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Simulation-Based Performance Evaluation of Hierarchical Routing Protocols for Wireless Sensor Networks

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ABSTRACT

Wireless Sensor Networks (WSNs) find widespread use in monitoring and data collection for many applications but are faced with tremendous challenges such as limited energy resources, scalability, and latency. Efficient routing protocols are essential in alleviating these challenges, extending network lifetime, and optimizing energy consumption. Among the numerous solutions proposed, hierarchical routing protocols have emerged as effective strategies for improving energy efficiency, minimizing latency, and enhancing network scalability. Despite their potential, comprehensive comparative evaluations of multiple hierarchical routing protocols under diverse operational conditions remain limited in the literature. This paper addresses this gap by conducting an extensive simulation-based performance evaluation of four hierarchical clustering protocols—Low-Energy Adaptive Clustering Hierarchy (LEACH), Energy-Aware Multi-Hop Multi-Path Hierarchical (EAMMH), Power-Efficient Gathering in Sensor Information Systems (PEGASIS), and Hybrid Energy-Efficient Distributed (HEED)—for WSNs A MATLAB-based simulation approach was employed to analyze these protocols using key performance metrics: energy consumption, network lifetime, latency, throughput, and scalability. The results indicate that PEGASIS offers the best energy efficiency and has a longer network lifespan than the other algorithms and is thus suitable for large-scale, long-duration deployments. HEED has the lowest latency and is thus highly suitable for real-time applications, and EAMMH delivers the highest throughput, which is suitable for high data transmission. While LEACH is energy-consuming, it is still a viable option for small-scale networks due to its simplicity. However, it shows poor scalability and a shorter network lifetime compared to the other algorithms. This comparative study reveals essential trade-offs between energy efficiency, latency, scalability, and throughput of WSN clustering protocols and offers helpful insights for the selection of the most appropriate protocol based on some application requirements. The findings become part of the efforts to continue enhancing WSN performance and extend their applicability to diverse real-world applications.

1. INTRODUCTION

Wireless Sensor Network (WSN) is made up of many sensor nodes that communicate with one another in order to transmit data to a central node or sink. These sensor nodes are small sensing devices that are installed for the purpose of tracking, monitoring and measuring several physical phenomena such as temperature, pressure and so on. It was invented during the cold war and was first used in the military to monitor the activities of the enemy and was later advanced to cover many applications [1]. The sensor technology has advantages such as low cost, ease of implementation and flexibility, and is used in different applications such as wireless sensor networks, wireless network technologies and embedded chip engineering. Recent developments in communication technologies and the production of affordable wireless devices have facilitated the deployment of low-power wireless sensor networks. These networks are widely used due to the simplicity of their setup and the versatile functionality of sensor nodes, enabling applications such as environmental monitoring, temperature tracking and so on [2]. However, sensor networks face significant challenges, including limited energy and lifetime, design constraints, security threats, deployment, issues of scalability and quality of service requirements. Sensor nodes are battery-powered and replacing or recharging the batteries is often impractical or impossible. Therefore, energy efficiency is crucial to prolong the network lifetime. Moreover, the network is prone to node failures, leading to dynamic changes in network topology. This demands adaptable routing algorithms to minimize energy consumption and increase network lifetime, while maintaining efficient data transmission [3].

Routing in WSNs refers to the process of determining the paths for data transmission between sensor nodes and the base station, while considering factors like energy efficiency, network lifetime, data accuracy and so on. The main objective of WSN routing protocol is the accurate and effective formation of path among a pair of nodes, such that communications may be carried out with minimum energy dissipation and delay [4]. Routing protocols in WSNs can be categorized based on network architecture into; location-based, flat-based and hierarchical protocols [5]. Hierarchical routing protocols as protocols that impose a structure on the network to achieve energy efficiency, stability and scalability. It is divided into chain-based and cluster-based, where nodes are organized into chains or several clusters [6]. In the chain-based approach, sensor nodes are interconnected to form a chain, and every chain is assigned a chain leader that is responsible for transmitting the fused data to the sink node. It increases the network lifetime by transmitting data uniformly all over the sensor nodes [7]. In the cluster-based, sensor nodes are organized into clusters with a cluster head (CH) responsible for data collection, aggregation and transmission, which helps to minimize energy consumption by reducing the message load received by the base station (BS) [8]. Numerous studies have presented different routing protocols intended to reduce energy consumption in wireless sensor networks, and hierarchical routing protocols have proven to be advantageous due to their scalability and resilience to overload. Recent studies such as Patel and Ramesh [9] continue to emphasize the importance of comparative clustering evaluations to optimize energy and latency

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in next-generation WSN deployments [9]. Clustering is a useful technique for improving scalability, lifetime and energy efficiency of WSN. Each cluster is overseen by a specific CH selected from the nodes through specified methods to maximize network lifetime and throughput. CHs manage intra-cluster communication, with non-CH nodes transmitting data to their respective CHs [10]. By grouping the sensor nodes into clusters each headed by a CH, data from member nodes are collected and sent to the base station by the CH. This reduces the number of direct transmissions from individual nodes to the base station, and helps to prolong the lifetime of the network and conserve a significant amount of energy [11]. The efficient utilization and management of energy resources in WSNs is critical for extending network lifetime and ensuring effective data transmission. Clustering techniques have proved to be a suitable solution in addressing energy efficiency challenges in WSNs [12]. Some recent works on clustering techniques were reviewed so as to discuss their applications and limitations in WSNs, and also compared the clustering algorithms using different metrics such as energy, network lifetime, throughput and scalability, throughput and so on. This review provides a comprehensive understanding of the strengths and weaknesses of these protocols and will guide this work findings in this domain.

A comparative analysis of EAMMH and LEACH clustering algorithms was performed using metrics such as network lifetime, packet delivery ratio and energy consumption. Results from the simulation indicated that EAMMH has better energy efficiency and maximizes network lifetime compared to LEACH, making it a better alternative for WSN applications that require efficient energy utilization and extended network lifetime [13].

A comparative analysis of LEACH and HEED algorithms in WSNs was conducted. Simulation results show that HEED outperforms LEACH energy efficiency, average end-to-end delay reduction, average throughput enhancement and packet delivery ratio improvement. HEED’s superior performance is attributed to its efficient cluster head selection process [14].

PEGASIS and LEACH hierarchical routing protocols in WSNs was compared and evaluated based on different metrics such as energy consumption, throughput and network lifetime. The simulation results showed that PEGASIS outperforms LEACH in terms of network lifetime and energy efficiency, which makes it more suitable for applications that require long-term deployment. However, PEGASIS shows high latency due to long-distance communication and is suitable for delay-tolerant applications [15].

WSNs find ubiquitous applications in many fields, but they are afflicted with formidable challenges like scarce energy resources, scalability problems, high latency, and a limited lifetime. Though many clustering algorithms have been suggested to mitigate these challenges, no comparative studies have been conducted so far that judge the performance of these algorithms concerning various crucial parameters systematically. Current research tends to concentrate on either individual algorithms or narrow performance measures, thus resulting in gaps in the knowledge of comparative effectiveness of these algorithms in practical scenarios.

However, while many studies have explored these protocols individually or in pairs, few have conducted a comprehensive, simulation-based evaluation of multiple hierarchical clustering protocols under varied network conditions. The existing literature rarely addresses the trade-offs between energy consumption, latency, scalability, throughput, and network lifetime in a single study. Moreover, many studies focus on theoretical analysis, without incorporating simulation techniques that reflect practical deployment scenarios. Recent studies such as Patel and Ramesh [9] continue to emphasize the importance of comparative clustering evaluations to optimize energy and latency in next-generation WSN deployments.

This study addresses those gaps by:

i. Conducting an extensive MATLAB-based simulation to compare LEACH, PEGASIS, HEED, and EAMMH protocols under varying network sizes.
ii. Evaluating five critical performance metrics: energy consumption, network lifetime, latency, throughput, and scalability.

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iii. Highlighting application-specific trade-offs that inform real-world protocol selection.

By simulating different node densities ranging from 50 to 250, this research contributes a practical framework for protocol evaluation, helping network designers choose the most appropriate routing mechanism for their specific WSN applications.

2. METHODS

This paper adopts a simulation-based experimental approach using MATLAB. The approach was chosen due to its effectiveness in the modelling and analysis of complex systems like wireless sensor networks, without the need for physical deployment. The use of simulations give room for controlled manipulation of variables and parameters, as well as correct measurement of results.

2.1. Network Model

The network model for the simulations is based on a typical wireless sensor network that comprises a set number of sensor nodes with a random topology, where sensor nodes are randomly deployed in a predefined area. The network consists of a BS and a number of SNs that interact with each other. The random topology simulates a realistic WSN deployment scenario, where sensor nodes are scattered arbitrarily across the area of interest. Random topologies for 50, 100, 150, 200 and 250 nodes network sizes will be created to assess energy consumption, lifetime, latency, throughput and scalability of the clustering algorithms.

The network sizes selected, ranging from 50 to 250 nodes are consistent with prior simulation studies evaluating clustering protocols in WSNs [22][23]. These ranges allow assessment of algorithm performance across small to large-scale networks, as also adopted by Younis and Fahmy [18] and Alı-Gburyı et al. [14].

2.2 Hierarchical Routing Algorithms under Study

There are several types of WSN algorithms as proposed in different literatures. Among these are the four algorithms under study in this project work. These include; LEACH, EAMMH, PEGASIS and HEED. Each of these algorithms has its own strengths and weaknesses, as explained below.

2.2.1 Low-Energy Adaptive Clustering Hierarchy (LEACH)

LEACH is a hierarchical routing algorithm that utilizes randomized rotation of local cluster heads to evenly distribute energy consumption among nodes. It is the most popular and the most used clustering algorithm for WSN that exploits randomized rotation of local CH for energy distribution between the network sensors. The process of LEACH is split into rounds, where in each round there are two phases: set-up phase and steady-state. In each round, the nodes choose themselves as CHs with a certain probability and send their status. This allows non-cluster head nodes to choose the nearest cluster head CH to join [16].

2.2.2 Power Efficient Gathering Information System (PEGASIS) Protocol

PEGASIS is the remotest preferred chain-based hierarchical protocol. In this protocol, the nodes are organized in the form of a chain for the transition and gathering of the data establishment of chain can be centralized based on the application. The formation of chain starts from the endmost node from sink and its immediate neighbor are elected as next node in chain and so on. The node before sink acts as a leader of the node and the last node must be the sink. The operation like data-processing and data aggregation are adopted by leader node. The aggregated data moves from node to node, it get combined, and thereafter a cluster head transmits these aggregate data to the base station [17].

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2.2.3 Hybrid Energy-Efficient Distributed Clustering (HEED)

The hybrid energy-efficient distributed (HEED) technique is also an important clustering protocol used in WSN. The parameters utilized by the sensor node to pick CH are remaining energy and cost for intra-cluster communication. The basic goal of the HEED algorithm is to ensure that all CHs inside the system are circulated consistently. This saves more energy and is more scalable. The Hybrid Energy-Efficient Distributed Algorithm often selects excess CH, which is a drawback. As CHs use extra energy, the energy of the network decreases [18].

2.2.4 Energy Aware Multi-Hop Multi-Path Hierarchical (EAMMH) Routing Protocol

The EAMMH clustering protocol was created by combining the capabilities of energy aware routing with multi-hop intra cluster routing. The EAMMH protocol operates in rounds, with each round beginning with a set-up phase in which the clusters are organized, followed by a steady-state phase in which data is sent to the base station. Following node deployment, neighbor detection occurs during the setup phase. The setup phase runs in the cluster head CH selection and cluster formation. In the data transmission phase, the sensor nodes are allotted timeslots to send the data once the clusters are created. Assuming nodes always have data to send, they transmit it at their allotted time interval. When a node receives data from one its neighbors, it aggregates it with its own data. While forwarding the aggregated data, it has to choose an optimal path from its routing table entries [19].

2.3 Energy Consumption Models

Energy consumption models are tools used to estimate the environmental impact of wireless sensor networks. This section covers energy dissipation during communication and computation of data. A typical sensor node consists mainly of a sensing circuit for signal conditioning and conversion, digital signal processor, and radio links. The following summarizes the energy-consumption models for each sensor component.

2.3.1 Communication Energy Dessipation

The main energy parameters for communication in WSN are; the energy/bit consumed by the transmitter electronics, energy dissipated in the transmitter amplifier, and energy/bit consumed by the receiver electronics. When sending a packet, the energy consumption is proportional to the distance between the sender and receiver, but the reception energy is expressed per packet received. The energy model used in this paper is based on the widely accepted first-order radio model introduced by Heinzelman et al. [16], and later adapted in various clustering protocol evaluations [24][25]. Equations (1) – (6) are derived from this foundational model, capturing transmission, reception, and data aggregation energy costs. The transmission and reception energy are mathematically modeled as [20]:

$$E_{tx}\left(b,d\right)=E_{elec}\times b+\varepsilon_{amp}\times b\times d^2 \tag{1}$$

$$E_{rx}\left(b\right)=E_{elec}\times b \tag{2}$$

Where $E_{tx}\left(b,d\right)$ is the transmission energy, $E_{rx}\left(b\right)$ is the reception energy, E_{elec} is the energy consumed by the transmitter electronics per bit, ε_{amp} is the energy consumed by the transmitter amplifier per bit per square meter, b is the number of bits in the packet, and d is the distance between the sender and receiver.

Assuming there are n number of nodes uniformly distributed in a specific area and C number of clusters that can be formed in the given area, the average number of nodes that might be distributed in a particular cluster is n/C.

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The CH dissipates its energy when receiving signals from $(n/C-1)$ nodes, aggregating sensed data by itself and other nodes in the same cluster, and also when transmitting the aggregated data to the sink. The dissipated energy by CH and non-CH nodes are given as [20]:

$$E_{CH} = \left(\frac{n}{C}-1\right)\times E_{rx} + \frac{n}{C}\times b\times E_{da} + E_{tx} \tag{3}$$

$$E_{non-CH} = b\times E_{elec} + b\times \varepsilon_{fs}\times d^2{}_{toCH} \tag{4}$$

Where E_{da} is the energy dissipated to aggregate data by CH, ε_{fs} is the Friss free space loss and d_{toCH} is the distance of the non-CH node to the CH.

Each non-CH node needs to transmit its sensed data to the elected CH node. The energy dissipated in every cluster per round is equal to [21]:

$$E_{cluster} \approx E_{CH} + \frac{n}{C}\times E_{non-CH} \tag{5}$$

The energy dissipated in the entire network for packet transmission and reception is:

$$E = b\left(2n.E_{elec} + n.E_{da} + \varepsilon_{fs}\left(C.d^2{}_{toMS} + d^2{}_{toCH}\right)\right) \tag{6}$$

2.3.2 Computation Energy Dessipation

The energy required for data computation or processing $\left(E_{proc}\right)$ is also important, and includes the computational energy used for executing the clustering algorithms on the sensor nodes. This energy is usually directly proportional to the complexity of the clustering algorithm and the amount of data that requires processing.

2.4 Performance Metrics

The performance of the clustering algorithms was evaluated using the following performance metrics mentioned below. The metrics were briefly explained and their mathematical models were also highlighted for better understanding of the project work. Latency, throughput, and scalability metrics are modeled similarly to prior works such as [25] and [26], where latency is computed as average end-to-end delay, and throughput as total successfully delivered data per unit time.

2.4.1 Energy Consumption

The energy consumption is the total energy consumed by the network over the simulation period. The goal of clustering is to minimize energy consumption and extend the network's operational lifetime. The mathematical model of this metric is given as:

$$E_{Total} = E + \sum_{i=1}^{n} E_{proc}(i) \tag{7}$$

Where E is given in Equation (6), $E_{proc}(i)$ is the computation energy dissipation of node i and n is total number of nodes in the WSN.

2.4.2 Network Lifetime

Network lifetime can be defined as the time until the first node depletes its energy (the time when the first node dies) or the time until a significant portion of the network becomes non-functional (for example, the time when 50% of nodes die) or the time until all the nodes in the WSN deplete their energy. The network lifetime consider in this paper is the time taken for all the nodes in the network to deplete their energy.

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2.4.3 Latency

Latency refers to the end-to-end delay in data transmission from sensor nodes to the base station. It is the average amount of time between the start of disseminating a data and its arrival at a node interested in receiving the data and is given as:

$$D_{avg} = \frac{1}{K}\sum_{k=1}^{K} D_k \tag{8}$$

Where D_k is the delay of the k^{th} packet and K is the total number of the transmitted packets.

2.4.4 Scalability

Scalability refers to the algorithm's ability to handle an increasing number of nodes without a significant drop in performance. This metric assesses how well the clustering algorithms performs as the size of the network increases. It is measured by observing the changes in energy consumption and network lifetime with increasing number of nodes.

2.4.5 Throughput

Throughput refers to the total amount of data successfully transmitted to the base station or sink, within the network's lifetime. The mathematical model of throughput is given as:

$$Th = \frac{\sum_{k=1}^{K} P_k}{T} \tag{9}$$

Where P_k is the size of the k^{th} packet and T is the total simulation time.

2.5 Simulation Scheme

The simulation was implemented in MATLAB R2021a environment. The following outlines the key steps taken in achieving the results:

i. **Initialization:** Define WSN area, node energy, BS location, and number of rounds.
ii. **Deployment:** Randomly scatter nodes across the area using a uniform distribution.
iii. **Protocol Execution:** For each protocol (LEACH, HEED, PEGASIS, EAMMH), simulate cluster formation, data transmission, and energy depletion over multiple rounds.
iv. **Metric Calculation:** For each round, compute energy consumed, number of alive nodes, data packets delivered, and delay experienced.

The simulation was repeated for node sizes: 50, 100, 150, 200, and 250. Each experiment was averaged over 10 runs to minimize randomness. Simulation-based validation using tools like MATLAB remains widely adopted for WSN analysis, as confirmed by Zhang et al. [26].

The simulation for evaluating the performance of the four hierarchical routing protocols: LEACH, PEGASIS, HEED, and EAMMH was conducted using MATLAB. To evaluate the clustering behavior and scalability of each protocol, the number of clusters formed during simulation was recorded for each network size (50–250 nodes). For LEACH, HEED, and EAMMH, the number of cluster heads (CHs) selected per round was tracked, while PEGASIS was treated as a single-chain structure forming one cluster. For each network size, the simulation was run across 1000 rounds, and the average number of clusters was computed. The following pseudocode describes the process:

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A. During each simulation round:

```
num_clusters(round_num) = length(cluster_heads);  % For LEACH, HEED, EAMMH
num_clusters(round_num) = 1;  % For PEGASIS
```

B. After all rounds for each node size:

```
avg_clusters(i) = mean(num_clusters);  % i = index for each node size
```

C. Store results per protocol:

```
LEACH_clusters(i) = avg_clusters(i); % repeat per protocol
```

D. Plot cluster trends vs. node count:

```
node_sizes = [50 100 150 200 250];
plot(node_sizes, LEACH_clusters, '-o', ...); % continue with styled plotting
```

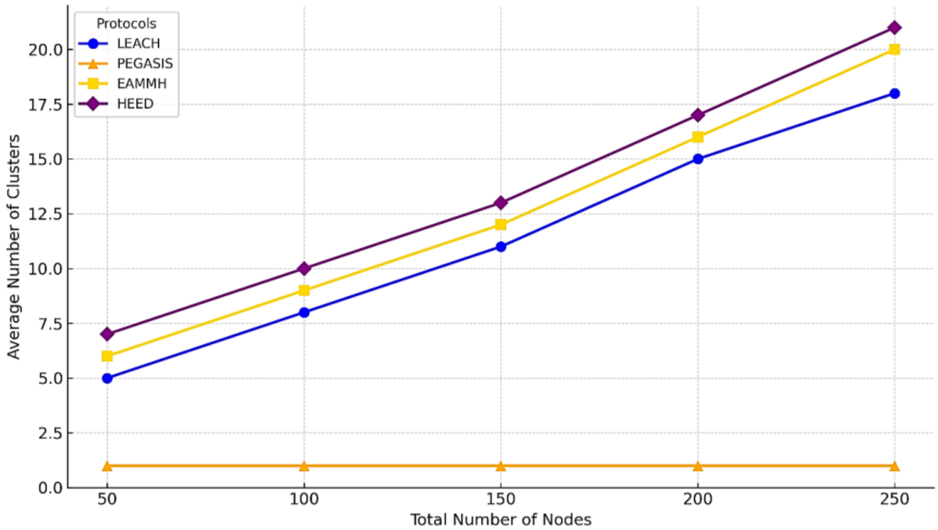

Figure 1. Number of Clusters vs. Total Node Count

This procedure produced the "Number of Clusters vs. Total Node Count" plot shown in Figure 1, which highlights the clustering scalability and organizational structure of each routing protocol under increasing node densities.

3. RESULTS AND DISCUSSION

The simulation results were obtained after running the codes in MATLAB simulator for the four aforementioned clustering algorithms; LEACH, PEGASIS, HEED, and EAMMH. The results are presented in the following tables and plots of these algorithms are shown as well. The simulation parameters used are given in Table 1. The simulation area of 100m × 100m was selected as it reflects a standard scale frequently used in WSN performance evaluations [16][27]. This size offers a realistic balance between node density and communication range, especially for low-power sensor nodes with typical transmission capabilities of 20–50 meters. Furthermore, many benchmark studies evaluating LEACH, HEED, and PEGASIS protocols adopt a similar area to enable consistent comparison across routing strategies [16][18][27].

The process flow for each protocol is presented below in pseudocode format:

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Hierarchical Protocol Simulation In MATLAB

```
Begin Simulation

Input:
    Network_Area ← 100m x 100m
    Node_Count ← [50, 100, 150, 200, 250]
    Initial_Energy ← 0.5 Joules
    Simulation_Time ← 1000 rounds
    BS_Location ← Center of area
    Protocols ← [LEACH, PEGASIS, HEED, EAMMH]

For each node_count in Node_Count:
    Deploy node_count sensor nodes randomly within Network_Area
    Initialize energy for each node to Initial_Energy

    For each protocol in Protocols:
        Set protocol-specific parameters

        For round = 1 to Simulation_Time:
            Select Cluster Heads or Chains according to protocol rules
            Form Clusters or Chains

            For each node:
                If node is alive:
                    Transmit data to CH or next node
                    Update residual energy after transmission

            For each CH or leader:
                Aggregate data
                Transmit aggregated data to Base Station
                Update residual energy after aggregation and transmission

            Record metrics:
                Total_Energy_Consumed
                Network_Lifetime (based on alive nodes)
                Latency (average time to BS)
                Throughput (bits successfully sent)
                Scalability (nodes per cluster or chain)

        Average results over multiple simulation runs
        Store results for plotting

Plot graphs:
    Energy vs Node_Count
    Lifetime vs Node_Count
    Throughput vs Node_Count
    Latency vs Node_Count
    Scalability vs Node_Count

End Simulation
```

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Table 1. Simulation Parameters

Parameter	Value
E_{elec}	$5\,nJ/bit$
ε_{amp}	$100\times10^{-12}\,J/bit$
E_{da}	$5\,nJ/bit$
Area of WSN	$100m\times100m$
Initial Energy	$0.5J$
Transmission Range	$50m$
Simulation Time	$1000s$
ε_{fs}	$100\,pJ/bits/m^2$

Note: A 100m × 100m area is commonly adopted in WSN simulations to balance transmission range with node density.

3.1 Energy Consumption

The total energy consumption of the wireless sensor network was determined for each algorithm. This measure refers to the instantaneous amount of energy exhausted, i.e., the energy difference from the beginning of the round until its end. A uniform initial energy of 0.5 Joules was used during the simulation and the number of nodes has been increased from 50, 100, 150, 200 to 25. The results for energy consumption are summarized in the Figure 1.

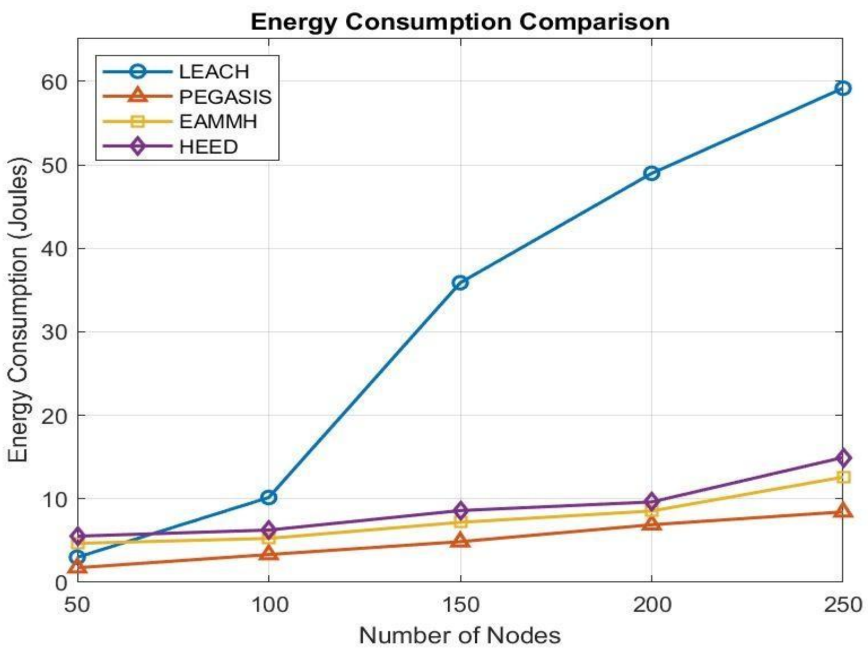

Figure 2. Comparison of Energy Consumption

From Figure 2, LEACH exhibits a steep increase in energy consumption as the number of nodes grows. This is primarily due to its random cluster head (CH) selection mechanism, which does not consider node density or residual energy. As the network scales, more CHs are selected sub-optimally, resulting in inefficient clustering and longer communication distances.

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Moreover, LEACH relies on single-hop transmission from CHs to the base station (BS), which becomes increasingly energy-intensive in larger networks. These factors collectively lead to its significantly higher energy usage at higher node counts. HEED shows a consistent and low energy consumption across all node densities compared to LEACH, from 5.5308 Joules at 50 nodes to 14.9611 Joules at 250 nodes. EAMMH has an energy consumption that increases at a moderate rate compared to LEACH and shows a consistent increase slightly below HEED as the number of nodes increase. Its energy consumption is 4.6686 at 50 nodes but stabilizes to 12.6083 at 250 nodes. PEGASIS shows the lowest energy consumption among all the algorithms, showing a gradual increase as the number of nodes increases. Even at 250 nodes, the energy consumption is significantly lower compared to LEACH, EAMMH and HEED.

3.2 Network Lifetime

The network lifetime of the four clustering algorithms is computed at 50, 100, 150, 200 and 250 nodes, showing the duration of time for which, the network remains operational as a certain percentage of nodes die due to energy depletion. The simulation results of the network lifetime for LEACH, EAMMH, PEGASIS and HEED are presented in Figure 2.

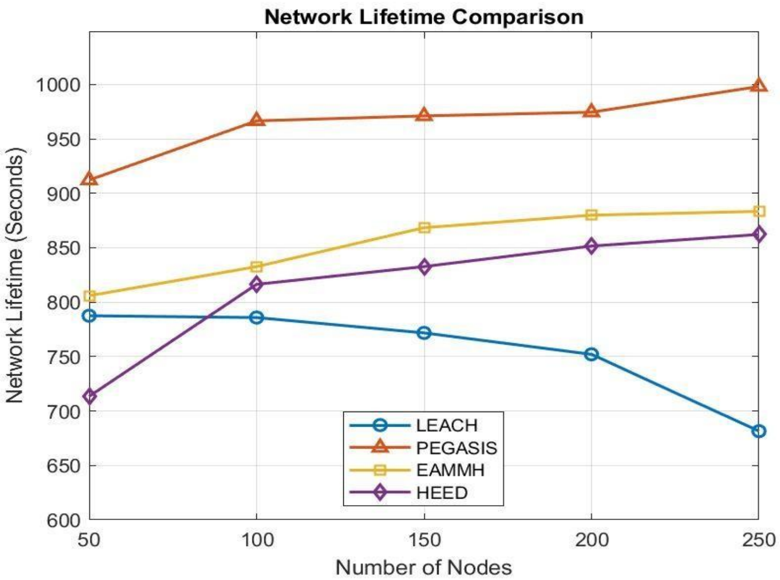

Figure 3. Comparison of Network Lifetime

From Figure 3 above, LEACH shows a decreasing network lifetime as the number of nodes increases, starting with around 800 seconds at 50 nodes and continuously decreasing up to 250 nodes. HEED maintains a relatively high and stable network lifetime ranging from 713.46 to 862.15 seconds across all the node counts. EAMMH shows a better and increasing trend in network lifetime, starting with 805.88 seconds at 50 nodes and grows continuously to 883.35 seconds at 250 nodes. PEGASIS provides the highest lifetime across all node counts, ranging from above 900 seconds at 50 nodes to almost 1000 seconds at 250 nodes.

PEGASIS achieves the longest network lifetime due to its chain-based structure, which minimizes the number of transmissions per node and balances energy usage more evenly. EAMMH also maintains a strong lifetime by combining energy-aware CH selection with multi-hop paths that reduce long-range transmissions. HEED uses residual energy in CH selection but can occasionally create unbalanced clusters, leading to faster node drain in high-density scenarios. LEACH suffers the most due to random CH selection and long-distance single-hop transmissions, which lead to early node failures as network size increases.

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3.3 Throughput

The throughput (in bits per second) of the four algorithms is compared as the number of nodes increases from 50, 100, 150, 200 up to 250 nodes, calculating the rate at which data is successfully transmitted from the sensor nodes to the base station or sink. Figure 3 presents the simulation results of the four clustering algorithms.

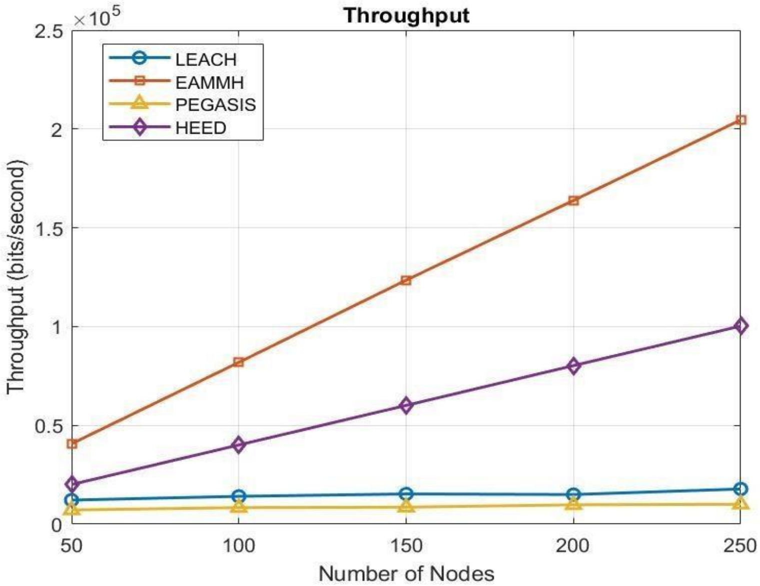

Figure 4. Comparison of Throughput

From Figure 4, EAMMH exhibits the highest throughput among the four clustering algorithms with a steady rise particularly beyond 100 nodes and reaches a greater value at 250 nodes. HEED shows a steady increase in throughput with increase in network size, being lower than EAMMH but higher than LEACH and PEGASIS. LEACH shows a relatively constant throughput with a small rise as the number of nodes rises, being lower than EAMMH and HEED, but higher than PEGASIS. PEGASIS shows the lowest throughput, with a slight increase among all the protocols.

EAMMH demonstrates the highest throughput because it utilizes multi-hop intra-cluster routing and data aggregation, allowing efficient high-volume data transmission. HEED, with more structured CH selection and balanced clusters, also supports good throughput. LEACH maintains moderate throughput but is hampered by its simplistic clustering, which leads to congestion in poorly balanced networks. PEGASIS has the lowest throughput due to its sequential chain-based structure, which introduces delay and potential packet loss if a node fails.

3.4 Scalability

The scalability of LEACH, EAMMH, PEGASIS and HEED clustering algorithms is calculated for different network sizes. This performance metric shows how well the algorithms adapt to increasing number of nodes. A highly scalable algorithm is expected to efficiently handle a more nodes per cluster without a major decrease in the wireless sensor network's performance.

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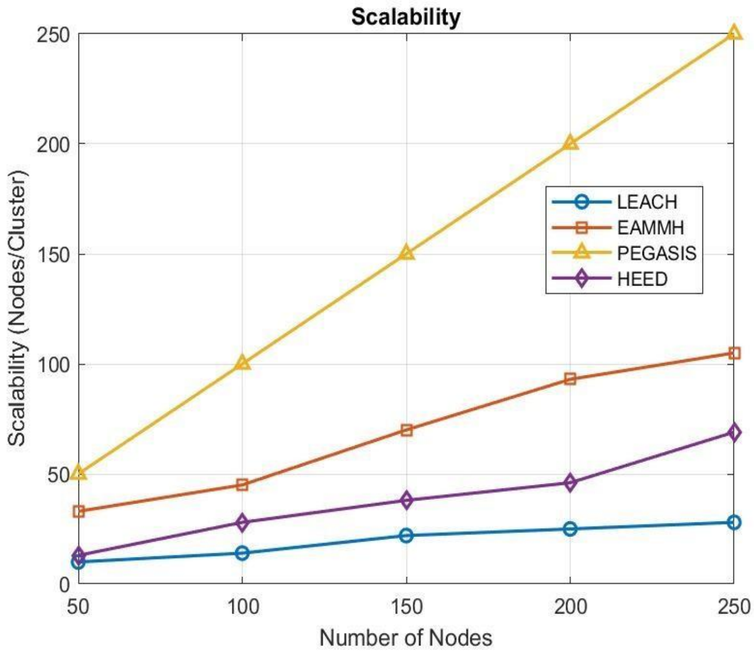

Figure 5. Comparison of Scalability

Figure 5 shows the simulation results for scalability, obtained from MATLAB simulator. PEGASIS shows the best scalability among all the four clustering algorithms, with a steep and linear increase in the number of nodes per cluster as the network size grows. It starts with 50 nodes per cluster and reaches 250 nodes per cluster, as the network size increases from 50 up to 250 nodes. EAMMH comes second in terms of scalability, having a moderate scalability that gradually increase in the number of nodes per cluster. It starts with 33 nodes per cluster at 50 nodes reaching up to 105 nodes per cluster at 250 nodes. HEED shows a moderate scalability, maintaining a relatively flat pattern with a slight increase as the number of nodes grow from 50 to 250. The algorithm with the lowest scalability is LEACH, with a range of 10 to 28 nodes per cluster.

PEGASIS scales efficiently because its chain structure inherently supports linear growth, each node only communicates with immediate neighbors regardless of network size. EAMMH, through its multi-hop and energy-aware routing, adapts well as node count increases. HEED shows limited scalability since its CH selection becomes inefficient in denser networks due to overhead. LEACH's scalability is the poorest, as it lacks a mechanism to control cluster size or optimize CH placement when node density increases.

Furthermore, to evaluate the scalability and clustering behavior of the protocols, Figure 1 presents the number of clusters (or nodes per chain) in PEGASIS, formed by each protocol as the total number of sensor nodes increases. LEACH forms clusters based on a probabilistic threshold, leading to a relatively low and inconsistent number of clusters, which explains its poor scalability. HEED maintains a moderate number of evenly distributed clusters, benefiting from its energy-and-communication cost-based CH selection. EAMMH increases cluster numbers proportionally as node density grows, balancing load and preserving energy efficiency. PEGASIS, being chain-based, typically forms a single linear chain, hence resulting in just one cluster regardless of the node count, showcasing its linear scalability but also explaining its higher latency.

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3.5 Latency

The latency is also calculated for the four clustering algorithms as the network size grows from 50, 100, 150, 200 to 250 nodes. This shows the delay or time taken for data to be transmitted from sensor nodes to the base station. Lower latency is generally preferred as it implies quicker data transmission. Figure 3.5 shows the simulation results obtained for latency performance metric.

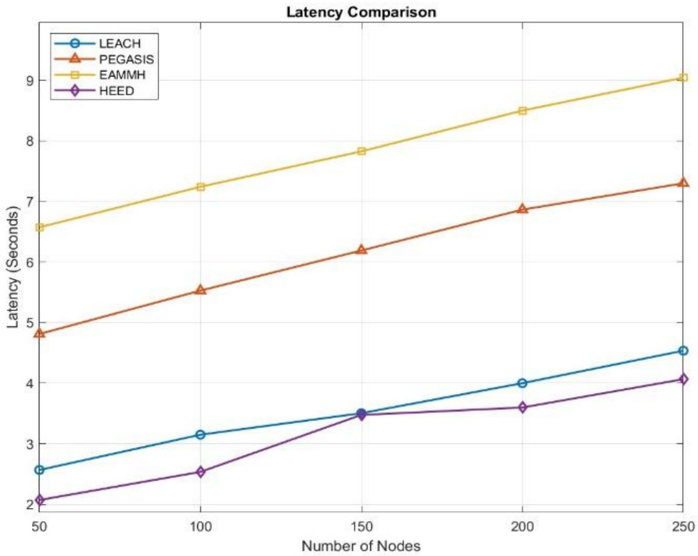

Figure 5. Comparison of Latency

Figure 5 above presents the simulation results obtained from MATLAB simulator. EAMMH displays the highest latency among the four algorithms, with latency at around 7 seconds at 50 nodes and increasing to almost 10 seconds for 250 nodes. PEGASIS shows a relatively steady increase in latency that is lower compared to EAMMH, starting at 4.812 seconds and reaching up to 7.300 seconds at 250 nodes. This pattern aligns with Ibraheem and Chinedu [29], who observed that while PEGASIS conserves energy well, its latency rises in dense deployments due to long chain structures [29]. LEACH has a latency range of 2.567 seconds to 4.536 seconds between 50 to 250 nodes. HEED algorithm shows the best latency performance, starting from around 2 seconds at 50 nodes and reaching up to over 4 seconds at 250 nodes.

HEED achieves the lowest latency because it maintains well-distributed CHs and uses efficient intra-cluster communication, reducing transmission delays. LEACH also offers low latency in small networks due to simple CH selection and direct transmission. EAMMH has the highest latency since it uses multi-hop routes with several relays, increasing overall transmission time. PEGASIS introduces delay as data must travel node-to-node through a chain, making it unsuitable for time-sensitive applications.

3.6 Comparative Analysis of the Four Protocols

The performance of these algorithms varies depending on number of nodes in terms of energy efficiency, latency, network lifetime, throughput and scalability. The key findings are summarized as follows.

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i. Energy Consumption: LEACH has the highest energy consumption, making it suitable for small-scale networks. HEED exhibits a moderate and stable energy consumption, making it more suitable for medium-scale networks. EAMMH and PEGASIS show better energy efficiency especially in large-scale networks.
ii. Network Lifetime: LEACH has the shortest network lifetime, especially in larger networks. HEED ensures a moderate and consistent network lifetime across all network sizes. EAMMH extends network lifetime more efficiently than LEACH and HEED, especially in larger networks. PEGASIS provides the longest network lifetime, making it ideal for large-scale networks.
iii. Throughput: EAMMH has the highest throughput, making it suitable high data transmission. HEED shows good throughput that increases steadily with network size. LEACH has low but stable throughput. PEGASIS offer the lowest throughput due to delays in chain-based communication.
iv. Scalability: PEGASIS is the most scalable, handling large node counts effectively. EAMMH also exhibits good scalability for larger networks. HEED is suited for small to medium-sized networks. LEACH has poor scalability, making it more suitable for smaller networks.
v. Latency: HEED has the lowest latency, making it ideal for real-time applications. LEACH also offers low latency for small networks. PEGASIS has higher latency due to its chain-based model. EAMMH has the highest latency making it less suitable for real-time applications.

This evaluation reveals that the selection of an appropriate clustering algorithm depends heavily on the specific requirements of the WSN application, whether it prioritize energy efficiency, fast data delivery, longer lifetime or the ability to handle large number of nodes.

3.6.1 Critical Observations for Each Protocol

i. LEACH performs adequately at 50-node scale, but energy consumption spikes rapidly beyond 150 nodes due to its random CH selection and single-hop communication. This makes it unsuitable for dense or large-scale deployments.
ii. EAMMH provides highest throughput, especially noticeable beyond 100 nodes, but suffers from exponential latency increases past 200 nodes due to multi-hop congestion.
iii. PEGASIS is most energy efficient and scales linearly, but latency sharply increases beyond 150 nodes, making it unsuitable for time-critical applications.
iv. HEED maintains low latency and moderate energy use, but its scalability levels off at higher densities. It also tends to over-select CHs, leading to excess energy use in denser networks.

These critical conditions suggest that each protocol operates within a *performance envelope* and breaks down when pushed beyond it. Application-specific considerations such as real-time requirements or large-area coverage must guide protocol selection accordingly.

4. CONCLUSION

Wireless Sensor Networks (WSNs) are vital across many application domains, yet remain constrained by energy limitations, latency requirements, and scalability demands. In this study, we evaluated four widely used hierarchical clustering protocols: LEACH, PEGASIS, HEED, and EAMMH through MATLAB-based simulations across varying node densities (50 to 250 nodes).

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The results highlight distinct strengths and limitations:

i. PEGASIS exhibited the lowest energy consumption across all node densities, consuming only 7.3 Joules at 250 nodes compared to 14.9 Joules in HEED and >20 Joules in LEACH. It also achieved the longest network lifetime, approaching 1000 seconds at maximum density, but showed higher latency (up to 7.3 seconds) making it more suitable for delay-tolerant applications.
ii. HEED consistently offered the lowest latency, starting from ~2 seconds at 50 nodes to just over 4 seconds at 250 nodes. It also maintained moderate energy use and stable throughput, making it ideal for real-time applications in medium-sized networks.
iii. EAMMH achieved the highest throughput, especially in larger networks (up to 0.9 Mbps at 250 nodes), but incurred the highest latency (up to 10 seconds) and moderate energy consumption.
iv. LEACH, while simple and easy to implement, recorded the highest energy consumption and the shortest network lifetime, especially beyond 150 nodes, due to its inefficient CH selection.

These findings underscore that no single protocol dominates across all performance metrics. The choice of protocol must be tailored to application-specific needs: PEGASIS for long-term monitoring, HEED for real-time systems, EAMMH for data-intensive applications, and LEACH for simplicity in small-scale networks.

While this study provides meaningful insights through MATLAB-based simulations, it remains limited to idealized conditions and fixed network assumptions. In real-world WSN deployments, environmental factors such as interference, physical obstacles, node mobility, and unpredictable signal attenuation can significantly impact performance. Future research should incorporate more advanced models that simulate such environmental disturbances or validate clustering algorithms in physical testbeds. Additionally, hybrid approaches that dynamically switch between protocols based on network conditions, or use AI-driven CH selection strategies, could offer more resilient and adaptive solutions. These directions will help bridge the gap between theoretical efficiency and practical reliability in Wireless Sensor Network design.

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