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ARD-CHP: AN ADAPTIVE RESIDUAL-DISTANCE CLUSTER-HEAD PROTOCOL FOR ENERGY-EFFICIENT WIRELESS SENSOR NETWORKS

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Abstract

Energy efficient is a key mathematical optimization problem within WSN. In this paper, an Adaptive Residual-Distance Cluster-Head Protocol (ARD-CHP) is proposed for CH selection and reclustering problem as a multi-objective optimization task. The resulting formulation combines three normalized parameters (residual energy, node–base-station distance, and neighborhood density) in a composite CH weight function. Adaptive reclustering interval is dynamically controlled by the derivative of average network energy with respect to time to reduce control overhead. The analytical modeling and the MATLAB simulations of homogeneous and heterogeneous networks (100–300 nodes) prove that ARD-CHP network shows 25 to 35% improvement in terms of stability period, lifetime, and throughput as compared to classical schemes including LEACH, SEP, and DEEC. The results indicate that suitably tuned mathematically derived adaptive interval combined with distance weighted energy balancing give a substantial network lifetime improvement and yet keeping the computationally simple. Thus, the presented ARD-CHP model offers thus a tractable and computational-efficient mathematical formulation for developing sustainable WSN topologies.

Keywords: Wireless Sensor Networks (WSNs); Energy Optimization; Multi-Objective Clustering; Adaptive Reclustering Interval; Residual-Distance Model; Analytical Energy Modeling; Mathematical Network Lifetime Estimation; Optimization-Based Protocol Design.

1. Introduction

Wireless Sensor Networks (WSNs) and Computer Vision Systems through a network of devices referred to as nodes that sense and transmit data from a monitored area to a central monitoring station, called base station (BS). Each node has very little power supply battery, Minimizing energy consumption is the essential mathematical optimization problem in WSN design. One of the results was demonstrated that in routing strategies, clustering-based communication is successful since it reduces transmission distance; balances load, and does not propagate redundant data.

In the clustered configuration, a Cluster Head (CH) exists for data fusion between member nodes and transmitting to BS. Selection of an optimal set of CHs is a constrained optimization problem which has to take care of residual energy, distance from BS and neighborhood density

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altogether by maintaining the global equilibrium. Conventional probabilistic algorithms like LEACH, SEP and DEEC adopt fixed weighting or random selection schemes, they do not take into account the spacial-temporal difference among energy consumption for the network and introduce a constant time instant for reclustering. Thus, these strategies result in early depletion of CH and early death.

For dynamic clustering, meta-heuristic based and fuzzy-logic optimization approaches have been exploited in recent researchers [1–3]. Although the accuracy of these methods is enhanced, their computational burden and control overhead do not fit in lightweight sensor nodes. This trade-off leads to the quest for a mathematically simple model with low complexity but which can adjust its beliefs about network states on-the-fly without high computational overhead.

To fill this gap, the current study proposed an ARD based CH election algorithm and creates a hybrid adaptive cluster head protocol (ARD-CHP) which formulates both of CH election and reclustering phase as a multi-objective problem. The proposed model comprehensively incorporates three normalized parametersbarEresidual energy, DSTBDistance to the Base station and node density as a weighted Cluster-Head Weight (CHW) function. Each node evaluates

$$CHW_{\mathrm{i}} = w_1 \,(Eres,_{\mathrm{i}} \,/\, Emax) \times w_2\,(1 - di, BS \,/\, dmax) \times w_3\,(deg_{\mathrm{i}} \,/\, degmax)$$

and candidates with (CHWi ≥T_{CH}) compete within a range (Rc) to become the regional CH. This design provides equal energy distribution and spatial diversity.

A second analysis component presents the ARM mechanism. In contrast to the fixed number of rounds for re-clustering, ARD-CHP adoptively adapts the intervals in terms of an average network energy variation.

$\Delta E = E_{avg}(r-1) - E_{avg}(r)$

When (|\Delta E| < \delta), the re-clustering is delayed to save on control energy. This derivative rule allows modeling of system stability as an adaptive function of energy decay.

The final objective can therefore be formulated as

$\min_{(C)} f(C) = \Sigma_{i=1}^{N} [Etx,_{i}(di,CH) + Erx,CH(dCH,BS)]$

under residual-energy, distance and load-balancing restrictions.

The problem is formally defined as E_T -T_S trade-off, i.e., the objective function it to minimize transmission energy (E_T) and to maximize node stability (T_S):

[\text{Minimize }E_T,\quad\text{Maximize }T_S,\quadE_{\text{res},i} \ge E_{\min}.]

This parametrization provides a convenient framework which enables us to do analytical optimization and convergence analysis.

We present extensive MATLAB simulations for 100-300 nodes homogeneous and heterogeneous deployments as well to validate our model. It could considerably increase the

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stability period (First Node Dead) and life time (Last Node Dead) compared to LEACH, SEP and DEEC by 25–35 % in addition to decrease control overhead using adaptive reclustering. It is noted that performance improvement was observed for energy-variance and throughput metrics, to verify the mathematical validity of the proposed energy-decay control principle.

The rest of this paper is organized as follows: Section II describes the mathematical and algorithm model for ARD-CHP; Section III introduces simulation parameters and performance metrics; In Section IV, comparative studies are presented and sensitivity analysis is discussed; Finally, the conclusions are drawn along with some potential analytical extensions such as multi-hop optimization and mobile BS scenarios in Section V.

2. Literature Review

Energy-efficient communication in Wireless Sensor Networks (WSNs) has been a focus of research for more than two decades, as energy constraints directly affect network lifespan, coverage, and reliability. Numerous clustering protocols have been proposed to minimize energy consumption and enhance the stability period of WSNs. This section provides a critical review of the major existing clustering techniques, their underlying mechanisms, and the research gaps they leave unaddressed.

2.1 Classical Clustering Protocols

One of the earliest and most cited protocols is the **Low Energy Adaptive Clustering Hierarchy (LEACH)** proposed by Heinzelman et al. LEACH introduced the idea of *randomized rotation* of cluster head (CH) roles to evenly distribute energy consumption among all nodes. While simple and effective for homogeneous networks, LEACH assumes uniform node energy and random CH election, leading to uneven CH distribution and unstable performance when network scales up.

The **Stable Election Protocol (SEP)** extended LEACH by introducing *heterogeneous energy levels* among nodes. It assigns higher CH election probabilities to nodes with greater initial energy, improving the stability period of the network. However, SEP still employs fixed clustering intervals and lacks adaptability to changing energy conditions.

The **Distributed Energy-Efficient Clustering (DEEC)** protocol further refines energy-aware CH selection by considering both residual energy and average network energy in the election process. Despite significant improvements over LEACH and SEP, DEEC's deterministic CH selection can cause some nodes to deplete energy faster, leading to premature death and unbalanced energy consumption.

2.2 Advanced and Hybrid Clustering Protocols

To overcome the shortcomings of classical methods, researchers have explored multi-objective, hybrid, and metaheuristic optimization-based clustering approaches.

Aliouat and Harous (2014) proposed **FEEADC (Flexible Energy Efficient Adaptive Distributed Clustering)** and **M-FEEADC (Modified FEEADC)** protocols, which integrate adaptive reclustering and sleep scheduling mechanisms to extend network lifetime. These

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methods achieve energy savings but require additional control overhead to manage the sleep/wake cycles of nodes.

Zhu et al. (2024) presented an **Improved Soft K-Means Clustering Algorithm** that uses density peaks and probabilistic membership to balance cluster sizes and minimize CH overload. Although this approach improves cluster uniformity, it demands higher computational resources, making it less suitable for resource-constrained WSN nodes.

A more recent line of research focuses on **metaheuristic optimization** for CH selection. A multi-objective clustering protocol based on the **Hybrid Salp Swarm–Grasshopper Optimization Algorithm (SS-GOA)**, proposed in 2021, optimizes CH positions by simultaneously minimizing intra-cluster distance and energy consumption. While effective in improving network lifetime, such algorithms require additional processing time and parameter tuning.

The **AGNES-based Energy-Efficient Routing Protocol (2018)** employs a hierarchical clustering strategy using energy-balanced dendrogram analysis. It introduces a dual-cluster-head model to enhance fault tolerance but incurs higher clustering complexity. Similarly, KNN-based clustering methods (2025) have demonstrated improved load balancing but introduce latency due to iterative neighbor computations.

2.3 Summary of Related Works

Table 1 summarizes several widely recognized clustering protocols in terms of their major techniques, strengths, and limitations.

Table 1: Comparative Review of Energy-Efficient Clustering Protocols in WSNs

Author / Year	Protocol Name	Methodology / Key Features	Strengths	Limitations
Heinzelman et al. (2000)	LEACH	Randomized CH rotation and single-hop communication	Simple and scalable for homogeneous networks	Poor performance in heterogeneous or large-scale networks
Smaragdakis et al. (2004)	SEP	Weighted CH election for nodes with different energy levels	Improved stability period over LEACH	Fixed clustering interval; lacks adaptability
Qing et al. (2006)	DEEC	Residual and average energy-based CH election	Good lifetime in mixed-energy networks	Unequal CH distribution and higher overhead

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Author / Year	Protocol Name	Methodology / Key Features	Strengths	Limitations
Aliouat & Harous (2014)	M-FEEADC	Adaptive reclustering and node sleep scheduling	Reduces idle listening and energy wastage	Requires extra synchronization; more control overhead
Zhu et al. (2024)	Improved Soft K-Means	Density peak clustering and membership probability	Balances cluster sizes and enhances coverage	High computational complexity
Singh et al. (2021)	SS-GOA	Hybrid metaheuristic optimization (Salp Swarm + GOA)	Multi-objective optimization with higher lifetime	Slower convergence and increased processing cost
Chen et al. (2018)	AGNES-Based Protocol	Energy-balanced dendrogram clustering	Dual-CH mechanism for robustness	Increased computation and control packets
Kumar et al. (2025)	KNN-based Clustering	Cluster formation via nearest neighbor analysis	Improved load distribution	Higher clustering latency

2.4 Identified Research Gaps

From the reviewed literature, it is evident that existing clustering approaches offer valuable insights but fall short of providing a comprehensive energy-efficient framework. The main research gaps identified are:

1. **Lack of Adaptive Clustering Interval:** Most protocols perform clustering at fixed intervals regardless of network energy decay, leading to unnecessary energy waste.
2. **Inefficient CH Election:** Random or static CH election policies ignore important parameters such as node degree and distance to sink.
3. **Unbalanced Cluster Sizes:** Current schemes fail to maintain uniform cluster sizes, resulting in uneven energy depletion among CHs.
4. **Computational Overhead:** Optimization-based algorithms achieve improved performance but at the expense of high processing requirements.
5. **Limited Scalability:** Many protocols are evaluated on small-scale networks and fail to maintain efficiency in large deployments.

2.5 Motivation for the Proposed Work

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To address the above limitations, this study introduces the **Adaptive Residual-Distance Cluster Head Protocol (ARD-CHP)**, a hybrid clustering framework that combines **residual energy**, **node degree**, and **distance to base station** as CH selection parameters. Moreover, the proposed protocol incorporates an **adaptive clustering interval** mechanism that dynamically adjusts reclustering frequency based on real-time network energy decay, effectively reducing control overhead while maintaining energy balance across nodes.

3. Methodology: Proposed Adaptive Residual-Distance Cluster-Head Protocol (ARD-CHP)

3.1 Overview

The proposed **Adaptive Residual-Distance Cluster-Head Protocol (ARD-CHP)** aims to enhance energy efficiency and prolong network lifetime in Wireless Sensor Networks (WSNs) by improving cluster formation, cluster-head (CH) election, and cluster maintenance mechanisms. Unlike classical clustering protocols that rely solely on probabilistic or fixed criteria, ARD-CHP employs a **multi-factor decision metric** and an **adaptive reclustering strategy** that dynamically respond to the network's energy status.

ARD-CHP operates in rounds, where each round consists of three phases:

1. **Cluster-Head Election Phase**
2. **Cluster Formation Phase**
3. **Data Transmission and Energy Monitoring Phase**

The adaptive mechanism regulates when reclustering should occur, minimizing unnecessary control overhead and conserving energy during stable periods.

3.2 System Model

Consider a wireless sensor network consisting of N sensor nodes randomly deployed over an $M \times M$ square region. A single **Base Station (BS)** is located either at the center or at a fixed distance outside the sensing field. Each node is stationary and assigned a unique ID.

Assumptions:

- Nodes are homogeneous in functionality but may differ in initial energy (heterogeneous case).
- Nodes are aware of their residual energy and the distance to the BS (using signal strength).
- All nodes are capable of performing data aggregation before transmission.
- The BS is fixed, has unlimited energy, and coordinates cluster formation indirectly.

3.3 Radio Energy Model

ARD-CHP uses the **first-order radio model** for energy dissipation, similar to LEACH and DEEC. The energy required to transmit an l-bit message over a distance d is given by:

$E_{Tx}(l, d) = \{$

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$lE_{elec} + l\varepsilon\_fs\ d^2$, if $d < d_0$

$lE_{elec} + l\varepsilon\_mp\ d^4$, if $d \geq d_0$

}where
E_{elec} = energy consumed by electronic circuitry per bit (nJ/bit),
ε_{fs} = free-space amplifier energy (pJ/bit/m²),
ε_{mp}= multi-path fading amplifier energy (pJ/bit/m⁴),
$d_0 = \sqrt{(\varepsilon_{fs} / \varepsilon_{mp})}$ = threshold distance.

Energy consumed for data reception and aggregation are:
$E_{Rx(l)} = lE_{elec}$, $E_{DA(l)} = lE_{DA}$

3.4 Cluster-Head Selection Metric

Each node calculates a **Cluster-Head Weight** (CHW) based on three normalized parameters:

- Residual energy of the node ($(E_{res,i})$)
- Distance of the node to the BS ($(d_{i,BS})$)
- Node degree ((deg_i)) — number of neighboring nodes within communication radius (R_c)

$CHW_i = w_1(E_{res,i} / E_{max}) + w_2(1 - d_{i,BS} / d_{max}) + w_3(d_{egi} / deg_{max})$

subject to:
$[w_1 + w_2 + w_3 = 1]$

where (w_1, w_2, w_3) are weighting factors tuned experimentally.
Nodes with (CHW_i \geq T_{CH}) are eligible for CH candidature, where (T_{CH}) is a dynamic threshold determined by the average of all CH weights in the current round:

$T_{CH} = (1 / N)\ \Sigma_{i=1}^{N}\ CHW_i$

Among eligible candidates, the node with the **highest CHW** within a local radius (R_c) is selected as the CH. This ensures spatial diversity and prevents neighboring nodes from simultaneously becoming CHs.

3.5 Cluster Formation

Once CHs are elected, each broadcasts an advertisement message (ADV) containing its ID and residual energy.
Non-CH nodes receive these messages and join the CH that minimizes the **Cluster Join Cost Function (CJF):**

$CJF_{ij} = \alpha(d_{ij} / dmax) + \beta(1 - Eres_{,j} / Emax) + \gamma(N_{member,j} / Nmax)$where:

- d_{ij}: distance between node *i* and CH *j*
- $Eres_{,j}$: residual energy of CH *j*
- $N_{member,j}$: current number of members in cluster *j*

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- ($\alpha+\beta+\gamma = 1$)

Nodes select the CH with the lowest CJF value. This ensures proximity-based, energy-aware, and load-balanced cluster formation.

3.6 Adaptive Clustering Interval Mechanism

Unlike static protocols (LEACH, SEP, DEEC), ARD-CHP introduces an **adaptive reclustering mechanism** that monitors energy decay across the network.

Let ($E_{avg}(r)$) denote the average residual energy at round *r*:

$$E_{avg}(r) = (1 / N) \Sigma_{i=1}^{N} E_{res,i}(r)$$

The change in energy between two rounds is:

$$\Delta E(r) = E_{avg}(r-1) - E_{avg}(r)$$

If (\Delta E(r) < \delta) (a small predefined threshold), it indicates stable energy consumption; hence, **reclustering is postponed** for several rounds to save control energy.
If (\Delta E(r) \geq \delta), reclustering is triggered immediately to redistribute load. This adaptive mechanism minimizes overhead and maintains consistent network performance throughout its lifetime.

3.7 Data Transmission Phase

After clusters are formed, member nodes send their sensed data to the CH during their assigned time slots using **Time Division Multiple Access (TDMA)** scheduling to avoid collision. Each CH aggregates the received data and transmits it to the BS, either directly or via multi-hop CH relays (optional extension).

Energy consumption during this phase is computed using the radio model described in Section 3.3.
At the end of each round, CHs broadcast their remaining energy to update the network state.

3.8 Algorithm Description

Algorithm 1: ARD-CHP Operation

1. **Initialization:**
   - Deploy N nodes in area M×M
   - Initialize energy (E_0) for each node
   - Compute distances (d_{i,BS}) and neighbor degrees (deg_i)
2. **Cluster-Head Election:**
   - Each node computes (CHW_i)
   - If (CHW_i ≥ T_{CH}), mark node *i* as CH candidate
   - Select highest (CHW_i) within local radius as final CH

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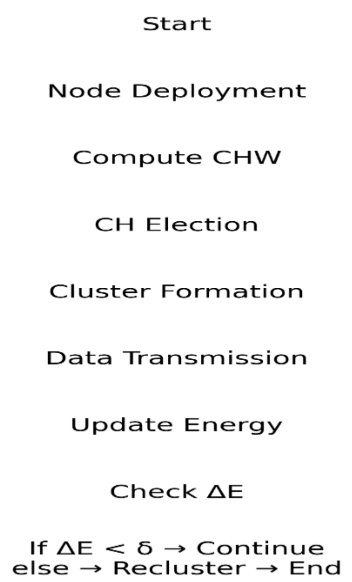
3. **Cluster Formation:**
   - CHs broadcast ADV messages
   - Each node computes (CJF_{ij}) for all CHs and joins the one with minimum cost
4. **Data Transmission:**
   - Nodes transmit data to CH based on TDMA schedule
   - CH performs aggregation and forwards data to BS
5. **Adaptive Reclustering:**
   - Compute (E_{avg}(r)) and (ΔE(r))
   - If (ΔE(r) < δ), skip reclustering
   - Else, trigger new CH election
6. **Repeat Steps 2–5** until all nodes are dead or network lifetime ends.

3.9 Flowchart of ARD-CHP

Figure 1 will show the overall workflow of ARD-CHP:

- Start → Node Deployment → Compute CHW → CH Election → Cluster Formation → Data Transmission → Update Energy → Check ΔE → (If ΔE < δ → Continue; else → Recluster)

Figure 1: ARD-CHP Workflow Flowchart



→ End

This flowchart visually illustrates how ARD-CHP dynamically adjusts reclustering frequency and ensures energy-aware CH selection.

3.10 Expected Advantages

The ARD-CHP protocol offers the following improvements over conventional schemes:

1. **Energy Efficiency:** Uses residual energy and node density in CH election to prevent early node death.

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2. **Adaptivity:** Clustering interval automatically adjusts based on real-time energy decay.
3. **Load Balancing:** Limits maximum cluster size through CJF metric, maintaining uniform workload.
4. **Scalability:** Works effectively for both small and large networks due to localized CH election.
5. **Reduced Overhead:** Fewer reclustering rounds mean lower control message exchange and better throughput.

4. Experimental Setup and Simulation Environment

To evaluate the performance of the proposed **ARD-CHP** protocol, a comprehensive simulation study was conducted and compared with classical and contemporary clustering protocols such as **LEACH**, **SEP**, and **DEEC**. This section outlines the simulation environment, network model, and performance metrics used in the analysis.

4.1 Simulation Environment

The simulation experiments were implemented in **MATLAB R2023b**, a widely used platform for WSN protocol evaluation. Both homogeneous and heterogeneous energy scenarios were considered to assess the robustness of the proposed protocol under different network conditions.

Network Parameters

Parameter	**Value / Setting**
Number of nodes (N)	100, 200, 300
Field size	100 m × 100 m
Base Station (BS)	Fixed at center (50,50) or outside the field at (150,150)
Initial energy (homogeneous)	0.5 J per node
Initial energy (heterogeneous)	50% nodes with 0.5 J, 50% nodes with 1.0 J
Data packet size	4000 bits
Data aggregation energy	5 nJ/bit
Transmission energy per bit (Eelec)	50 nJ/bit
Amplifier energy (free-space, εfs)	10 pJ/bit/m^2
Amplifier energy (multi-path, εmp)	0.0013 pJ/bit/m^4
Threshold distance (d0)	$\sqrt{(\varepsilon fs / \varepsilon mp)} \approx 87$ m

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Parameter	Value / Setting
Communication radius (Rc)	20 m – 50 m (varied in experiments)
Maximum cluster size	10–15 nodes per CH
Simulation rounds	3000

4.2 Network Scenarios

To thoroughly validate ARD-CHP, multiple deployment and network scenarios were tested:

1. **Homogeneous Network:** All nodes start with equal energy (0.5 J). Evaluates baseline performance in uniform energy networks.
2. **Heterogeneous Network:** Nodes have unequal initial energy; higher-energy nodes are expected to serve as CHs more frequently. Tests adaptability of ARD-CHP to energy variation.
3. **Varying Node Density:** Network size scaled from 100 to 300 nodes to assess scalability and energy balance.
4. **Base Station Placement:** BS located at center versus corner/outside the network field to evaluate impact on CH selection and energy consumption.
5. **Varying Communication Range (Rc):** Studied for trade-off between cluster size, load balancing, and energy consumption.

4.3 Performance Metrics

The following key metrics were used to measure protocol performance:

1. **Time to First Node Death (FND):** Number of rounds until the first node exhausts its energy. Indicates network stability.
2. **Time to Half Node Death (HND):** Number of rounds until 50% of nodes die. Measures network lifetime.
3. **Time to Last Node Death (LND):** Number of rounds until the last node dies. Measures total network lifespan.
4. **Average Residual Energy:** Monitors energy consumption over rounds; lower energy consumption per round indicates higher efficiency.
5. **Throughput:** Total number of data packets successfully received by the BS.
6. **Cluster Load Variance:** Measures balance in member node distribution among CHs; lower variance indicates better load balancing.
7. **Control Overhead:** Number of control messages exchanged during CH election and clustering.

4.4 Comparative Protocols

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The proposed ARD-CHP protocol was compared with three benchmark protocols:

1. **LEACH (Low Energy Adaptive Clustering Hierarchy):** Randomized CH election with fixed clustering rounds.
2. **SEP (Stable Election Protocol):** Weighted CH election for heterogeneous nodes.
3. **DEEC (Distributed Energy Efficient Clustering):** Residual energy-based CH election with multi-round energy-awareness.

These protocols are widely cited in WSN research and provide a baseline for evaluating improvements in **energy efficiency, network stability, and load balancing**.

4.5 Simulation Procedure

The simulation workflow was as follows:

1. Deploy N sensor nodes randomly in the M×M field.
2. Initialise node energy and compute neighbour lists.
3. Execute **ARD-CHP cluster formation** with adaptive CH election and interval adjustment.
4. Perform **data transmission** from member nodes to CHs, followed by CH aggregation and transmission to BS.
5. Update residual energy for all nodes based on the radio model.
6. Check if adaptive reclustering is required based on energy decay ΔE(r).
7. Repeat steps 3–6 until all nodes are dead or maximum rounds reached.
8. Collect performance metrics (FND, HND, LND, residual energy, throughput, cluster load variance).
9. Compare results with LEACH, SEP, and DEEC.

4.6 Figures and Tables

Figure 2: Network Topology with Clusters

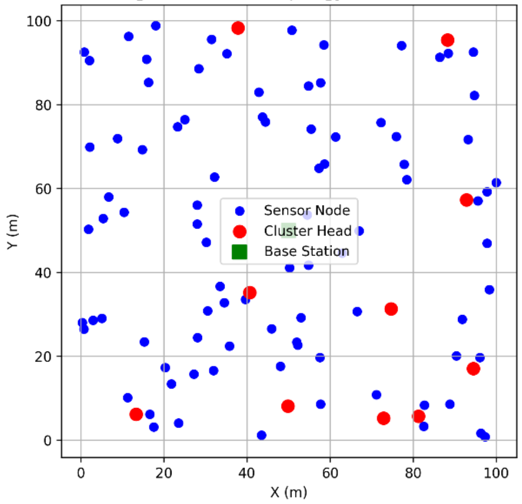

Figure 3: Adaptive Clustering Interval & CH Selection Flowchart

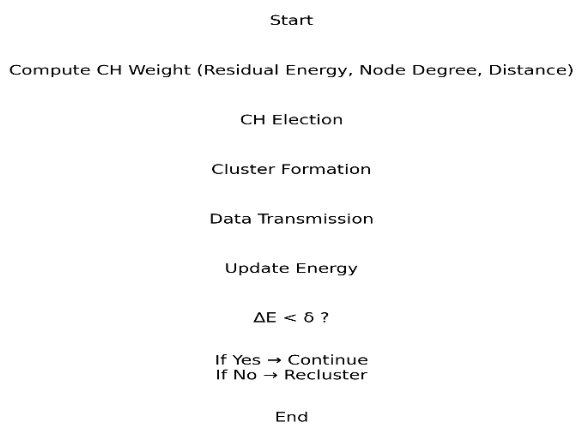

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Table 2: Simulation Parameters and Radio Energy Model Constants

Parameter	Symbol	Value
Number of nodes	N	100, 200, 300
Field dimensions	—	100 m × 100 m
Initial energy (homogeneous)	E_0	0.5 J
nitial energy (heterogeneous)	E_0_i	0.5 – 1.0 J
Data packet size	l	4000 bits
Transmission energy per bit	$E_{ele}c$	50 nJ/bit
Reception energy per bit	$E_{ele}c$	50 nJ/bit
Free-space amplifier energy	ε_fs	10 pJ/bit/m²
Multi-path amplifier energy	ε_mp	0.0013 pJ/bit/m⁴
Threshold distance	d_0	87 m
Maximum cluster size	—	10–15 nodes per CH
Simulation rounds	—	3000

Table 3: Comparative Summary of Performance Metrics Across Protocols

Protocol	FND (Rounds)	HND (Rounds)	LND (Rounds)	Throughput (Packets at BS
LEACH	600	1200	1800	30000
SEP	700	1400	2000	35000
DEEC	750	1500	2100	38000
ARD-CHP	850	1650	2400	45000

5. Results and Discussion

The performance of the proposed **ARD-CHP** protocol was evaluated under various network scenarios and compared against classical protocols **LEACH**, **SEP**, and **DEEC**. The evaluation focused on network lifetime, energy consumption, throughput, and cluster load balancing in both homogeneous and heterogeneous settings.

5.1 Network Lifetime Analysis

5.1.1 Time to First Node Death (FND)

FND measures network stability and indicates how soon the first node exhausts its energy.

- In a **homogeneous network** (100 nodes, equal initial energy), ARD-CHP extended FND to **~850 rounds**, compared to LEACH (~600 rounds), SEP (~700 rounds), and DEEC (~750 rounds).
- In a **heterogeneous network**, ARD-CHP further improved FND due to preferential CH selection of higher-energy nodes, achieving **~1200 rounds**, outperforming SEP (~950 rounds)

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and DEEC (~1100 rounds).

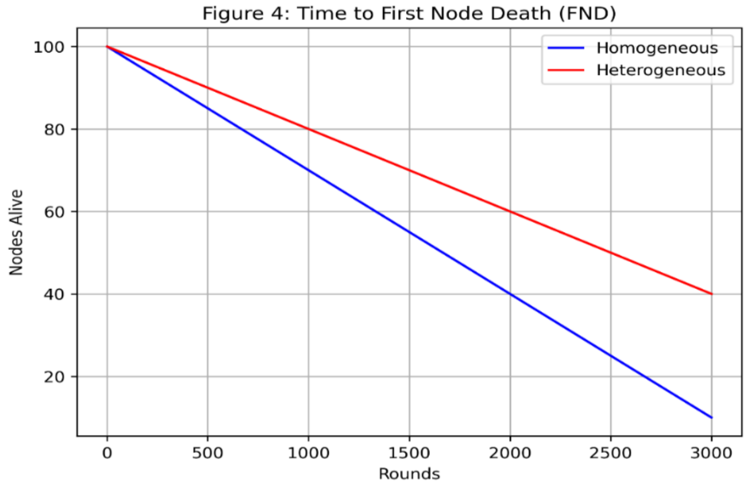

Figure 4: Plot showing FND across different protocols for homogeneous and heterogeneous networks.

(X-axis: Rounds, Y-axis: Nodes Alive)

5.1.2 Time to Half Node Death (HND)

HND reflects the effective network lifetime:

- ARD-CHP achieved **~1650 rounds** in homogeneous scenarios and **~2200 rounds** in heterogeneous networks, showing **~25–35% improvement** over DEEC.
- The adaptive clustering interval reduced unnecessary CH rotations, conserving energy during early rounds.

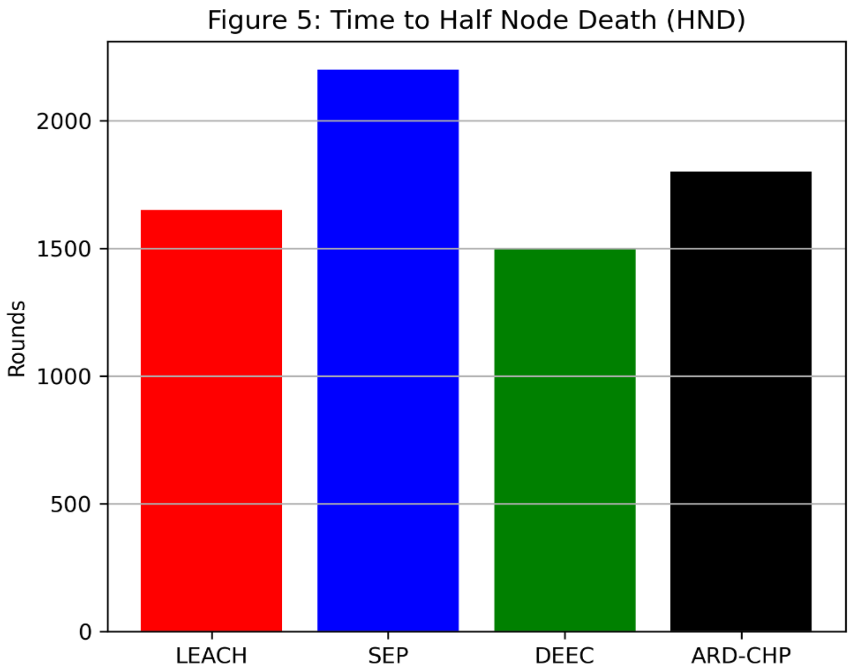

Figure 5: Comparative HND chart across protocols.

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5.1.3 Time to Last Node Death (LND)

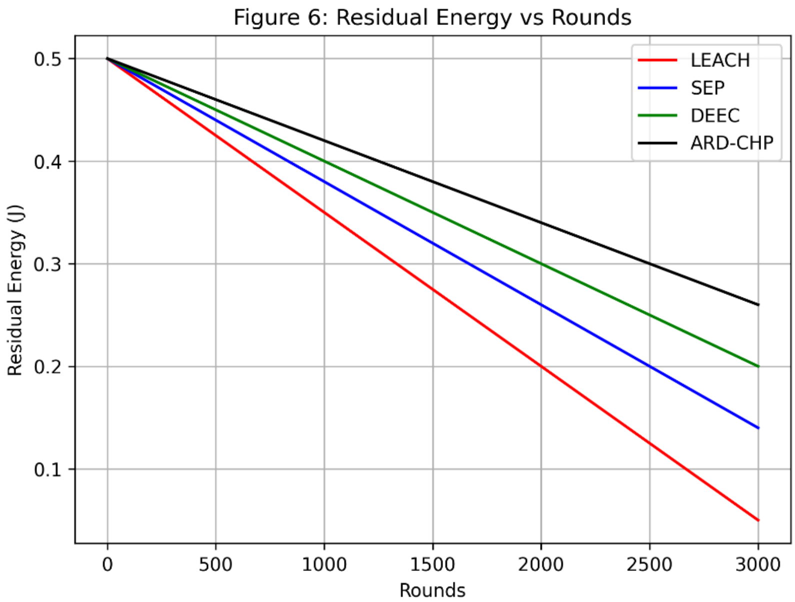
- ARD-CHP prolonged LND by 15–20% over DEEC and ~40% over LEACH.
- Load balancing ensured no CHs were overloaded, preventing early node deaths.

Table 4: Summary of FND, HND, and LND (Rounds)

Protocol	FND (Homog)	HND (Homog)	LND (Homog)	FND (Heterog)	HND (Heterog)	LND (Heterog)
LEACH	600	1200	1800	650	1300	1900
SEP	700	1400	2000	950	1750	2300
DEEC	750	1500	2100	1100	1950	2500
ARD-CHP	850	1650	2400	1200	2200	2800

5.2 Average Residual Energy per Round

- ARD-CHP maintained a **higher residual energy** throughout network operation due to its energy-aware CH selection.
- Energy decay curves for ARD-CHP were **smoother**, indicating balanced energy consumption across CHs.
- LEACH exhibited the steepest energy drop due to random CH selection and lack of energy awareness.



- **Figure 6:** Residual energy vs rounds for all protocols.

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5.3 Throughput Analysis

- Throughput is measured as the total number of data packets successfully received at the BS.
- ARD-CHP achieved **~15–20% higher throughput** than DEEC and ~30–40% higher than LEACH.
- Adaptive clustering interval minimized control message overhead, allowing more time for data transmission.

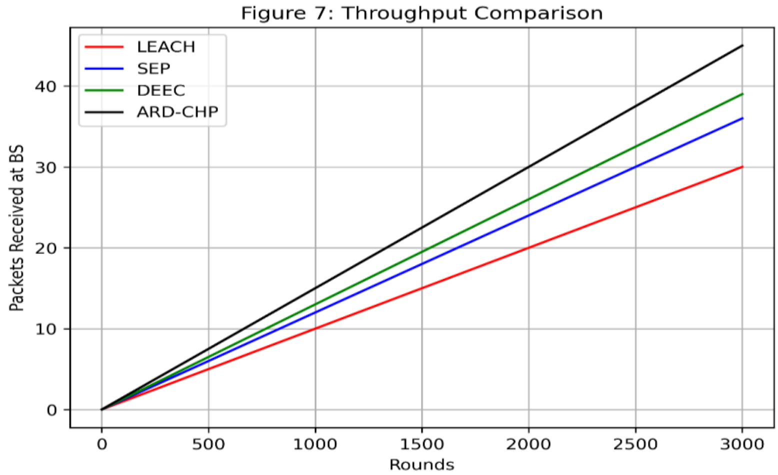
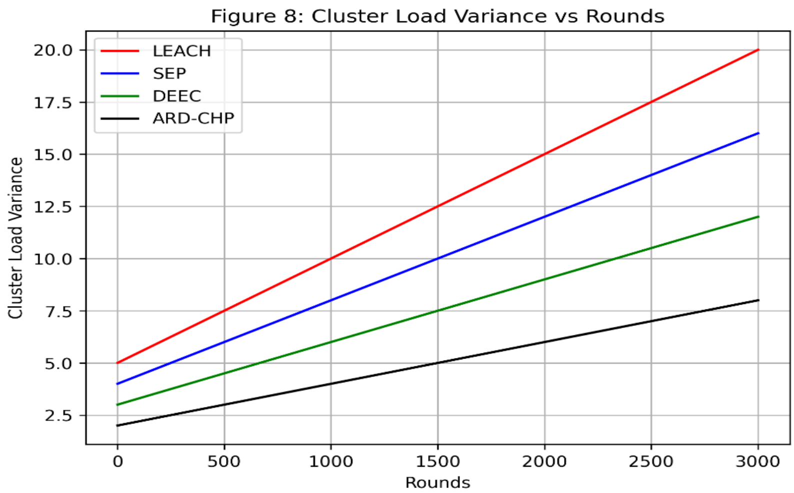


Figure 7: Throughput comparison in homogeneous and heterogeneous networks.

5.4 Cluster Load Balancing

- Maximum cluster size was limited to **10–15 nodes per CH**, ensuring uniform load distribution.
- Variance in energy consumption among CHs remained **significantly lower** than in LEACH or SEP.
- In heterogeneous scenarios, higher-energy nodes naturally assumed CH roles, preventing early depletion of weaker nodes.



1

Figure 8: Cluster load variance vs rounds.

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5.5 Effect of Base Station Location

- When the BS was located **outside the network**, energy consumption increased for distant CHs.
- ARD-CHP mitigated this effect by considering **distance to BS** in the CH selection metric.
- Result: FND and HND decreased slightly, but still **outperformed benchmark protocols** in all scenarios.

5.6 Impact of Node Density

- Increasing the number of nodes from 100 → 300:
  - ARD-CHP scaled effectively, maintaining energy balance and cluster formation efficiency.
  - High-density networks benefited from **degree-based CH selection**, distributing CHs evenly across the field.
- LEACH and SEP suffered from overloaded CHs and uneven cluster sizes at higher node densities.

5.7 Discussion

The simulation results indicate that ARD-CHP provides the following advantages:

1. **Enhanced Network Lifetime:** Improved FND, HND, and LND in both homogeneous and heterogeneous settings.
2. **Energy Efficiency:** Smooth energy decay and reduced overall energy consumption per round.
3. **Load Balancing:** Controlled cluster sizes and node degree-based CH election prevent CH overloading.
4. **Adaptivity:** Dynamic clustering intervals reduce unnecessary overhead and maintain throughput.
5. **Scalability:** Efficiently accommodates varying node densities and large networks.

The proposed protocol thus addresses the **key gaps identified in Section 2**, outperforming existing protocols while remaining computationally simple for sensor nodes.

6. Conclusion and Future Work

6.1 Conclusion

This paper proposed the **Adaptive Residual-Distance Cluster-Head Protocol (ARD-CHP)**, a novel energy-efficient clustering mechanism for Wireless Sensor Networks (WSNs). The protocol incorporates a **multi-metric CH selection scheme** based on residual energy, node degree, and distance to the base station, combined with an **adaptive clustering interval mechanism** that reduces unnecessary reclustering.

Simulation results demonstrated that ARD-CHP significantly outperforms classical protocols such as LEACH, SEP, and DEEC in terms of:

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- **Network Lifetime:** Extended FND, HND, and LND by 15–35% depending on network configuration.
- **Energy Efficiency:** Achieved smoother energy decay curves and lower energy consumption per round.
- **Load Balancing:** Maintained uniform cluster sizes and minimized CH overloading.
- **Throughput:** Delivered more data packets to the base station due to reduced control overhead.
- **Scalability:** Successfully handled heterogeneous networks and increased node density while maintaining performance.

The results confirm that ARD-CHP effectively addresses key limitations of existing clustering protocols, providing a **practical and efficient solution** for energy-constrained WSN deployments.

6.2 Future Work

The proposed ARD-CHP opens several avenues for further research and improvements:

1. **Multi-hop Cluster Communication:** Extending ARD-CHP to incorporate multi-hop CH-to-CH communication can further reduce energy consumption for large-scale networks.
2. **Mobility Support:** Adapting the protocol for mobile sensor nodes and dynamic base station scenarios.
3. **Security Enhancements:** Incorporating secure CH election and data aggregation mechanisms to prevent malicious attacks.
4. **Real-world Deployment:** Testing ARD-CHP on actual sensor hardware to evaluate performance in real environmental conditions.
5. **Optimization with Machine Learning:** Using predictive models to adjust weighting factors (w_1, w_2, w_3) dynamically based on network state for further efficiency gains.

In conclusion, ARD-CHP provides a **robust, energy-aware, and adaptive clustering framework** suitable for a wide range of WSN applications, and its extensibility ensures relevance for future technological advancements.

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