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A Hotspot-Aware Load-Balanced Clustering and Routing Protocol for Energy-Efficient Wireless Sensor Networks

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ABSTRACT

Wireless Sensor Networks (WSNs) are widely used in environmental monitoring, healthcare, industrial automation, and Internet of Things (IoT) applications. However, limited energy resources and hotspot formation near the base station significantly reduce network lifetime and communication efficiency. This study proposes a Hotspot-Aware Load-Balanced Clustering and Routing Protocol (HALBCRP) to improve energy utilization and mitigate hotspot formation in WSNs. The proposed protocol integrates energy-aware cluster formation, hotspot-aware cluster head selection, dynamic load balancing, and fault-tolerant multi-hop routing into a unified framework. Sensor nodes are grouped using an energy-distance-based clustering strategy, while cluster heads are selected based on residual energy, connectivity, traffic load, and proximity to the base station. To prevent energy holes and traffic congestion, overloaded cluster heads dynamically redistribute traffic to neighboring cluster heads. The performance of HALBCRP was evaluated using MATLAB and compared with ITSA-UCHSE, HHDAP, Q-DAEER, and IPSO based on energy consumption, average throughput, number of alive nodes, number of dead nodes, and network lifetime. Simulation results show that HALBCRP achieves lower energy consumption (0.605–1.053 J), maintains a higher number of alive nodes throughout the simulation, and attains an average throughput of 28.62 packets per round. Furthermore, the protocol records superior network lifetime values of FND = 800 rounds, HND = 1150 rounds, and LND = 1340 rounds. These results demonstrate that HALBCRP effectively mitigates hotspot formation, balances network load, and significantly extends network lifetime compared with existing approaches.

KEYWORDS: *Wireless Sensor Networks, Hotspot Mitigation, Load Balancing, Cluster Head Selection, Network Lifetime.*

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1. INTRODUCTION

Wireless Sensor Networks (WSNs) have emerged as a key enabling technology for a wide range of applications, including environmental monitoring, healthcare, industrial automation, military surveillance, and Internet of Things (IoT) systems. A typical WSN comprises a large number of sensor nodes deployed to collect and transmit information to a sink or base station. Due to the limited battery capacity and computational resources of sensor nodes, energy efficiency remains one of the most critical challenges in the design of WSNs (Akyildiz et al., 2002).

To improve network scalability and reduce energy consumption, clustering-based routing protocols have been extensively investigated. In cluster-based architectures, sensor nodes are grouped into clusters, and cluster heads are responsible for aggregating and forwarding data to the sink. Among the earliest and most widely adopted clustering protocols is the Low-Energy Adaptive Clustering Hierarchy (LEACH), which employs randomized rotation of cluster heads to distribute energy consumption and prolong network lifetime (Kaur et al., 2025). Subsequently, several energy-efficient clustering schemes, such as Hybrid Energy-Efficient Distributed Clustering

(HEED), have been proposed to achieve better cluster formation and balanced energy utilization (Juwaied & Jackowska, 2025). Despite these advances, conventional clustering and routing protocols are vulnerable to the hotspot problem, where sensor nodes located near the sink deplete their energy faster because they are required to relay traffic from distant nodes. This uneven energy consumption leads to the formation of energy holes, resulting in network partition and premature degradation of network performance (Sun *et al* 2026). Furthermore, unequal cluster sizes and unbalanced traffic distribution may impose excessive communication burdens on certain nodes, thereby reducing throughput, packet delivery ratio, and network lifetime.

Therefore, there is a growing need for routing protocols that jointly address hotspot mitigation and load balancing to achieve efficient energy utilization in WSNs. Motivated by these challenges, this paper proposes a Hotspot-Aware Load-Balanced Clustering and Routing Protocol (HALBCRP) for energy-efficient wireless sensor networks. The proposed protocol incorporates hotspot awareness into the clustering and routing processes to distribute communication loads more uniformly and prevent excessive energy depletion around the sink region. In addition, an energy-aware routing mechanism is employed to enhance network lifetime and improve overall communication performance.

The major contributions of this work are summarized as follows:

1. A novel Hotspot-Aware Load-Balanced Clustering and Routing Protocol (HALBCRP) is proposed to improve energy efficiency in WSNs.
2. A hotspot-aware mechanism is introduced to mitigate energy-hole formation and balance energy consumption among sensor nodes.
3. A load-balanced clustering strategy is developed to distribute communication overhead uniformly across the network.
4. An energy-aware routing scheme is employed to establish efficient transmission paths and enhance network lifetime.
5. The effectiveness of the proposed protocol is evaluated in terms of energy consumption, throughput, packet delivery ratio, and network lifetime.

The remainder of this paper is organized as follows. Section 2 reviews related studies on clustering and routing protocols for WSNs. Section 3 presents the system model and problem formulation. Section 4 describes the proposed Hotspot-Aware Load-Balanced Clustering and Routing Protocol. Section 5 discusses the simulation setup and performance evaluation results. Finally, Section 6 concludes the paper and outlines future research directions.

2. Related Works

Recent studies have proposed various clustering and routing techniques to mitigate hotspot formation and improve energy efficiency in Wireless Sensor Networks (WSNs). Prince et al. (2025) developed a multi-level clustering and prediction-based routing protocol that improves energy utilization and reduces hotspot formation through workload balancing and mega-cluster organization. However, its centralized architecture may limit scalability in large-scale deployments. Vijayaragavan *et al.* (2024) proposed FOAEAUC-SARP, which integrates unequal clustering with Fox Optimization and Snake Algorithms to improve energy efficiency and network lifetime. Although the approach achieves better cluster formation and routing performance, it requires extensive parameter tuning and computational resources. Patil and Kohle (2024) introduced a genetic-based Clustering and Routing Protocol (CGRP) to enhance scalability and reduce communication latency. While the protocol improves routing efficiency, the optimization process introduces computational overhead and may not adequately address hotspot formation near the Base Station. Wang and Duan (2025) proposed FQ-UCR, which combines unequal clustering, fuzzy logic, and Q-learning to improve network stability and lifetime. The protocol achieves balanced energy consumption; however, the integration of fuzzy inference and reinforcement learning increases processing complexity, making it less suitable for resource-constrained sensor nodes. Amutha et al. (2022) developed a hybrid optimization approach that combines unequal clustering with a mobile sink to reduce energy consumption and prolong network lifetime. Although the method improves energy efficiency, sink mobility introduces additional deployment and management complexity. Chauhan and Soni (2021) proposed an energy-aware unequal clustering algorithm with multi-hop routing through low-degree relay nodes. Their approach improves energy distribution and reduces hotspot formation. However, relay-node selection becomes increasingly challenging as network density increases. Despite these contributions, existing approaches largely depend on computationally intensive optimization algorithms, fuzzy systems, reinforcement learning, or mobile sink mechanisms, which increase implementation complexity and processing overhead. Therefore, there remains a need for a lightweight hotspot-aware clustering and routing protocol that can provide balanced energy consumption, effective load distribution, and prolonged network lifetime while maintaining low computational complexity in large-scale WSNs.

Table 1: Summary of Related Studies

Author(s)	Approach	Strengths	Limitations
Prince et al. (2025)	Multi-level clustering and prediction-based routing	Improves energy utilization and hotspot mitigation	Centralized structure limits scalability
Vijayaragavan et al. (2024)	FOAEAUC-SARP	Enhances energy efficiency and network lifetime	Requires extensive parameter tuning
Patil and Kohle (2024)	Genetic-based Clustering and Routing Protocol (CGRP)	Improves scalability and routing efficiency	Computational overhead and hotspot issues
Wang and Duan (2025)	FQ-UCR (Unequal Clustering, Fuzzy Logic, and Q-Learning)	Improves network stability and lifetime	High processing complexity
Amutha et al. (2022)	Unequal clustering with mobile sink	Reduces energy consumption and extends network lifetime	Mobile sink management complexity
Chauhan and Soni (2021)	Energy-aware unequal clustering with multi-hop routing	Improves energy distribution and hotspot mitigation	Relay-node selection challenges in dense networks

2.1. Concepts of Clustering Approaches

Clustering techniques have been widely adopted in wireless sensor networks (WSNs) to improve scalability, reduce energy consumption, and enhance network lifetime. In cluster-based architectures, sensor nodes are grouped into clusters, where a cluster head (CH) is responsible for aggregating data and forwarding it to the sink node. One of the earliest and most influential clustering protocols is the Low-Energy Adaptive Clustering Hierarchy (LEACH), which introduced randomized rotation of cluster heads to evenly distribute energy consumption among nodes (Heinzelman et al., 2002).

Following LEACH, several clustering protocols have been proposed to improve energy efficiency and address its limitations. The Hybrid Energy-Efficient Distributed clustering (HEED) protocol selects cluster heads based on residual energy and communication cost, leading to more balanced cluster formation (Younis & Fahmy, 2004). In addition, various energy-efficient clustering schemes have been developed to support multi-hop communication, heterogeneous networks, and large-scale deployments. A comprehensive classification of clustering techniques highlights their role in reducing communication overhead and improving network scalability (Abbasi & Younis, 2007).

Despite these improvements, many clustering approaches still face challenges such as uneven cluster distribution, excessive inter-cluster communication, and energy imbalance near the sink, which contribute to the hotspot problem and reduced network lifetime (Pantazis et al., 2013).

2.2. Cluster Head Selection Approaches

Cluster head selection is a critical factor in the performance of clustering-based routing protocols in WSNs. The selection process directly influences energy consumption, load balancing, and network stability. Early approaches, such as LEACH, use probabilistic and randomized methods for cluster head selection, ensuring that each node has an equal chance of becoming a cluster head (Heinzelman et al., 2002). However, this approach does not consider residual energy or node location, leading to inefficient energy utilization in heterogeneous networks.

To overcome these limitations, energy-aware cluster head selection methods have been introduced. For example, HEED selects cluster heads based on residual energy and communication cost metrics, ensuring that nodes with higher energy have a higher probability of becoming cluster heads (Younis & Fahmy, 2004). Similarly, several protocols incorporate distance to sink, node density, and load balancing factors into the selection process to improve network performance.

Recent research has also explored optimization-based and intelligent techniques for cluster head selection, including genetic algorithms, particle swarm optimization, and fuzzy logic systems. These approaches aim to achieve optimal cluster head distribution while minimizing energy consumption and balancing network load (Pantazis et al., 2013). However, challenges such as computational complexity and scalability remain open issues in large-scale WSN deployments.

3. Network Model

The network consists of N homogeneous sensor nodes randomly deployed in a two-dimensional sensing area of size 100 x 100^2. The set of sensor nodes is defined as:

$$SN = \{SN_1, SN_2, SN_3, \ldots\ldots SN_N\} \quad (1)$$

Where SN_i represents the i^{th} sensor node. A stationary Base Station (BS) is located outside the sensing field at coordinates (50,150) m. This placement is intentionally used to model hotspot formation near the sink region. The BS collects aggregated data from CHs using single-hop or multi-hop communication (Prince *et at.,* 2025).

3.1. Energy Consumption Model

The first-order radio energy model is adopted from (Prince *et at.,* 2025). In this model, the energy consumed during transmission depends on the distance between sender and receiver.

Transmission Energy

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

The threshold distance d_0 is given by:

$$d_0 = \sqrt{\frac{\epsilon_{fs}}{\epsilon_{mp}}} \quad (3)$$

The energy consumed during reception of a *k*-bit message is expressed as:

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

The energy consumed for data aggregation of *m* received packets, each of size *k* bits, is given by:

$$E_{DA}(m, k) = E_{agg} \cdot m \cdot k \quad (5)$$

Where $E_{tx}(k)$ represents the energy dissipated per bit by the transmitter or receiver circuitry, while ϵ_{fs} and ϵ_{mp} denote the amplifier parameters for the free-space and multipath fading channel models, respectively. The threshold distance d_0 determines whether the free-space or multipath model is applied, based on the transmission distance between nodes, ensuring an accurate and realistic estimation of energy consumption in the network (Prince *et at.,* 2025).

3.2. Proposed Hotspot-Aware Load-Balanced Clustering and Routing Protocol (HALBCRP)

The proposed Hotspot-Aware Load-Balanced Clustering and Routing Protocol (HALBCRP) is designed to enhance energy efficiency and mitigate hotspot formation in WSNs.

Initially, sensor nodes are randomly deployed within the sensing area. Clusters are then formed using a weighted energy-distance metric. Subsequently, cluster heads are selected based on residual energy, connectivity, and distance from the Base Station (BS), traffic load, and hotspot awareness. During network operation, overloaded cluster heads redistribute traffic to neighboring cluster heads to prevent hotspot formation. Furthermore, a fault-tolerant routing mechanism ensures uninterrupted communication in the event of node or link failures.

Figure 1 presents the architecture of the proposed HALBCRP. Sensor nodes are organized into clusters, each containing a Primary Cluster Head (PCH) and a Secondary Cluster Head (SCH). Member nodes transmit sensed data to the PCH through intra-cluster communication, while the PCH forwards aggregated data to the Base Station through inter-cluster communication. The SCH acts as a backup node to improve reliability and support load balancing.

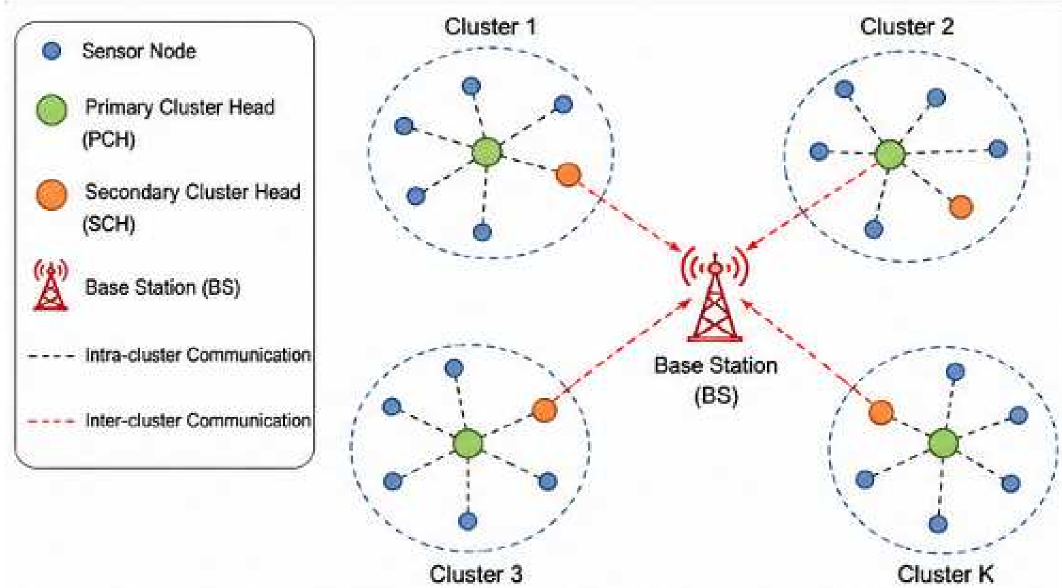

Figure 1. Architecture of the Proposed HALBCRP

3.3. Improved Cluster Formation Model

The proposed HALBCRP employs a distance-based clustering mechanism to group sensor nodes into clusters. The Euclidean distance is used to determine the proximity of a sensor node to a cluster center. This enables nodes to be associated with the nearest cluster, thereby reducing communication overhead and energy consumption.

The distance between a cluster node and the cluster center is computed as:

$$d - \sqrt{(x_{cn} - x_{cc})^2 + (y_{cn} - y_{cc})^2} \qquad (6)$$

Where d is the distance between the node and the cluster center, x_{cn} and y_{cn} represent the x and y coordinates of the Cluster Node (cn) and x_{cc} and y_{cc} denote the x and y coordinates of the Cluster Center (cc) (Patil and Kohle, 2024).

To achieve balanced cluster formation and reduce communication overhead, each sensor node computes a Cluster Formation Score (CF) based on its residual energy, proximity to the Base Station, and neighborhood density. The score is defined as (Alsola *et al.,* 2023).

$$CF_i = \alpha E_n + \beta(1 - D_{BS}) + \gamma N_d \qquad (7)$$

$$E_n = \frac{E_i^{res}}{E_i^{init}},\ D_{BS} = \frac{d_{i,BS}}{d_{max}},\ N_d = \frac{N_i}{N_{max}} \qquad (8)$$

where E_n represents the normalized residual energy of node i, E_i^{res} is the residual energy of node i, and E_i^{init} is its initial energy of node i. D_{BS} and D_{CH} denote the normalized distances from node iii to the Base Station and Cluster Head, respectively, where $d_{i,BS}$ is the distance between node i and the Base Station, N_i is the number of neighboring nodes within the communication range of node i, and N_{max} is the is the maximum neighbor count in the network. A higher Cluster Formation Score indicates that a node is more suitable for cluster participation because of its higher residual energy and shorter communication distance. The parameters α, β, and γ are weighting coefficients that determine the contribution of energy and distance metrics to the cluster formation process and satisfy.

3.4. Hotspot-Aware Cluster Head Selection

To minimize hotspot formation and balance energy consumption, CHs are selected using a hotspot-aware fitness function.

First, the Hotspot Factor (HF) is calculated as (Patil and Kohle, 2024):

$$HF_i - \frac{Traffic_i}{E_i^{res}} \qquad (9)$$

where Traffic $_i$ represents the traffic handled by node i and E_i^{res} denotes the residual energy of node i. A high HF_i value indicates a greater probability of hotspot formation.

The CH selection fitness function is given by (Kaur et al., 2025):

$$F_{CH} = w_1 E_r + w_2 (1 - D_i) + w_3 N_n + w_4 (1 - L_i) - w_5 HF_i \quad (10)$$

where E_r is the normalized residual energy, Di is the normalized distance to the Base Station, N_n is the normalized neighbor density, L_i denotes the normalized traffic load, and HF_i is the hotspot factor. The parameters w1, w2, w3, w4, and w5are weighting coefficients that determine the contribution of each metric to the CH selection process. Nodes with the highest fitness values are selected as Cluster Heads to achieve balanced energy consumption and mitigate hotspot formation.

3.5. Dynamic Load Balancing Mechanism

To prevent cluster head congestion and hotspot formation, a dynamic load balancing strategy is incorporated into the proposed HALBCRP. The mechanism continuously monitors the traffic load and residual energy of each Cluster Head (CH) to identify potential hotspot regions.

The Load Index (LI) of Cluster Head iii is calculated as (Kaur *et al.,* 2025):

$$LI_i = \frac{P_{in,i}}{E_i^{res}} \quad (11)$$

Where $P_{in,i}$ the presents incoming packet rate at Cluster Head I and E_i^{res} denotes the residual energy of Cluster Head i. A larger Load Index indicates a higher traffic burden relative to the available energy resources.

A hotspot condition is detected when:

$$LI_i > LI_{th} \quad (12)$$

Where LI_{th} denotes the predefined Load Index threshold. Once a hotspot is detected, neighboring Cluster Heads are evaluated and the optimal candidate for traffic redistribution is selected as:

$$CH_{opt} = \operatorname{argmin}(LI_j) \quad (13)$$

where LI_j represents the Load Index of neighboring Cluster Head j.

The excess traffic is then transferred from the overloaded Cluster Head to the selected neighboring Cluster Head according to:

$$T_{red} = P_{in,i} - P_{th} \quad (14)$$

Where T_{red} represent the amount of traffic to be redistributed and P_{th} denoted the allowable traffic threshold.

To quantify the effectiveness of load distribution across the network, the Load Balancing Factor (LBF) is defined as(Kaur et al 2025):

$$LBF = 1 - \frac{\sigma LI}{LI} \quad (15)$$

Where σL represent the standard deviation of the Load Index values of all Cluster Heads and LI denoted the average Load Index of all Cluster Heads. An LBF value approaching unity indicates a balanced traffic distribution among Cluster Heads, while lower values indicate increasing load imbalance and hotspot formation. Through continuous monitoring and redistribution of traffic loads, the proposed load balancing mechanism minimizes energy depletion disparities, reduces hotspot occurrence, and prolongs network lifetime.

Figure 2 illustrates the load balancing mechanism of HALBCRP. The Load Index of each Cluster Head is continuously monitored and compared with a predefined threshold. When a Cluster Head becomes overloaded, excess traffic is redirected to neighboring Cluster Heads with lower loads. This process prevents traffic concentration and mitigates hotspot formation.

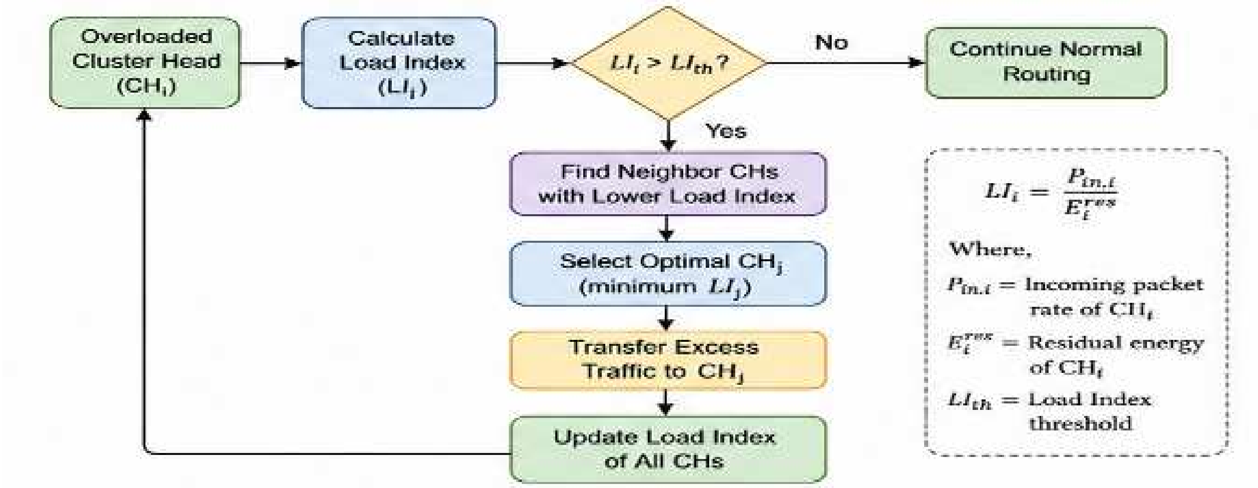

Figure 2. Load Balancing and Traffic Redistribution Process

3.6. Fault-Tolerant Routing Strategy

A multipath routing strategy is adopted to enhance network reliability and ensure continuous data delivery. In the event of a primary Cluster Head (CH) failure, data is rerouted through secondary CHs selected based on residual energy and link quality. The Route Selection Metric is expressed as:

$$R_s = \delta E_r + (1 - \delta) Q_{link} \quad (16)$$

where Q_{link}represents the link quality indicator and δ is the weighting factor that balances the influence of residual energy and link quality in route selection. This approach ensures reliable communication and uninterrupted data transmission even under node or link failure conditions.

Figure 3 shows the fault-tolerant routing process of HALBCRP. Under normal conditions, data are transmitted through the primary route. When a route failure occurs, the protocol activates the Secondary Cluster Head or establishes an alternative route through neighboring Cluster Heads. This mechanism improves network reliability and reduces packet loss (Kaur et al 2025):

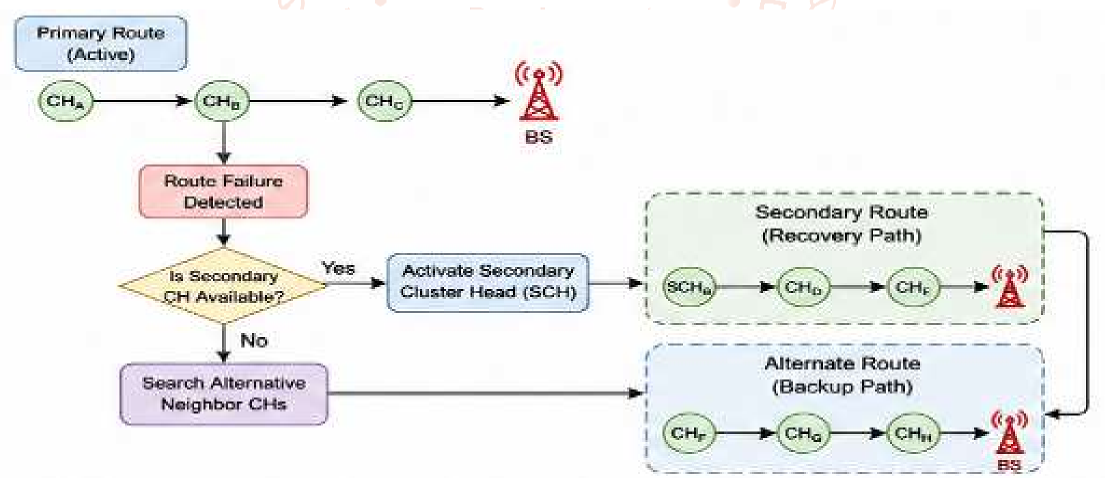

Figure 3. Fault-Tolerant Routing Framework

3.7. Optimization Objective

The proposed HALBCRP aims to improve network lifetime and communication efficiency by maximizing energy utilization, load balancing, and routing reliability while minimizing hotspot formation and communication cost. The overall objective function is formulated as:

$$F_{HALBCRP} = \alpha E_r + \beta LBF + \gamma Q_{link} - \delta HI - \Theta D \quad (17)$$

Where E_r represents the average residual energy of the network, LBF is the Load Balancing Factor, Q_{link} denotes the average link quality, HI is the Hotspot Index, and D represents the average communication distance. The parameters α\alphaα, β, γ, δ, and θ are weighting coefficients that determine the contribution of each metric to the optimization process and satisfy:

$$\alpha + \beta + \gamma + \delta + \theta - 1 \quad (18)$$

The optimization is subject to the following constraints:

$$E_r > E_{th}$$

$$HI < HI_{th} \quad (19)$$

$$0 \leq LBF \leq 1$$

$$Q_{link} \geq Q_{th}$$

Where E_{th} , I_{th}, and Q_{th} denote the minimum residual energy threshold, maximum allowable hotspot threshold, and minimum acceptable link quality threshold, respectively. By maximizing $F_{HALBCRP}$, the proposed protocol achieves balanced energy consumption, efficient traffic distribution, reliable routing, and reduced hotspot occurrence, thereby extending the operational lifetime of the Wireless Sensor Network.

Figure 4 presents the operational flow of HALBCRP. The algorithm performs node deployment, cluster formation, hotspot-aware Cluster Head selection, route establishment, load monitoring, traffic redistribution, and fault recovery. The process continues iteratively until the network reaches its termination condition.

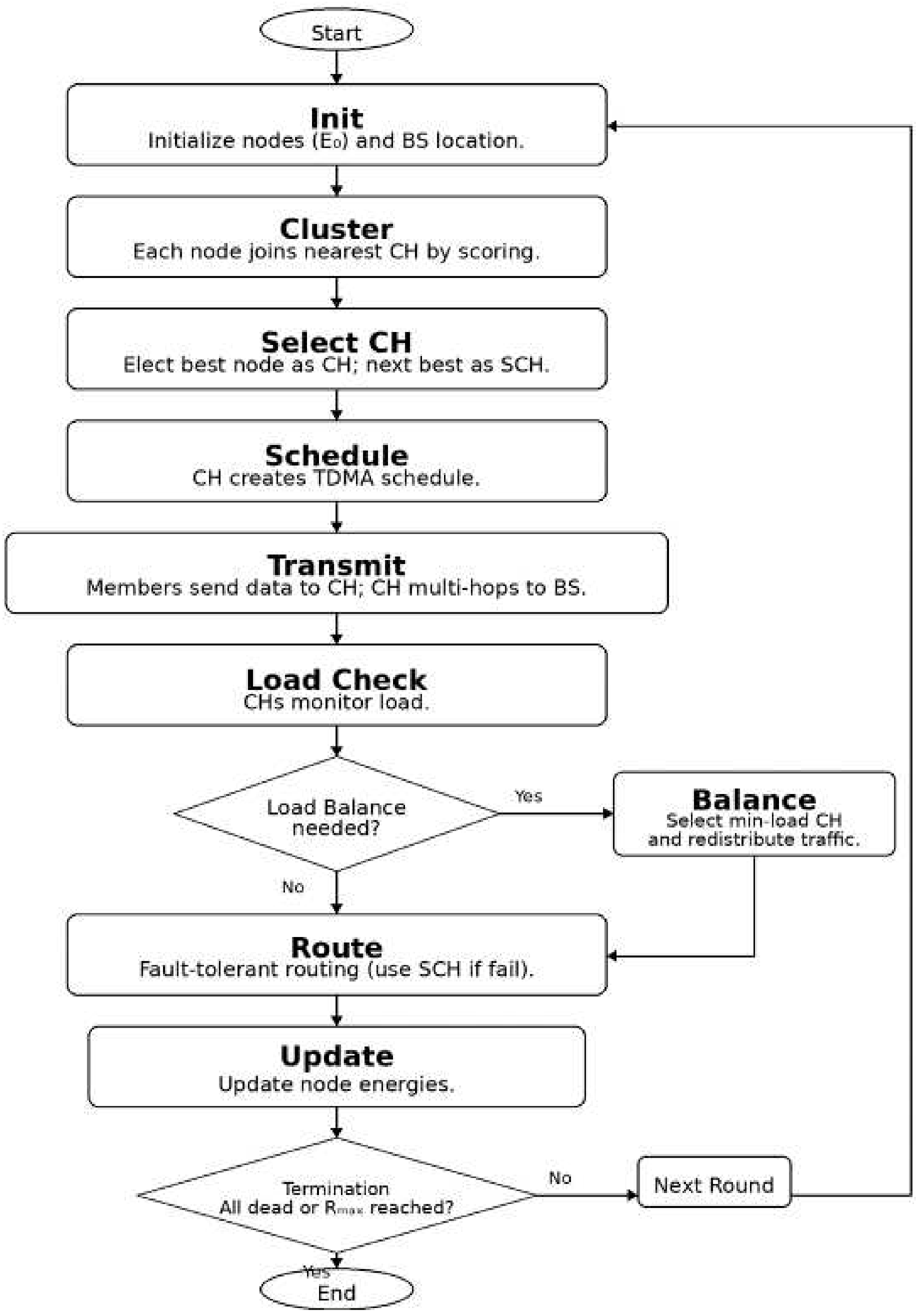

Figure 4. Flowchart of the Proposed HALBCRP Algorithm

4. Simulation Setup

This section describes the simulation environment used to evaluate the performance of the proposed Hotspot-Aware Load-Balanced Clustering and Routing Protocol (HALBCRP). The protocol is implemented and tested using MATLAB R2022a. to analyze its effectiveness in terms of energy efficiency, network lifetime, load balancing, and hotspot mitigation. The performance of the proposed method is compared with conventional clustering protocols with ITSA-UCHSE, HHDAP, Q-DAEER, and IPSO under identical network conditions.

The simulation considers a two-dimensional square sensing field where sensor nodes are randomly deployed. After deployment, nodes remain static throughout the simulation. A single base station (sink) is assumed, which is located outside the sensing field to realistically model hotspot formation near the sink region. The network operates in discrete time intervals called rounds**,** where each round consists of Cluster formation phase, Cluster head selection phase, Data transmission phase and Energy update phase.

The radio energy consumption follows the first-order radio energy model**,** which accounts for transmission, reception, and data aggregation energy costs

4.1. Simulation Parameters

The simulation parameters are carefully selected based on standard WSN literature to ensure fair comparison and realistic modeling. The key parameters used in MATLAB simulation are summarized in Table 2.

Table 2: Simulation Parameters and its values

Parameter	Value
Network Area	100 m × 100 m
Number of Sensor Nodes (N)	100 – 300
Base Station Position	(50, 150) m
Initial Energy per Node (E_0)	0.5 J
Packet Size	4000 bits
Control Packet Size	200 bits
Eelec	50 nJ/bit
Efs	10 pJ/bit/m²
Emp	0.0013 pJ/bit/m⁴
Data Aggregation Energy (EDA)	5 nJ/bit
Threshold Distance (d_0)	87 m
Simulation Rounds	1000 – 5000
Performance Runs	10–20 iterations

5. Performance Comparison and Results Analysis

This section presents the performance evaluation of the proposed Hotspot-Aware Load-Balanced Clustering and Routing Protocol (HALBCRP). The protocol is compared with ITSA-UCHSE, HHDAP, Q-DAEER, and IPSO under identical simulation settings. The evaluation focuses on Energy Consumption (EC), Number of Alive Nodes (AN), Number of Dead Nodes (DN), Average Throughput (AT), and Network Lifetime metrics including First Node Dies (FND), Half Nodes Die (HND), and Last Node Dies (LND).

5.1. Energy Consumption Analysis

Figure 5.1 and Table 3 show the energy consumption of the proposed HALBCRP and existing protocols under different numbers of sensor nodes. As expected, energy consumption increases for all protocols as the network size grows due to higher communication, routing, and data transmission overhead. Among all the evaluated protocols, HALBCRP consistently achieves the lowest energy consumption. At 50 nodes, HALBCRP consumes 0.605 J, which is lower than ITSA-UCHSE (0.666 J), HHDAP (0.729 J), Q-DAEER (0.781 J), and IPSO (0.847 J). Similarly, at 400 nodes, HALBCRP records an energy consumption of 1.053 J, compared to 1.169 J, 1.361 J, 1.738 J, and 1.933 J for ITSA-UCHSE, HHDAP, Q-DAEER, and IPSO, respectively. The improved performance of HALBCRP can be attributed to its hotspot-aware cluster-head selection and load-balancing mechanisms, which distribute network traffic more evenly and prevent excessive energy depletion in heavily loaded nodes. This enables the protocol to utilize energy more efficiently across the network. Although ITSA-UCHSE achieves the second-best performance, HHDAP, Q-DAEER, and IPSO consume considerably more energy as network size increases. Overall, the results demonstrate that HALBCRP improves energy efficiency, reduces hotspot formation, and extends network lifetime compared to the existing approaches.

Table 3: Energy Consumption (EC) Analysis of the HALBCRP System with Existing Approaches under Distinct Nodes

No. of Nodes	HALBCRP (j)	ITSA-UCHSE	HHDAP	Q-DAEER	IPSO
50	0.605	0.666	0.729	0.781	0.847
100	0.753	0.842	0.962	1.053	1.171
200	0.860	0.955	1.157	1.441	1.570
300	0.980	1.110	1.308	1.691	1.826
400	1.053	1.169	1.361	1.738	1.933

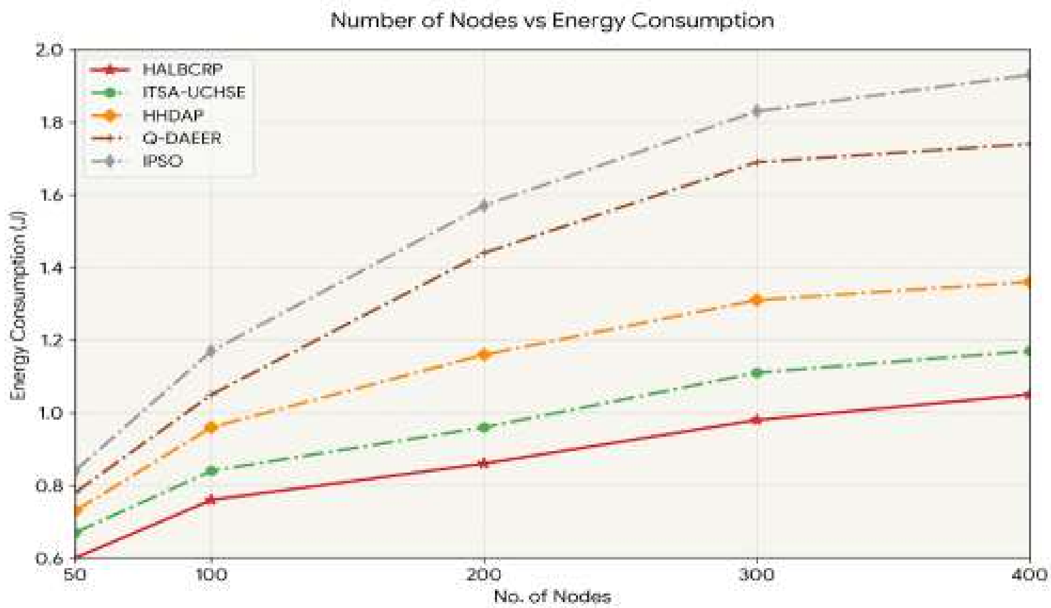

Figure 5.1. Energy Consumption analysis of HALBCRP system under distinct nodes

5.2. Average Throughput (AT) Analysis

Table 4 and Figure 5.2 present the Average Throughput (AT) performance of HALBCRP and the benchmark protocols under different network sizes. The results show that HALBCRP consistently achieves the highest throughput across all node densities. At 50 nodes, HALBCRP records a throughput of 36.5, outperforming ITSA-UCHSE (34.7), HHDAP (34.0), Q-DAEER (32.4), and IPSO (31.0). Similarly, at 200 nodes, HALBCRP achieves 29.5, while the competing protocols attain lower throughput values. Even at 400 nodes, HALBCRP maintains the highest throughput of 18.5 compared to 14.8, 10.0, 8.5, and 6.3 for ITSA-UCHSE, HHDAP, Q-DAEER, and IPSO, respectively. Although throughput decreases for all protocols as the number of nodes increases due to higher traffic and communication overhead, HALBCRP experiences a slower decline in performance. This improvement is attributed to its hotspot-aware cluster-head selection, dynamic load balancing, and fault-tolerant routing mechanisms, which reduce congestion and packet loss while ensuring efficient data forwarding. Overall, the results demonstrate that HALBCRP delivers more reliable data transmission and better communication efficiency than the existing approaches, making it well suited for large-scale Wireless Sensor Networks.

Table 4. Average. Throughput (AT) analysis of HALBCRP system with existing approaches under distinct nodes.

No. of Nodes	HALBCRP	ITSA-UCHSE	HHDAP	Q-DAEER	IPSO
50	36.50	34.70	34.00	32.40	31.00
100	33.80	31.50	27.20	23.30	21.20
200	29.50	26.40	23.20	20.30	18.40
300	24.80	21.30	17.80	14.80	13.30
400	18.50	14.80	10.00	8.50	6.30

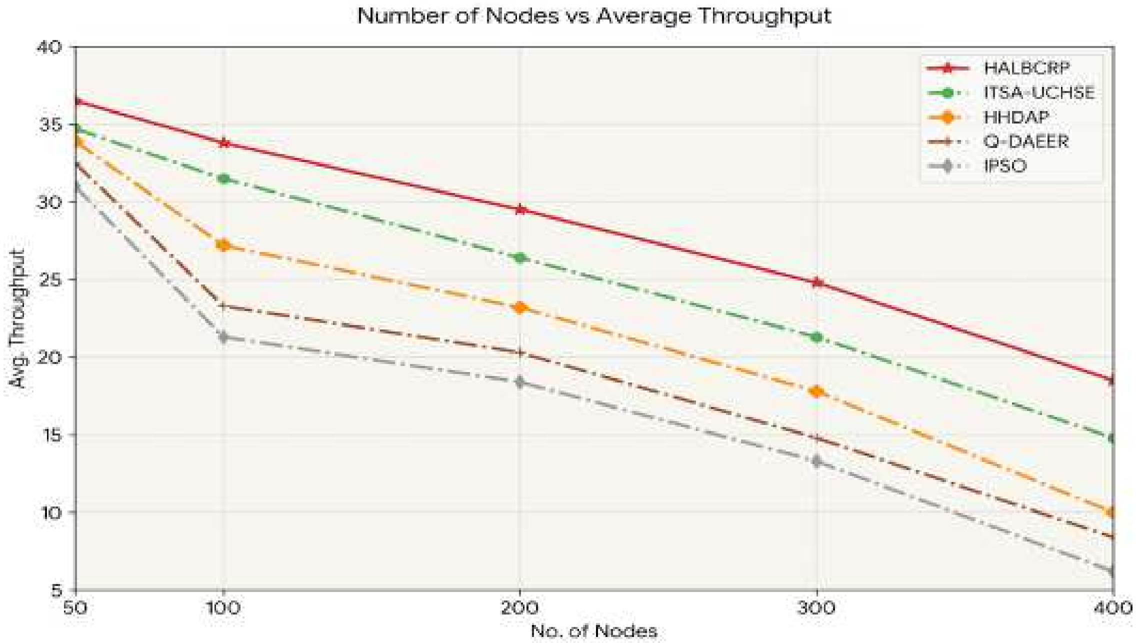

Figure 5.2 AT analysis of HALBCRP system under distinct nodes

5.3. Number of Alive Nodes Analysis

Figure 5.3 and Table 5. show the Number of Alive Nodes (AN) for HALBCRP and the benchmark protocols over different simulation rounds. While all protocols start with 100 alive nodes, HALBCRP maintains more active nodes throughout the simulation. At 900 rounds, HALBCRP retains 90 alive nodes, compared to 77, 27, 0, and 0 nodes for ITSA-UCHSE, HHDAP, Q-DAEER, and IPSO, respectively. At 1000 rounds, HALBCRP still maintains 78 active nodes, whereas ITSA-UCHSE retains only 52 nodes and the remaining protocols have completely depleted their nodes. The superior performance of HALBCRP is attributed to its hotspot-aware cluster-head selection, dynamic load balancing, and fault-tolerant routing mechanisms, which promote balanced energy consumption and delay node failures. Overall, HALBCRP achieves the longest network lifetime, retaining 60 alive nodes after 1200 rounds, while all benchmark protocols have exhausted their energy resources.

Table 5: Network Lifetime Analysis of HALBCRP System with Existing Approaches under Different Simulation Rounds

Rounds	HALBCRP	ITSA-UCHSE	HHDAP	Q-DAEER	IPSO
0	100	100	100	100	100
100	100	100	100	100	100
200	100	100	100	100	100
300	100	100	100	100	100
400	100	100	100	99	95
500	100	100	95	91	94
600	100	100	90	74	90
700	100	97	63	19	65
800	100	93	40	12	0
900	90	77	27	0	0
1000	78	52	0	0	0
1100	72	31	0	0	0
1200	60	0	0	0	0

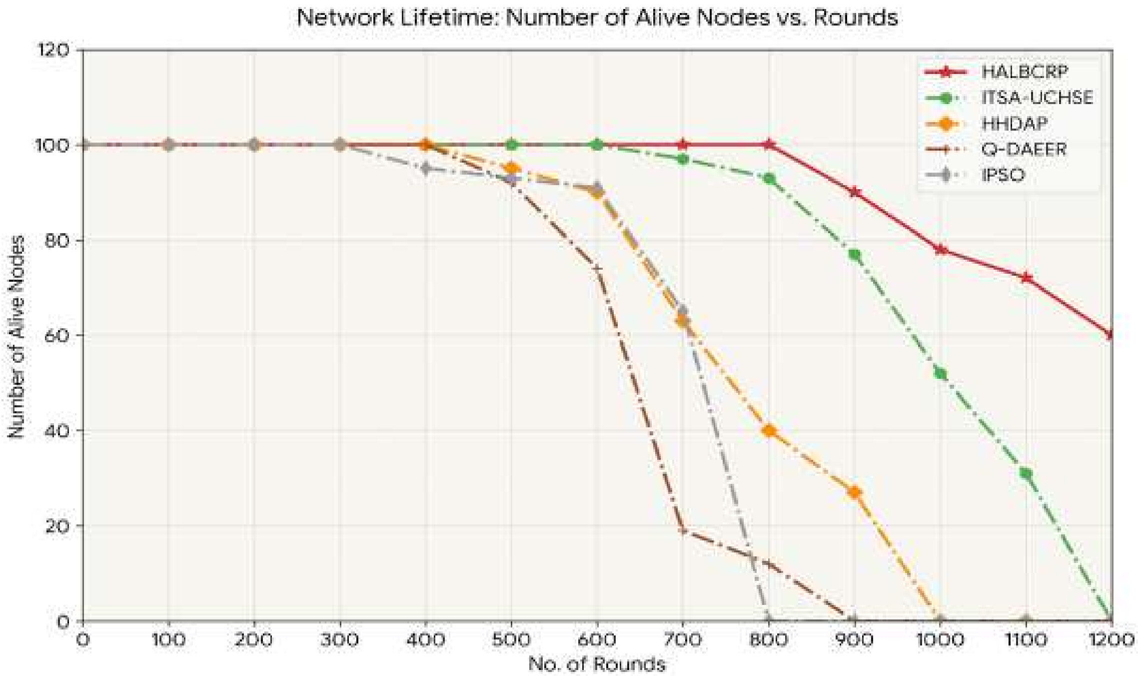

Figure 5.3 AN analysis of HALBCRP system under different rounds

5.4. Number of Dead Nodes Analysis

Figure 5.4 and Table 6 show the number of dead nodes for HALBCRP and the benchmark protocols across different simulation rounds. The metric reflects network lifetime and energy efficiency, where fewer dead nodes indicate better performance. The results indicate that HALBCRP consistently achieves the lowest number of dead nodes. No node failure occurs up to 800 rounds, showing strong energy balancing and effective hotspot mitigation. At around 900 rounds, only about 10 nodes have died, while most nodes remain active. By the end of the simulation (1200 rounds), HALBCRP records just 40 dead nodes, meaning a large proportion of the network is still operational. In comparison, the benchmark protocols show earlier and faster node deaths. ITSA-UCHSE performs better than HHDAP, Q-DAEER, and IPSO but still exhausts all nodes by 1200 rounds. HHDAP reaches about 100 dead nodes at 1000 rounds, while Q-DAEER and IPSO experience quicker energy depletion and complete failure around or before 1000 rounds. IPSO shows the poorest performance, with rapid node deaths occurring as early as 800 rounds. The improved performance of HALBCRP is due to its hotspot-aware cluster head selection and balanced load distribution. By sharing traffic evenly among cluster heads and avoiding energy concentration near the base station, it reduces energy holes and delays node failures. In addition, its fault-tolerant routing reduces retransmissions and further conserves energy.

Table 6: Number of Dead Nodes (DN) Analysis of the HALBCRP System with Existing Approaches under Different Simulation Rounds

Rounds	HALBCRP	ITSA-UCHSE	HHDAP	Q-DAEER	IPSO
0	0	0	0	0	0
100	0	0	0	0	0
200	0	0	0	0	0
300	0	0	0	0	0
400	0	0	1	0	5
500	0	0	5	8	10
600	0	0	10	26	9
700	0	3	37	81	35
800	0	7	60	88	100
900	10	23	73	100	100
1000	22	48	100	100	100
1100	28	69	100	100	100
1200	40	100	100	100	100

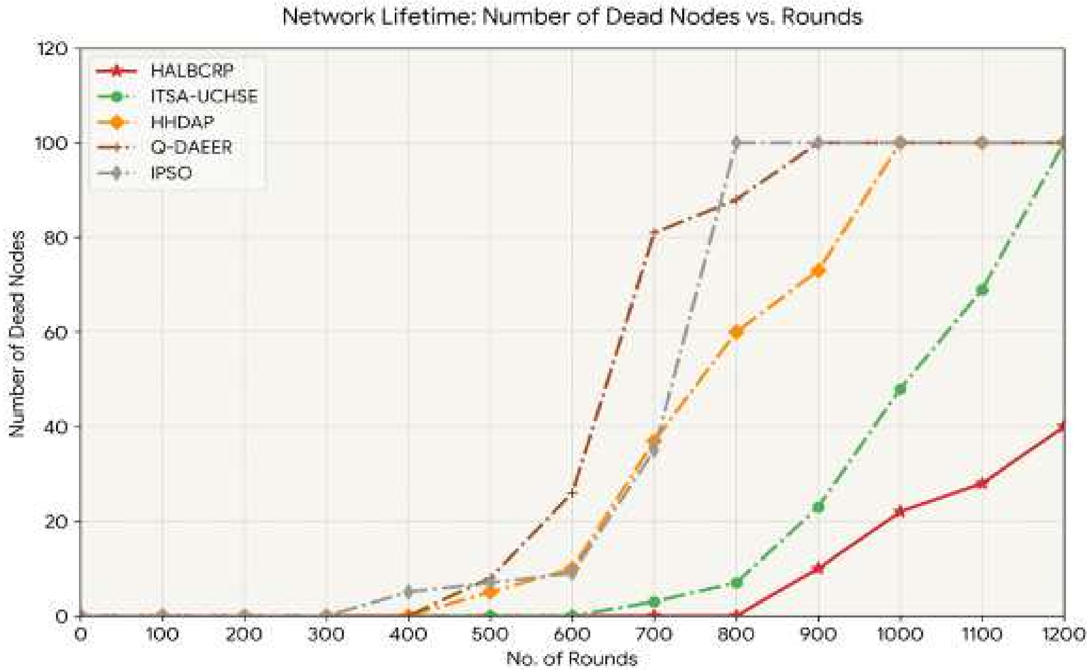

Figure 5.4 DN analysis of HALBCRP system under distinct rounds.

5.5. Average Network Lifetime Analysis

Table 7 and Figure 5.5 present the average network lifetime results in terms of FND, HND, and LND. HALBCRP achieves the best performance across all metrics compared to the benchmark protocols. For FND, HALBCRP records 800 rounds, higher than ITSA-UCHSE (668), HHDAP (472), Q-DAEER (448), and IPSO (359). For HND, HALBCRP reaches 1150 rounds, outperforming ITSA-UCHSE (1041), HHDAP (768), Q-DAEER (639), and IPSO (712). Similarly, for LND, HALBCRP attains 1340 rounds, while ITSA-UCHSE, HHDAP, Q-DAEER, and IPSO achieve 1200, 1000, 900, and 800 rounds respectively. These results show that HALBCRP consistently delays node failures and sustains network operation longer than the other methods. This improvement is due to its adaptive load balancing and efficient cluster head selection, which distribute energy usage more evenly across the network.

Table 7: Average lifetime analysis of HALBCRP system with other approaches

Metric	HALBCRP	ITSA-UCHSE	HHDAP	Q-DAEER	IPSO
FND	800	668	472	448	359
HND	1150	1041	768	639	712
LND	1340	1200	1000	900	800

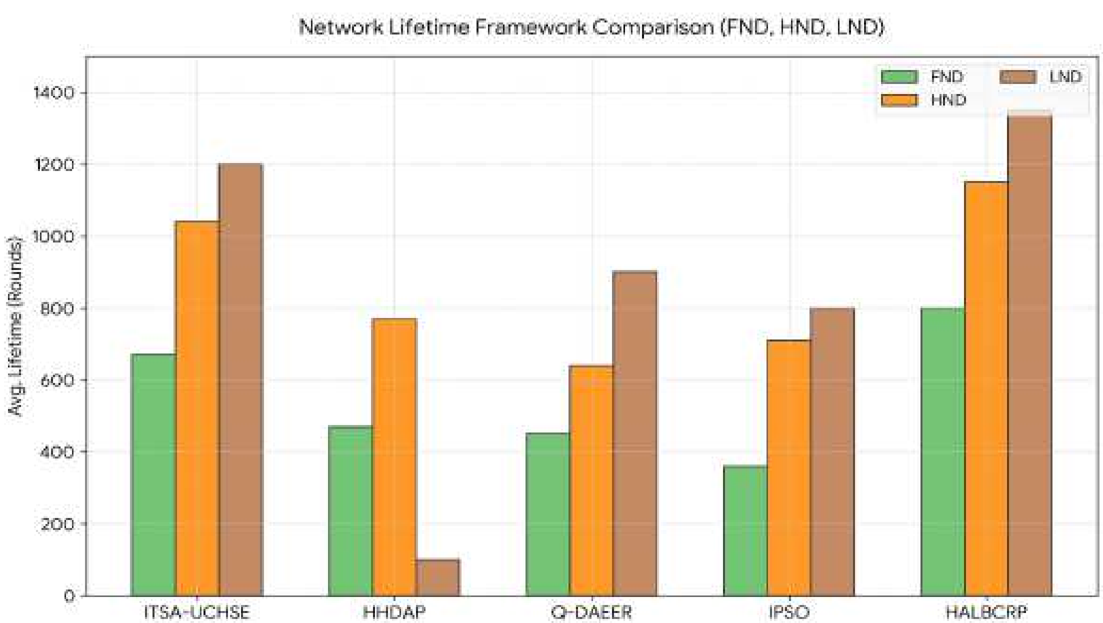

Figure 5.5 Average LFT analysis of HALBCRP system with other methods

6. Conclusion and Future Work

This study proposed a Hotspot-Aware Load-Balanced Clustering and Routing Protocol (HALBCRP) to improve energy efficiency, reduce hotspot formation, and extend network lifetime in Wireless Sensor Networks. The protocol was evaluated against ITSA-UCHSE, HHDAP, Q-DAEER, and IPSO using energy consumption, alive and dead nodes, throughput, and network lifetime (FND, HND, and LND). The results show that HALBCRP consistently outperforms all benchmark protocols. It records the lowest energy consumption (0.605–1.053 J), maintains 100 alive nodes up to 800 rounds, and still retains 60 nodes at 1200 rounds, while all benchmark protocols exhaust their nodes earlier. It also records only 40 dead nodes at 1200 rounds, compared to complete node failure in the other methods. In terms of throughput, HALBCRP achieves the highest values (36.50–18.50), outperforming ITSA-UCHSE, HHDAP, Q-DAEER, and IPSO across all scenarios. For network lifetime, it achieves FND = 800, HND = 1150, and LND = 1340, all higher than the comparison schemes. These improvements are due to its hotspot-aware cluster head selection, balanced load distribution, and fault-tolerant routing, which ensure efficient energy use and stable network operation. Future work will focus on extending the protocol to mobility-based and large-scale IoT environments, as well as integrating machine learning techniques for more adaptive and intelligent cluster head selection.

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