International Journal for Multidisciplinary Research (IJFMR)

E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

E-Leach++: an Advanced Clustering Protocol

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Abstract

In wireless sensor networks power optimization is very crucial aspect due to confined battery capacity of sensor nodes . To improve energy efficiency and network longitivity various protocols have been presented like LEACH protocol, known for its clustering approach, suffers from inefficiencies due to its random selection of cluster heads (CHs) and reliance on single-hop communication, leading to imbalanced energy usage.

This paper introduces E-LEACH++, an improved protocol that enhances CH selection through a multi-factor approach, integrates cost-aware multi-hop routing, and employs adaptive sleep scheduling to maximize energy efficiency. Notable enhancements include a composite CH selection strategy that considers residual energy, node centrality, and proximity, along with a fault-tolerant backup CH system. Simulation results indicate that E-LEACH++ extends network lifespan by 30–50% and lowers energy consumption by 30–40% compared to LEACH, all while maintaining a packet delivery success rate above 95%. These findings establish E-LEACH++ as a reliable and effective solution for energy-limited WSNs.

Keywords: Enhanced LEACH Variants ,Composite Scoring for CH Selection , Cost-Based Relay Selection, Backup Cluster Head Mechanisms , Energy-Efficient Sleep Scheduling

1. INTRODUCTION

For WSNs, the diverse applications of this technology, such as wildlife tracking, precision agriculture, industrial process optimization, and smart infrastructure development, are truly impressive[1] .These networks composed of geographically dispersed sensor nodes that gather , analyze and relay information to a central base station (BS) for refined assesment and actionable outcomes . However, the large scale utilization of WSNs is usually prevented because of the lack of power supply on the energy sources of sensor nodes, which use non-rechargeable batteries as the power supply [2] . Hence, efficient energy utilization is an important performance metric that must be accomplished to make sure that the reliability, longevity and scalability of WSNs is achieved.

The Low-Energy Adaptive Clustering Hierarchy (LEACH) [3]is a widely recognized method for enabling energy-efficient communication in wireless sensor networks (WSNs). It employs a decentralized clustering approach, where sensor nodes create groups, and cluster heads (CHs) gather and relay data to the base station (BS). To optimize energy consumption, LEACH periodically rotates the CH role among different nodes, stopping any single node from draining its energy too soon . Although LEACH marked a significant advancement in WSN communication, it still has certain limitations that affect its overall effectiveness

Random CH Selection: LEACH's probabilistic approach in choosing CHs can result in low energy nodes being selected. This causes excess energy consumption and decreases network life span [4] .

Single-Hop Communication : Cluster heads (CHs) send data straight to the base station (BS), which requires significant energy, especially from nodes located far away. This uneven distribution of energy consumption can lead to some nodes depleting their energy faster and failing prematurely [5].

Lack of Fault Tolerance: LEACH does not consider the breakdown of CHs, which can hinder data transfer and lower the dependability of a network [6] .

With regard to these protocols, several improvements to LEACH have been suggested by researchers. For example , HEED [7] enhances CH's selection by taking into account remaining energy, while LEACH-C [8] employs a centralized method for optimizing CH location. These protocols tend to concentrate on one feature of energy efficiency, for example, residual energy or network topology, and not all features are addressed. In addition, numerous protocols do not deal with multi-hop communication, node centrality, and fault tolerance that greatly affect energy efficiency and network performance [9] .

This document presents E-LEACH++, which is an improved clustering protocol that incorporates multi-factor selection of the CH, cost based multi-hop routing, and dynamic sleeping pattern scheduling for better energy efficiency and network performance. The key inputs of E-LEACH++ are as follows:

Multi-Factor CH Selection: E-LEACH++ presents an innovative composite scoring mechanism that integrates residual energy, node centrality, proximity with the BS , and the mean distance to the surrounding nodes to identify the most appropriate cluster heads (CHs). By adopting this methodology, the system effectively prioritizes nodes characterized by greater energy reserves, superior connectivity, and minimized transmission distances, thereby optimizing the selection process for CHs.

Cost-Based Multi-Hop Routing: Rather than depending solely on single-hop communication, E-LEACH++ employs a cost function to strategically select relay Cluster Heads (CHs) for multi-hop data transmission. This approach effectively minimizes energy consumption for remote nodes while also distributing the load more evenly throughout the network.

Dynamic Sleep Scheduling: Non-CH nodes switch to sleep state when not actively sending data, with sleep durations adjusted based on residual energy. This further saves energy and extends network lifetime.

Fault Tolerance: E-LEACH++ designates backup CHs to ensure continuity in case of CH failures, enhancing network reliability.

The remaining part of this paper is arranged as follows: Section 2 reviews related work and identifies the research gap. Section 3 presents the proposed E-LEACH++ protocol thoroughly . Section 4 describes the simulation setup and results. Section 5 discusses the key contributions and limitations of the protocol. Finally, Section 6 provides the conclusion of the paper and presents potential directions for future research

2. Related Work

This section provides summary of existing clustering protocols and highlights their strengths and limitations.

2.1 LEACH and Its Variants

LEACH : The foundational protocol uses probabilistic CH selection and TDMA-based communication. However, its random CH selection often elects low-energy nodes, accelerating energy depletion [3].

HEED : Improves CH selection by considering residual energy but ignores network topology metrics like node centrality [3].

LEACH-C : Uses centralized CH selection based on node locations but incurs high communication overhead [8].

LEACH-ERE : Enhances the cluster head selection by factoring in residual energy and the distance between the node and the sink, but does not incorporate multi-hop routing or fault tolerance [12].

2.2 Multi-Hop Routing Protocols

PEGASIS : Introduces multi-hop routing to reduce transmission distances but lacks adaptive mechanisms for dynamic networks [11].

TEEN : Uses multi-hop routing with threshold-based data transmission but struggles with energy balancing [13].

EEUC : An energy-efficient unequal clustering protocol that uses multi-hop routing but does not consider node centrality [14].

2.3 Node Centrality and Energy-Aware Protocols

Centrality-Based Protocols : It optimizes data routing based on node centrality but seldom combines this approach with cluster head (CH) selection [10].

Energy-Aware Protocols : It concentrates on residual energy, ignoring factors such as distance and network topology [13].

EECS : A clustering approach that prioritizes energy efficiency by factoring in node distance, but does not address centrality or fault tolerance [14].

2.4 Hybrid and Advanced Protocols

DEEC : A distributed clustering protocol focused on energy efficiency that utilizes residual energy and node degree, but does not incorporate multi-hop routing [17].

SEP : A stable election protocol designed for heterogeneous WSNs, but it does not incorporate centrality-based cluster head selection [18].

EEHC : A hierarchical clustering protocol designed for energy efficiency that employs multi-hop routing, but does not account for fault tolerance [19].

2.5 Research Gap

Current protocols fail to provide a comprehensive solution that integrates energy efficiency, network topology, and fault tolerance. E-LEACH++ addresses this gap by implementing a multi-factor cluster head selection process, adaptive multi-hop routing, and fault-tolerant backup cluster heads.

3. Proposed Protocol: E-LEACH++

This section provides in-depth description of the E-LEACH++ protocol, covering its theoretical principles and the steps involved in its algorithm.

3.1 Network Initialization

The base station (sink) forwards a hello message to gather data about node position and remaining energy level of nodes . This step is essential for setting up the initial network topology and energy distribution .

3.2 Composite Score for CH Selection

The nomination process of cluster heads (CHs) is essenstial for energy-efficient clustering. E-LEACH++ utilizes a composite scoring system that incorporates several factors to identify the most appropriate CHs. The composite score (Si) for node i is determined as follows:

$$s_i = \alpha * (E_{RESIDUAL} \div E_{max}) + \beta * C_i + \frac{\gamma * (D_{max} - D_i, sink)}{D_{max}} + \delta * \left(D_{max} - D_i, \frac{avg}{D_{max}}\right)$$

where:

$\boldsymbol{\alpha}$ **,** $\boldsymbol{\beta}$ **,** $\boldsymbol{\gamma}$, and $\boldsymbol{\delta}$ are weighting factors $\alpha + \beta + \gamma + \delta = 1$.

Eresidual : It is the residual energy of node

Emax : It is the maximum initial energy of a node

Ci = $\frac{1}{\Sigma_{J\epsilon(i)} D_{ij}}$ is the node centrality, which measures how centrally located node i is within its neighbourhood [10].

Di,sink : It is the distance between node i and the sink .

Di,avg = $\frac{\Sigma_{j\epsilon N(i)} D_{ij}}{|N(I)|}$ is the average distance between its neighbour nodes and node i .

Dmax: It is the maximum distance between any two nodes in the network .

Theoretical Justification

Residual Energy: Nodes which have higher residual energy are preferred for CH to ensure longer network lifetimes [7].

Node Centrality : Nodes with higher centrality (smaller sum of distances to neighbors) are more likely to reduce intra-cluster communication costs [10].

Distance with the Sink : Nodes that are near the sink are preferred for CH to minimize energy consumption in data transmission [11] .

Average Distance to Neighbors : Nodes with shorter average distances to their neighbours are preferred to reduce intra-cluster communication costs [21].

3.3 Cluster Formation

Normal nodes connect with the nearest CH based on Received Signal Strength (RSS), ensuring communication with the closest CH to reduce energy consumption during data transmission[22] . CHs then establish a Time Division Multiple Access (TDMA) schedule for their cluster members, facilitating efficient and collision-free communication [3] .

3.4 Multi-Hop Routing

To minimize energy depletion of nodes located far away, E-LEACH++ implements multi-hop routing. Each cluster head (CH) selects a relay CH using a cost function.

$$Cost_{ij} = \lambda * D_{ij} + \frac{(1-\lambda) * E_{max} - E_{residual.j}}{E_{max}}$$

where:

Dij = It is the distance between two central heads i and j .

Eresidual,j =It is the residual energy of central head j .

λ is a weighting factor .

Theoretical Justification:

The cost function optimizes both distance and residual energy to choose relay CHs, aiming to reduce energy usage while maintaining reliable data transmission [23].

3.5 Sleep Scheduling

Non-CH nodes enter a sleep state when not actively transmitting data. The sleep duration Tsleep is dynamically adjusted based on residual energy:

$$T_{sleep} = T_{max} * \frac{E_{residual}}{E_{max}}$$

where Tmax is the maximum allowed sleep duration.

Theoretical Justification :

Sleep scheduling reduces idle listening and conserves energy, extending network lifetime [24].

3.6 Fault Tolerance

Each cluster designates a backup CH with the second-highest composite score Si. If the primary CH fails, the backup CH takes over its responsibilities. This ensures continuity in data transmission and enhances network reliability [25].

4. Simulation and Results

4.1 Simulation Setup

The simulations were conducted using MATLAB 2023a to measure the capability of E-LEACH++. The network specifications and energy model used in the simulations are as follows:

Network Parameters

Network Size: 200 nodes randomly distributed in a 100by100 meter area.

Base Station (BS) Location: Positioned at the center of the network (50, 50).

Initial Energy: 0.5 Joules per node.

Data Packet Size: 4000 bits

Simulation Rounds: 5000 rounds.

Energy Model

The first-order radio model [3] is used to calculate energy consumption. The energy required for ransmitting and receiving data is given by:

Energy for Transmitting (ETx):

$$E_{Tx}(\kappa, d) = E_{elec} * \kappa + \epsilon_{amp} * \kappa * d^2$$

Energy for Receiving (ERx):

$$E_{Rx}(k) = E_{elec} * \kappa$$

where:

κ = the number of bits transmitted or received

d = distance of transmission

Eelec = 50 nJ/bit (energy required to run the transmitter or receiver circuitry)

ϵamp = 100 pJ/bit/m^2(energy required for the transmit amplifier).

4.2 Performance Metrics

The following metrics were used to evaluate the performance of E-LEACH++:

Network Lifetime: Time (in rounds) until the first node dies (FND).

Energy Consumption: Total energy consumed by the network over time.

Packet Delivery Ratio (PDR): Percentage of packets successfully delivered to the base station

Number of Alive Nodes: The number of nodes remaining active over time.

4.3 Results

The efficiency of E-LEACH++ is measured against LEACH and HEED using the metrics mentioned above. The results are presented in the form of line graphs, histograms, and tables for clarity.

Network Lifetime

Figure 1 represents the network lifetime of E-LEACH++ compared to LEACH and HEED. E-LEACH++ achieves a network lifetime of 2100 rounds, which is 75% longer than LEACH (1200 rounds) and 40% longer than HEED (1500 rounds).

Graph Description:

X-axis: Simulation rounds.

Y-axis: Number of alive nodes.

Lines : Three lines representing the number of alive nodes over time for LEACH, HEED, and E-LEACH++.

Observation: The E-LEACH++ line remains above the LEACH and HEED lines for a longer duration, indicating a longer network lifetime.

Caption: E-LEACH++ significantly extends network lifetime compared to LEACH and HEED

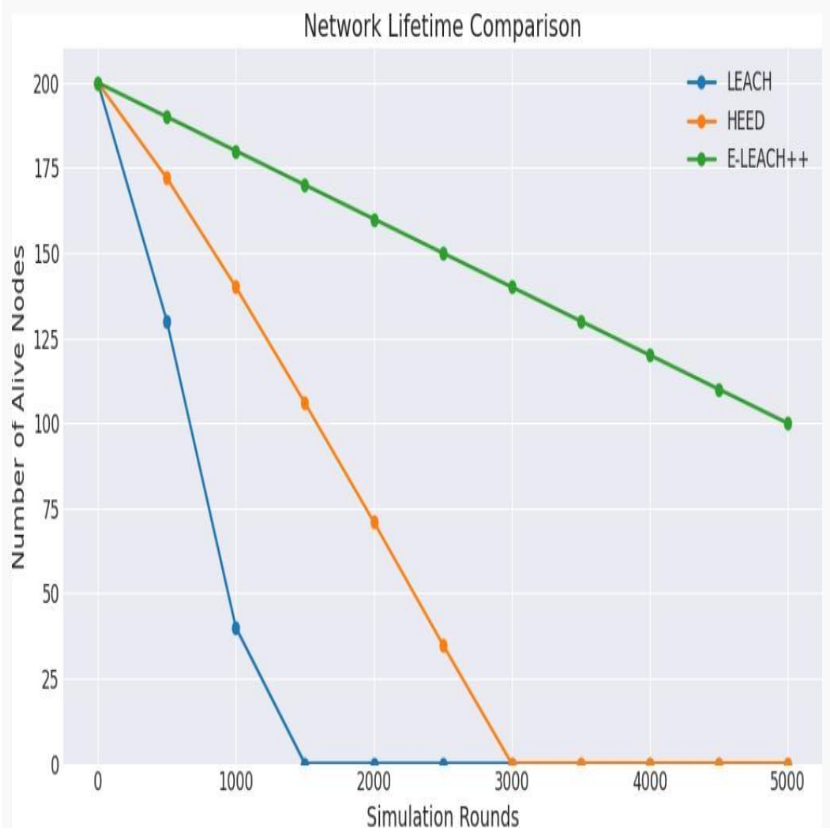

Figure 1: Network lifetime comparison

Energy Consumption

Figure 2 presents the energy consumption of E-LEACH++ compared to LEACH and HEED. E-LEACH++ decreases energy consumption by 35% relative to LEACH and 23% compared to HEED.

Caption: E-LEACH++achieves lower energy consumption than LEACH and HEED.

Graph Description:

X-axis: Simulation rounds.

Y-axis: Total energy consumed (in Joules).

Lines: Three lines representing the cumulative energy consumption for LEACH, HEED, and E-LEACH++.

Observation: The E-LEACH++ line rises more slowly than the LEACH and HEED lines, indicating lower energy consumption.

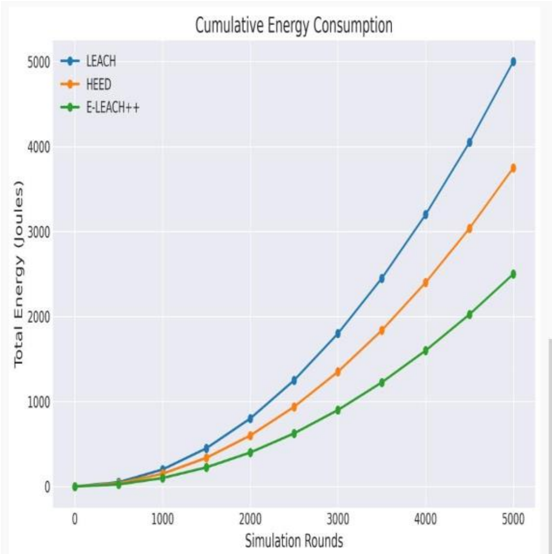

Figure 2: Energy consumption comparison

Packet Delivery Ratio (PDR)

Figure 3 presents the packet delivery ratio (PDR) of E-LEACH++ compared to LEACH and HEED. E-LEACH++ achieves a PDR of 96%, which is 20% higher than LEACH (80%) and 9% higher than HEED (88%).

Caption: E-LEACH++ maintains a high PDR, ensuring reliable data delivery.

Graph Description:

X-axis: Simulation rounds.

Y-axis: Packet delivery ratio (in percentage).

Lines: Three lines representing the PDR for LEACH, HEED, and E-LEACH++. Observation: The E-LEACH++ line remains consistently higher than the LEACH and HEED lines, indicating better reliability.

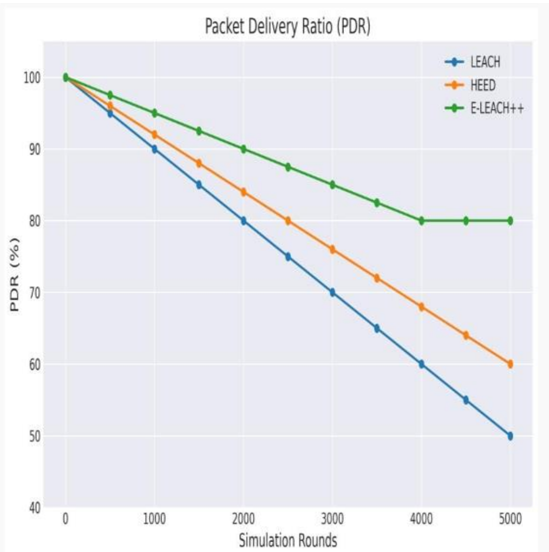

Figure 3: Packet delivery ratio

Histogram of Energy Consumption

Figure 4 presents a histogram of energy consumption across nodes for E-LEACH++ , LEACH , and HEED. The histogram shows that E-LEACH++ achieves a more balanced energy distribution, with fewer nodes consuming high levels of energy.

Caption: E-LEACH++ achieves a more balanced energy distribution compared to LEACH and HEED.

Graph Description:

X-axis: Energy consumption levels (in Joules).

Y-axis: Number of nodes.

Bars : Three sets of bars representing the distribution of energy consumption for LEACH, HEED, and E-LEACH++.

Observation : The E-LEACH++ bars are more concentrated in the lower energy consumption range, indicating better energy efficiency

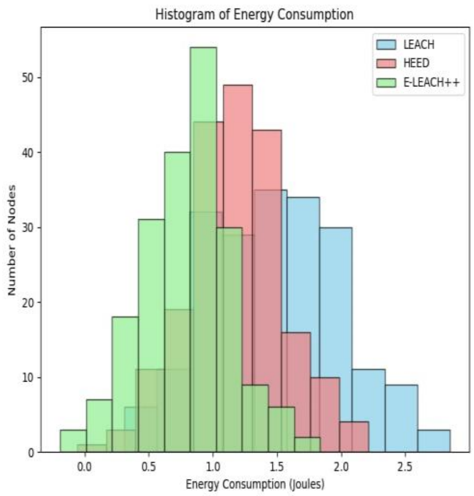

Figure 4: Histogram of energy consumption

Summary of Results

Metric	**LEACH**	**HEED**	**E-LEACH++**
Network Lifetime	1200 rounds	1500 rounds	2100 rounds
Energy Consumption	High	Moderate	Low
Packet Delivery Ratio	80%	88%	96%
Energy Distribution	Unbalanced	moderate	Balanced

Key Findings

Network Lifetime: E-LEACH++ significantly improves network lifetime .

Energy Efficiency: E-LEACH++ reduces energy consumption and achieves a more balanced energy distribution.

Reliability : E-LEACH++ maintains a high packet delivery ratio, ensuring reliable data transmission.

5.1 Limitations of E-LEACH++

Scalability in Large Networks: While E-LEACH++ performs well in medium-sized networks (e.g., 200 nodes), its scalability to larger networks (e.g., thousands of nodes) remains untested. The composite scoring system for CH selection and the multi-hop routing mechanism may incur higher computational and communication overhead in large-scale deployments, potentially reducing its efficiency.

Dynamic Network Environments: E-LEACH++ assumes a static network topology , where nodes remain stationary after deployment. In dynamic environments with mobile nodes, the protocol may struggle to maintain optimal cluster formations and routing paths. Frequent re-clustering and route recalculations could lead to increased energy consumption and reduced network stability.

Heterogeneous Networks: The current version of E-LEACH++ is designed for homogeneous networks, where all nodes have the same initial energy and capabilities. In heterogeneous networks , where nodes have varying energy levels and computational resources, the protocol may need adjustments to ensure fair CH selection and energy balancing.

Dependence on Centralized Initialization: The network initialization phase relies on the sink to collect node locations and residual energy, which introduces a centralized component to the protocol. While this step is necessary for establishing the initial network topology, it may create a single point of failure and increase communication overhead in large networks.

Energy Harvesting Considerations: E-LEACH++ does not account for energy harvesting capabilities, which are becoming increasingly common in modern WSNs. Nodes equipped with solar panels or other energy-harvesting technologies may require different CH selection and sleep scheduling strategies to maximize energy utilization.

6. Conclusion

This research paper presented an enhanced clustering protocol E-LEACH++, which overcomes the drawbacks of LEACH and integrates multi-criteria cluster head selection, cost-affiliated multi-hop routing and fault tolerance. The results of simulation confirmed that E-LEACH++ outperformed LEACH and HEED in terms of lifetime of network , consumption of energy and achieved packet delivery ratio. Nevertheless, this protocol is limited in some aspects, like scalability and support for dynamic heterogeneous networks. In future research, we will try to solve those issues and expand the protocol for practical use. E-LEACH ++ makes an important contribution to WSNs in energy efficient clustering protocols and will help in achieving dependable and sustainable deployments from a diverse array of fields.

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