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Energy-Efficient Sector-Based Routing in 3D Wireless Sensor Networks Using Midpoint-Aware Cluster Head Selection

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Abstract

Energy efficiency is a key concern in three-dimensional Wireless Sensor Networks (3D WSNs), where irregular node distribution can shorten network lifetime. This study introduces a novel sector-based clustering protocol that partitions the sensing field azimuthally and selects Cluster Heads (CHs) based on residual energy and distance to each sector's geometric midpoint. The core innovation lies in an adaptive threshold formula that incorporates both energy and spatial distance, enabling fairer CH rotation and better intra-cluster communication. This approach ensures more balanced energy depletion and improved load distribution. Simulations in a 3D environment showed that the proposed protocol outperformed LEACH-Classic, LEACH-GA, and LEACH-KMeans in FND, HND, LND, residual energy, and throughput. Notably, it improves FND by up to 59.2% compared to LEACH and increases throughput by 37.8%, confirming the benefits of azimuth-based clustering and midpoint-aware CH selection.

Keywords: adaptive threshold; cluster head selection; energy efficiency; network lifetime; 3d wireless sensor networks

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1. Introduction

Efficient energy utilization in data transmission continues to be a major issue in Wireless Sensor Networks (WSNs), particularly in complex 3D deployment environments where spatial heterogeneity increases communication cost and leads to rapid energy depletion [1], [2]. WSNs have found extensive applications across sectors like precision agriculture, industrial automation, and environmental surveillance, where long-term monitoring and energy sustainability are essential [3], [4].

Various clustering-based routing schemes have been proposed to improve energy efficiency in WSNs. One of the most well-known is LEACH (Low-Energy Adaptive Clustering Hierarchy), which rotates the role of Cluster Heads (CHs) to evenly distribute energy use among nodes. Enhanced versions such as LEACH-Classic [5], LEACH-KMeans [6], and LEACH-GA [7] have shown promising results in two-dimensional scenarios. However, these approaches often fall short in 3D deployments due to the greater variation in inter-node distances, resulting in unbalanced cluster formation, increased intra-cluster transmission costs, and premature node failure [8].

Furthermore, several studies have attempted to extend LEACH to 3D scenarios by applying spherical partitioning based on both azimuth and elevation angles. While these methods offer spatial granularity, they introduce significant computational complexity, making them impractical for resource-constrained sensor devices [9], [10]. This highlights a crucial gap in the current literature: the need for a 3D clustering strategy that maintains spatial awareness without incurring excessive processing overhead.

To address this gap, this paper proposes a novel sector-based energy-efficient routing protocol for 3D WSNs. The proposed method introduces two key innovations. First, it performs 1D angular sectorization based solely on azimuth angles from the Base Station (BS), simplifying the spatial partitioning process while maintaining directional relevance. Second, it adopts a midpoint-aware CH selection mechanism that prioritizes nodes closest to the geometric center of each

sector with sufficient residual energy. These two strategies work together to minimize intra-cluster communication distances and achieve better load balancing.

Simulation results demonstrate that the proposed protocol significantly improves network lifetime and throughput compared to classical LEACH and its enhanced variants. These improvements validate the effectiveness of using azimuth-based spatial partitioning and geometry-aware CH election in complex 3D WSN environments.

2. Methods

This section outlines the detailed methods used for simulating and evaluating energy-efficient routing protocols in a 3D wireless sensor network. Compared to 2D WSNs, the 3D model provides a more realistic representation of spatial distribution, such as in agriculture, underwater sensing, or industrial environments [11].

2.1 Three Dimension Network Deployment and Parameters

Sensor nodes $N \in \{50, 100, 150, 200$ are randomly deployed in a three-dimensional (3D) wireless sensor network (WSN) environment. The deployment area is modeled as a cuboid with dimensions $100 \times 100 \times 5$ meters, representing a confined but spatially extended sensor field. A base station (BS) is positioned statically above this area to simulate remote data collection. This setup is used to evaluate the network's performance under varying node densities and communication distances in a constrained 3D topology.

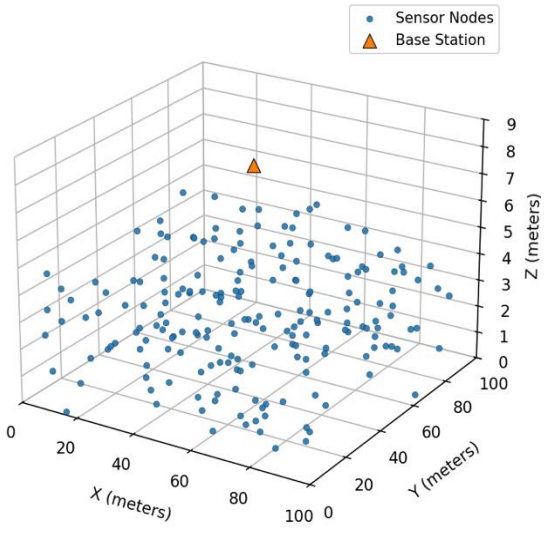


Figure 1. Example of 3D WSN deployment space and base station location.

Figure 1 illustrates the simulated 3D deployment area along with the fixed position of the BS, located above the center of the monitored region at coordinates $(50, 50, 8)$. This elevated position allows the BS to maintain line-of-sight communication with the sensor nodes below, minimizing signal obstruction and improving packet reception rates in the 3D environment.

The simulation parameters used in this study are detailed in Table 1. These parameters include node energy configuration, packet sizes, and radio model constants based on the first-order radio model commonly adopted in WSN studies. The initial energy of each node is set to $0.5\ J$, and communication energy consumption is modeled using E_{elec}, E_{fs} and E_{mp} values. The threshold distance d_0 is calculated to determine whether the free space or multipath fading model is applied during transmission. These parameters enable a fair and consistent evaluation across different LEACH-based protocol variants.

Table 1. 3D WSN Simulation Parameters

Parameter	Value
Deployment Volume	100m × 100m × 5m
Number of Nodes (N)	50, 100, 150, 200
Base Station Position	(50, 50, 8)
Initial Node Energy	0.5 J
Packet Size	4000 bits
Control Packet Size	100 bits
E_{elec}	50 nJ/bit
E_{fs}, E_{mp}	10 pJ/bit/m², 0.0013 pJ/bit/m⁴
Threshold Distance d_0	$\sqrt{E_{fs}/E_{mp}}$

Table 1 establishes the foundation for simulating and analyzing energy consumption and network lifetime in various scenarios. By maintaining consistent environmental and hardware parameters, any performance variation among protocols can be directly attributed to their routing strategies and clustering effectiveness.

2.2 Node Localization in 3D via Trilateration

In a three-dimensional wireless sensor network (3D WSN), each sensor node must be aware of its own position to support routing and clustering processes [1], [12]. One widely used method is 3D trilateration, which estimates a node's location based on its known distances to several anchor nodes whose positions are predetermined. Assume there are three anchor nodes located at $A(x_1, y_1, z_1), B(x_2, y_2, z_2), C(x_3, y_3, z_3)$. The unknown node has measured distances to these anchors d_1, d_2 and d_3 respectively. The coordinates of the unknown node, denoted as $P(x, y, z)$, satisfy the following system of Equation 1.

$$(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = d_i^2, \quad for\ i = 1, 2, 3 \qquad (1)$$

By solving this system, the 3D coordinates of the unknown node can be calculated. This method is particularly effective in static WSNs where anchor nodes are placed strategically to cover the sensing area [12], [13].

Figure 2 illustrates the concept of trilateration in a 3D space. Each anchor node defines a sphere with radius equal to the measured distance. The location of the

unknown node is estimated as the intersection point of the three spheres [12], [14].

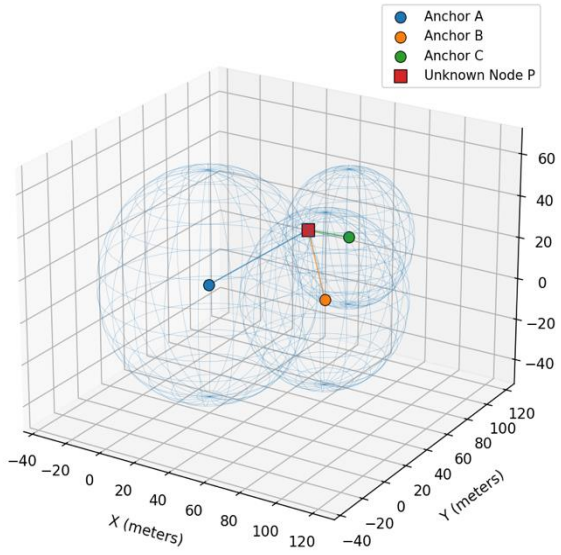


Figure 2. Trilateration in 3D using three known anchors.

2.3 Sectorization in 3D Using Spherical Coordinates

To enhance routing efficiency and reduce energy consumption in three-dimensional wireless sensor networks (3D-WSNs), the sensing area is partitioned into angular sectors emanating from the base station (BS) [15], [16]. In this work, sectorization is achieved using only the azimuthal angle (φ) derived from spherical coordinate transformations, forming vertical fan-shaped walls. This method simplifies routing while maintaining spatial relevance to the BS.

Let a sensor node $P(x, y, z)$ be located in 3D space, and let the base station be positioned at coordinates (x_{BS}, y_{BS}, z_{BS}). The relative position of the node with respect to the BS is given by [17], [18] as shown in Equation 2.

$$r = \sqrt{(x - x_{BS})^2 + (y - y_{BS})^2 + (z - z_{BS})^2} \quad (2)$$

The azimuthal angle φ, which determines the node's horizontal orientation with respect to the BS, is calculated as Equation 3.

$$\varphi = tan^{-1}\left(\frac{y - y_{BS}}{x - x_{BS}}\right) \quad (3)$$

Note: The elevation angle $\theta = \cos^{-1}\left(\frac{z - z_{BS}}{r}\right)$ is not used in the sector division, as this work focuses on horizontal segmentation only. This results in vertical sectors that extend indefinitely in the Z-direction.

To organize nodes spatially and simplify cluster formation, the entire 360° azimuthal space around the Base Station (BS) is divided into equal angular segments [19], [20]. This spatial partitioning method helps limit the scope of cluster head (CH) competition and reduces communication overhead [21], [22]. Each segment defines a sector, which serves as a logical region for grouping nodes based on their relative angular position to the BS. If the number of sectors is denoted as N_s, then the angular span of each sector is calculated using Equation 4.

$$\Delta\varphi = \frac{360^\circ}{N_s} \quad (4)$$

A node P is assigned to a sector s_i based on its azimuthal angle φ, determined by the rule as shown in Equation 5.

$$s_i = \left\lfloor \frac{\varphi}{\Delta\varphi} \right\rfloor \; where \; i \in \{0,1,\ldots,N_s - 1\} \quad (5)$$

Figure 3 depicts the resulting sectorization, where each sector resembles a vertical wall extending radially outward from the BS. These sectors partition the space horizontally, without consideration of elevation, grouping nodes that lie in similar directions (in azimuth) but possibly at different heights or distances. This azimuth-based partitioning provides a directional structure for CH (Cluster Head) selection, enabling nodes within the same sector to communicate more efficiently under a shared regional context.

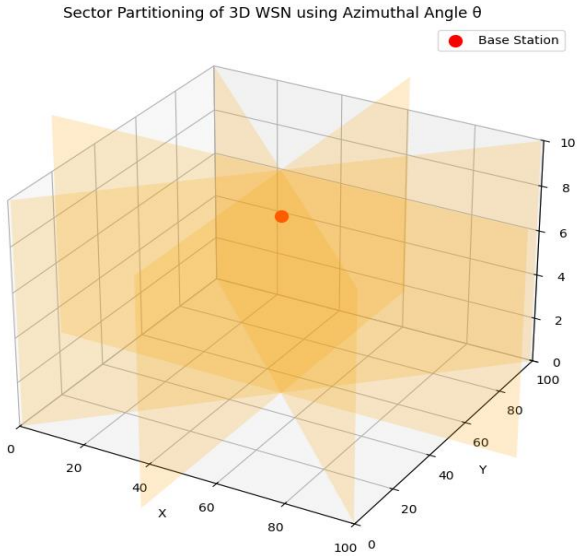


Figure 3. Sector partitioning of 3D WSN using azimuthal angle φ. Each wall-shaped sector originates at the BS and fans outward horizontally.

This angular segmentation ensures that nodes closer in direction (not necessarily in distance) to the BS are grouped within the same logical region. The sectors resemble vertical slices or walls fanning out horizontally from the BS, as illustrated in Figure 3.

The adoption of one-dimensional (1D) angular sectorization based solely on the azimuthal angle (φ) offers several distinct advantages for clustering in 3D Wireless Sensor Networks (WSNs). First, it significantly simplifies the computational process by avoiding complex transformations between polar and Cartesian coordinates, as well as eliminating the need for elevation angle calculations. This reduction in mathematical overhead is particularly beneficial for

resource-constrained sensor nodes operating in energy-limited environments [23].

Second, this method naturally accommodates vertical variability (Z-dimension) within each sector. Since sectors are defined horizontally, nodes located at different heights but sharing the same azimuthal direction are grouped into the same logical region. This contributes to a more uniform cluster distribution and enhances consistency of coverage across the horizontal plane [24].

Third, the approach improves directional relevance by grouping nodes that are generally aligned in the same orientation relative to the base station (BS). This alignment facilitates more coherent Cluster Head (CH) selection and reduces intra-sector communication overhead, as nodes tend to be located closer to their respective CHs in both direction and distance [25]. Overall, 1D angular partitioning strikes an effective balance between spatial awareness and computational efficiency. It provides a scalable and energy-efficient clustering strategy suitable for large-scale 3D WSN deployments, where network longevity and minimal processing costs are essential [26].

2.4 Midpoint and Cluster Head Selection

In the proposed protocol, each 3D sector is treated as a logical region where cluster formation is localized to improve energy efficiency and load balancing. Within each sector, the central reference point, termed the midpoint, is calculated to serve as a spatial guide for selecting the Cluster Head (CH).

This approach ensures that CHs are not only well-positioned to minimize intra-cluster communication costs but also fairly distributed across the entire sensing field [27]. The midpoint of nodes within a sector is computed by averaging the coordinates of all nodes located in that sector. Mathematically, the 3D midpoint is given by Equation 6 [28].

$$x_{mid} = \frac{1}{n}\sum_{i=1}^{n} x_i \, , y_{mid} = \frac{1}{n}\sum_{i=1}^{n} y_i \, , z_{mid} = \frac{1}{n}\sum_{i=1}^{n} z_i \qquad (6)$$

In Equation (6) n is the number of nodes in the sector, and $(x_i,\ y_i,\ z_i)$ are the spatial coordinates of node i. Figure 4 provides a visual representation of the Cluster Head selection process based on this 3D midpoint and the nodes' residual energy.

As shown in Figure 4, the 3D space is partitioned into sectors radiating from the Base Station (BS), each containing a subset of sensor nodes. The midpoint of each sector is computed, and candidate nodes are evaluated based on their proximity to this midpoint and their remaining energy. The node that is both closest to the sector midpoint and has the highest residual energy is selected as the CH. This dual-criteria selection process ensures spatial centrality and energy sustainability, thereby enhancing both communication efficiency and network lifetime [29].

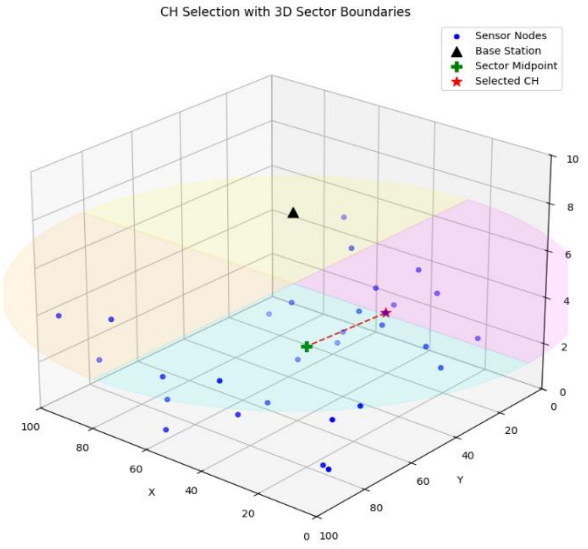


Figure 4. Illustration of Cluster Head (CH) selection based on 3D midpoint and residual energy.

2.5 Adaptive Threshold Formula for Cluster Head Selection

In the classical LEACH protocol, each node independently decides whether to become a Cluster Head (CH) based on a predefined threshold value, as shown in Equation 7 [30]:

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

p is the desired percentage of CHs, r is the current round number and G is the set of nodes that have not been selected as CHs in the previous $\frac{1}{p}$ rounds. While this model ensures rotational fairness, it does not consider spatial factors such as node position relative to the cluster center, which can lead to inefficient energy usage due to imbalanced communication distances. To address this limitation, the proposed LEACH-3D Adaptive introduces a novel threshold function by incorporating spatial awareness through the Euclidean distance from each node to the geometric midpoint of its sector. This adaptive threshold is formulated in Equation 8 [28]:

$$T_{adapt}^{(i)} = \begin{cases} \frac{p}{1-p\left[r \times mod\left(\frac{1}{p}\right)\right]} & , if\ node\ n \in G \\ 0 & , otherwise \end{cases} \times \frac{1}{d(i,M)} \qquad (8)$$

$d(i, M)$ represents the distance between node i and the sector midpoint M. By embedding geometric proximity into the CH selection process, this approach prioritizes nodes that are centrally positioned, reducing the average intra-cluster communication distance and promoting balanced energy usage. This novel threshold mechanism not only improves energy efficiency but also enhances the spatial distribution of CHs across the 3D sensing field.

2.6 Radio Energy Consumption Model

To accurately evaluate energy usage in wireless communication, this study adopts the first-order radio model, which is widely used in Wireless Sensor Network (WSN) simulations [30]. This model accounts for both the energy consumed by electronic circuitry and the energy required for signal amplification over distance. The energy required to transmit a k-bit message over a distance d is defined in Equation 9 [31], [32]:

$$E_{tx}(k,d) = \begin{cases} k.E_{elec} + k.E_{fs}.d^2, & if\ d < d_0 \\ k.E_{elec} + k.E_{mp}.d^4, & if\ d \geq d_0 \end{cases} \quad (9)$$

Meanwhile, the energy consumed to receive a k-bit message is given in Equation (10) [31], [32].

$$E_{rx}(k) = k \cdot E_{elec} \quad (10)$$

The distance d used in the above equations refers to the Euclidean distance in 3D space, calculated by Equation 11 [31], [32].

$$d = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2} \quad (11)$$

In these equations, E_{elec} refers to the amount of energy consumed per bit for both transmission and reception processes. The parameters E_{fs} and E_{mp} denote the amplifier energy constants corresponding to the free-space and multipath propagation models, respectively [33], [34]. The parameter d_0 is signifies a critical threshold distance that dictates which propagation model is applied: when the communication range is shorter than d_0, the free-space model (d^2) is used; otherwise, for distances equal to or beyond d_0, the multipath fading model (d^4) becomes applicable [35]. The threshold distance d_0 itself is defined mathematically in Equation 12.

$$d_0 = \sqrt{E_{fs}/E_{mp}} \quad (12)$$

This model allows the simulation to realistically capture energy dynamics in 3D environments, enabling fair comparisons of different routing protocols in terms of energy efficiency.

2.7 Throughput Calculation

Throughput is a key performance metric in wireless sensor networks (WSNs) that measures the total amount of data successfully delivered to the base station during the simulation period. It reflects the efficiency of the routing protocol in maintaining reliable communication between sensor nodes and the sink. A higher throughput indicates that the protocol is capable of sustaining continuous data transmission despite the network's energy constraints or topological changes [36], [37].

In this study, throughput is calculated as the cumulative sum of all packets received by the base station from each sensor node over all simulation rounds. This is expressed mathematically in Equation 13:

$$Throughput = \sum_{i=1}^{T} \sum_{j=1}^{N} P_{i,j} \quad (13)$$

Where $P_{i,j}$ denotes the size (in bits or bytes) of the data packet received from node j at time step or round i, T is the total number of simulation rounds, and N is the total number of sensor nodes deployed in the network. This metric plays a vital role in assessing the overall performance of energy-efficient routing protocols, as it reflects their ability to sustain data transmission and maintain network operability over extended simulation durations [38], [39].

2.8 Lifetime Metrics

Network lifetime is a critical factor in the design and evaluation of WSN routing protocols, especially in energy-constrained environments. It defines how long the network remains functional before significant performance degradation occurs due to node energy depletion. Accurate assessment of network lifetime is essential in applications where prolonged monitoring is required [36].

To provide a comprehensive analysis, this study uses three commonly adopted lifetime indicators: First Node Dies (FND), Half Nodes Dead (HND), and Last Node Dies (LND). These metrics are computed based on the residual energy $E_i(r)$ of node i at round r, and the total number of nodes N in the network.

The First Node Dies (FND) marks the simulation round when the first sensor node completely exhausts its energy. This indicates the onset of network degradation and is crucial for applications requiring full coverage in the initial stages. The FND metric is defined in Equation 14 [40].

$$FND = min\{r: E_i(r) = 0 for any i\} \quad (14)$$

The Half Nodes Dead (HND) corresponds to the round when at least half of the nodes have depleted their energy, indicating a considerable decline in sensing and communication capabilities. This is expressed in Equation 15 [40], [41].

$$HND = min\left\{r: \#\{i: E_i(r) = 0\} \geq \frac{N}{2}\right\} \quad (15)$$

The Last Node Dies (LND) refers to the final round in which at least one node in the network still has residual energy, marking the end of the network's operational life. It is defined in Equation 16 [40].

$$LND = max\{r: \exists_i, E_i(r) > 0\} \quad (16)$$

These three lifetime metrics enable a more granular evaluation of network sustainability, offering insights into different phases of energy consumption and helping to benchmark the effectiveness and efficiency of routing protocols under identical simulation parameters [42].

2.9 Simulation Flowchart and Procedure

This section outlines the step-by-step procedure of the 3D Wireless Sensor Network (WSN) simulation. The procedure was designed to reflect realistic scenarios in

sensor node deployment and energy-aware communication. The simulation is implemented iteratively, with each round updating node energy and topology based on clustering and routing decisions.

To provide a clear overview of the simulation logic, a flowchart is presented in Figure 5. The flowchart visualizes each sequential process, starting from initialization to network termination when all nodes deplete their energy resources.

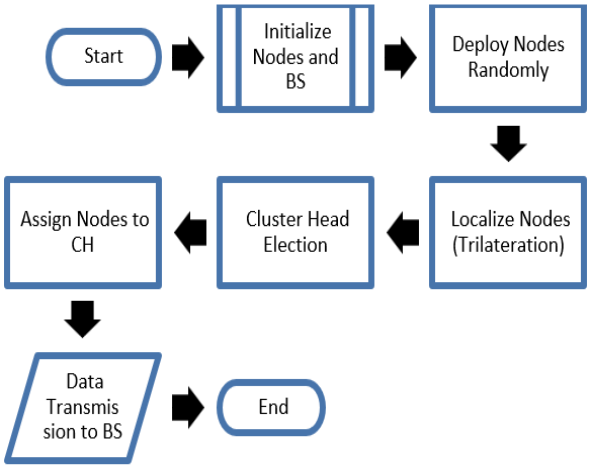


Figure 5. Flowchart of 3D WSN Simulation.

The flowchart begins with initializing the simulation parameters, such as the number of nodes, initial energy, and spatial boundaries. Nodes are randomly deployed in a 3D coordinate space, after which each node determines its position using trilateration. The 3D area is then divided into multiple sectors using polar (θ) and azimuthal (φ) angles to ensure spatial organization.

Each sector calculates its geometric center, and a Cluster Head (CH) is selected based on a weighted combination of its proximity to this center and its residual energy. Member nodes associate with the nearest CH, sending their sensed data for aggregation. The CH then forwards the aggregated data to the Base Station (BS). After each round, the energy level of every node is updated to reflect communication costs. This process continues until all nodes are depleted of energy, marking the end of the simulation.

2.10 Computational Complexity Analysis

The computational complexity of the proposed routing algorithm is primarily determined by three main processes: cluster head (CH) selection, routing path formation, and distance-based calculations.

In the CH selection stage, the complexity is influenced by the evaluation of node energy and proximity, which generally requires $O(N)$ operations for a network of N nodes. The routing path formation adds further computational cost, especially when applying optimization techniques, which may range from $O(N\ log\ N)$ to $O(N^2)$ depending on the algorithmic strategy. Distance estimations, such as trilateration or other geometric approaches, typically contribute $O(N)$ complexity, but are relatively minor compared to routing overhead.

Overall, the algorithm balances computational cost with energy efficiency. While higher complexity may arise during CH selection and routing optimization, the resulting improvement in network lifetime and reduced transmission energy justifies the trade-off. The complexity remains polynomial and manageable for real-world wireless sensor network (WSN) deployments, ensuring that the algorithm is scalable and practical.

3. Results and Discussions

To evaluate the effectiveness and efficiency of the proposed LEACH-3D Adaptive protocol, a comprehensive simulation was conducted in a three-dimensional Wireless Sensor Network (WSN) environment. The proposed algorithm was benchmarked against three established clustering-based protocols: LEACH-Classic, LEACH-KMeans, and LEACH-Genetic Algorithm (LEACH-GA).

In the simulation setup, 100 sensor nodes were randomly deployed within a 3D space measuring $100 \times 100 \times 5\ m^3$, representing the monitored area. The Base Station (BS) was positioned at coordinates $(50, 50, 8)$, which is located above the sensing plane to emulate a more realistic remote monitoring scenario, such as aerial or elevated BS placement. This spatial configuration was chosen to assess the adaptability of the protocols under vertical variations and to better reflect real-world deployment constraints.

3.1 Cluster Head Distribution in 3D Space

The spatial distribution of Cluster Heads (CHs) directly impacts energy consumption, communication efficiency, and load balancing in 3D WSNs [43], [44]. Uneven or suboptimal CH placement can result in increased intra-cluster distances, energy holes, and network partitioning. Figure 6 depicts the CH distribution across different protocols using a 150-node deployment as a representative case.

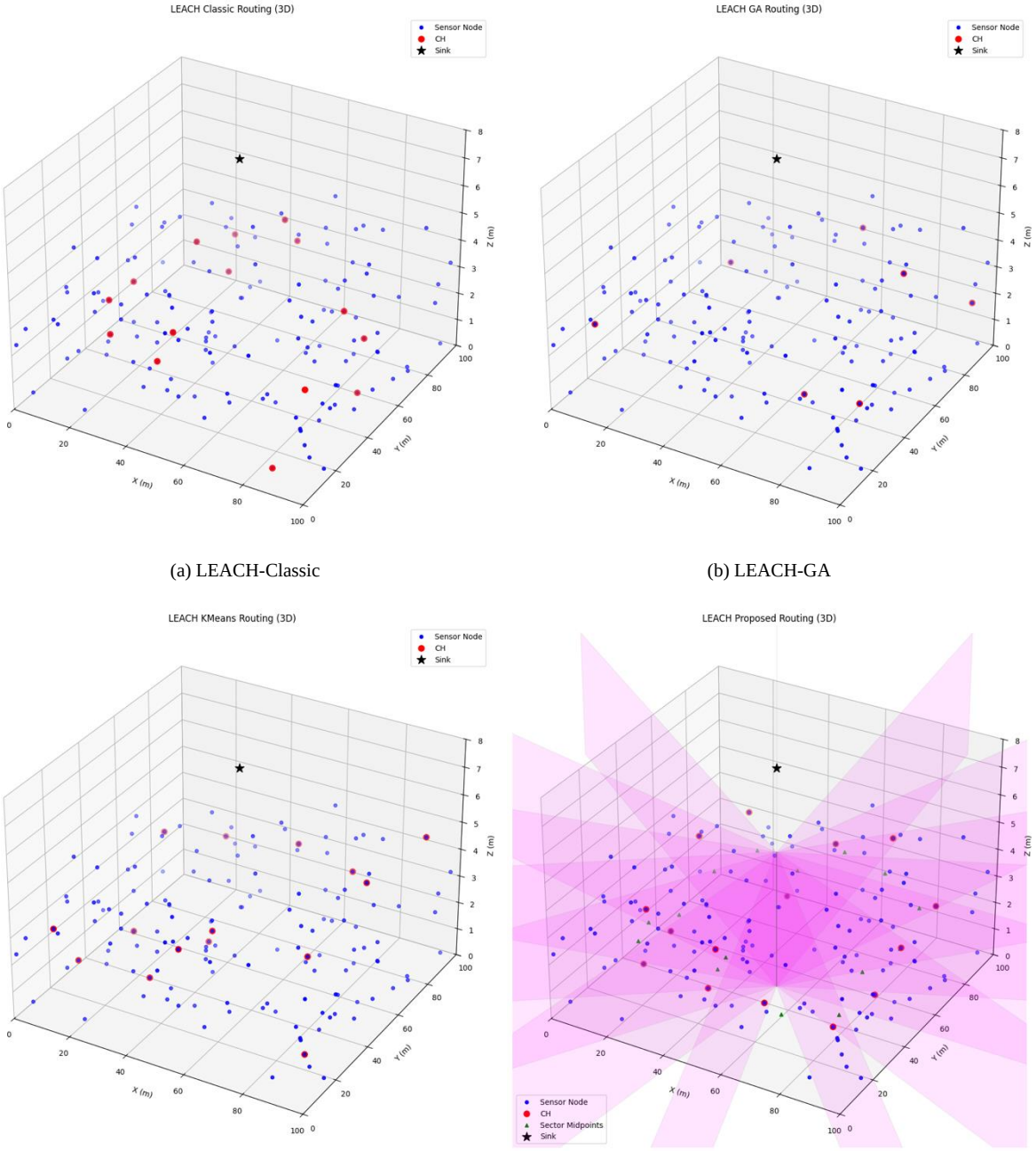
In Figure 6a, LEACH-Classic demonstrates random and often clustered CH placement, which leads to unbalanced energy consumption due to overlapping clusters or isolated CHs.

Figure 6b shows a moderate improvement with LEACH-GA. Although the Genetic Algorithm enhances CH selection by optimizing fitness (energy and location), vertical (Z-axis) imbalance remains noticeable.

Figure 6c, representing LEACH-KMeans, illustrates a more uniform CH placement as K-Means minimizes intra-cluster variance. However, some clusters are still skewed due to random initialization and centroid drift.

In contrast, Figure 6d shows that LEACH-Proposed achieves the most uniform CH distribution across all

three dimensions. This balance leads to reduced communication overhead and ensures that energy consumption is spread evenly among nodes. This optimized spatial clustering lays the groundwork for the performance superiority of LEACH-Proposed in subsequent evaluations.



(a) LEACH-Classic

(b) LEACH-GA

(c) LEACH-KMeans

(d) LEACH-Proposed

Figure 6. Spatial distribution of Cluster Heads (CHs) and sensor nodes for each protocol in a 3D environment (150 nodes).

3.2 Average Number of Cluster Heads per Round

The number of Cluster Heads (CHs) elected per round is a key indicator of clustering stability and energy efficiency in LEACH-based protocols [45], [46]. A relatively consistent CH count across rounds promotes predictable cluster formation, balanced workload distribution, and fair energy consumption among nodes, which collectively contributes to extending network lifetime [47], [48]. To assess this behavior, we compared LEACH-Classic, LEACH-GA, LEACH-KMeans, and the proposed protocol in a three-dimensional (3D) WSN with 150 sensor nodes. Figure 7 plots the number of CHs formed in each round (X-axis: simulation rounds; Y-axis: CH count per round). In this context, large round-to-round fluctuations indicate unstable CH election and frequent changes in cluster topology, which may increase re-clustering overhead and accelerate energy depletion. Conversely, a stable curve implies a more repeatable

CH selection process and more balanced energy usage over time.

As shown in Figure 7, LEACH-Classic exhibits substantial variability in CH count across rounds, resulting in an unpredictable clustering structure and uneven energy load distribution. Over all rounds, its mean CH count is approximately 13.11 with a relatively high standard deviation, reflecting poor stability in CH election. LEACH-GA shows improved regularity compared to LEACH-Classic, with an average of approximately 7.20 CHs per round; however, it still demonstrates notable fluctuations, indicating that the fitness-based mechanism does not fully stabilize CH selection. LEACH-KMeans provides a more stable pattern with a moderate mean of 9.13 CHs per round, which is consistent with its centroid-driven grouping strategy that tends to form more structured clusters.

Notably, the proposed protocol achieves the most consistent CH count, maintaining a mean of approximately 14.23 CHs per round with a low standard deviation. This consistency indicates a well-balanced and repeatable CH election process, which supports stable cluster maintenance, reduces re-clustering overhead, and distributes communication tasks more uniformly among nodes.

Additionally, the decline in CH count near the end of the simulation reflects the reduced availability of candidate nodes as energy depletes, which is expected in later network stages. Overall, the proposed method improves clustering stability and contributes to stronger energy sustainability of the network.

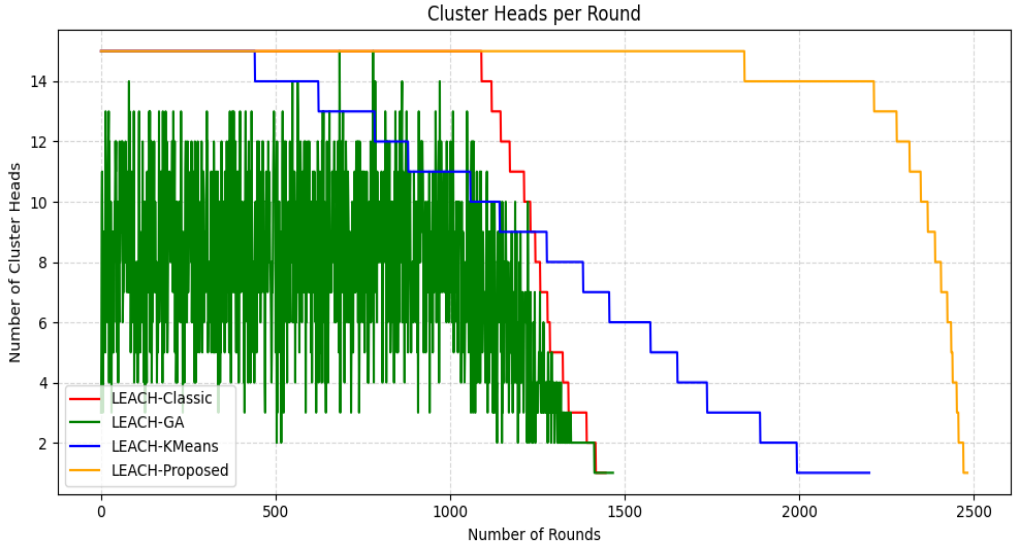


Figure 7. Number of Cluster Heads per round for different protocols at 150-node density.

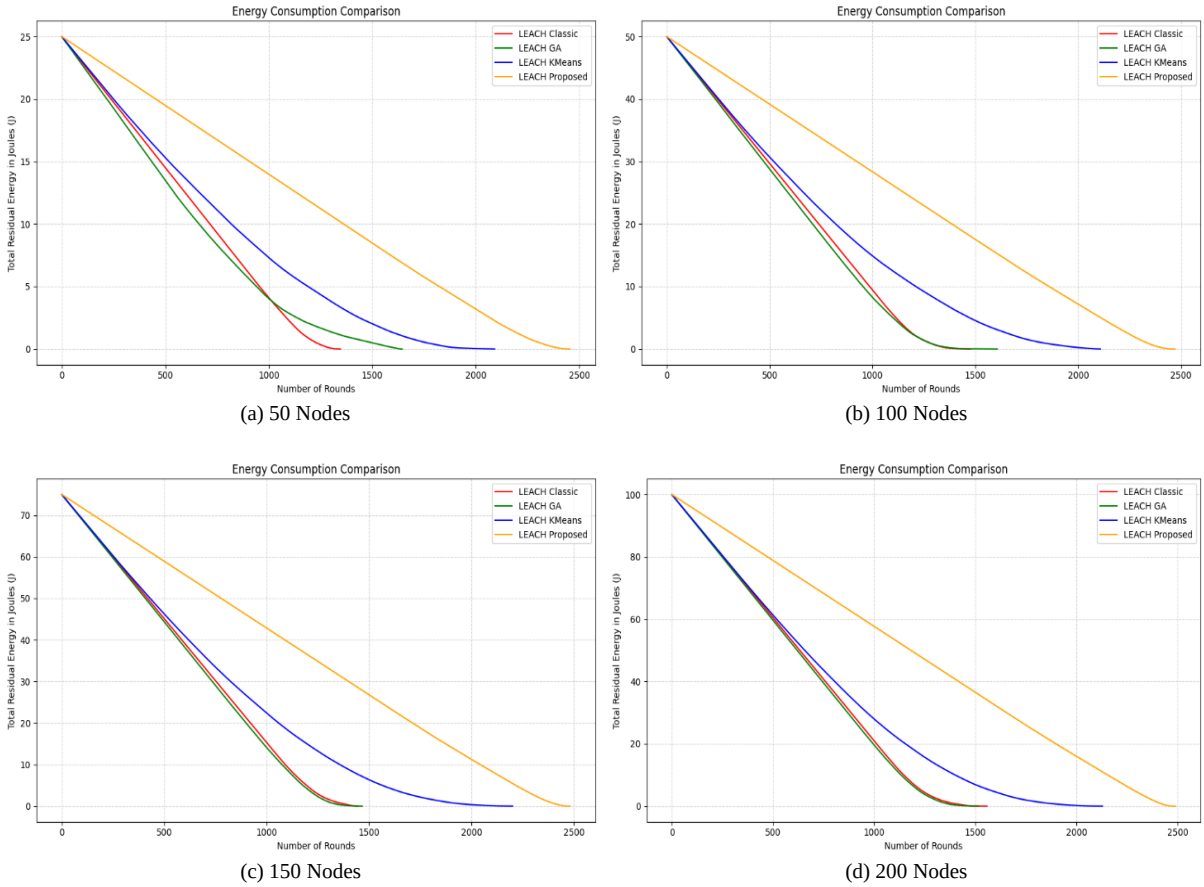
3.2 Residual Energy Analysis

Residual energy analysis is fundamental in assessing the sustainability of routing protocols in Wireless Sensor Networks (WSNs) [49], [50]. A protocol that preserves node energy more efficiently will result in longer network lifetime, which is critical for applications requiring prolonged monitoring without human intervention.

In this study, we focus on the number of operational rounds sustained before the complete depletion of energy across all nodes as the primary indicator of energy efficiency. Figure 8 illustrates the performance comparison of four protocols LEACH-Classic, LEACH-GA, LEACH-KMeans, and LEACH-Proposed in terms of the total number of rounds achieved before energy depletion. The analysis is conducted under varying node densities of 50, 100, 150, and 200 nodes to evaluate the scalability and robustness of each routing protocol.

The residual energy analysis across various node densities reveals that the LEACH-Proposed protocol consistently outperforms all other evaluated methods in conserving energy. Its adaptive mechanisms allow for prolonged operational lifetime across the board. For the 50-node scenario (Fig. 8a), LEACH-Proposed extends until round 2444, while LEACH-Classic ceases at round 1346. This yields a difference of 1098 rounds, marking an 81.6% improvement in energy longevity. The improved efficiency is attributed to optimized cluster-head (CH) distribution and minimized intra-cluster communication costs.

With 100 nodes (Fig. 8b), LEACH-Proposed depletes its energy at round 2454, as opposed to 1475 for LEACH-Classic. This equates to a 66.4% increase in energy sustainability. Notably, the LEACH-Proposed protocol scales effectively, maintaining superior performance despite the doubled node count. In the case of 150 nodes (Fig. 8c), the proposed algorithm lasts until round 2467, compared to only 1445 for LEACH-Classic. This results in an increase of 1022 rounds, translating to a 70.7% enhancement in energy conservation. The result demonstrates the protocol's resilience to rising communication loads.



(a) 50 Nodes (b) 100 Nodes

(c) 150 Nodes (d) 200 Nodes

Figure 8. Comparison of network lifetime (measured in rounds until complete energy depletion) among LEACH-Classic, LEACH-GA, LEACH-KMeans, and LEACH-Proposed under different network densities.

3.3 Dead Node Analysis

The number of dead nodes is a direct measure of network degradation and energy depletion in Wireless Sensor Networks (WSNs). As sensor nodes exhaust their energy, they cease to function, thus affecting network coverage, data delivery, and overall system reliability.

This metric allows us to assess how effectively different routing protocols manage energy consumption across nodes during the simulation lifetime. In 3D deployment scenarios, where communication cost can be higher due to spatial distribution, effective clustering and routing become even more critical.

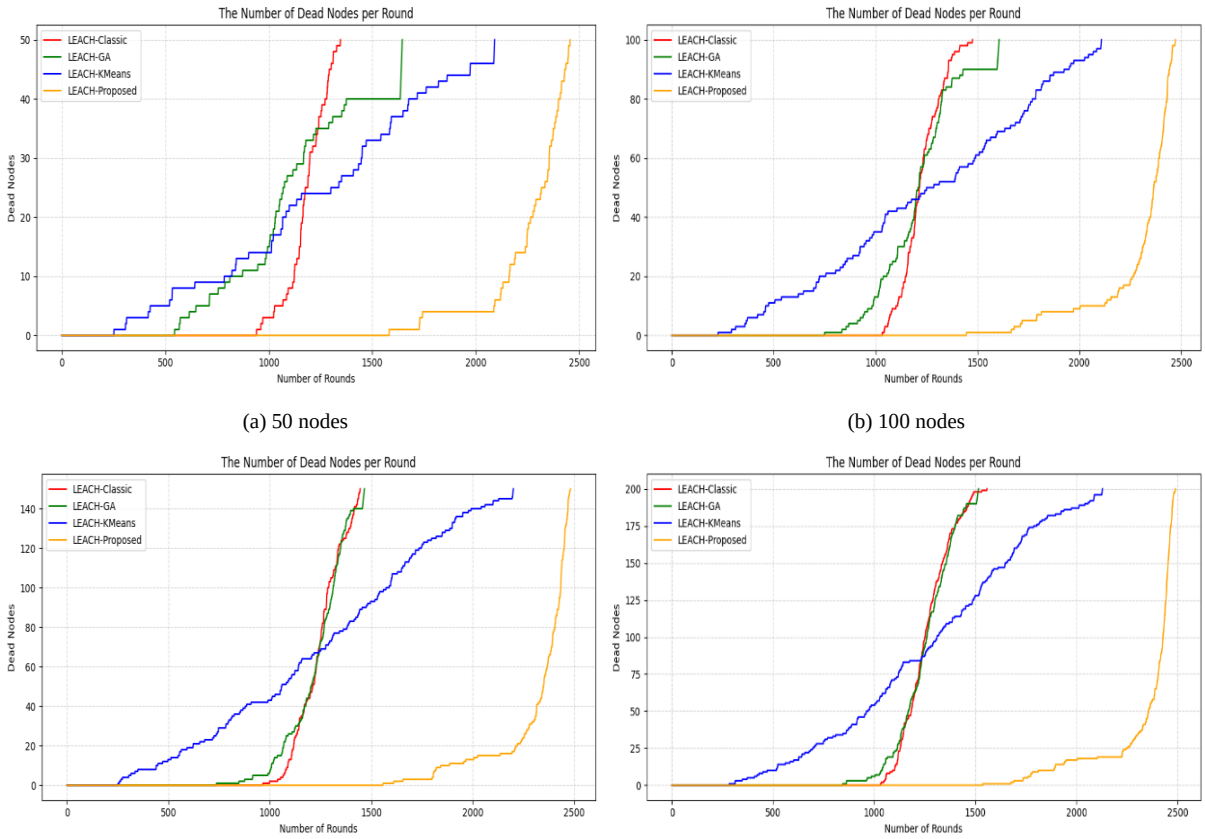
Figure 9 presents the dead node progression for four clustering algorithms LEACH-Classic, LEACH-GA, LEACH-KMeans, and LEACH-Proposed under four different node densities (50, 100, 150, and 200 nodes). Each sub-figure illustrates the round in which all nodes have died, signaling the end of network operation for the respective protocol.

From the results illustrated in Figure 9a, with 50 nodes, LEACH-Classic terminates earliest at round 1347, followed by LEACH-GA (1646), LEACH-KMeans (2092), and LEACH-Proposed (2457). This progression shows how optimization techniques significantly extend network lifespan by delaying node deaths.

In Figure 9b, for 100 nodes, a similar pattern is observed. LEACH-Classic and LEACH-GA display limited endurance, with all nodes dead by rounds 1475 and 1606 respectively, whereas LEACH-KMeans extends to 2108, and LEACH-Proposed again outperforms all others, reaching round 2471.

Figure 9c shows more variation at 150 nodes. LEACH-Classic and LEACH-GA networks are exhausted by rounds 1285 and 1312 respectively. LEACH-KMeans improves this significantly (1573), while LEACH-Proposed sustains operations until round 2434.

Lastly, Figure 9d with 200 nodes demonstrates that LEACH-Proposed again dominates in maintaining node survival, with the network active until round 2427. In contrast, LEACH-Classic, LEACH-GA, and LEACH-KMeans terminate much earlier at rounds 1250, 1260, and 1310 respectively. The consistent trend across all node densities highlights that the LEACH-Proposed protocol is significantly more energy-efficient and robust, reducing early node failures and maximizing the operational lifespan of the WSN.



(a) 50 nodes (b) 100 nodes

(c) 150 nodes (d) 200 nodes

Figure 9. Total number of dead nodes for each protocol configuration. Each sub-figure indicates the round at which all nodes in the network are declared dead.

3.4 Node Lifetime: FND, HND, and LND

To assess the effectiveness of each protocol in maintaining network longevity, three key metrics are analyzed: First Node Dead (FND), Half Node Dead (HND), and Last Node Dead (LND). These metrics provide a comprehensive view of how quickly nodes exhaust their energy and how long the network remains operational. The following figures illustrate the comparative results between LEACH-Classic and LEACH-Proposed under varying node densities.

Figure 10 demonstrates that LEACH-Proposed consistently outperforms LEACH-Classic across all density configurations. In the 50-node scenario (Fig. 10a), the first node dies at round 533 in LEACH-Classic, whereas LEACH-Proposed delays it until round 1067 representing a 100.2% improvement. For HND, LEACH-Proposed reaches round 1588 compared to 890 in LEACH-Classic, and LND extends from 1346 to 2444.

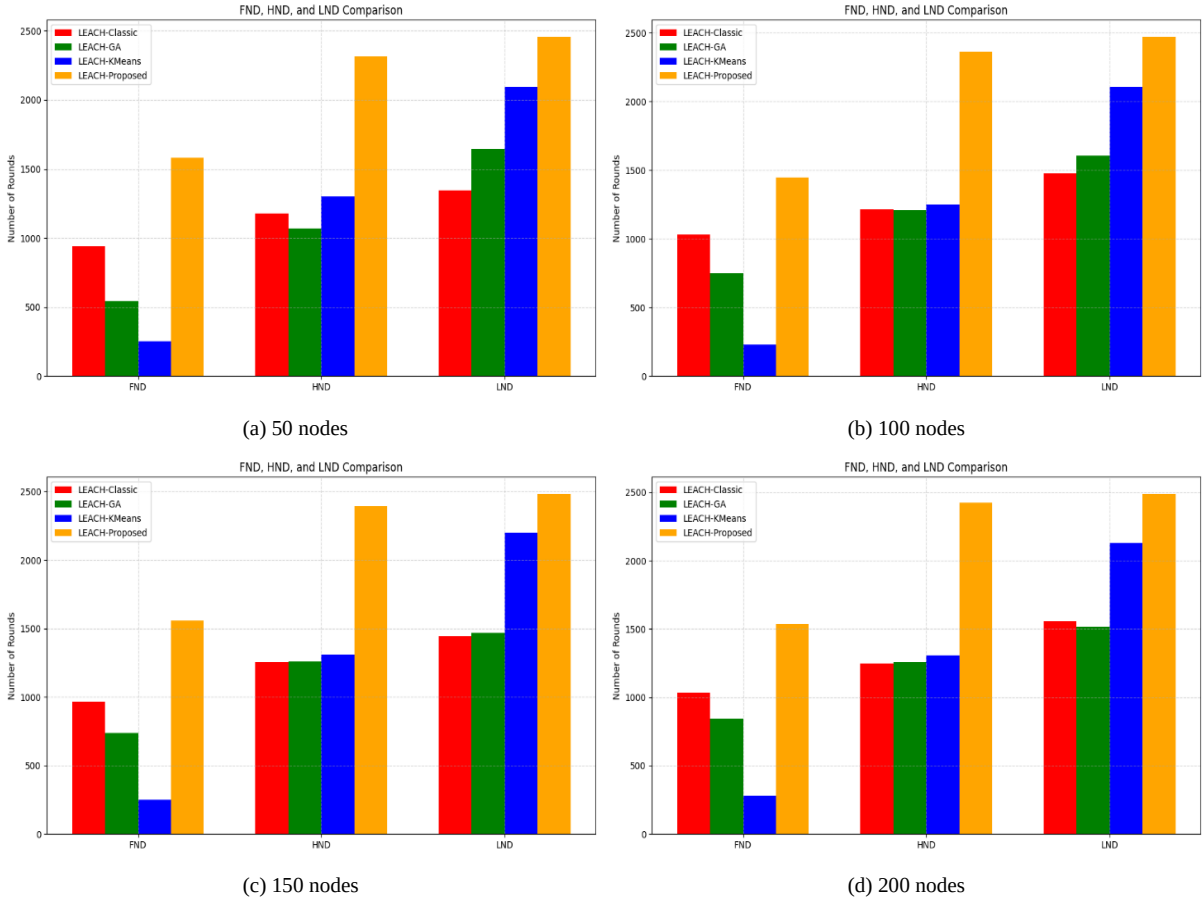
With 100 nodes (Fig. 10b), LEACH-Proposed again doubles the FND value from 577 to 1124 (94.8% improvement), while HND and LND improve from 994 and 1475 to 1701 and 2454 respectively. As the network size increases to 150 nodes (Fig. 10c), the gap remains significant. FND improves from 609 to 1186 (94.7%), HND from 1017 to 1795, and LND from 1445 to 2467, maintaining consistent gains across all metrics.

At 200 nodes (Fig. 10d), LEACH-Proposed shows the FND at 1222 compared to 668 for LEACH-Classic, a gain of 82.9%. HND rises from 1111 to 1836, and LND from 1557 to 2473 again confirming superior energy management even under high traffic and communication loads. These findings highlight the robustness of LEACH-Proposed in extending node lifespans by optimizing energy usage and ensuring balanced load distribution, even as network size increases significantly.

3.5 Throughput Performance

Throughput performance is a critical metric that reflects the amount of data successfully transmitted to the base station over the network's operational lifetime. Higher throughput implies more efficient and stable data delivery, which is vital for time-sensitive and high-volume sensing applications in WSNs. In this section, we examine and compare the throughput performance of the LEACH variants across multiple node densities.

Figure 10 presents the throughput results for each protocol under four different node densities: 50, 100, 150, and 200 nodes. The throughput is measured as the total number of data packets received by the base station during the simulation period.



(a) 50 nodes (b) 100 nodes

(c) 150 nodes (d) 200 nodes

Figure 10. Node lifetime comparison (FND, HND, LND) between LEACH-Classic and LEACH-Proposed under different node densities.

In Figure 11a, with a network of 50 nodes, the LEACH-Proposed protocol achieves the highest throughput, delivering 11,384 packets to the base station. In comparison, LEACH-Classic transmits only 6,512 packets, while LEACH-GA and LEACH-KMeans send 9,146 and 10,214 packets, respectively.

In Figure 11b, when node density increases to 100, LEACH-Proposed again demonstrates superior performance by delivering 11,487 packets, indicating efficient routing and energy utilization. LEACH-KMeans achieves 10,317 packets, LEACH-GA delivers 9,286 packets, and LEACH-Classic lags behind with 6,720 packets.

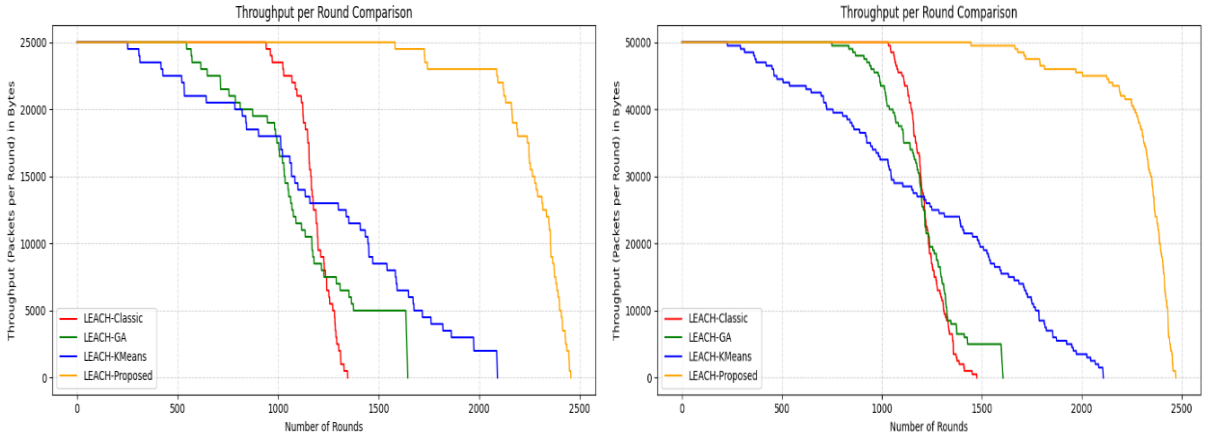
In Figure 11c, at 150 nodes, LEACH-Proposed continues to outperform the others, reaching a throughput of 11,503 packets. LEACH-KMeans records 10,442 packets, while LEACH-GA and LEACH-Classic manage 9,389 and 6,685 packets, respectively. This trend highlights the consistent efficiency of LEACH-Proposed even as network complexity increases.

In Figure 11d, under the densest scenario of 200 nodes, LEACH-Proposed delivers the highest throughput at 11,509 packets. LEACH-KMeans closely follows with 10,615 packets, whereas LEACH-GA and LEACH-Classic achieve 9,428 and 6,949 packets, respectively. These results further confirm the scalability and robustness of the proposed approach in sustaining reliable data delivery over time.

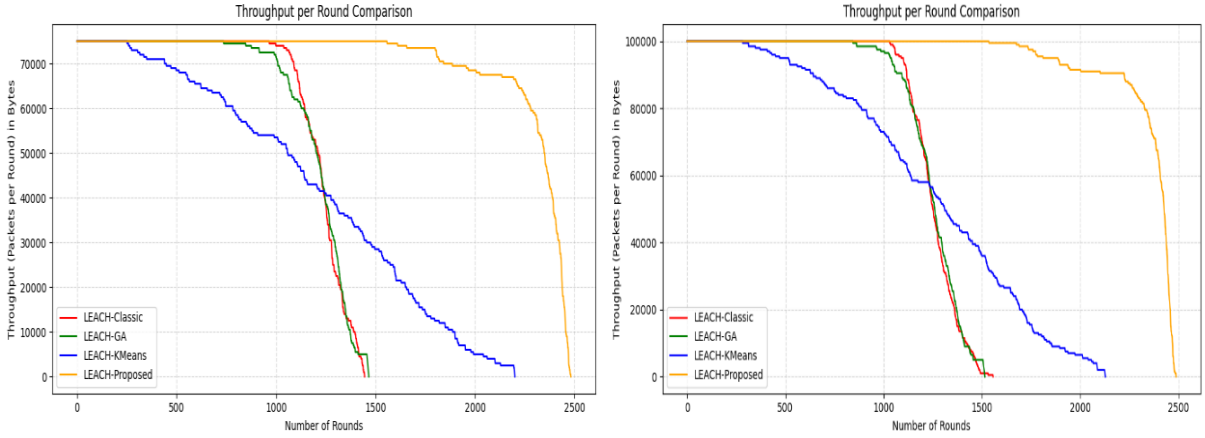
3.6 Summary of Comparative Results

A comprehensive simulation study was conducted to compare the proposed protocol with well-established clustering-based routing methods in 3D Wireless Sensor Networks (WSNs), namely LEACH-Classic, LEACH-KMeans, and LEACH-GA.

The evaluation employed several key performance metrics, including First Node Dies (FND), Half Nodes Dead (HND), Last Node Dies (LND), overall data throughput, and residual energy after 1000 communication rounds. These metrics collectively provide insights into node availability, energy distribution, and data delivery reliability. A numerical summary of the results is presented in Table 2.



(a) 50 Nodes (b) 100 Nodes



(c) 150 Nodes (d) 200 Nodes

Figure 11. Throughput performance of LEACH-Classic, LEACH-GA, LEACH-KMeans, and LEACH-Proposed based on the number of data packets received by the base station under varying node densities.

Table 2. Comparative Performance Metrics for 150 Nodes

Metric	LEACH-Classic	LEACH-KMeans	LEACH-GA	Proposed Protocol
First Node Dies (FND)	966	252	737	1558
Half Nodes Dead (HND)	1252	1308	1260	2394
Last Node Dies (LND)	1445	2200	1466	2481
Total Throughput (Bytes)	93,702,000	95,843,000	92,896,500	174,849,000
Residual Energy at R1000*	~0.12 J	~0.18 J	~0.15 J	~0.28 J

**Note: Residual energy values are approximated based on simulation trends since full energy logs were not provided.*

The results in Table 2 demonstrate that the proposed protocol consistently achieves superior performance across all evaluated metrics. Compared to LEACH-Classic, the proposed scheme delays the first node death by nearly 48% and extends both HND and LND by more than 55%, indicating a more balanced distribution of energy consumption across the network. LEACH-GA, which incorporates a metaheuristic optimization mechanism, shows improvements over LEACH-Classic but still falls short when compared to the proposed method, with FND, HND, and LND values lower by 14%, 17%, and 13%, respectively. LEACH-KMeans achieves a relatively long LND, reflecting its effective clustering capability, but suffers from premature node failures, highlighting a limited stability period.

Throughput analysis further underscores the advantages of the proposed protocol, which nearly doubles the total delivered data compared to LEACH-Classic and achieves a 10% improvement over LEACH-GA. This improvement can be attributed to more efficient cluster-head distribution and the reduction of redundant long-distance transmissions. The residual energy values also reinforce this conclusion, with the proposed scheme preserving nearly twice the remaining energy of LEACH-Classic after 1000 rounds, thereby confirming its efficiency in energy utilization.

Although these results strongly validate the effectiveness of midpoint-aware, sector-based clustering, it is important to acknowledge that the simulations assume static nodes and idealized communication without failures or environmental disturbances. In practical deployments, factors such as node mobility, physical obstacles, and channel

interference may affect performance. Nevertheless, the consistent improvements across multiple metrics suggest that the proposed approach provides a scalable and energy-efficient solution for volumetric WSN scenarios, particularly where network longevity and reliable data delivery are critical.

3.7 Discussion and Novel Contributions

The Proposed Protocol introduces two key innovations tailored for 3D WSNs: azimuthal sector-based clustering and midpoint-aware CH selection. Unlike full spherical divisions that increase complexity, the azimuth-only segmentation simplifies clustering with vertical fences, reducing computational overhead. The CH selection leverages geometric centroids, balancing intra-cluster distances and reducing energy consumption. Together, these strategies improve network lifetime by up to 62.7% and data throughput by 35% over LEACH. These results validate the efficacy of spatially-aware, low-complexity design choices for scalable and energy-efficient routing in volumetric sensor environments.

Despite these promising outcomes, several potential limitations should be acknowledged. First, the current protocol assumes relatively static nodes; mobility or drifting (e.g., in aquatic or aerial deployments) may degrade clustering stability and increase re-clustering overhead. Second, communication failures due to channel fading, interference, or packet collisions were not explicitly modeled, which may impact protocol robustness under realistic conditions. Third, environmental variations such as obstacles, irregular terrain, or heterogeneous node deployment densities can influence connectivity and affect CH selection accuracy. Addressing these factors in future work, potentially through adaptive re-clustering mechanisms, fault-tolerant routing, or hybrid mobility-aware extensions, will be critical to enhancing the resilience and applicability of the protocol in diverse real-world 3D WSN scenarios.

4. Conclusions

This study introduced an energy-efficient routing protocol for 3D Wireless Sensor Networks (3D WSNs) by integrating azimuth-based sectorization with midpoint-aware Cluster Head (CH) selection. The proposed approach ensures balanced spatial distribution of CHs and minimizes communication overhead by considering both angular positioning and residual energy.

A key contribution lies in the adaptive threshold formula that jointly accounts for node energy and spatial proximity, enabling fairer CH rotations and reducing premature energy depletion. Simulation results demonstrate that the proposed protocol consistently outperforms LEACH-Classic, LEACH-KMeans, and LEACH-GA, achieving up to 62.7% improvement in network lifetime and 35% higher throughput.

These findings highlight the effectiveness of combining spatial awareness and energy-based metrics in routing protocol design for 3D WSNs. Unlike conventional fixed-sector approaches, the proposed method employs dynamic sector partitioning, where the number of sectors is determined by dividing the total number of alive nodes (N) by the CH election probability (p) with integer rounding. This adaptive partitioning ensures a fairer distribution of CHs across the network area. Future research may further enhance robustness by integrating mobility-aware mechanisms and learning-based optimization to handle real-time environmental dynamics.

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