents a comprehensive evaluation of the proposed Sector-Based Midpoint-Driven Enhanced LEACH protocol compared with LEACH Original, LEACH-KMeans, LEACH-C, and LEACH-GA. The discussion goes beyond descriptive reporting by analyzing the underlying factors that influence performance outcomes, linking observations to theoretical expectations in LEACH-based routing, and interpreting their implications for real-world Wireless Sensor Network (WSN) applications. The results are based on single-run simulations per configuration, without statistical averaging; thus, future work should incorporate multiple independent runs with variance analysis to assess robustness.

A. Node Survival Distribution

Figure 6 illustrates the node survival distribution at round 1000 under Proposed Protocol. The visualization highlights alive nodes, dead nodes, and the corresponding Cluster Heads (CHs), offering insight into how each clustering mechanism influences early energy depletion.

At round 1000, the proposed protocol maintains a significantly higher number of active nodes compared to other variants. This is primarily due to its midpoint-driven CH placement, which restricts excessively long transmissions and preserves node energy in outer regions. In contrast, LEACH Original exhibits earlier node failures caused by random CH placement, leading to unbalanced clusters and energy hotspots. LEACH-KMeans improves initial cluster geometry but suffers from early CH exhaustion because it does not consider residual energy during CH selection. These results confirm that spatially balanced CH placement plays a critical role in extending node lifespan.

B. Determining The Success of The Device

One critical metric to evaluate the efficiency of clustering protocols in wireless sensor networks (WSNs) is the rate at which nodes deplete their energy and become non-functional, or "dead nodes." The comparison of dead nodes across different LEACH variants provides insight into the energy efficiency and longevity of each protocol. This analysis evaluates the performance of the LEACH Original, LEACH-KMeans, LEACH-C, LEACH-GA, and the proposed LEACH variant based on the number of dead nodes at different simulation rounds.

To evaluate long-term stability, Figure 7 compares the progression of dead nodes for all variants. Figure 7 shows the comparison of dead nodes across five LEACH variants: LEACH Original, LEACH K-Means, LEACH-C, LEACH-GA, and the proposed LEACH. The x-axis represents the simulation rounds, while the y-axis indicates the cumulative number of dead nodes.

The proposed LEACH protocol, represented by the purple line, demonstrates the most gradual increase in dead nodes, signifying superior energy efficiency and prolonged network lifespan compared to the other variants. LEACH Original, shown by the blue line, experiences the fastest depletion of node energy, with most nodes becoming dead early in the simulation. LEACH K-Means, LEACH-C, and LEACH-GA, represented by the orange, green, and red lines, respectively, show intermediate performance, with LEACH-GA exhibiting better longevity than the other two.

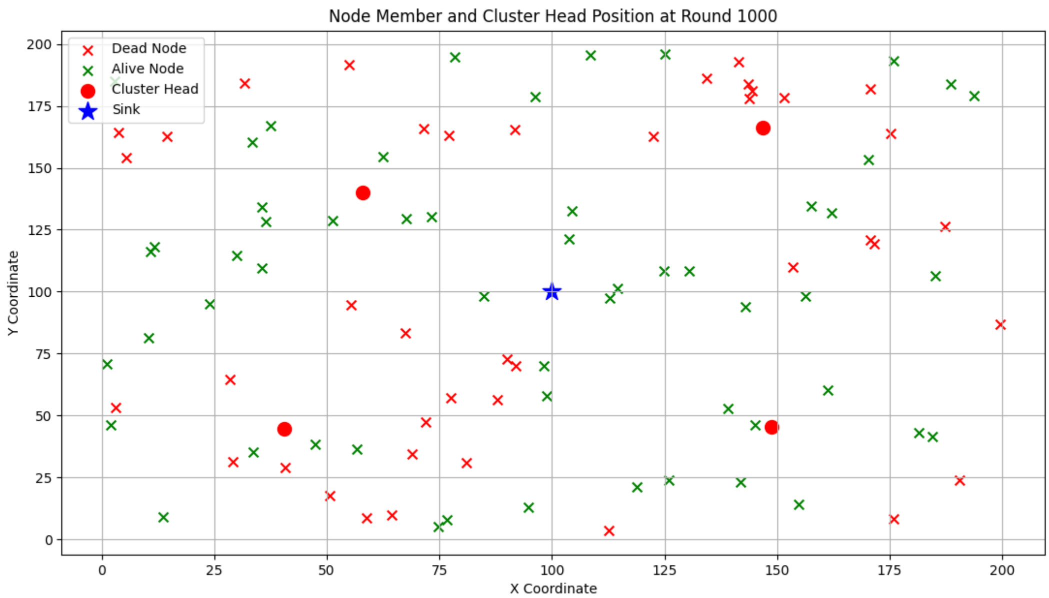

Figure 6. Spatial distribution of alive nodes, dead nodes, and CHs at round 1000 under proposed protocol.

The results highlight the effectiveness of the proposed LEACH protocol in maintaining node energy balance and extending the operational stability of the network, making it a suitable choice for applications requiring long-term network functionality.

C. Cluster head stability

The number and stability of Cluster Head nodes (CHs) significantly affect the overall performance of a Wireless Sensor Network (WSN). CHs are responsible for data aggregation and communication with the sink node, making their distribution and maintenance critical for energy efficiency and network longevity. Cluster Head stability is evaluated through the CH count per round, as shown in Figure 8.

Figure 8 illustrates the variation in the number of Cluster Head nodes for each LEACH variant throughout the simulation. The horizontal axis represents the simulation rounds, while the vertical axis shows the number of Cluster Head nodes active at a given round.

The proposed LEACH variant, represented by the purple line, demonstrates a stable and controlled number of CHs, especially in the later rounds, indicating efficient energy management and longer network stability. The LEACH Original protocol,

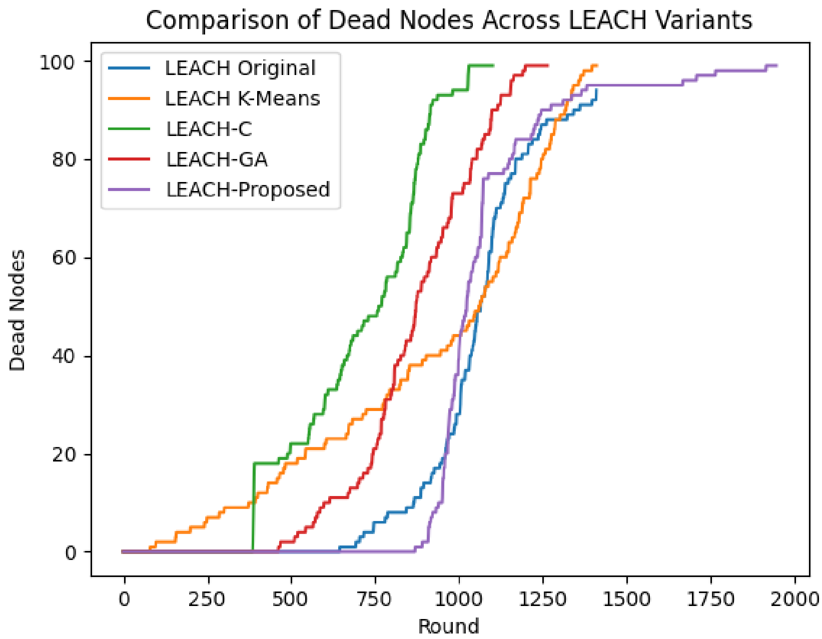

Figure 7. Comparison of dead nodes across LEACH variants over simulation rounds.

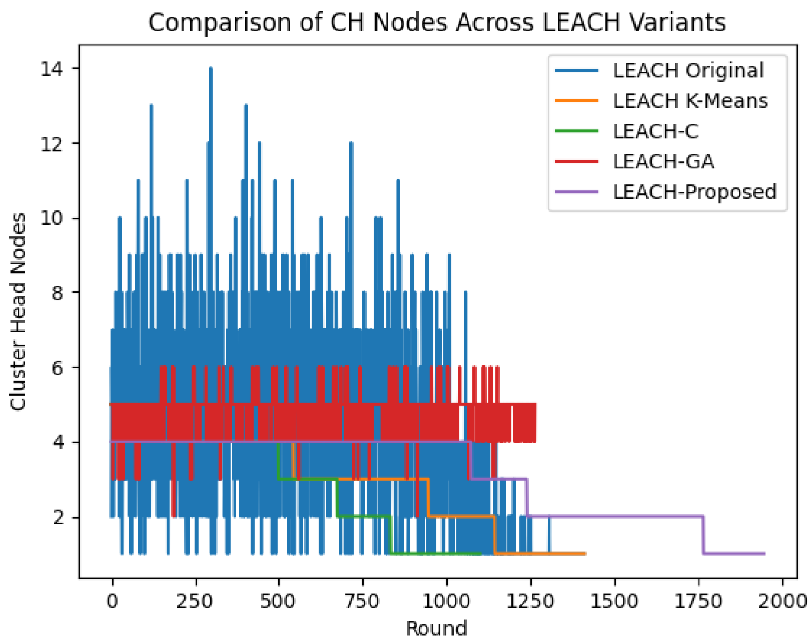

Figure 8. CH formation stability for all protocols, showing the consistency of CH counts over simulation rounds.

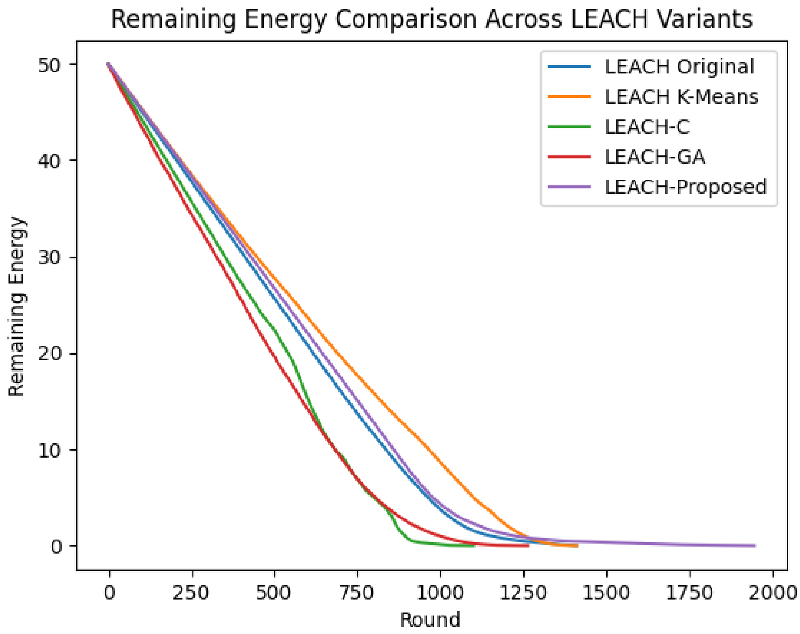

Figure 9. Total remaining energy across simulation rounds for each LEACH variant, demonstrating differences in long-term energy efficiency.

shown with the blue line, exhibits high variability in the number of CHs, reflecting inefficiencies in CH selection, which result in rapid energy depletion.

The red line representing LEACH-GA shows a consistent number of CHs but begins to decline significantly in later rounds, highlighting its moderate performance in maintaining CH stability. LEACH-C (green line) and LEACH K-Means (orange line) show similar behavior, with both maintaining fewer CHs compared to LEACH Original and LEACH-GA, but still less stable than the proposed LEACH variant.

Overall, the proposed LEACH protocol outperforms the others by maintaining an optimal number of CHs, resulting in enhanced network performance and energy efficiency. This stability contributes to its ability to prolong the network lifetime and maintain better load distribution among nodes.

D. Remaining energy analysis

Energy consumption is a critical factor in evaluating the performance of wireless sensor networks, as it directly impacts the network's lifetime and reliability. Figure 9 presents a comparison of the remaining energy levels for five LEACH variants: LEACH Original, LEACH K-Means, LEACH-C, LEACH-GA, and the proposed LEACH over the simulation rounds.

Figure 9 illustrates the trend of remaining energy in the network as the simulation progresses. The horizontal axis represents the number of simulation rounds, while the vertical axis indicates the remaining energy in the network.

The proposed LEACH protocol, represented by the purple line, exhibits a slower decline in energy levels compared to other variants, showcasing its superior energy efficiency. By the final rounds, it retains more energy than the other variants, highlighting its capability to extend the network's operational period.

The orange line, representing LEACH K-Means, and the blue line, representing LEACH Original, demonstrate moderate energy consumption rates but deplete energy more rapidly compared to the proposed LEACH. LEACH-GA, shown with the red line, and LEACH-C, shown with the green line, exhibit faster energy depletion, especially during the later rounds, indicating less efficient energy management. Overall, the proposed LEACH protocol's ability to conserve energy effectively ensures prolonged network lifetime, making it a more reliable solution for energy-constrained WSN applications.

E. Lifetime metrics: FND, HND, and AND

In this study, three key metrics are utilized to evaluate the performance of the LEACH protocol and its variants: First node death (FND), half nodes death (HND), and all nodes death (AND). The first node death (FND) metric identifies the round in which the first node in the network depletes its energy and ceases to function [35][36][37]. Mathematically, FND is determined using equation (8).

$$FND = min\{r_i | E_i(r) = 0, i \in [1, N]\} \quad (8)$$

where N denotes the total number of nodes, r_i is the round when the energy of node i becomes zero, and $E_i(r)$ represents the residual energy of node i at round r. This metric highlights the protocol's ability to delay the failure of the first node, indicating how well energy conservation strategies are implemented in the network. The half nodes death (HND) metric determines the round at which half of the nodes in the network have failed [35][36][37]. It is determined using equation (9).

$$HND = min\left\{r_k \left|\sum_{i=1}^{N} 1_{E_i(r)=0} \geq \frac{N}{2}\right.\right\} \tag{9}$$

where $1_{E_i(r)=0}$ is an indicator function that equals 1 when the energy of node i is zero, and the summation calculates the cumulative number of dead nodes. This metric provides insights into the balance of energy consumption among nodes and reflects the overall energy efficiency of the protocol, as it indicates when half of the network becomes non-operational. The all nodes death (AND) metric captures the round in which the last operational node in the network exhausts its energy [35][36][37]. It is determined using equation (10).

$$AND = max\{r_i | E_i(r) = 0, i \in [1, N]\} \tag{10}$$

The variable r_i represents the round at which the energy of node i is depleted. This metric measures the maximum operational lifespan of the network and reflects the overall endurance of the protocol in sustaining node activity. Together, the metrics first node death (FND), half nodes death (HND), and all nodes death (AND) provide a comprehensive evaluation of the network's energy efficiency, revealing early degradation behavior, mid-lifetime stability, and total system longevity. These metrics are therefore used to compare the performance of LEACH Original, LEACH K-Means, LEACH-C, LEACH-GA, and the proposed LEACH-enhanced protocol.

To present the performance differences clearly, Table 2 summarizes the values of FND, HND, and AND obtained from the simulation, along with the percentage improvement relative to LEACH Original.

The results in Table 2 show that LEACH-Proposed consistently achieves higher values across all lifetime metrics. The substantial improvements indicate that the midpoint-driven CH selection mechanism effectively balances energy consumption, delays early node failures, and extends overall network operation.

To visualize these results, Figure 10 presents the comparative FND, HND, and AND values for all LEACH variants. Figure 10 compares the lifetime metrics of all protocols in terms of the rounds at which the first node death (FND), half nodes death (HND), and all nodes death (AND) occur. As summarized in Table 2, LEACH Original reaches FND, HND, and AND at rounds 645, 1064, and 1410, respectively, whereas the proposed sector-based midpoint protocol delays these events to rounds 869, 1400, and 1946. This corresponds to approximate improvements of 34.8 % in FND, 31.4 % in HND, and 37.9 % in AND relative to LEACH Original, indicating that the proposed CH placement strategy more effectively balances energy consumption and prolongs overall network lifetime.

F. Throughput analysis

Throughput in wireless sensor networks is a crucial metric that measures the total data packets successfully transmitted to the base station over the network's operational lifespan. It is a strong indicator of the efficiency and reliability of the protocol. The throughput comparison across various LEACH protocol variants is determined using equation (11).

$$Throughput = \sum_{r=1}^{R} \sum_{i=1}^{N} Pi(r) \tag{11}$$

where R represents the total number of rounds, N denotes the total number of nodes, and $Pi(r)$ is the number of packets successfully transmitted by node i during round r. A higher throughput signifies better protocol performance in data delivery and reliability in maintaining communication. Figure 11 presents the throughput comparison across protocols:

Figure 11 presents the throughput comparison among different LEACH protocol variants. The x-axis represents the number of operational rounds, while the y-axis shows the cumulative number of packets transmitted to the base station. The LEACH-Proposed protocol demonstrates the highest throughput among all variants, maintaining superior packet delivery performance throughout the network's operational lifespan.

Table 2.
Summary of lifetime metrics (FND, HND, AND) and improvement over LEACH original.

Protocol	FND	HND	AND	Improvement over LEACH original
LEACH original	645	1064	1410	—
LEACH-KMeans	80	550	1411	−87.6 % / −48.3 % / +0.07 %
LEACH-C	386	761	1101	−40.1 % / −28.5 % / −21.9 %
LEACH-GA	462	900	1264	−28.3 % / −15.4 % / −10.4 %
LEACH-proposed	869	1400	1946	+34.8 % / +31.4 % / +37.9 %

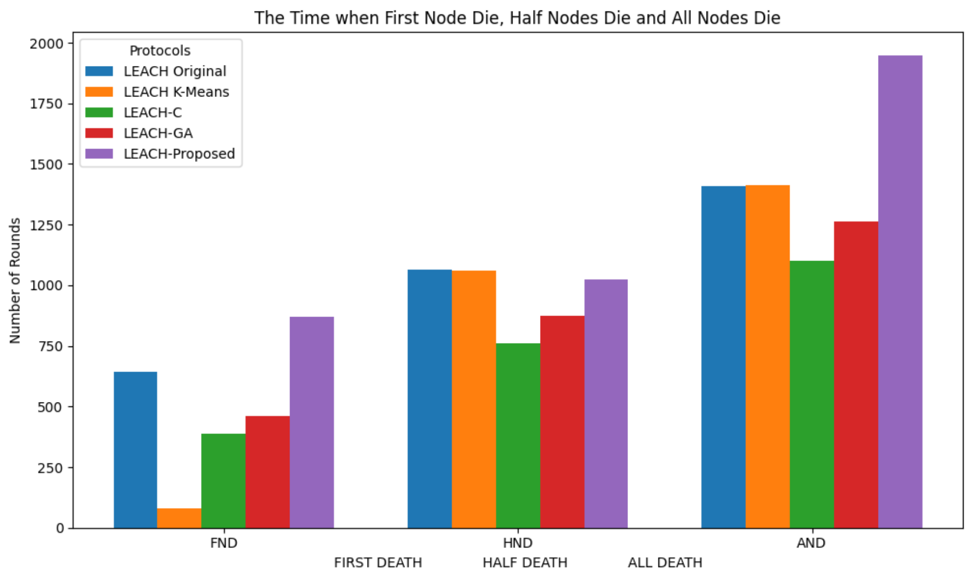

Figure 10. Comparison of rounds at first node death (FND), half nodes death (HND), and all nodes death (AND) across LEACH variants.

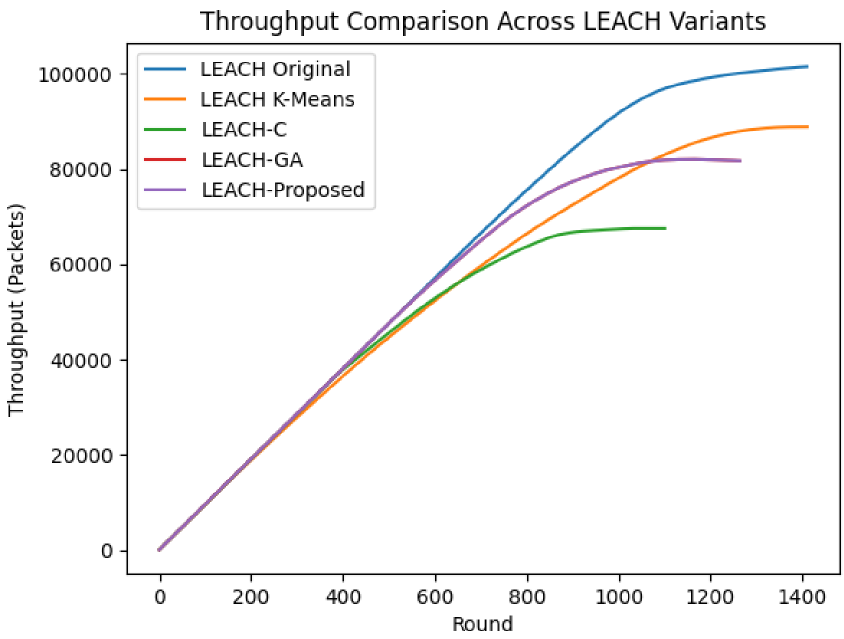

Figure 11. Throughput comparison for all protocols, showing the total number of packets successfully delivered over the network lifetime.

LEACH K-Means also performs well, achieving higher throughput than both LEACH-C and LEACH-GA. LEACH-C and LEACH-GA exhibit moderate throughput, while the LEACH original protocol shows the lowest performance. These results highlight the benefits of the proposed variant's enhanced clustering and energy-efficient communication strategies, which contribute to prolonged node operation and improved data transmission efficiency.

IV. Conclusion

This study introduced a sector-based midpoint-driven enhanced LEACH protocol designed to improve energy efficiency and extend the operational lifetime of wireless sensor networks (WSNs). By integrating sector partitioning with midpoint-guided cluster head (CH) selection, the proposed method significantly reduces the average distance between nodes and their CHs, yielding more balanced energy consumption throughout the network. Simulation results demonstrate substantial improvements across key lifetime indicators. The proposed protocol achieves increases of 34.8 % in first node death (FND), 31.4 % in half nodes death (HND), and 37.9 % in all nodes death (AND) compared with the original LEACH. These gains indicate that midpoint-driven CH placement effectively stabilizes communication ranges, prevents energy hotspots, and distributes load more evenly among nodes. Furthermore, the method consistently preserves more residual energy and maintains higher throughput over the network's lifetime, confirming its robustness in long-duration sensing applications. Beyond numerical improvements, the significance of these results lies in the protocol's scalability and computational simplicity. Unlike optimization-based variants such as LEACH-GA or centralized approaches like LEACH-C, the proposed method maintains LEACH's lightweight characteristics while resolving key deficiencies related to CH randomness and cluster imbalance. This makes the protocol highly suitable for real-world IoT applications where sensor nodes must operate autonomously for extended periods, such as smart agriculture, environmental monitoring, structural health inspection, and remote sensing networks. Future work may explore integrating residual energy weighting, dynamic sector resizing, or multi-hop enhancements to further optimize communication paths. Additionally, combining midpoint-guided clustering with machine learning-based CH prediction presents an opportunity to enhance adaptability in highly dynamic WSN deployments. Overall, the proposed approach provides a practical and energy-aware clustering solution that advances the efficiency, reliability, and longevity of WSN communication systems.

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Declarations

Author contribution

All authors contributed equally as the main contributor of this paper. All authors read and approved the final paper.

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Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The use of AI or AI-assisted technologies

During the preparation of this work, the authors used ChatGPT to paraphrase text and improve sentence clarity and grammar. After using this tool, the authors reviewed and edited the content as necessary and takes full responsibility for the content of the publication.

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