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Article

Dynamic Threshold-Based Distance-Aware Clustering for Stable and Energy-Efficient Wireless Sensor Networks (DT-DAC)

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Abstract: Wireless sensor networks consist of numerous tiny sensor nodes and have gained widespread acceptance because of their diverse applications in the real world. It has critical role in military operations, forest fire detection, environmental monitoring, healthcare and precision agriculture. Sensor node's life is dependent on its battery. For extending network lifetime, energy efficient routing is essential. Replacement of battery cannot be possible in many cases. Therefore, reducing energy usage is a key design issue for WSNs. The primary goal of routing protocols is to reduce consumption of energy and maximize the network lifetime. Studies already conducted show that the overhead associated with frequent rotation of cluster heads and clustering processes lead to considerable energy usage. After evaluating a variety of current energy efficient routing approaches, a method is proposed that uses optimize the number of cluster heads and perform clustering just once during network initialization. Proposed approach eliminates the energy and time costs related to re-clustering. Instead of replacing the CHs in every round, proposed approach replaces CHs only when their energy drops below a certain level. CHs are selected based on how close they are to the cluster center and the highest remaining energy. Experimental results indicate that presented methodology outperforms traditional approaches in terms of lifetime of the network.

Keywords: Network Lifetime, Wireless Sensor Network, Energy, Cluster Head, Routing.

1. INTRODUCTION

Wireless sensor nodes have attracted a lot of attention in the communication field because of their affordable, compact size and battery powered architecture. These networks are characterized by dense deployment, limited resources, susceptibility to failure and often changing topology [1, 2]. The four major parts of a sensor node are Sensing unit, Processing unit, Power supply unit and Communication unit [3]. WSNs consist of a numerous low cost nodes whose main functions are sensing, monitoring, measuring, and data collection. These nodes collect data from surrounding field and transmit it to the BS, where users can access it remotely. WSNs continue to be a prominent area of research because of their wide ranging applications in healthcare, military and civilian domains [4-7].

The network lifetime is dependent on battery power. Lower battery consumption leads to increased network lifetime. Therefore, the major task is to develop routing that uses less energy to increase lifetime of the network [8-10]. Battery replacement is not feasible and impractical. Therefore, designing energy saving approaches is so essential. Data aggregation techniques are designed to minimize energy consumption and identifying optimal paths from source to the destination. [11-13]. Data aggregation helps to reduce duplicate data transmission and thereby reducing the energy consumption. The goal is to extend network lifetime by decreasing the energy consumption.

The rest of the paper is structured as follows: The existing routing techniques for energy efficiency in wireless sensor networks are discussed in section II. The proposed methodology is described in Section III. Results and analysis are summarized in section IV. Conclusions and future research directions are presented in section V.

2. RELATED WORK

The Low-Energy Adaptive Clustering Hierarchy (LEACH) procedure was proposed in [14], where CHs are chosen randomly. In each round, nodes use a stochastic procedure on their own to identify whether they will become a CH. Every node generates a random number between 0 and 1 for the current round. If the generated number is below a predetermined threshold, then the node takes up the role of the CH. Cluster heads sends their status to all nodes and other sensor nodes join the cluster with the strongest received signal. Data transmission is scheduled using Time Division Multiple Access strategy. LEACH is not effective for large scale networks.

Genetic Algorithm and heuristics based approach is used to produce energy efficient hierarchical clusters [15]. An evolutionary based routing algorithm is proposed to optimize the selection of cluster head [16]. In every round, during the cluster formation it will generate initial populations of solutions. Then fitness function is applied and parents are selected based on fitness value. After that new population is generated by applying recombination and mutation operators. In [17], authors have proposed LEACH-B protocol which is based on node's residual energy and optimum no. of cluster head selection. LEACH-B ensures that the cluster's division is uniform and balanced.

The cluster head is chosen using the distance based residual energy of the sensor node as in [18]. A hybrid protocol DRESEP uses proactive and reactive strategy for data transmission. Proactive strategy is used from cluster head to the base station and reactive strategy is used within the cluster for data transmission. Clustering based improved LEACH (E-LEACH) protocol is proposed in [19]. Selection of cluster head is based on distance and energy. It considers two parameters: (i) the distance between nodes and base station for selecting cluster head (ii) average value of node residual energy. The Hybrid Energy-Efficient Distributed Clustering (HEED) protocol prioritizes nodes based on communication cost and residual energy [20], thereby selecting nodes with lower transmission costs and higher energy. Clustering process is performed dynamically; therefore, HEED has a large overhead.

To address this issue, a Low-Energy Adaptive Tier Clustering Hierarchical routing procedure was described in [21]. It reduces overhead by introducing mini clusters inside bigger clusters. A modified LEACH protocol was introduced in [22] for balance usage of energy and optimize CH selection. A distributed energy efficient clustering method that chooses cluster heads on the basis of the node's leftover energy divided by the network's average energy and suffers from the hot spot issue [23]. The Energy-Efficient Uneven Clustering Protocol (EEUC) was proposed for balanced energy consumption [24]. It forms clusters of unequal sizes with clusters nearer to the base station are smaller and those farther away are larger.

To further reduce the hot spot issue, a fuzzy based energy aware unequal clustering approach was eventually proposed in [25]. The approach presented in [26] incorporates the midpoint approach for improved centroid initialization and uses residual energy and Euclidean distance for cluster head selection. The Energy-Efficient Semi-Static Routing algorithm [27], in which nodes are arranged in a predetermined list and cluster heads are automatically selected based on this order. This method successfully addresses energy hole issues and demonstrates scalability. Metaheuristic-based clustering approaches have been explored in other studies. For CH selection, a hybrid method combining Optimization based on Artificial Bee Colony and Ant Colony was introduced in [28]. For CH selection, it uses residual energy, proximity to base station, node degree and distance to neighbors. Ant colony methods are used to find optimal energy efficient route between CHs and the BS.

Mobile sink-based solutions have also been studied. In [29], a mobile sink-based intelligent data routing strategy was proposed. It works in two stages: a configuration mode in which cluster heads are selected to ensure consistent energy consumption, and an operational mode in which sensor nodes gather and send data with minimal overhead. A genetic algorithm is used to find the optimal sink path. The network lifetime was significant increased in [30] by using an Adaptive Remora Optimization Algorithm applied for cluster head selection.

Recently, bio-inspired algorithms and machine learning have been included into clustering and routing. For energy-efficient data distribution, a Graph Neural Network (GNN) combined with the Crayfish Optimization Algorithm was suggested in [31]. Cluster head selection considered energy, distance, delay, and traffic density, while the GNN ensured efficient data delivery. Likewise, a fuzzy clustering and routing strategy based on an improved Particle Swarm Optimization (PSO) algorithm was proposed in [32]. In this approach, one fuzzy inference system forms optimal clusters by evaluating residual energy, centrality distance, and node degree deviation, minimizing inter-cluster communication costs. A second fuzzy system then performs routing by considering base station distance, data load deviation, and residual energy. Simulation results confirmed significant reductions in overall energy consumption. Following is the summary table for existing methods:

Table 1. Summary of Existing Methods

Protocol	CH Selection Criteria	Key Features / Advantages	Limitations
LEACH [14]	Random selection using threshold probability	Simple, distributed, reduces direct communication with sink	Not scalable to large networks; frequent re-clustering causes overhead
HCR [15]	Residual energy + Distance	Reduce communication overhead, Scalability	Uneven energy depletion of CHs
ERP [16]	Evolutionary algorithm	Better load balancing, dynamic clustering	High Computational Complexity, Scalability Issues
LEACH-B [17]	Residual energy	Balanced energy consumption	Centralized Dependence, Reduces scalability
DRESEP [18]	Residual energy + Distance	Stability period increase; good performance for time critical applications	Multihop communication between CH and BS is not applied
E-LEACH [19]	Residual energy + Distance	Reduce energy imbalance	Scalability, Static network
HEED [20]	Residual energy + communication cost	Energy-balanced than LEACH; higher energy nodes favored as CH	Dynamic clustering introduces high overhead
Tier-based LEACH [21]	Mini-clusters within clusters	Reduces clustering overhead; improves scalability	Still incurs clustering cost; complexity increases
Modified LEACH [22]	Optimized CH selection	Balances energy consumption better than LEACH	Improvement depends on initial conditions
Distributed Energy-Efficient Clustering [23]	Residual energy / Avg. network energy	Energy-balanced clustering	Hot-spot problem near sink
EEUC [24]	Unequal cluster size (distance to sink)	Balances energy load; reduces hot-spot effect	Increased complexity in cluster formation
Fuzzy Energy-Aware Unequal Clustering [25–26]	Residual energy + distance + fuzzy inference	Solves hot-spot issue; improved CH selection	Higher computational overhead
Semi-Static Routing [27]	Predefined list order + residual energy	Scalable; reduces energy hole problems	Static nature may reduce adaptability
ABC + ACO Hybrid [28]	Residual energy + distance + node degree	Optimized CH selection & routing; efficient path discovery	Meta heuristic complexity; convergence time
Mobile Sink with GA [29]	Energy balancing + genetic algorithm path optimization	Uniform energy expenditure; reduces message overhead	Sink mobility adds complexity
Adaptive Remora Optimization [30]	Adaptive meta heuristic optimization	Extends network lifetime significantly	Requires more computation
GNN + Crayfish Optimization [31]	Energy, distance, delay, traffic density + ML-based routing	Intelligent routing; efficient data dissemination	High computational and training cost
Fuzzy + PSO [32]	Residual energy + centrality + node degree + fuzzy rules	Reduces inter-cluster cost; balances routing load	Complex; higher processing requirement

3. PROPOSED APPROACH

3.1 Objective

The main goal is to develop an energy efficient routing algorithm that enhances the operational lifetime of the WSNs. The goal is to enhance network functionality while reducing energy consumption. The performance is evaluated based on analyzing the round in which the first node dies half of the node dies and the last node dies. Also to measure the no. of nodes that remains operational versus those that fail after a predetermined number of rounds under varying energy levels.

3.2 Network Model

The suggested network model is designed under the following assumptions:

- Every sensor node is static and initialized with identical energy levels.
- Deployments of nodes are random within the designated sensing field.
- The network considered is homogeneous in nature.
- Each sensor node operates on a battery which is non rechargeable.
- Nodes are capable of determining their geographical location through GPS functionality.

3.3 Energy Model

For performance assessment, the energy model adopted in this work is aligned with the model utilized in the LEACH protocol [14]. Since communication processes dominate the overall energy consumption in WSNs, energy costs required for sensing and computation are considered negligible. In the communication phase, the primary energy expenditure arises from data transmission and reception, whereas monitoring consumes comparatively less energy.

The energy consumed for transmission of a data packet of length *k* bits over a distance *d* is represented as:

$$E_{TX} = K.E_{elec} + k.efs * d^2 \quad when\, d \leq d_0$$

$$E_{TX} = K.E_{elec} + k.efs * d^4 \quad when\, d \geq d_0 \qquad \text{------------} \quad (1)$$

Where:

- E_{TX} represents the required transmission energy,
- k represents the data packet size in bits,
- E_{elec} represents the energy required by the receiver or transmitter per bit,
- efs represents the free-space channel model coefficient (for path loss),
- emp represents the multi-path fading model coefficient (for path loss),
- d represents the communication distance,
- d_0 represents the threshold distance beyond which the multi-path model is used.

The formula for calculating the threshold distance is:

$$d_0 = \sqrt{\frac{efs}{emp}} \qquad \text{---------} \ (2)$$

The energy consumed for receiving a *k*-bit message is determined by the formula

$$E_{RX}(i) = K.E_{elec} \ \text{--------} \ (3)$$

In this case, E_{RX} is the reception energy consumption, and E_{elec} corresponds to the energy used by the receiver circuitry per bit.

3.4 Methodology

The proposed approach is designed to maximize energy efficiency and increase the lifespan of sensor networks. Figure 1 shows our detailed proposed methodology. Below is a summary of the key aspects:

- **Optimal Cluster Head Selection**: From a network of 100 deployed sensor nodes, 5 nodes, or 5% of the total are chosen as cluster heads [28].
- **Single-Time Clustering**: Clustering is carried out only once during the initialization phase, thereby avoiding the repeated energy and memory overhead of re-clustering. Unlike conventional approaches where cluster heads are replaced every round, in the proposed method a CH is replaced only when its residual energy falls below a predefined threshold.
- **Primary and Vice CH:** Primary CH is responsible for collecting data from the cluster nodes and sends it to the vice CH. Vice CH send data to the BS. The distance between the node and the clustering center as well as residual energy are used to choose the primary CH. The selection of vice CH is based on residual energy and the distance from the node to the base station.
- **Data Aggregation**: Each vice CH performs data aggregation by eliminating redundancy before transmitting the information to the BS.

3.4.1 Cluster Formation

The clustering formation is based on K-means clustering approach. The steps are as follow:

(1) The BS initializes K nodes among N nodes as the initial clustering centroids. From a network of 100 sensor nodes, 5 nodes (i.e., 5% of the total) are selected as cluster centroids [28].

(2) For remaining nodes, calculate the distance between them and the K initial clustering centers as per following formulas: (Euclidean distance)

$$dist = \sqrt{(x_{node} - x_{center})^2 + (y_{node} - y_{center})^2} \quad \text{---------- (4)}$$

(3) Assign each node to the cluster nearest to its centroid.

(4) Determine the new cluster centroid after the nodes have been assigned to clusters. Use each node's mean inside the same cluster as the new centroid for this. Consider the current clusters to be final and halt the algorithm's execution if the newly generated centroids match the centroids from the prior iteration. Proceed to step 2 if any of the newly generated centroids change from those from the prior iteration.

3.4.2 Primary CH Selection

The distance between the node and the clustering center as well as residual energy are used to choose the primary CH. The CH is chosen as the node with the most residual energy and the least distance from the cluster center. Until a cluster head's energy falls below the threshold, it is not replaced.

Selecting the cluster head whose energy is above threshold and which is close to the cluster center. The following is the calculation of the function f(x):

$$f(x) = \frac{\frac{1}{n}\sum_{i=1}^{n} d_{tocentre}(i)}{d_{tocentre}(i)} \quad \text{-------- (5)}$$

$$f(x) = \text{mean of all} \frac{d_{tocentre}(i)}{\text{Current } d_{tocentre}(i)} \quad \text{-------- (6)}$$

where $d_{tocentre}(i)$ represents the distance from sensor node i to the cluster center. If the node is closer to the cluster center then the value of f(x) becomes higher and the chances to become the CH are higher.

3.4.3 Vice CH Selection

The vice cluster head is chosen based on the residual energy and the distance between the node and the base station. The cluster head receives data from all member nodes and communicates with the base station and other cluster heads, increasing the cluster head's energy usage. To reduce the energy consumption of the primary CH, we propose to use the vice CH to interact directly with the BS. The vice CH and BS are closer than the CH and BS. Member nodes transmit data to the primary CH, which then forwards it to the vice CH, which then forwards it to the BS. It lowers the cluster head's transmission energy usage.

A vice CH is chosen from among the nodes in the same cluster whose residual energy is over the threshold and closest to the base station. The vice CH's energy usage for packet forwarding to the BS will be decreased. A function f(y) is used to select the optimum node that is close to the BS.

$$f(y) = \frac{\frac{1}{n}\sum_{i=1}^{n} d_{toBS}(i)}{d_{toBS}(i)} \quad \text{---------- (7)}$$

$$f(y) = \text{mean of all} \frac{d_{toBS}(i)}{\text{Current } d_{toBS}(i)} \quad \text{----------- (8)}$$

where $d_{toBS}(i)$ represents the distance from node i to the base station. The value of f(y) and the likelihood of becoming the vice cluster head increase with node i's proximity to the base station.

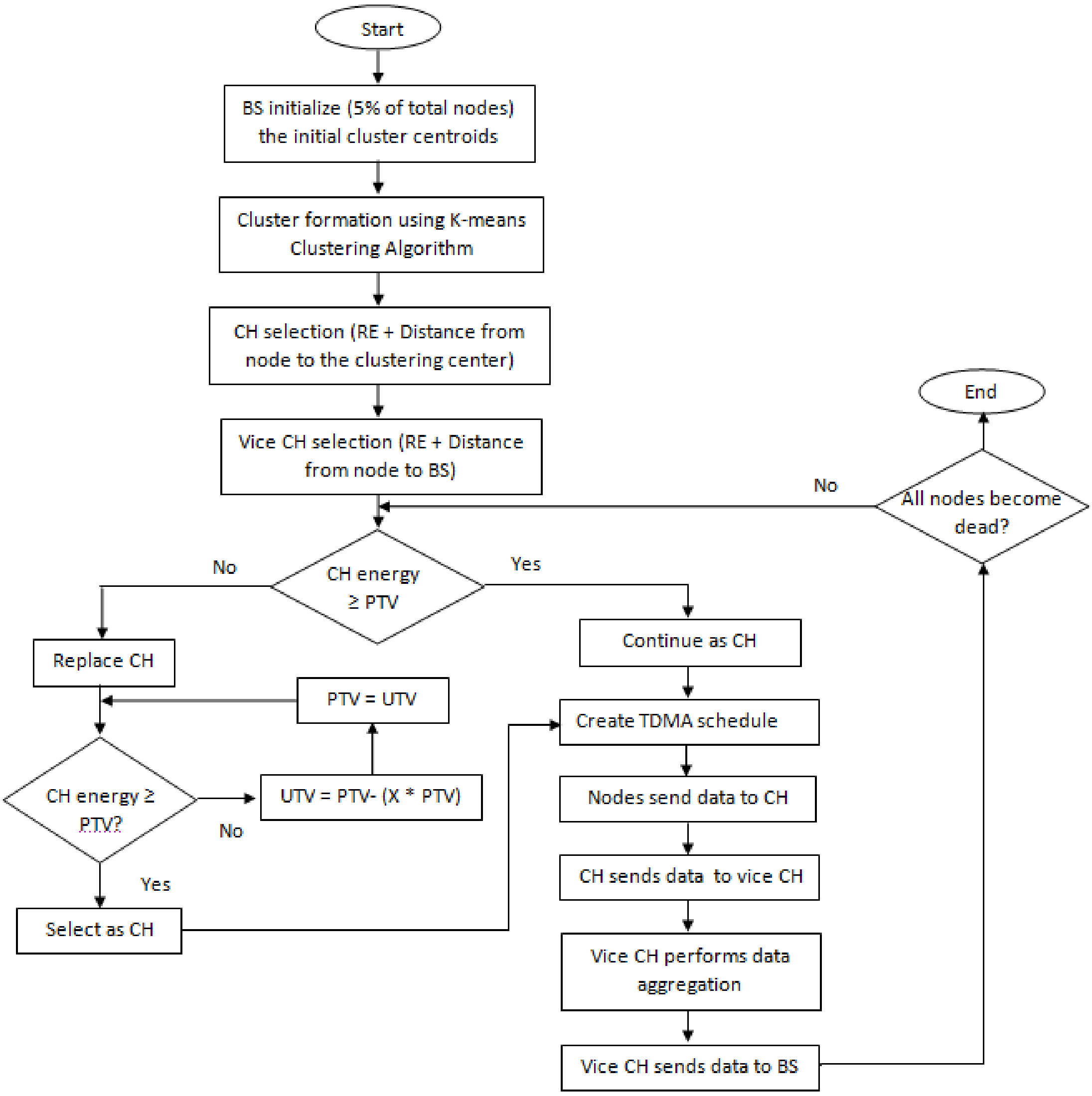

Figure 1 Proposed Methodology

3.4.4 Threshold-Based CH Replacement

A CH remains active until its residual energy falls below the threshold. When its energy falls below the threshold, a new CH is chosen from the cluster. If all nodes in a cluster drop below the current threshold, the threshold is updated using:

Updated Threshold Value = Present Threshold Value - (X * Present Threshold Value).

where value of X is between 0 and 1.

3.4.5 Data Transmission

Each CH creates a Time Division Multiple Access (TDMA) schedule and distributes to cluster members. It reduces unnecessary energy consumption by ensuring that nodes turn on their radios during assigned transmission slots. As per the TDMA schedule, member nodes transmit sensed data to the appropriate CHs. After receiving data, vice CHs aggregate, compress and forward it to the BS. This completes one round of data transmission. The protocol continues until every node runs out of energy in the network.

Key Advantage of the Proposed Method - Unlike current methods where frequent re-clustering leads to significant energy and memory cost, the suggested approach reduces this by performing clustering only once. Cluster heads are replaced adaptively based on energy thresholds and ensure longer network lifetime and effective energy utilization.

3.5 Performance Metrics

To assess the effectiveness of the proposed routing approach against current protocols, the following performance indicators are considered:

Network Lifetime - The number of rounds the network runs until the last node dies is known as the network lifespan. To assess the network's performance, we compare three metrics: First Node Dies (FND), Half of the Nodes Dies (HND), and Last Node Dies (LND). The number of rounds the network completes before the first sensor node runs out of power is known as FND. The number of network rounds until half of the nodes run out of energy is known as HND. The number of rounds that each node in the network runs out of energy is known as LND.

Energy Consumption – Energy is consumed for performing various communication tasks. The reduced energy consumption guarantees the better performance of the proposed methodology.

4. RESULT AND ANALYSIS

The parameters for experimental setup are as shown in Table 2:

Table 2. Simulation Parameters

Tool of Simulation	MATLAB
Network Area	100*100 m^2
Number of Nodes	100
Location of Base Station	(50,50)
Node's initial energy	0.25J, 0.5J, 1J
Dissipation energy (Efs)	10 pJ/ bit/ m2
Energy consumption on the circuit (Eelec)	50nJ/ bit
Reception energy (ERx)	50 nJ
Transmission energy (ETx)	50 nJ
Data aggregation energy	5 nJ/ bit/ report
Cluster to BS Amplification energy, d≤ d0, Emp	0.0013 pJ/bit/m2
Cluster to BS Amplification energy, d≥ d0, Efs	10 pJ/bit/m2
Intra Cluster Communication Amplification energy, d≤ d1	Emp /10 = Emp1
Intra Cluster Communication Amplification energy, d≥ d1	Ef s /10 = Efs1
Packets/message size	4000 bits

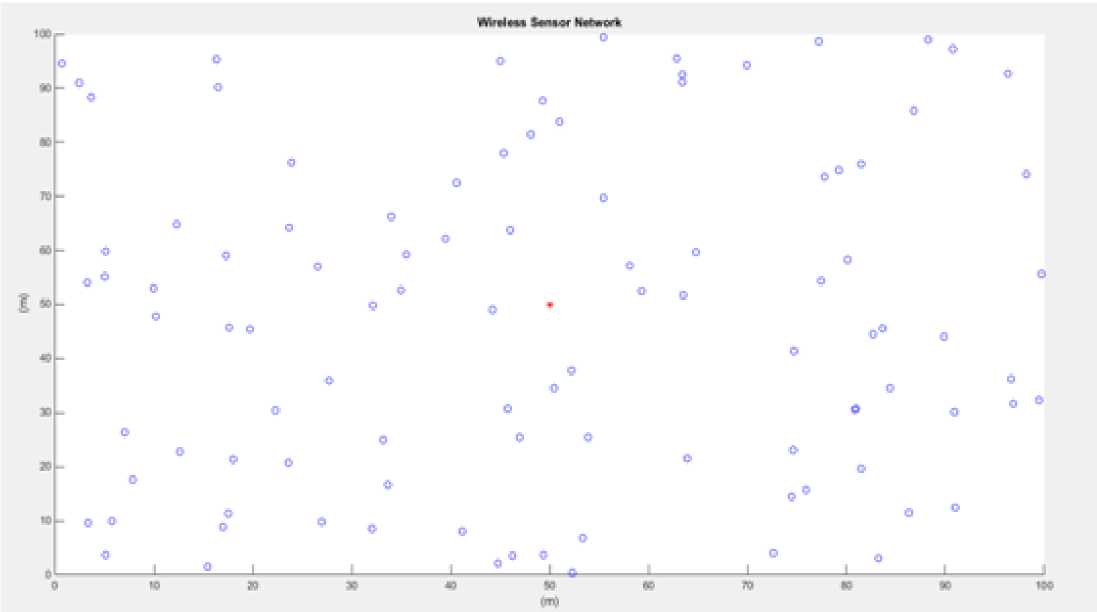

Figure 2 Simulation Scenario

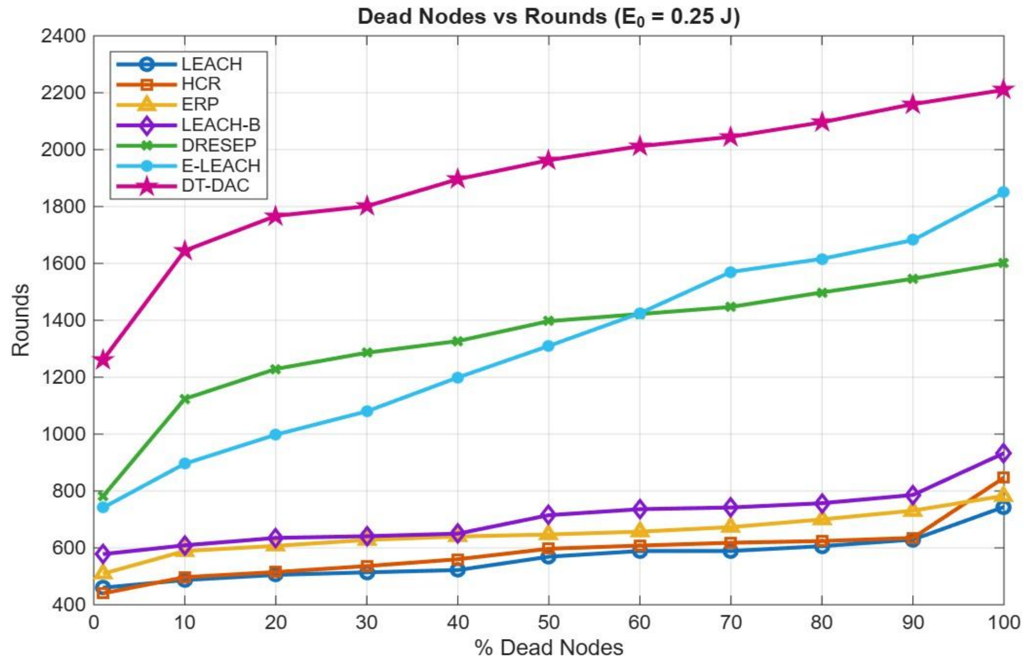

Figure 3 Dead nodes round history for E0=0.25 J (homogeneous setup)

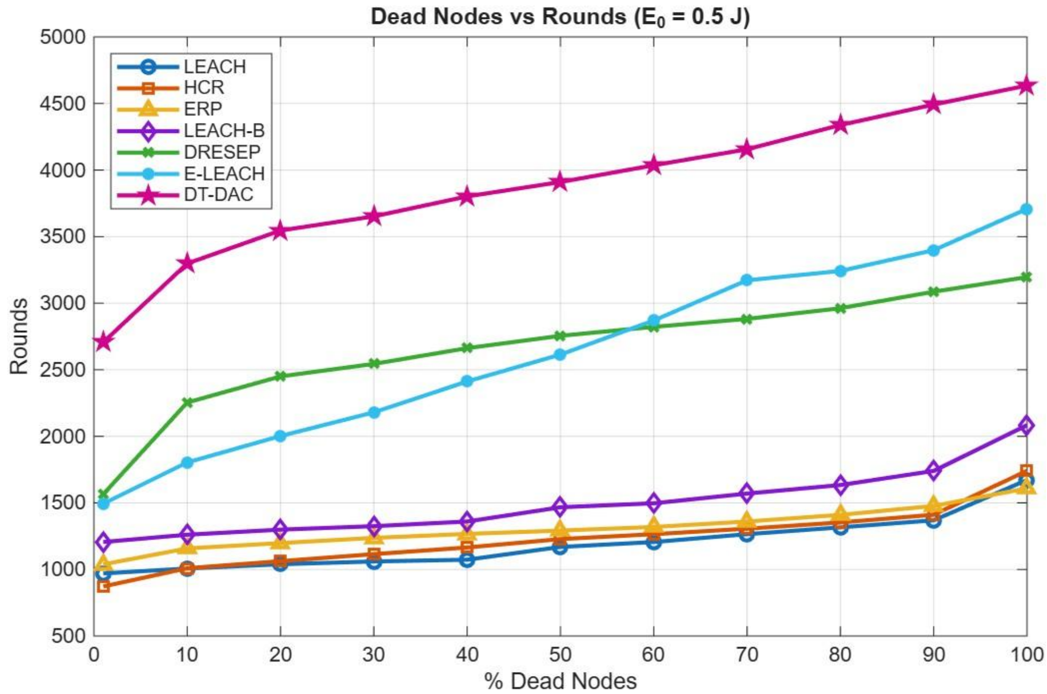

Figure 4 Dead nodes round history for E0=0.5 J (homogeneous setup)

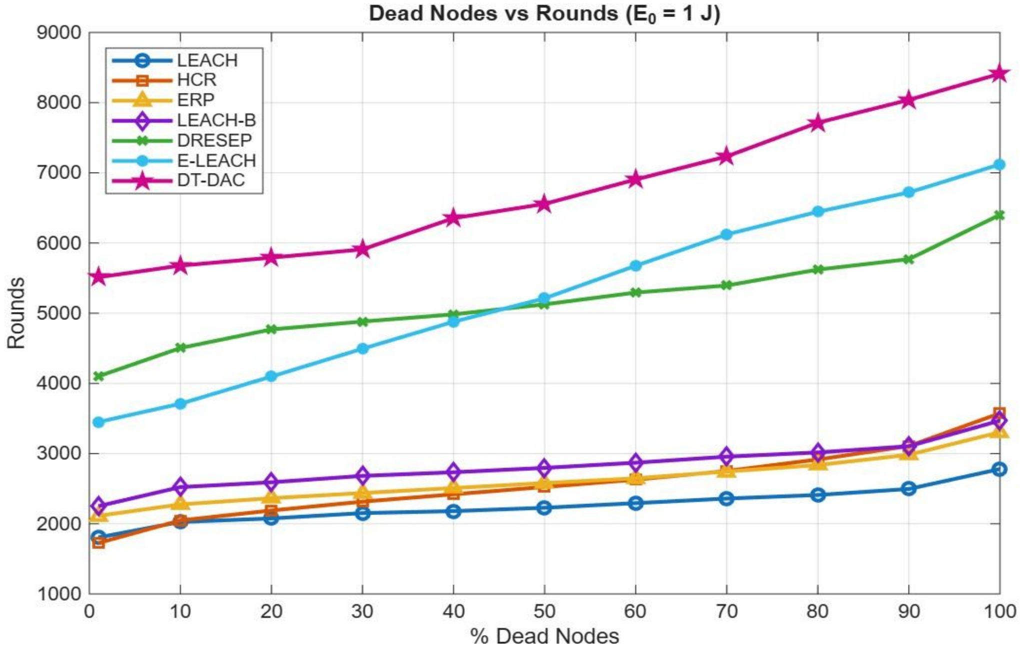

Figure 5 Dead nodes round history for E0=0.5 J (homogeneous setup)

Figure 2 shows a random deployment of sensor nodes over a 100×100 area in a wireless sensor network. Figure 3, 4 and 5 illustrate the relationship between percentage of dead nodes and network rounds for different protocols at energy levels of 0.25 J, 0.5 J, and 1 J. In all the three scenarios, the number of rounds increases as node deaths progress, reflecting the gradual depletion of network energy. It is observed that increasing the initial energy significantly enhances thenetwork lifetime for all protocols. The proposed DT-DAC protocol consistently achieves the highest performance**,** showing the longest stability period and overall lifetime at every energy level. Protocols likeE-LEACH [19] and DRESEP [18] also perform efficiently, especially at higher energy levels, indicating good scalability. In contrast, LEACH [14], HCR [15], and ERP [16] show comparatively lower performance due to less efficient energy utilization. The gap between advanced and basic protocols becomes more pronounced as energy increases from 0.25 J to 1 J. Table 3, 4 and 5 shows lifetime comparison of the sensor nodes for E0=0.25J, 0.5J and 1J.

Table 3. Lifetime comparison of the sensor nodes for E0=0.25 J

% dead nodes	LEACH [14]	HCR [15]	ERP [16]	LEACH B [17]	DRESEP [18]	E-LEACH [19]	DT-DAC
1 (FND)	460	440	509	578	781	741	1260
50 (HND)	569	597	647	715	1397	1310	1963
100 (LND)	744	847	783	933	1601	1850	2210

Table 4. Lifetime comparison of the sensor nodes for E0=0.5 J

% dead nodes	LEACH [14]	HCR [15]	ERP [16]	LEACH B [17]	DRESEP [18]	E-LEACH [19]	DT-DAC
1 (FND)	970	872	1038	1206	1565	1494	2706
50 (HND)	1169	1228	1292	1467	2755	2614	3910
100 (LND)	1672	1741	1609	2084	3196	3708	4635

Table 5. Lifetime comparison of the sensor nodes for E0=1 J

% dead nodes	LEACH [14]	HCR [15]	ERP [16]	LEACH B [17]	DRESEP [18]	E-LEACH [19]	DT-DAC
1 (FND)	1805	1726	2113	2251	4101	3450	5512
50 (HND)	2228	2524	2580	2796	5126	5212	6557
100 (LND)	2780	3574	3305	3470	6402	7120	8412

Figure 6, 7 and 8 shows FND, HND and LND comparison for varying initial energy of nodes. The presented approach outperforms other algorithms in terms of the overall network lifetime and the stability period. Overall network lifetime is the time until last node becomes dead. The stability of the network represents the time until the first node becomes dead. If the node density increases (in the same deployment area), the performance of the presented methodology improves significantly.

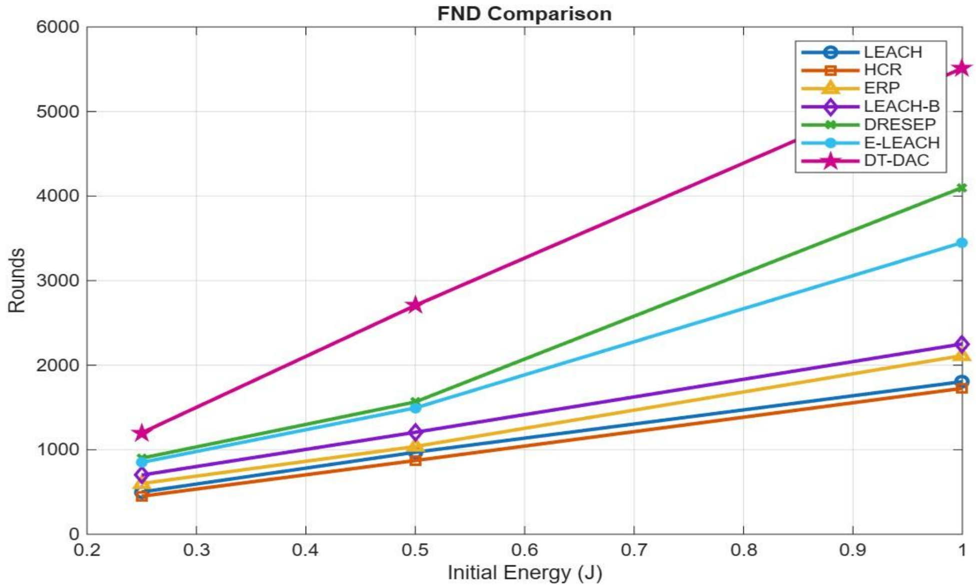

Figure 6 FND comparison for E0= 0.25J, 0.5J and 1J

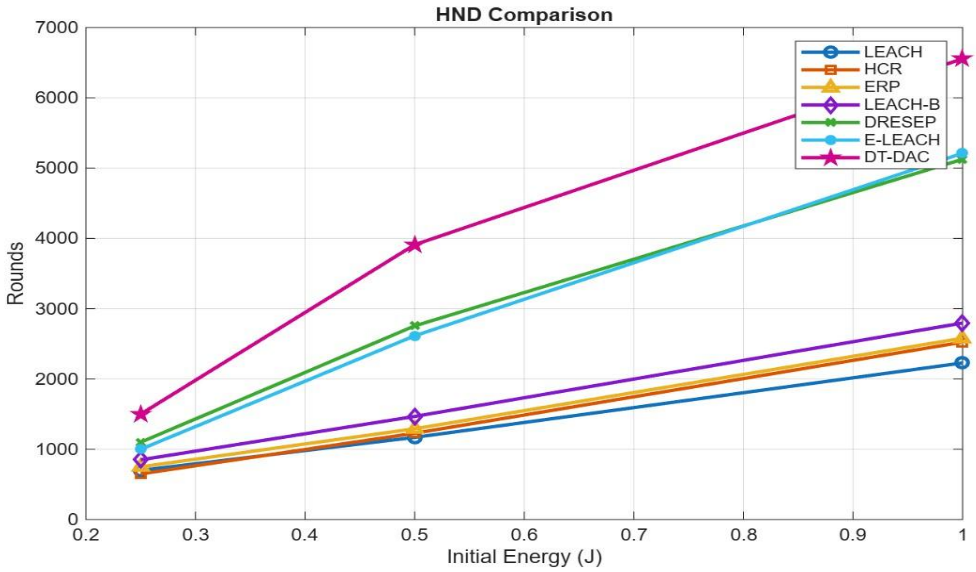

Figure 7 HND comparison for E0= 0.25J, 0.5J and 1J

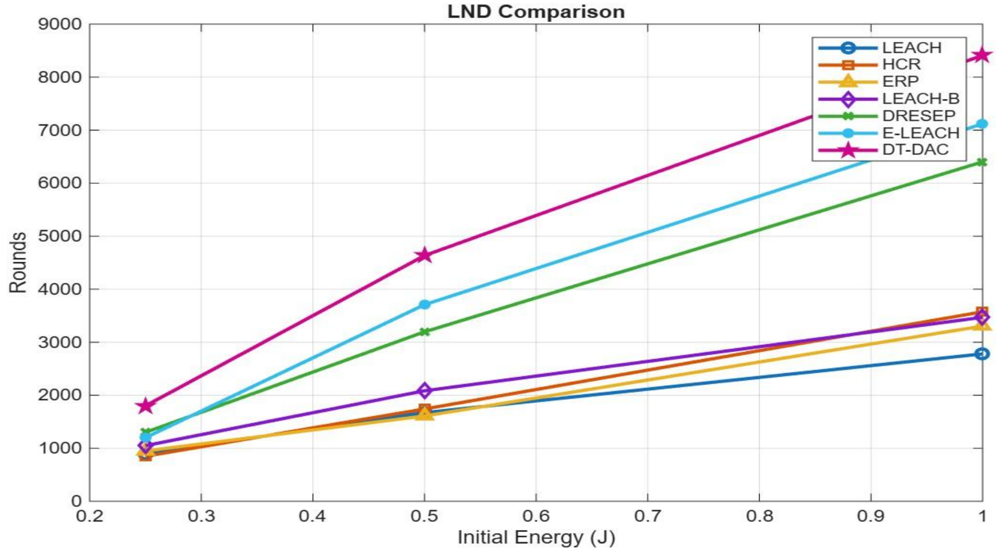

Figure 8 LND comparison for E0= 0.25J, 0.5J and 1J

5. CONCLUSION AND FUTURE WORK

Energy efficiency remains a critical factor for the design of wireless sensor networks (WSNs), as the lifespan of each sensor node is directly influenced by its battery capacity. Reducing energy usage is crucial to increasing the network lifetime. We have examined several current approaches designed to extend network lifetime and energy efficiency in WSNs. Our proposed method presents an optimized CH selection approach that considers the node residual energy and distance. Unlike conventional methods, our method eliminates the frequent replacement of cluster heads in every round. Rather, a cluster head is only replaced when its remaining energy falls below a defined threshold. The efficiency of the suggested methodology is demonstrated by the simulation results. It shows significant decrease in energy consumption and enhancement in network lifetime.

The CH selection process can be improved by incorporating density of node and the distance between each node and its corresponding CH. It involves comparing individual distances with the average cluster distance in addition to residual energy.

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