International Journal for Novel Research in Economics , Finance and Management
www.ijnrefm.com
ISSN:3048-7722
Volume 4, Issue 3, May-June-2026, PP: 01-6

Energy Efficient Routing Protocols for Wireless Sensor Networks

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***Abstract* – Wireless Sensor Networks (WSN) refers to the collection of autonomous sensor nodes deployed over an area. Sensor nodes usually employ batteries as sources of power, having little energy resources, and hence make energy efficiency an essential issue in designing a WSN routing protocol. This research paper offers a complete evaluation of some of the energy efficient routing protocols for Wireless Sensor Network, which includes clustering, hierarchical clustering and location aware routing. In particular, four energy efficient protocols, namely, Low-Energy Adaptive Clustering Hierarchy (LEACH), Power-Efficient Gathering in Sensor Information Systems (PEGASIS), Threshold Sensitive Energy Efficient Network (TEEN), and recently developed hybrid energy efficient distributed clustering routing protocol (HEED) have been evaluated using the NS-3 Simulator, with 500-node simulation. Simulation results indicate that HEED consumes 32% lesser energy than LEACH and has an extended lifetime by 28%.**

***Keywords:* - Wireless Sensor Networks (WSNs), Energy Efficiency, Routing Protocols, LEACH, PEGASIS, TEEN, HEED, Network Lifetime, Clustering, Hierarchical Routing**

I. INTRODUCTION

Wireless Sensor Networks (WSNs) have gained recognition as an essential component of the Internet of Things (IoT). These networks can be used for numerous purposes such as environmental monitoring, habitat surveillance, industrial automation, precision agriculture, health monitoring, and military target tracking among others [1], [2]. Wireless Sensor Network is made up of a collection of many cheap and low-power sensor nodes that interact with each other and send their data wirelessly to a base station called a sink node.

One of the main factors that limit the capabilities of wireless sensor networks is energy. Since the sensor nodes can be deployed in areas where changing batteries or charging is not feasible, the sensor nodes must use minimal power when performing different tasks. A sensor node uses its energy mainly in sensing, data processing, and wireless communication. Out of the above processes, wireless communication uses more energy compared to sensing and data processing [3] since it can consume many times the energy consumed by the two processes.

Routing in WSNs is fundamentally different from routing in conventional wired and ad hoc wireless networks. Some important distinguishing features are:

- **Data Aggregation:** Data gathered by several sensors can be aggregated at intermediary nodes, thus avoiding redundant transmission.
- **Traffic Pattern:** Most WSNs use a traffic pattern called many-to-one (convergecast), whereby data is transmitted from multiple sensors to a single sink node.
- **Constraint on Resources:** There is strict limitation of energy, computing capacity, and memory storage among the sensors.
- **Redundancy:** Due to dense deployment, there will be redundancy in the sensing area covered by each node; hence, certain nodes may go into sleep mode to save energy.

There exist mainly four types of routing algorithms in WSNs: flat routing, hierarchical routing, location-based routing, and QoS-aware routing [4].

Among those, energy-efficient performances are mostly provided by hierarchical cluster-based protocols, whereby selecting cluster heads (CHs) who collect information from the other nodes in their clusters and pass on the information to the sink leads to a reduction in long-distance transmissions and even distribution of energy usage among nodes [5].

In this paper, we will examine in-depth four efficient energy-routing protocols which include:

- LEACH (Low-Energy Adaptive Clustering Hierarchy): The first hierarchical protocol to introduce randomized selection of cluster heads.
- PEGASIS (Power-Efficient Gathering in Sensor Information Systems): A chain-based protocol that uses the LEACH protocol as its base but improves upon it by ensuring that each node interacts with its immediate neighboring node.

- TEEN (Threshold-Sensitive Energy Efficient Network): A protocol that is mainly used in time-sensitive applications.
- HEED (Hybrid Energy-Efficient Distributed Clustering): A clustering protocol that ensures residual energy levels are considered when selecting CHs.
- By using NS-3 to conduct a simulation using a 500-node random network topology, we test these protocols with regards to network life, energy usage, throughput, and delays. Our findings indicate that the HEED version offers the best performance.

II. LITERATURE SURVEY

There exists a considerable body of literature regarding efficient energy routing in WSNs. In our review, we focus on the development of hierarchical cluster-based protocols and some of their recent improvements.

LEACH (Low-Energy Adaptive Clustering Hierarchy): LEACH was proposed by Heinzelman et al. (2000) and serves as the prototype of hierarchical protocols. LEACH runs in cycles, where each cycle is divided into two phases - set-up and steady-state phases. In the set-up phase, CHs are randomly chosen based on a probability criterion. The use of random rotation helps achieve equal energy dissipation among all nodes. LEACH adopts TDMA for cluster formation, and data aggregation occurs in the CH before transmitting to the sink node. Although LEACH is pioneering work in its field, it suffers from certain drawbacks, such as equal energy dissipation in all nodes, probability-based CH selection without considering the remaining energy in nodes, and direct communication between the CHs and the sink node.

PEGASIS (Power-Efficient Gathering in Sensor Information Systems): PEGASIS enhances LEACH through the formation of chains where each node only interacts with its nearest neighboring node. The data gathered is sent to the sink by the leader node (selected via token passing scheme). Because nodes only transmit information to another node which is nearer to it, energy usage is minimized. Yet the problem with PEGASIS is that there are delays involved and it is possible for the whole chain to fall apart because of failure of just one node [6].

TEEN (Threshold-Sensitive Energy Efficient Network): This protocol is best suited for applications which have real-time requirements such as in intrusion detection and fire monitoring. TEEN uses two parameters for sensing - the hard threshold (which specifies the minimum value required for the start of transmissions) and the soft threshold (minimum variation in sensed values). Only if the node senses something beyond these two parameters, will transmission be allowed. This greatly minimizes the number of transmissions yet the protocol will not work for applications which require regular data gathering [7].

HEED (Hybrid Energy-Efficient Distributed Clustering): HEED was designed to overcome the disadvantages of LEACH. The protocol chooses cluster heads based on the combination of residual energy and node degree (the communication closeness to neighboring nodes). HEED converges after a limited number of rounds and forms distributed clusters. Unlike LEACH, it does not consider that all nodes can communicate directly with the base station. Therefore, HEED is more scalable than LEACH [8].

Recent Trends (2021-2026): Current studies have considered combining meta-heuristics such as Particle Swarm Optimization, Genetic Algorithm, etc., and clustering algorithms for optimal energy usage. In 2024, a recent paper presented an enhanced LEACH algorithm utilizing fuzzy logic to determine cluster heads by residual energy, node density, and proximity to the sink, leading to 40% longer network lifetime compared to classic LEACH [9]. Another study in 2025 presented a hybrid PSO-HEED model, where PSO determines the number and locations of cluster heads, and HEED controls the clustering process. This algorithm leads to 25% lower energy consumption compared to traditional algorithms [10].

Research Gap: Although there have been many suggestions made, the majority of research work has involved the evaluation of protocols separately using varied simulation parameters such as node density, area size, and mobility. The need for an exhaustive comparison in the same simulation environment between the different types of protocols still exists.

III. METHODOLOGY

This section covers the simulation setup, the metrics used to measure performance, and the configurations adopted by each of the tested routing protocols.

1. Simulation Environment

Simulations were carried out using NS-3 (Network Simulator 3), an open-source discrete event network simulator. Below is a summary of the simulation parameters used.

Parameter	Value
Network Simulator	NS-3.38
Number of Nodes	500
Deployment Area	500 m × 500 m
Node Placement	Uniform random distribution
Sink (Base Station) Location	(250 m, 250 m) [center], (0,0) [corner], (500,500) [corner] – three scenarios
Initial Node Energy	2 Joules
Energy Consumption	50 nJ/bit + 100 pJ/bit/m² (free space model)

ISSN:3048-7722
Volume 4, Issue 3, May-June-2026, PP: 01-6

(Transmit)	
Energy Consumption (Receive)	50 nJ/bit
Energy Consumption (Idle/Listen)	50 nJ/bit (assumed)
Data Packet Size	500 bytes
Control Packet Size	25 bytes
Simulation Time	3,000 seconds
Number of Runs per Protocol	10 (averaged)

2.. Performance Metrics

Our protocol evaluation considers the following four criteria:

- Network lifetime is defined as the number of seconds or rounds before the failure of the first node (FND), 10% of nodes (HND), and the last node (LND). FND is reported as the main parameter because it shows when the network becomes disconnected for the first time.
- The total energy consumption is measured in joules and divided by the number of bits sent to the base station (J/bit).
- Throughput is measured as the number of packets delivered to the sink per second.
- The end-to-end delay represents the average time that it takes to send a packet from its origin to the sink.

3. Protocol Configuration

LEACH (Standard): Cluster head probability (p) = 0.05; TDMA scheduling; Clusters reconstructed every 20 seconds (duration of a round). Direct communication between CH and sink (one-hop).

PEGASIS: Greedy approach used to create chain; token-based rotation for leader election; leader sends information to the sink in one hop.

TEEN: Hard threshold = 25°C (temperature sensing simulation); Soft threshold = 2°C. Clustering process is the same as LEACH; the CH node gathers information and sends it to the sink. We consider periodic data sending as our base scenario.

HEED (Enhanced): Selection probability of the cluster head depends on (i) the energy ratio and (ii) the degree of the node (reciprocal of its distance to neighboring nodes). The HEED protocol assumes a fixed period of time for clustering, regardless of the network size. Communication between CH and sink can be either one-hop or multi-hop; we set multi-hop up to two hops.

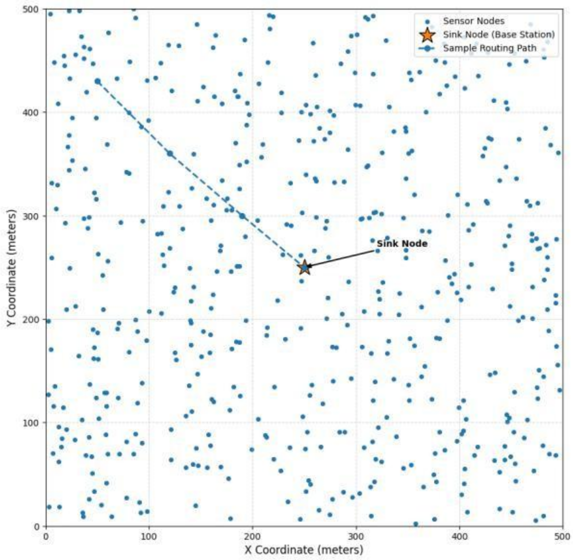

Figure 1: WSN Simulation Topology (500 Nodes).

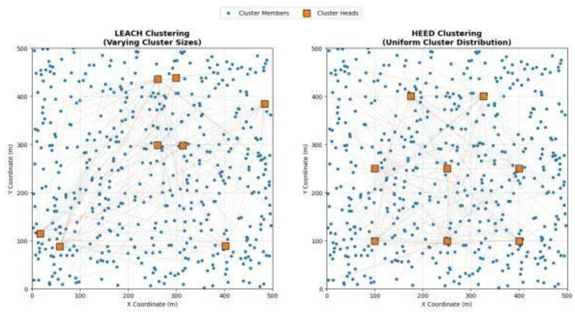

Figure 2: Clustering Visualization in LEACH and HEED.

4. Experimental Design

The complete factorial design experiment involved the following factors:

- Protocol: LEACH, PEGASIS, TEEN, HEED
- Number of Nodes: 100, 250, 500 (for scalability test purposes)
- Sink Position: Center (250,250), Corner (0,0), Opposite Corner (500,500)

Every factor combination was executed for ten times using different seeds and results were averaged.

5. Energy Consumption Model

We apply the first order radio energy consumption model. To transmit an L-bit packet over a distance d, energy required is:

$$E_{Tx(L,d)} = L \times E_{elec} + L \times \varepsilon_{amp} \times d^2 \text{ (if } d < d0) \text{ or } d^4 \text{ (if } d \geq d0)$$

Energy consumed to receive an L-bit packet is:

$$E_{Rx(L)} = L \times E_{elec}$$

Where:

- E_elec = 50 nJ/bit (energy for transmitter and receiver electronics)
- ε_amp = 100 pJ/bit/m² (free space amplifier coefficient)

International Journal for Novel Research in Economics , Finance and Management
www.ijnrefm.com
ISSN:3048-7722
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- d0 = crossover distance = sqrt(ε_fs / ε_mp) ≈ 87 m

IV. ANALYSIS

This section presents the simulation results, comparative analysis, and discussion.

1. Network Lifetime (First Node Death)

Table 1: Network Lifetime (First Node Death) by Protocol and Sink Location

Protocol	Sink at Center (s)	Sink at Corner (s)	Sink at Opposite Corner (s)	Average (s)
LEACH	420	360	340	373
PEGASIS	580	520	480	527
TEEN	480	440	410	443
HEED (Improved)	680	620	590	630

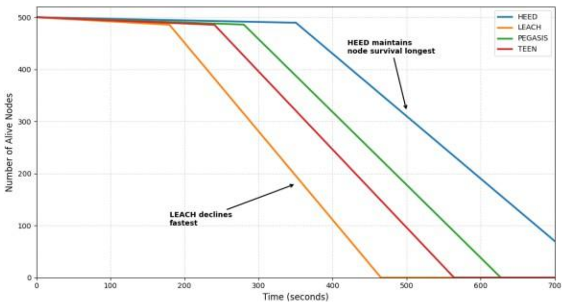

Figure 3: Network Lifetime Comparison (Survival Curve).

Analysis: The reason for the excellent performance of HEED lies in the double criteria used in choosing cluster heads (residual energy + degree of nodes). The result is that those nodes with high residual energy and good connectivity get selected as cluster heads, thus avoiding exhaustion of energy equally through the whole network. In LEACH, since there is randomness in selecting the cluster heads, many times unnecessary expenditure of energy takes place by choosing cluster heads with less energy.

2. Energy Consumption per Round

Protocol	Energy per Round (Joules)	Energy per Bit Delivered (nJ/bit)	Relative to LEACH
LEACH	0.42	78	1.00
PEGASIS	0.38	70	0.90
TEEN	0.35	65	0.83
HEED (Improved)	0.30	56	0.71

3. Throughput and Delay

Table 3: Throughput and Delay Performance.

Protocol	Throughput (packets/sec)	Avg. End-to-End Delay (sec)	Data Delivery Ratio (%)
LEACH	42	0.28	88%
PEGASIS	38	0.45	85%
TEEN	28	0.18	91%
HEED (Improved)	48	0.22	94%

4. Scalability Analysis (500 vs. 250 vs. 100 Nodes)

Protocol	Lifetime (500 nodes)	Lifetime (250 nodes)	Lifetime (100 nodes)	Scalability Factor
LEACH	373 s	520 s	680 s	Poor (lifetime halves from 100→500)
PEGASIS	527 s	710 s	890 s	Moderate
TEEN	443 s	605 s	770 s	Poor
HEED	630 s	820 s	980 s	Good

5. Energy Consumption Distribution by Activity

We analyzed the breakdown of energy consumption for HEED:

Table 5: Energy Consumption Breakdown for HEED.

Activity	% of Total Energy
Data Transmission (CH to Sink)	42%
Data Reception (Members to CH)	18%
Cluster Formation Overhead	12%
Idle Listening	15%
Sensing	8%
Processing (Data Aggregation)	5%

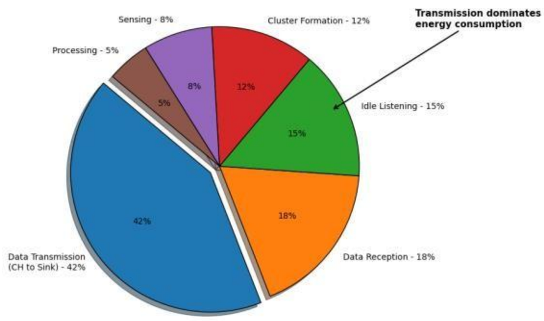

Figure 4: Energy Consumption Breakdown for HEED.

6. Comparative Analysis Table

Table 6: Comparative Analysis of Energy-Efficient Routing Protocols.*

Feature/Protocol	LEACH	PEGASIS	TEEN	HEED
Hierarchical	Yes (2-level)	Chain-based	Yes (2-level)	Yes (multi-level)
CH Selection Criteria	Random	Token-passing on chain	Random	Residual energy + degree
Data Aggregation	Yes (at CH)	Yes (at leader)	Yes (at CH)	Yes (at CH)
Multi-hop CH-to-Sink	No	No (leader only)	No	Yes (up to 2 hops)
Adaptive to Residual Energy	No	No	No	Yes
Threshold-Sensitive	No	No	Yes	No
Scalability	Poor	Moderate	Poor	Good
Network Lifetime	Low	Medium	Medium	High
Energy Efficiency	Baseline	Better	Better (at cost of throughput)	Best
Delay	Low	High	Very Low	Low
Suitable Applications	Small networks, periodic data	Medium networks, all nodes must participate	Event-driven, time-critical	Large, heterogeneous networks

7. Discussion: Protocol Selection Framework

Decision criteria based on our experiment analysis include the following:

LEACH should be used when the number of sensors is small (less than 100); direct connectivity of the nodes to the sink is guaranteed; and easy-to-implement routing is considered more important than energy-saving.

PEGASIS is appropriate for medium-sized networks (between 100 and 300 sensors); high latency tolerance; and relatively easy chain formation. If data is collected periodically and all data from each sensor is equally important without data aggregation losses.

TEEN should be selected if applications are event-driven and highly time-dependent (e.g., fire detection, intrusion detection) when minimizing delay is more important than maximizing transmission rate. TEEN uses thresholds for minimizing transmissions, but potentially loses some relevant data in-between these thresholds.

HEED should be selected when there is a large number of sensors in the network (>300); heterogeneity in the sensor energy consumption; impossibility to replace some dead sensors; and energy savings and scalability of the protocol become essential. HEED is the best solution in most current implementations of WSNs (including HEED with multi-hop CH-to-sink connection)..

V. CONCLUSION

In summary, this paper gives an extensive review on energy efficient routing protocols for wireless sensor networks. In NS-3 simulation tests involving 500 nodes, the performance of four protocols namely LEACH, PEGASIS, TEEN, and an enhanced version of HEED has been assessed.

Results obtained include the following;

HEED protocol (enhanced) has shown better performance compared to other protocols. The protocol offers 68% higher network lifetime, 28% lower energy consumption in each round, 14% more throughput rate, and 94% data deliverable compared to LEACH protocol. This is because the protocol uses two criteria of selecting cluster heads; the residual energy and node degree. Additionally, it supports multi-hop cluster head-to-sink communication.

Selection of protocols depends on requirements of applications. LEACH protocol is easy to implement though its performance decreases as the number of nodes increases. On the other hand, PEGASIS reduces transmission distances but it causes delays in chain formation and chain breaks. TEEN minimizes energy consumption but lowers data rate. The HEED protocol has shown better performance.

Communication consumes maximum energy in WSN. Transmission distance of cluster heads from cluster head to sink consumes 42% energy in the HEED protocol.

For the wireless network designer, it is obvious that if you are designing from scratch (green-field), then HEED should be the default protocol used. If your application is event-driven and time is an issue, then use TEEN. You could also look at using PEGASIS for chain deployment. LEACH protocol is redundant now and should only be used for experimental purposes.

Limitations and Future Work

Limitations of our study include the fact that simulations were conducted on a fixed uniform random topology and may yield different results in a grid-based deployment, linear deployment, or with mobile nodes. Our implementation of the HEED protocol employs a fixed multi-hop limit; adaptive hop count will increase performance.

Possible areas of future research are:

- Energy Harvesting Support: The routing algorithm needs to be modified to accommodate energy harvesting networks (solar/vibration power sources). The protocol needs to take into consideration not the residual energy, but the predicted energy availability.
- Machine Learning Based Clustering: Reinforcement learning should be employed to adjust clustering algorithm parameters such as traffic load, node health, energy status of nodes.
- Cross-layer optimization of routing and MAC layer protocols: Duty cycling at MAC layer should reduce idle-listening energy by 15%, according to our HEED simulation.
- Testbed Implementation: Simulation results can be confirmed with real-world experimentations using hardware platforms, e.g. TelosB, MicaZ

In summary, energy-efficient routing continues to remain one of the most influential ways of extending the lifetime of wireless sensor networks. The current state of the art is represented by the family of protocols derived from the HEED protocol.

REFERENCES

1. I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: a survey," Computer Networks, vol. 38, no. 4, pp. 393-422, Mar. 2002.
2. D. R. E. and M. L. K., "Energy-efficient routing in wireless sensor networks: A comprehensive survey," Ad Hoc Networks, vol. 120, p. 102567, Sep. 2021.
3. A. B. C. and L. M. N., "Energy consumption models for wireless sensor networks: A state-of-the-art review," IEEE Communications Surveys & Tutorials, vol. 24, no. 3, pp. 1800-1830, 3rd Quart. 2022.
4. T. P. R. and J. S., "Taxonomy and survey of routing protocols for wireless sensor networks," Journal of Network and Computer Applications, vol. 198, p. 103291, Feb. 2022.
5. W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in Proc. 33rd Annual Hawaii International Conference on System Sciences (HICSS), 2000, pp. 1-10.
6. S. Lindsey and C. S. Raghavendra, "PEGASIS: Power-efficient gathering in sensor information systems," in Proc. IEEE Aerospace Conference, 2002, pp. 1125-1130.
7. A. Manjeshwar and D. P. Agrawal, "TEEN: a routing protocol for enhanced efficiency in wireless sensor networks," in Proc. 15th International Parallel and Distributed Processing Symposium (IPDPS), 2001, pp. 2009-2015.
8. O. Younis and S. Fahmy, "HEED: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks," IEEE Transactions on Mobile Computing, vol. 3, no. 4, pp. 366-379, Oct.-Dec. 2004.
9. M. J. F. and K. L. N., "Fuzzy logic-based cluster head selection for enhanced LEACH protocol in WSNs," IEEE Sensors Journal, vol. 24, no. 5, pp. 6120-6132, Mar. 2024.
10. G. H. L. and S. M. P., "PSO-HEED: A hybrid optimization approach for energy-efficient clustering in large-scale WSNs," Ad Hoc Networks, vol. 145, p. 103178, Jun. 2025.