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HIGH LIFETIME ENERGY-AWARE CLUSTER HEAD-BASED CLUSTERING ALGORITHM USING LEACH FOR WSN

Chennakesavulu Nallamopu[1], Prasadu Peddi[2] and Santosh Kumar Byraboina[3]
[1,2]Department of Computer Science and Engineering, Shri Jagdishprasad Jhabarmal Tibrewala University, India
[3]Master of Computer Applications, Wesley P.G. College, India

Abstract

Energy management is a critical issue in Wireless Sensor Networks (WSNs) due to the limited battery capacity of nodes, which directly impacts the design of energy-efficient routing protocols aimed at extending the network's lifetime and conserving node energy. Each sensor node relies on its battery for vital functions in the network, making energy conservation essential for network sustainability. While the Low Energy Adaptive Clustering Hierarchy (LEACH) is a popular algorithm, it treats all nodes with varying energy levels uniformly, leading to premature node failure. To address this, the HLEACH-PSO (High Lifetime Energy-Aware Cluster Head Particle Swarm Optimization) is introduced as a modified version of LEACH. In this approach, the Cluster Head (CH) role is assigned to randomly distributed nodes across the network. The introduction of two new parameters—Base station connectivity and Average node lifetime—modifies the CH selection process to ensure that previously selected CHs are not re-elected. A Particle Swarm Optimization (PSO)-based clustering method, enhanced with an energy-constrained fitness function, is proposed to optimize both inter- and intra-cluster routing. Simulation results show that HLEACH-PSO outperforms traditional LEACH by reducing energy consumption, increasing network lifetime, and enhancing communication quality.

Keywords:

WSN, Energy Conservation, LEACH, HLEACH-LEACH, PSO, Fitness Function, Network Lifetime

1. INTRODUCTION

Sensor nodes in Wireless Sensor Networks (WSNs) are equipped with small, costly batteries that are difficult to recharge or replace, especially in remote locations. To increase the lifespan of WSNs while considering real-world challenges, it is crucial that each node operates with minimal energy consumption for data collection and transmission [1]. Various strategies for operation and clustering in WSNs have been explored by researchers. Clustering plays a significant role in reducing energy consumption across networks, while also enhancing the stability of the network topology and extending the network's overall lifetime [2]. Network lifetime is often measured by metrics such as the first node dies (FND), half of the nodes die (HND), and last node dies (LND) [3].

The process of dividing the WSN into multiple clusters is known as clustering, and it involves key processes such as cluster formation, Cluster Head (CH) selection, and routing between nodes and the base station (BS) [4]. A cluster consists of cluster heads and other nodes called cluster members (CMs). Thanks to its clustering-based routing protocol, this approach results in lower energy dissipation compared to other routing methods. Most research has primarily focused on cluster formation and various data transfer modes through communication links [5]. Figure 1 shows the architecture of a traditional clustered network.

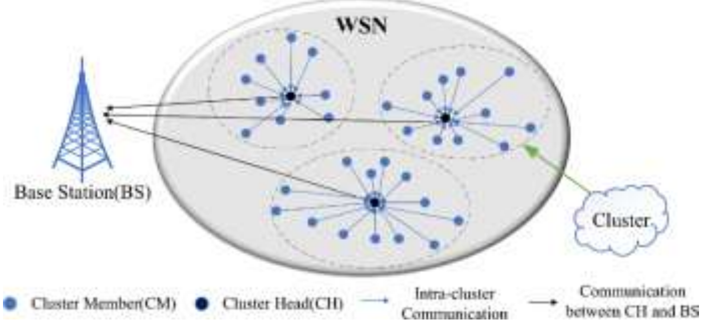

Fig.1. Network topology of a clustered WSN

Cluster-based routing protocols make more efficient use of sensor nodes in a network compared to non-clustering protocols. To minimize the amount of data transmitted and reduce the overall volume of data, each Cluster Head (CH) selects relevant data from its cluster members. The CH then aggregates the selected data and forwards it to the Base Station (BS). These protocols divide the sensor nodes into different clusters, which helps reduce energy consumption by limiting the need for long-distance communication between nodes [6]. The energy consumption in each node is significantly reduced through this approach, and since the energy depletion in CHs is higher than in other nodes, the workload is distributed more evenly across the network. As a result, clustering not only enhances the network's lifetime but also improves its energy efficiency. Furthermore, most clustering techniques implement an ideal CH selection process to prevent premature node failure and ensure the longevity of the network.

1.1 LEACH PROTOCOL

The LEACH protocol introduces the concept of rounds, where each round is divided into two phases: the setup phase and the steady phase [7]. During the setup phase, clusters are formed, and the network enters a self-healing mode. In the steady phase, data transmission occurs. The time taken for the setup phase can vary based on initialization speed. If initialization is quick, the setup phase takes less time, but if it's slower, the protocol payload takes longer to save, extending the setup phase.

LEACH operates in multiple rounds, and each round is split into two distinct phases: setup and steady [7]. The setup phase involves cluster formation and self-healing, while the steady phase involves data forwarding when the system is stable. The duration of each phase depends on how fast the initialization is, with longer setups resulting in extended round times.

1.1.1 Setup Phase:

During the initialization step, Cluster Head (CH) nodes are randomly selected within the network, and the clusters are dynamically formed. Each node generates a random number between 0 and 1, which determines its attractiveness to become a CH. If the node's residual energy is below a threshold value, it will announce itself as a CH for that round. This threshold function ensures that CH selection considers both current and historical node behavior. Once the CHs are selected, they broadcast their CH status to all non-CH nodes in the network. Non-CH nodes then send their IDs to their elected CH, based on the received signal strength. After the setup phase, each CH knows its member nodes, which reduces the distance between nodes and CHs, thus optimizing energy consumption. The CHs then create clusters with the nodes assigned to them, forming the network's structure.

1.1.2 Steady Phase:

After the clusters are formed, each CH assigns time slots to its member nodes. During the steady phase, each node transmits its data to the corresponding CH based on the assigned schedule. Once all data is collected from its members, the CH forwards the aggregated data to the base station (BS). In each round, new CHs are selected, and the clustering process is repeated.

1.2 LIMITATIONS IN LEACH

The main limitation of LEACH is that it selects cluster heads randomly in each round without considering the remaining energy of nodes. This approach can result in nodes with low residual energy being selected as CHs, causing them to fail prematurely and shortening the network's overall lifetime. Furthermore, member nodes select CHs without considering the reliability of the CH's lifetime, which leads to many node failures and frequent CH reselection.

To address these issues, this paper proposes a new version of LEACH, named HLCH-LEACH, which eliminates the uniformity of CH selection and resolves these problems. Two new parameters, Base Station Connectivity and Average Node Lifetime, are introduced to improve the CH selection process. These parameters prevent the re-election of the same CH in consecutive rounds and ensure a more efficient selection mechanism. Additionally, the proposed approach incorporates a Particle Swarm Optimization (PSO)-based clustering method, using a modified fitness function to select energy-efficient relays. The PSO fitness function evaluates important factors such as energy consumption and delay, leading to the selection of the optimal routing path. This multi-objective fitness function optimizes the overall routing and energy efficiency of the network.

1.3 CONTRIBUTIONS

- The newly proposed HLEACH-LEACH clustering algorithm resolves the energy imbalance issue seen in traditional LEACH by preventing the early failure of Cluster Heads (CHs).
- HLEACH-LEACH minimizes the frequency of CH selection by strategically handling JOIN requests, prioritizing nodes with longer lifetimes for CH roles.
- The enhanced PSO approach takes into account both energy and delay costs when selecting optimal routing paths, ensuring energy conservation, even in networks with low energy resources.

2. LITERATURE SURVEY

Mehta et al. [8] introduced a routing methodology based on guided sailing, focusing on improving energy efficiency in Wireless Sensor Networks (WSNs) through the Sailfish Optimizer (SFO) and clustering dependency. To address energy concerns, a fitness function was developed by setting individual goals for Cluster Head (CH) selection. This algorithm aims to reduce sensor node failures and minimize energy consumption. The function of SFO is to optimize data transmission from hosts to the sink node after selecting CHs.

Baradaran et al. [9] proposed the High-Quality Clustering Algorithm (HQCA), which introduces a standard to assess the quality of the clustering process. The HQCA method helps reduce clustering errors and enhances intra-cluster distance while increasing inter-cluster distance. It also considers factors such as the residual energy of each sensor node and the distance to the base station from each cluster. This technique offers advantages like higher reliability, lower clustering error rates, independence from critical CHs, scalability, and efficient performance in large-scale networks.

Priyanka et al. [10] developed a multi-level circular WSN with randomly distributed nodes that have higher node densities near the sink. The large circle is divided into several segments, and the Whale Optimization Algorithm is applied for dynamic CH selection within each sector. The network's lifetime and energy efficiency are evaluated in this method, showing that sectoring the WSN helps achieve nearly equal energy depletion across the network.

Sengathir et al. [11] proposed a cluster head selection method based on the Hybrid Modified Artificial Bee Colony Firefly Algorithm (HMABCFA) to maximize the lifetime of WSNs. This algorithm stabilizes energy, reduces delays, and minimizes inter-node distances. The HMABCFA approach combines Firefly optimization with the Artificial Bee Colony (ABC) algorithm to avoid early convergence and local optima, thus improving the clustering process.

Arunachalam et al. [12] designed a Squirrel Search Optimization-based Cluster Head Selection Technique (SSO-CHST) to extend the lifetime of sensor networks. This method uses gliding factors and reduces options based on data aggregation and dissemination. It calculates the fitness value for each sensor node, ordering them by their fitness level. The nodes with lower fitness values are chosen as cluster members, while those with higher fitness values are selected as potential CHs.

Dattatraya et al. [13] introduced a novel approach for selecting optimal CHs to enhance network and energy efficiency. Their method, based on the Fit-based Glowworm Swarm with Immigrant Scheme using the Fruit Fly Algorithm (FGF), draws inspiration from the Fruit Fly Optimization Algorithm (FFOA) and Glowworm Swarm Optimization (GSO).

Jayaraman et al. [14] proposed a fuzzy-based energy-efficient clustering algorithm aimed at extending the lifetime of WSNs. The approach uses a fuzzy logic system to identify the appropriate CH and employs a k-means clustering technique for efficient cluster formation. WSNs face challenges related to energy utilization, particularly due to the limitations of sensor power. Despite the development of various protocols to address energy issues, ensuring the long-term durability of the network remains a crucial consideration.

3. PROPOSED METHOD

3.1 PROPOSED LEACH CH SELECTION METHOD

The LEACH protocol selects Cluster Heads (CHs) using random number generation. Each node generates a random number between 0 and 1. If the generated number is less than a predefined threshold, the node becomes a Cluster Head (CH) for that round. While this method works under certain conditions, it lacks a mechanism to account for the remaining energy of the node when selecting the CH. This can lead to nodes with low energy being selected as CHs, which results in early death of those nodes and a shortened overall network lifetime.

To solve this, we propose the HLEACH-PSO (High Lifetime Energy-Aware Cluster Head Particle Swarm Optimization) approach. In this method, the CH selection process is enhanced by considering both base station connectivity and average node lifetime. This approach ensures that the CHs selected are more energy-efficient and have a higher probability of surviving longer, thus extending the lifetime of the network.

The HLEACH-PSO method modifies the CH selection process by introducing two key factors:

- **Base Station Connectivity (BS_con)**: This metric is used to evaluate how close a sensor node is to its CH, and it plays a critical role in determining the energy efficiency of the network. Nodes that are closer to their CHs require less energy to transmit data, thus conserving energy across the network. The BS_con parameter is computed by evaluating the proportion of nodes that are within a specified distance (d_0) from their CHs:

$$BS_{con} = ((d_0))/n$$

where,

$N_n(\min_{d2ch})$ is the number of nodes with a distance to the CH less than or equal to d_0.

n is the total number of nodes in the network.

d_0 is the distance threshold determined by the free space and multipath channel models.

- **Threshold Function Adjustment**: In HLEACH-PSO, a random number is multiplied by BS_con to modify the CH selection probability. This ensures that nodes with better connectivity (i.e., closer to their CH) have a higher chance of being selected as CHs:

$$\text{rand}(n_{new})=\text{rand}(n)*BS_{con}$$

Once the new random value is generated, it is compared to the node's threshold function ($TH(n)$):

$$\text{rand}(n_{new})\leq TH(n)$$

If the value of the random number is less than or equal to the threshold, the node becomes a CH for that round. This selection process prevents the premature death of nodes by giving preference to nodes that are energetically capable of serving as CHs.

3.2 MEMBER NODE CH SELECTION BASED ON AVERAGE NODE LIFETIME

In the HLEACH-PSO approach, once the CHs are selected, each CH broadcasts an advertisement message to the entire network, announcing its status as a CH. However, unlike traditional LEACH, in HLEACH-PSO, member nodes do not select their CH based purely on proximity. Instead, they select their CH based on the average node lifetime (A_{nl}), which represents the expected lifetime of each CH. The A_{nl} value is calculated as:

$$A_{nl}=\frac{\sum_{i=1}^{T_{CH}}\left(\frac{RE(i)}{a_t}\right)}{T_{CH}}$$

where:

$RE(i)$ is the residual energy of the node i.

a_t is the average transmission power required for sending data to the base station.

T_{CH} is the total number of CHs in the network.

The average lifetime A_{nl} is a critical factor because it ensures that nodes with higher energy reserves and better stability are more likely to be selected as CHs. Non-CH nodes choose the CH with the highest $A_{nl}1$ to ensure they are connected to a node that can sustain its role for a longer period. After this selection process, a TDMA (Time Division Multiple Access) schedule is created by the CH to allocate time slots for data transmission from member nodes.

3.3 OPTIMAL ROUTING PATH SELECTION USING PSO

After CHs are selected and member nodes are assigned to their respective CHs, the next challenge is to find the optimal routing path for data transmission from CHs to the base station. This is where Particle Swarm Optimization (PSO) is utilized.

PSO is an optimization technique inspired by the social behavior of birds flocking or fish schooling. It is used to find the optimal paths for data transmission, based on two main objectives:

1. Minimizing energy consumption during data transmission.
2. Minimizing delay costs, ensuring that data is transmitted efficiently.

The optimization process involves the initialization of particles, where each particle represents a potential path between CHs and the base station. The PSO algorithm uses two key objectives:

- **Energy cost function** $e_c(i)$ calculates the energy consumed by a node during data transmission and reception:

$$e_c(i)=e_t(l_i,d)+ e_r(l_i)$$

where, $e_t(l_i,d)$ is the energy consumed during transmission, $e_r(l_i)$ is the energy consumed during reception.

- **Delay cost function** $d_c(i)$ calculates the total delay through a link from node iii to the CH:

$$d_c(i)_{2CH}=q_i+ t_i+ p_i$$

where, q_i is the queuing delay, t_i is the transmission delay, p_i is the propagation delay.

PSO works by updating the position of each particle in the search space based on its own previous best position and the global best position found by the swarm. The fitness function is a weighted combination of the energy cost and delay cost:

$$F(i)=\omega_1 * e_c+\omega_2 * d_c$$

where, ω_1 and ω_2 are weights assigned to the energy and delay costs, respectively.

The particles update their positions based on the fitness values, aiming to find the optimal routing path that minimizes both energy consumption and delay.

4. FITNESS FUNCTION AND PARTICLE UPDATES

The PSO algorithm uses the fitness function to evaluate the optimal position of each particle (i.e., the optimal routing path). Each particle adjusts its position iteratively until the stopping criteria are met. The best path for data transmission is chosen when the fitness value is minimized, ensuring energy-efficient and timely data transfer.

The HLEACH-PSO method enhances the traditional LEACH protocol by introducing more sophisticated CH selection based on node lifetime and connectivity, ensuring better energy efficiency and longer network lifetime. The integration of PSO for optimal routing path selection further improves the network's performance by minimizing both energy and delay, leading to a more efficient wireless sensor network with improved scalability and stability.

Algorithm

For all the nodes 'n' where $n \in N$

Divide the nodes as 'k' clusters

End for

CH selection

For all node 'n' where $n \in k$

Calculate BS_{con}

Calculate $TH(n)$

Estimate $rand(n)$

$rand\ (n_{new}) = rand(n) * BS_{con}$

If $rand\ (n_{new}) \leq TH(n)$

$CH -> n;$

End if

End for

Data transmission using modified PSO

For all nodes 'n'

Find $fitness$

$fitness = \omega_1 * e_c + \omega_2 * d_c$

End for

Calculate $pbest$

If $pbest_j > pbest_i$

$pbest = pbest_j$

End if

If $pbest_j > Gbest$

$Gbest = pbest_j$

End if

Compute relay nodes using $Gbest$

End for

5. RESULTS AND DISCUSSION

5.1 SIMULATION PARAMETERS

The proposed algorithm was simulated and tested using the NS2 tool to evaluate its performance in comparison to other clustering methods. Sensor nodes were deployed in the field, with the network area set to 1000m by 500m. In the experiment, all sensor nodes were initialized with 100 joules of energy, and the network size was varied from 50 to 250 nodes. A Constant Bit Rate (CBR) traffic agent was used during data transmission to simulate regular network traffic. Data communication was conducted using UDP. The experimental parameters and their corresponding values are presented in Table 1.

Table.1. The experimental parameters

Parameter	Value
Network area	1000 m x500 m
Number of nodes	50 to 200
Cluster size	4
Initial energy	100j
Packet size	1024 bytes
Routing protocol	AODV

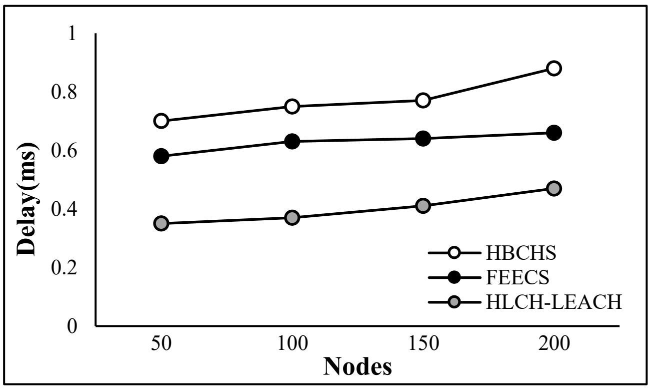

Fig.2. Delay

This time represents the duration required to transmit a data packet from the source to the destination within the network. The values in the table represent the end-to-end delay time evaluation for the proposed technique. The stable Cluster Head (CH) selection and efficient data aggregation through relay nodes, selected based on the PSO fitness function, effectively minimize communication delays between sensor nodes. The new model demonstrates the least average delay of 0.4 ms, while the previous method experiences a significantly higher delay of 0.88 ms, as shown in above table.

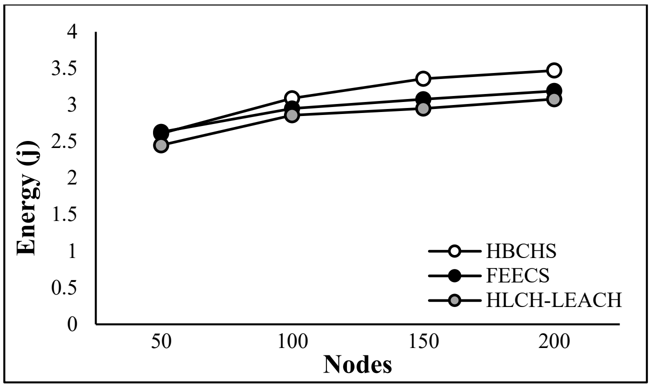

Fig.3. Energy

At the beginning, all sensor nodes are initialized with 100 joules of energy when they join the network. Network activities gradually deplete this energy with each operation. The goal is to maximize the energy efficiency of each node to ensure the network remains operational for an extended period. The random number stabilization based on energy correlation, along with the modified PSO-based optimal selection of relay nodes, helps minimize retransmissions, thereby reducing the overall energy footprint. As a result, the network experiences lower energy consumption. In the proposed method, the average power consumption was 2.83 joules.

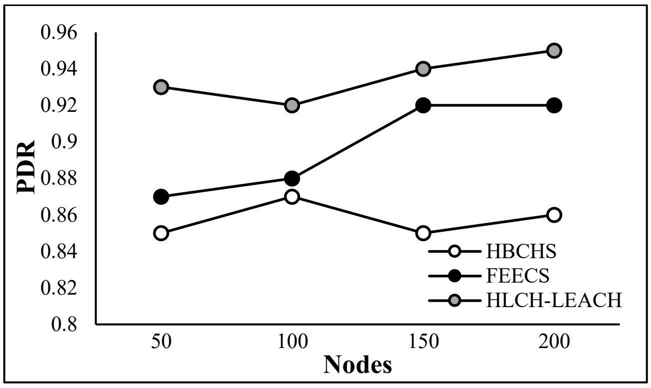

Fig.4. PDR

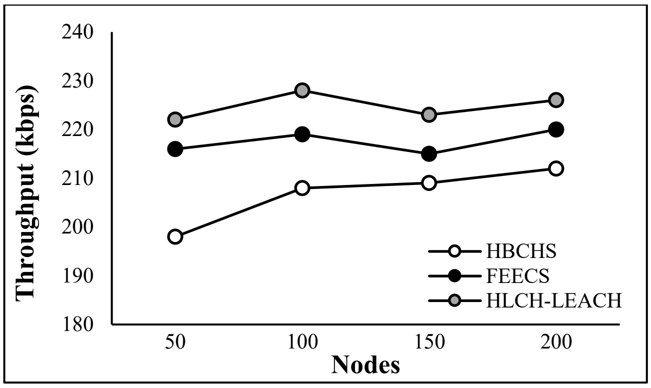

Fig.5. Throughput (kbps)

PDR (Packet Delivery Ratio) refers to the number of packets successfully transmitted by the sender and received by the receiver. To reduce in-network energy consumption and increase the delivery rate, data aggregation is employed, and better relay selection is made through an adaptive PSO-based routing approach. This phase focuses on selecting stable and balanced CHs, along with optimal relay nodes for data forwarding, ensuring no packet loss. The proposed method achieves a peak PDR of 0.95%, whereas existing methods show a much lower average PDR of 0.82%, which is significantly smaller than the ideal real-world PDR rate.

Throughput refers to the amount of data (or number of packets) that a node can process within a given time. By using a stable random number and maintaining optimal Cluster Head (CH) selection, data aggregation is made more efficient. The table above indicates that the proposed method achieves higher throughput compared to other methods. It outperforms the others, achieving throughput rates of up to 226 kbps, which represents a significant improvement in throughput over previous methods tested under similar experimental conditions.

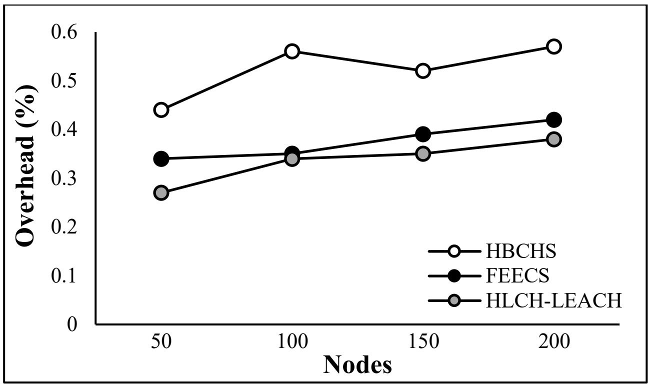

Fig.6. Overhead (%)

The figure above illustrates the simulation results for network overhead. Overhead is measured as a ratio relative to the number of control packets flooded in the network to perform a networking task. The proposed method recorded an overhead of approximately 0.34%. This reduction in overhead is due to the minimized frequency of CH failures, as CHs are selected with high-energy join messages, ensuring stable CH selection. As a result, the proposed system maintains a significantly lower overhead compared to others.

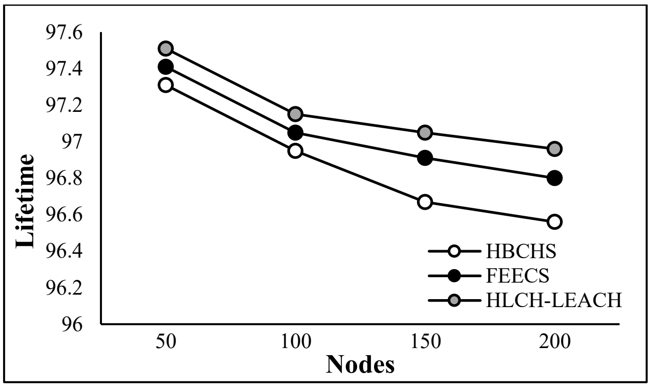

Fig.5. Overhead (%)

This refers to the network's lifetime, or the time until the first sensor node, or a certain number of nodes, exhaust their energy. Most of our test cases assessed the network's lifetime based on the available energy after completing its functions. In simple terms, the more remaining energy there is, the longer the network can operate. The values in the preceding table demonstrate that the proposed method significantly improves network lifetime compared to existing methods.

6. CONCLUSION

LEACH (Low Energy Adaptive Clustering Hierarchy) is an efficient algorithm for Wireless Sensor Networks (WSNs), but it has certain limitations. This paper introduces a new version, HLEACH-LEACH (High Lifetime Energy-Aware CH-LEACH), where the responsibility of the Cluster Head (CH) is equally and fairly distributed among all sensor nodes. It incorporates parameters such as Base Station Connectivity and Average Node Lifetime to guide CH selection, ensuring that previously elected CH nodes are not reselected. This mechanism associates the CH selection threshold with node energy in every round. To optimize the combination of application protocol and cluster size, new multi-objective fitness functions are introduced, focusing on inter- and intra-cluster routing. Simulation results demonstrate that the proposed method significantly enhances WSN performance, improving CH stability, reducing energy consumption, and extending network lifetime.

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