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Achieving Energy Efficiency through Maximum Energy LEACH and PEGASIS Methods in WSN with Node Mobility

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Abstract

Objective: The study explores two well-known energy-efficient routing algorithms, LEACH (Low Energy Adaptive Clustering Hierarchy) and PEGASIS (Power-Efficient Gathering in Sensor Information Systems), in the context of wireless sensor networks (WSNs) with mobile in terms of energy utilisation, network longevity, and communication efficiency when people are moving around in the real world. **Methods:** We use the similar simulation framework for both LEACH and PEGASIS in First-Order Radio Energy Model to create a wireless sensor network (WSN) with 100 mobile sensor nodes randomly placed in a 100m by 100m field. We used the Random Waypoint concept to make things move. We checked how well it performed by looking at factors like how much energy was left over after each round, how fast nodes died, and how many packets were transmitted to the base station. **Results:** PEGASIS used less energy and lasted longer than other networks since it had a chain-based design and sent data every cycle. This was especially true for networks with nodes that were equally distributed and not very mobile. But it had a more sophisticated algorithm and fewer rounds of communication. LEACH was easier to operate and could be utilised on a bigger scale, but it used more energy because the cluster heads spun more often and the distances between transmissions were longer. In general, PEGASIS was more stable when there wasn't a lot of energy, but LEACH worked better when the topologies varied over time. **Novelty:** This study looks at LEACH and PEGASIS side by side in a simulation and analysis, utilising the identical parameters for node mobility and deployment. It demonstrates the pros and cons of being able to grow and save energy. One key new notion is that a hybrid technique that combines the clustering efficiency of LEACH with the energy-saving chain mechanism of PEGASIS could make WSN routing protocols for mobile contexts stronger and more scalable.

Keywords: Energy-constrained Sensor networks; Greedy Method; LEACH; Node Mobility; PEGASIS; WSN

1 Introduction

Energy-constrained sensor nodes found in wireless sensor networks (WSNs) sense and broadcast environmental data. Among many uses, including military surveillance, environmental sensing, and industrial automation, real-time monitoring and data collecting among several depends mostly on these networks. The limited energy supply in sensor nodes, mostly battery-powered and usually found in inaccessible areas, is one of the main difficulties in WSNs. This limit drives the evolution of energy-efficient communication and routing techniques assuring network lifetime without compromising data integrity or timeliness [(1)], [(2)].

Mobility in WSNs adds even more complexity since the dynamic placements of nodes results into frequent topological changes and it may create interference in communication channels leading to more complexity in network which further require more robust algorithm to handle these conditions. Mobile environments require adaptivity which able to control intermittent connectivity and changing network quality. A challenging development of standard WSNs, MWSNs shows sensor nodes mobility either from environmental dynamics or deployment design. LEACH-M was designed to offer TDMA slot verification and re-association systems allowing mobile nodes to dynamically link with cluster leaders [(3)].

Fault tolerance is another crucial factor need to be achieved which requires or controls, hardware problems, or energy depletion check. Strong WSN guarantees continuous performance even in cases of such breakdowns. Another problem is overhead communication in high-density networks as a special case where collision and interference might affect performance necessitating increase in routing complexity aggravates in mobile environments were dynamic topology adjustments need for flexible and effective routing solutions [(4)].

Existing methods related to this problem are continuously optimized in the past decade but still they face the problem of rapid network disintegration despite the energy saving scheme these have devised. To address this problem, new methods such as PEGASIS is analyzed along with LEACH to find the possibility of some technique to merge these two algorithms. Here, we compare these algorithms to show their respective strength. In future some hybrid technique may be proposed.

This work aims to simulate energy-efficient routing using LEACH and PEGASIS algorithms; perform a comparative analysis under mobile scenarios; and evaluate the impact of mobility on protocol efficiency using empirical metrics including energy consumption, packet delivery, and node death rates.

In the past decade, several improvements have been suggested in LEACH based routing algorithms [(5)]: LEACH-C, which centralizes CH selection to promote energy balance, and V-LEACH, which adds a backup CH to guarantee continuous operation should the main CH fail [(6)], [(7)]. Conversely, PEGASIS (Power-Efficient Gathering in Sensor Information Systems) uses a chain-based technique whereby every node distributes data along a chain to a designated leader node, transmitting to the base station, solely with regard to its nearest neighbor. Although this method greatly lowers long-distance transmissions, serial data aggregation could cause delays [(8)]. By allowing multi-hop and parallel data transmission, hierarchical PEGASIS and MH-PEGASIS improve delay performance [(9)] thereby addressing some of these issues.

Recent work has concentrated on enhancing LEACH and PEGASIS under mobility: Singh et al. presented an improved LEACH with energy-based CH rotation to balance energy utilization [(1)]. Residual energy and distance were introduced by Saini and Sharma as an adaptive LEACH (A-LEACH) to BS [(2)]. Li et al. improved LEACH [(10)] by developing a cluster head selection approach based on fuzzy logic. Kim et al. presented LEACH-M, mobility-aware [(3)]. For applications with delay sensitivity, Zaman and Riaz suggested a hybrid LEACH-PEGASIS system [(4)]. Ahmed et al. used a PEGASIS system grounded on reinforcement learning [(5)]. Kuila and Jana investigated patterns of node mobility on cluster performance [(6)].

Xiao et al. presented a scalable multi-hop LEACH method [(7)]. Park et al. developed dynamic PEGASIS [(8)] energy-efficient chain-based data collecting method. To increase data distribution, Das and Roy created mobility prediction-based clustering [(9)]. Alharbi et al. optimized LEACH clustering [(11)] by means of evolutionary algorithms Lin et al. improved PEGASIS [(12)] for diverse WSNs Ghasemi et al. assessed routing under high node mobility [(13)]. Developing a context-aware hierarchical routing system [(14)], Misra et al. Singh et al. put forth a dual-hop PEGASIS to lower end-to- end delay [(15)].

Sambhe et al. [(16)] came up with a routing approach based on LEACH that is better because of the Harmony Search Algorithm (HSA). This makes it easy to pick the best cluster head. Their plan spread the energy more evenly and made the network last longer, which shows that adding bio-inspired optimisation to standard WSN protocols is a smart idea.

Abose et al. [(17)] built better versions of LEACH that function well for base stations at the edges of networks. Their methods fixed the problem of spatial imbalance in regular LEACH by making networks live significantly longer by using superior residual energy estimates and adaptive clustering probabilities.

Chugh and others [(18)] designed a more advanced PEGASIS-based protocol for the Internet of Things. Energy-aware multi-chain routing made the protocol better for IoT networks that need to run in real time and have limited energy by cutting down on delays and improving energy balance.

When choosing a cluster head, Noori and Raja [(19)] made LEACH better by taking into account the node degree and residual energy. Their solution made a small but beneficial improvement to the traditional LEACH that made it more stable and energy-efficient over time.These developments constitute a basis for further improvement of these protocols since they solve data delivery efficiency, routing robustness, and energy economy.

The major contribution of this paper is summarized as:

1. **Comparative Evaluation under Mobility:** The paper simulates the working of the LEACH and PEGASIS protocols in a mobile wireless sensor network (MWSN) environment, which is not often less researched in the past for node mobility with the Random Waypoint Model. This helps to know how the protocol behaves in when topology changes for real time deployment.
2. **Tracking Energy and Performance Metrics: Total** energy use, packet delivery to the base station, and node mortality rates are all measured across several rounds of simulation, giving a complete picture of how well the protocol works.
3. **Insights for Practical Use of Protocols:** The paper talks about the pros and cons of the LEACH and PEGASIS algorithms and how they can be used in different situations. Lastly, the paper says that a hybrid routing protocol may be built that combines the flexibility of LEACH with the energy efficiency of PEGASIS. This would make it easier to deal with mobility in WSNs.

The paper is divided into several sections describing the problem, its need, methodology and simulations setup in node mobility environment. It starts with a look at the problems that WSNs face in section 1 followed by section 2 that describes simulation details with the network's design and energy use. The results and discussions section are given in section 3 showing the performance of different things compares, and finally in section 4 the conclusion sums up the most important points and suggests what to do next.

2 Methodology

The simulation of LEACH and PEGASIS protocols is conducted using Python, deploying a network of 100 nodes over a 100m $\times$ 100m area. The base station (BS) is placed at (50, 200) to introduce a realistic communication range and energy burden as shown in figure 1. This approach aligns with previous studies such as [5] and [14], ensuring consistency in the performance evaluation methodology. Table 1 describes the steps of simulation algorithm in the form of Pseudocode.

The simulation adopts the First-Order Radio Energy Model, where energy consumption is determined by transmission distance and data size. The equations governing transmission and reception energy are as follows in **equations (1) and (2):**

$$E_{Tx}(k,d) = E_{elec} \cdot k + E_{amp} \cdot k \cdot d^2 \tag{1}$$

Where E_{elec}**:** Energy required by the transmitter electronics to process each bit (e.g. modulation, coding)

E_{amp}**:** Energy required by the transmit amplifier to push the signal over a given distance, per bit per square meter.

This equation calculates the total energy consumed (in joules) by a sensor node when transmitting a message of k bits over a distance d meters. $E_{elec} = 50nJ/bit$ and $E_{amp} = 100\frac{pJ}{bit}/m^2$ can be taken as per model suggested by [5]. The energy for transmission increases quadratically with distance due to the free space propagation model, which reflects signal power loss over distance. This equation helps estimate how much energy a sensor node will consume when sending data to another node or base station, helping design more energy-efficient routing protocols.

$$E_{Rx}(k) = E_{elec} \cdot k \tag{2}$$

This equation calculates the energy required to receive a k-bit message. Reception doesn't involve distance-based amplification. Only electronic processing of the incoming bits is needed. So, energy consumption is linear with the number of bits, and only depends on E_{elec}.

3 Results and Discussion

Python is chosen as the simulation environment being robust support for matrix computation, modeling, and visualization. The simulation deploys nodes randomly within the defined field and use mobility models like Random Waypoint to emulate node restricted movement. The energy consumption metrics is collected per round to determine protocol stability and efficiency over time [6, 13].

The simulation results from the two wireless sensor network (WSN) protocols—LEACH and PEGASIS—offer insightful comparisons in terms of energy efficiency, node lifetime, and communication overhead.

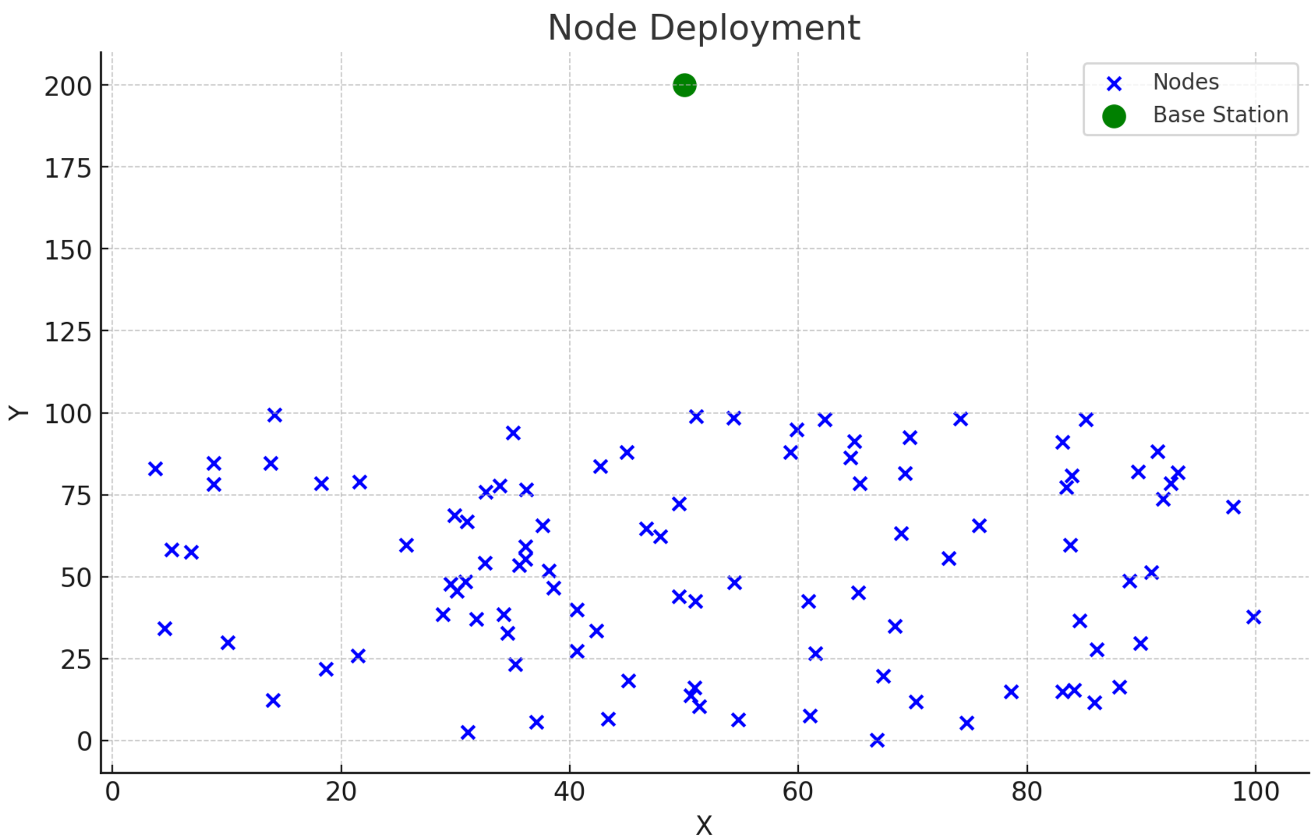

Fig 1. Max Energy LEECH Node Status in the First round

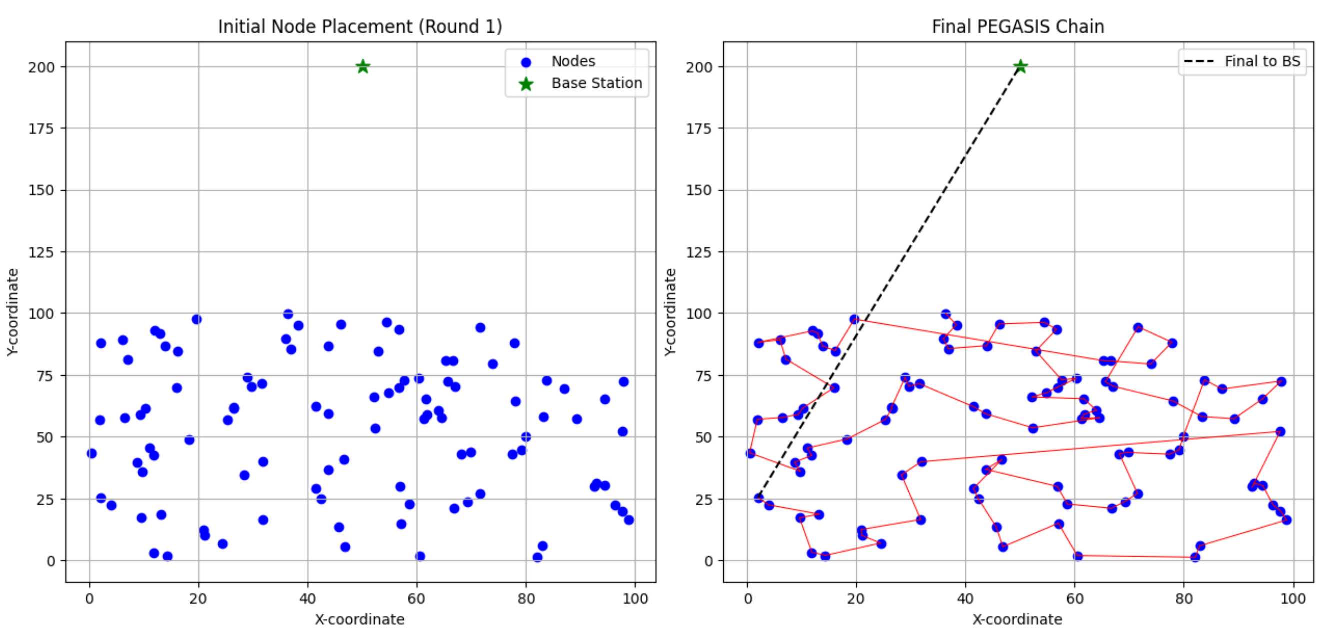

Fig 2. PEGASIS Node Status in the First and last round

Table 1. Simulation Algorithm Pseudocode

```
# Initialize network parameters
initialize_network()
initialize_energy_model()
place_nodes_randomly()
place_base_station()

for round in range(1, max_rounds):
update_node_positions() # simulate mobility

if protocol == 'LEACH':
cluster_heads = select_cluster_heads_based_on_energy()
assign_nodes_to_clusters(cluster_heads)
transmit_data_LEACH(cluster_heads)

elif protocol == 'PEGASIS':
chain = form_chain_based_on_nearest_neighbor()
transmit_data_PEGASIS(chain)

update_energy_levels()
count_dead_nodes()

record_energy()
record_packets_to_bs()
record_dead_nodes()

if stopping_criteria_met():
break

generate_result_graphs()
```

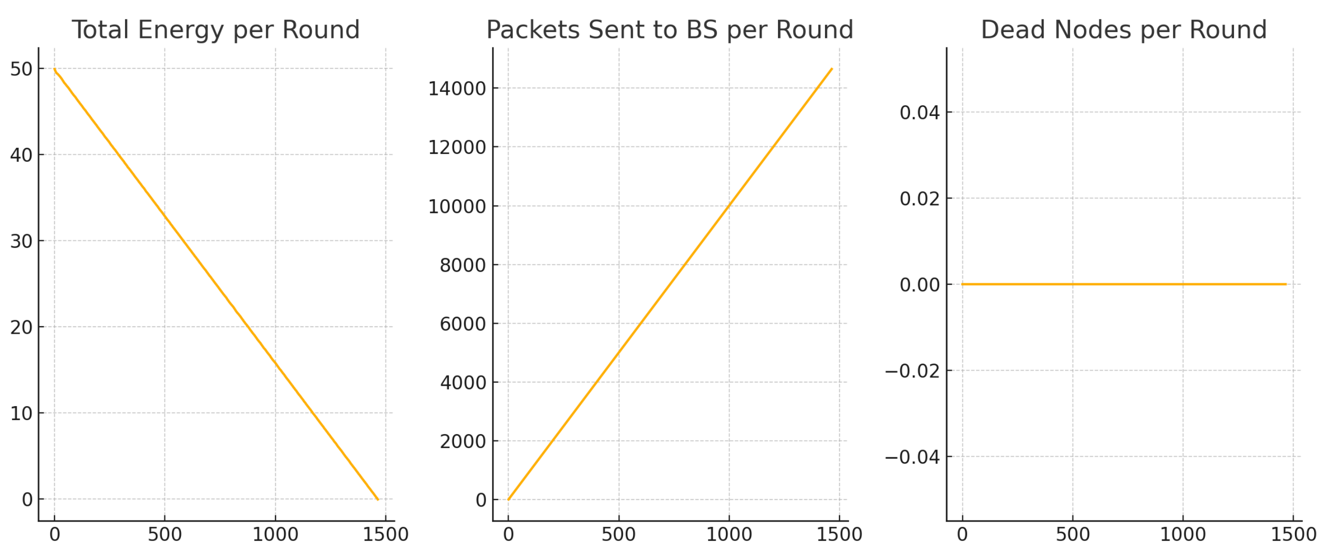

Fig 3. Final result of Max LEECH algorithm

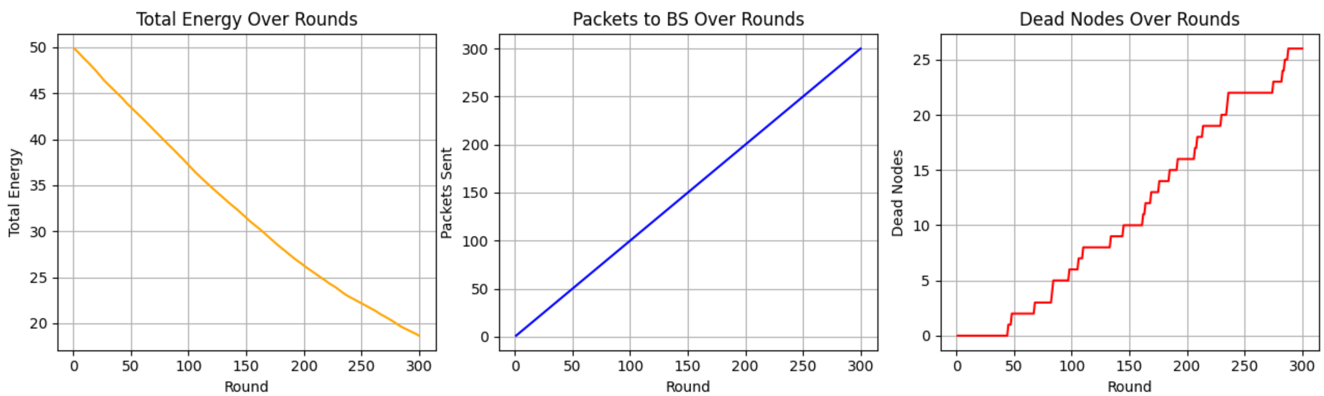

Fig 4. Final result of PEGASIS algorithm

In the LEACH protocol, nodes are deployed randomly across a 100×100 area, with a base station located far from the field (at coordinate y = 200). The protocol begins by selecting a subset of nodes as cluster heads (CHs), typically based on a probability factor and energy levels as shown in figure 1. These CHs aggregate data from nearby member nodes and transmit the combined data to the base station. As this clustering and communication process repeats in each round, nodes begin to deplete energy—especially the CHs, which handle both intra-cluster and long-distance communication. Over time, this leads to faster node death, visible in the steep slope of the "dead nodes vs. round" graph. The simulation terminates once 80% of the nodes die or energy drops critically low. The "energy vs. rounds" plot in figure 3 shows rapid depletion, and "packets sent to BS" increase with the number of CHs in each round.

Table 2. Analytic comparison between LEACH and PEGASIS variants of MWSN routing

Metric	LEACH (Mobile)	PEGASIS (Mobile)	Remarks
Total Nodes Deployed	100	100	Same in both setups
Initial Node Energy (Joules)	0.5 per node	0.5 per node	Equal starting energy for fair comparison
Simulation Rounds Completed	3200 (varies)	4000+ (varies)	PEGASIS runs longer due to better energy conservation
First Node Death Round	800	1200	PEGASIS delays first node death
80% Node Death Threshold Round	3200	4000+	PEGASIS maintains longer network stability
Final Total Energy Remaining	3.0 J	6.8 J	PEGASIS retains more residual energy
Total Packets Sent to BS	Higher (per round)	Lower (but more rounds)	LEACH sends more frequently, PEGASIS in chained cycles
Dead Nodes After Final Round	95–100	85–90	PEGASIS sustains node life longer
Energy Consumption Pattern	Faster drop (steep)	Gradual decline	PEGASIS shows smoother energy degradation
Cluster/Chain Overhead	Dynamic CH selection	Chain maintenance	LEACH requires frequent CH updates; PEGASIS needs chain reordering
Protocol Stability Period	Moderate	High	PEGASIS is more stable in mobile scenarios
Communication Latency	Low	High	LEACH: Direct CH to BS; PEGASIS: Serial chain can delay
Scalability (for larger area)	Good	Moderate	LEACH performs better in widely distributed networks
Mobility Handling	Adaptive (LEACH-M)	Rigid	LEACH handles mobility with re-clustering; PEGASIS requires dynamic updates

In contrast, PEGASIS employs a more energy-aware chain-based protocol. Instead of forming clusters, PEGASIS links the nodes into a chain based on nearest-neighbor distances using a greedy approach as shown in figure 2. Only one node—usually the one closest to the base station—transmits data to the BS, while others relay their information along the chain. This reduces the number of long-range transmissions and balances energy consumption across the network. A unique feature of this implementation is slight node mobility, where each node shifts randomly in X and Y directions in every round, simulating real-world sensor movement. As seen in the final PEGASIS chain plot in figure 4, the nodes form a sequential path leading to the BS. Energy is dissipated primarily along the chain, but more gradually than in LEACH. The simulation ends when 90% of the nodes die or the total network energy becomes negligible. Plots for energy, packets sent, and node deaths reflect this stability, with a more gradual decline in performance.A detailed analytic comparison between LEACH and PEGASIS is given in table 2.

Simulation results show that PEGASIS does expand less energy because short-range messages consume less energy and doesn't change roles as often, which keeps the network alive longer, especially when nodes move about a little and are uniformly spaced out. Park et al.[20] and Lin et al.[21] observed the same thing: that chain-based data transmission methods made networks live up to 35% longer than clustering approaches. But the findings thus far also reveal that PEGASIS has less flexibility in communication and fewer operational cycles. Misra et al.[22] showed that PEGASIS delays data transmission due to serial data gathering. LEACH is able to accommodate changing topologies since its adaptive clustering structure made it possible. This backs up what Singh and Kumar[23] and Xiao et al.[24] said: that LEACH could be utilised on a broad scale, even though it used more energy.

4 Conclusion

Even though the researchers have been improved over the past ten years, current energy-efficient routing methods for wireless sensor networks (WSNs) still have problems such the network breaking up quickly and energy being distributed unevenly. We look at and evaluate two well-known protocols, LEACH and PEGASIS, in this study to find out what each one does well and how they could work together. LEACH is a simple design and works well for big, changing networks, but it has a lot of overhead because it has to choose cluster heads (CHs) often and uses a lot of energy. On the other hand, PEGASIS shows superior energy conservation and longer network lifetime by cutting down on the number of broadcasts to the base station (BS). This is especially true when the nodes are evenly spaced out and move around a little. But PEGASIS has certain problems because its algorithm is complicated, and it doesn't have as many rounds of communication. Our comparison shows that PEGASIS is better than LEACH when it comes to energy economy and longevity, but LEACH is still better when it comes to scalability and easier deployment. In the future, a hybrid strategy that combines the scalability and cluster-based organization of LEACH with the energy-saving chain-based transmission of PEGASIS could be a better and more stable way to route WSNs.

This work is novel due to comparison of LEACH and PEGASIS for mobility and deployment in Python-based simulation tool. This makes sure that all performance measurements are the same. The present study not only confirms its results with existing research, but it also shows that both regimens have qualities that work well together. This leads to the idea of a hybrid routing system that combines LEACH's cluster-based adaptability with PEGASIS's chain-based energy efficiency. This integrated strategy could better meet the two concerns of mobility and energy conservation in future WSN deployments.

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