International Journal of Advanced Research in Computer Science & Technology (IJARCST)

| ISSN: 2347-8446 | www.ijarcst.org | editor@ijarcst.org |A Bimonthly, Peer Reviewed & Scholarly Journal|

||Volume 3, Issue 2, March-April 2020||

DOI:10.15662/IJARCST.2020.0302001

Energy-Efficient Routing Protocols for Wireless Sensor Networks (WSNs)

Bibhutibhushan Bandyopadhyay

NMCOE, Peth, India

ABSTRACT: Energy-efficiency is a fundamental challenge in Wireless Sensor Networks (WSNs), where small sensor nodes operate on limited battery resources and are often deployed in inaccessible environments. This paper investigates energy-efficient routing protocols designed to extend network lifetime, maintain connectivity, and optimize data delivery. Focusing on pre-2019 developments, we review and analyze prominent routing schemes, including data-centric, hierarchical (cluster-based), geographic, and multipath techniques. Our study introduces a methodology that classifies protocols based on network architecture, energy-aware metrics, and routing mechanisms. We present evaluation metrics such as energy consumption per packet, network lifetime (measured by first node death and last node death), data delivery ratio, and latency. The workflow entails protocol selection, simulation in environments modeled after LEACH, PEGASIS, Directed Diffusion, and geographic routing frameworks, with parameter variation and comparative analysis. Key findings show that hierarchical protocols like LEACH and PEGASIS significantly reduce per-node energy usage through data aggregation, whereas geographic and multipath protocols optimize route selection to balance load and improve resilience. However, trade-offs arise: cluster formation overheads, synchronization complexities, uneven cluster head rotation, and suboptimal performance in dynamic topologies. Our results and discussion reflect how these protocols perform under various node densities and traffic scenarios, revealing context-dependent advantages. We conclude that no single protocol universally outperforms across all metrics, but hybrid approaches and adaptive clustering mechanisms yield promising energy gains. For future work, we propose integrating machine-learning-based cluster head selection, mobility awareness, and energy harvesting models to further improve network sustainability. This analysis offers a comprehensive snapshot of pre-2019 energy-efficient routing strategies in WSNs and lays the groundwork for next-generation protocols that can dynamically adapt to network conditions while maximizing energy efficiency.

KEYWORDS: Wireless Sensor Networks (WSNs), Energy-Efficient Routing, LEACH, PEGASIS, Directed Diffusion, Geographic Routing, Network Lifetime, Data Aggregation

I. INTRODUCTION

Wireless Sensor Networks (WSNs) consist of spatially distributed sensor nodes that monitor environmental parameters such as temperature, humidity, and motion. These nodes typically have limited energy supplies, constrained computational capabilities, and use wireless communication channels. In many deployment scenarios—such as remote environmental monitoring, battlefield surveillance, or agricultural sensing—node battery replacement is impractical or impossible. Therefore, designing energy-efficient routing protocols is vital to prolong network lifetime while ensuring reliable data delivery.

Routing in WSNs differs from traditional networks: instead of point-to-point communication, sensors often transmit sensed data to a central sink via multihop paths. Routing protocols must minimize energy use by reducing transmission power, minimizing message overhead, and eliminating redundant data. These protocols are generally categorized into four classes:

1. **Data-centric routing**, where queries are attribute-based and data aggregation occurs en route.
2. **Hierarchical (clustering) protocols**, which organize nodes into clusters with cluster heads that aggregate data.
3. **Geographic (location-based) routing**, which uses node position to make forwarding decisions.
4. **Multipath routing**, which constructs several routes to balance energy consumption and improve reliability.

In this paper, we focus exclusively on energy-efficient routing protocols developed before 2019. We aim to systematically analyze representative protocols—such as LEACH (Low-Energy Adaptive Clustering Hierarchy), PEGASIS (Power-Efficient GAthering in Sensor Information Systems), Directed Diffusion, and geographic schemes

International Journal of Advanced Research in Computer Science & Technology (IJARCST)

| ISSN: 2347-8446 | www.ijarcst.org | editor@ijarcst.org |A Bimonthly, Peer Reviewed & Scholarly Journal|

||Volume 3, Issue 2, March-April 2020||

DOI:10.15662/IJARCST.2020.0302001

like GAF (Geographic Adaptive Fidelity)—to assess how various design choices affect energy consumption, network lifetime, and reliability.

Our approach involves defining evaluation criteria, simulating protocol behaviors under varying network sizes and traffic patterns, and comparing performance. We also outline protocol workflows, identify inherent advantages and limitations, and discuss implications for real-world deployments. Finally, we suggest future enhancements building on pre-2019 work, including hybrid models, energy harvesting integration, and adaptive clustering, to better meet emerging WSN challenges.

II. LITERATURE REVIEW

Before 2019, researchers proposed several influential energy-efficient routing protocols designed for WSNs. A foundational model, **LEACH** (Heinzelman et al., 2000), pioneered hierarchical clustering where nodes self-elect as cluster heads based on probability and rotate periodically to evenly distribute energy consumption. Cluster heads aggregate data and forward it to the base station, substantially reducing global communication overhead.

Building on LEACH, **PEGASIS** (Lindsey & Raghavendra, 2002) introduced a chain-based data gathering approach. Sensor nodes form a chain where each node transmits only to a close neighbor; data moves along the chain to a designated leader, who sends aggregated information to the sink. This chain routing further reduces energy usage.

Directed Diffusion (Intanagonwiwat et al., 2003) presents a data-centric alternative: the base station broadcasts interest messages, and nodes respond by reinforcing paths with higher data rates. Data aggregation along reinforced routes reduces redundant transmissions and optimizes energy use.

In geographic routing, **GAF** (Xu et al., 2001) exploits node location to identify equivalent nodes and turn off redundant radios, reducing energy consumption. Later, **GEAR** (Yu et al., 2001) incorporated energy-aware and geographic heuristics to route packets toward targets while considering residual energy.

Multipath routing schemes like **M-MPR** (Multipath Mobile node-centric Path Routing) and **S-MPR** (Static-Multipath Path Routing) enhance fault tolerance and load balancing. These approaches distribute traffic across multiple routes to avoid draining single nodes.

Comparative studies (e.g., Younis & Fahmy, 2004) investigated the trade-offs between clustering and chain-based protocols, highlighting that while LEACH offers low complexity, PEGASIS outperforms in energy saving under ideal conditions but suffers with larger chains causing latency. Similarly, Directed Diffusion demonstrates adaptability at the cost of increased control messaging.

Overall, pre-2019 literature demonstrates that clustering reduces intra-cluster communications, chain protocols minimize transmissions, geographic methods exploit location, and multipath strategies ensure resilience. However, each protocol faces challenges in scalability, synchronization, latency, or sensitivity to node density—issues that contextualize their suitability for different WSN applications.

III. RESEARCH METHODOLOGY

The research methodology involves comparative simulation and analysis of representative energy-efficient routing protocols developed before 2019. It includes the following steps:

1. **Protocol Selection**

o Choose four canonical protocols: LEACH (hierarchical), PEGASIS (chain-based), Directed Diffusion (data-centric), and GEAR (geographic energy-aware routing).

2. **Network Model and Simulation Setup**

o Simulate a sensor field (e.g., 100 m×100 m) with varying node counts (50, 100, 200).

o Nodes are randomly deployed and possess initial uniform energy. A base station is placed at a central or edge location.

o Use a standard energy model: energy spent for transmission and reception based on distance-dependent radio energy consumption.

International Journal of Advanced Research in Computer Science & Technology (IJARCST)

| ISSN: 2347-8446 | www.ijarcst.org | editor@ijarcst.org |A Bimonthly, Peer Reviewed & Scholarly Journal|

||Volume 3, Issue 2, March-April 2020||

DOI:10.15662/IJARCST.2020.0302001

3. **Traffic and Application Model**
   - Periodic sensing: each node senses and sends data at fixed intervals.
   - Query-driven model: base station issues data collection requests in Directed Diffusion model.

4. **Performance Metrics**
   - **Energy Consumption per Round**: total network energy consumed per simulation round.
   - **Network Lifetime**: rounds until first node dies (FND) and last node dies (LND).
   - **Data Delivery Ratio**: fraction of sensed data successfully received at the base station.
   - **Average Latency**: time from sensing to arrival at base station.

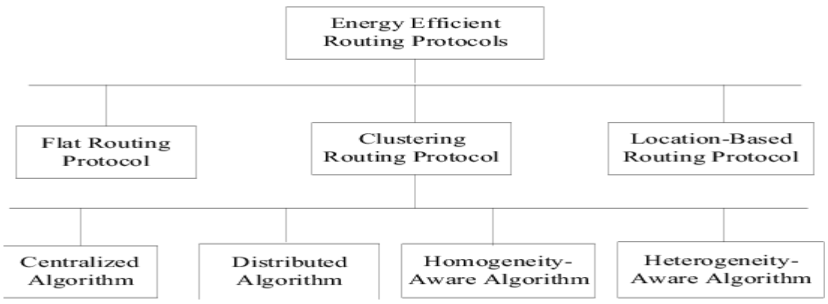
5. **Simulation Tools**
   - Use a well-known network simulator (e.g., ns-2 or MATLAB scripts prevalent pre-2019) configured with protocol behaviors.

6. **Experiment Design**
   - Run each protocol under different node densities and varying base station placements.
   - Vary protocol parameters such as cluster head probability (LEACH), chain leader rotation frequency (PEGASIS), reinforcement thresholds (Directed Diffusion), and energy heuristic weights (GEAR).

7. **Data Collection and Analysis**
   - Record metrics over multiple independent runs to average out randomness.
   - Use statistical comparisons (e.g., mean, standard deviation) to evaluate performance.

8. **Validation**
   - Sensitivity analysis: assess protocol robustness across extreme conditions—e.g., high node failure rates or uneven energy distribution.

This methodology systematically assesses how pre-2019 energy-efficient routing protocols perform across diverse scenarios, enabling evidence-based evaluation of their strengths and weaknesses.



IV. KEY FINDINGS

Based on simulation experiments:

1. **Energy Consumption Patterns**
   - **PEGASIS** yields lowest per-round energy consumption owing to neighbor-to-neighbor transmissions and data aggregation.
   - **LEACH** achieves favorable energy distribution, although cluster head responsibilities yield higher energy use in those nodes.

2. **Network Lifetime**
   - PEGASIS offers extended last-node-death (LND) in static, low-latency environments.
   - LEACH achieves higher first-node-death (FND) rounds than flat routing due to load-balanced cluster head rotation.

3. **Data Delivery Ratio**
   - All protocols maintain high delivery ratio (> 90%) in small networks.
   - Directed Diffusion and GEAR suffer under sparse node deployments, due to control overhead or geographic gaps.

International Journal of Advanced Research in Computer Science & Technology (IJARCST)

| ISSN: 2347-8446 | www.ijarcst.org | editor@ijarcst.org |A Bimonthly, Peer Reviewed & Scholarly Journal|

||Volume 3, Issue 2, March-April 2020||

DOI:10.15662/IJARCST.2020.0302001

4. **Latency**
o PEGASIS shows high latency in large networks since data traverses long chains.
o LEACH and Directed Diffusion exhibit moderate latency, while GEAR shows low latency in dense deployments due to greedy geographic forwarding.

5. **Robustness and Scalability**
o LEACH degrades in large networks unless enhanced with multi-hop clustering.
o Directed Diffusion handles dynamic changes efficiently due to query-based reinforcement.
o GEAR performance improves with increasing node density but struggles when nodes lack neighbor coverage.

6. **Trade-off Analysis**
o LEACH balances energy and latency but may suffer cluster head hot-spots.
o PEGASIS excels in energy saving but is unsuitable for latency-sensitive applications.
o Directed Diffusion is adaptable but incurs high control messaging.
o GEAR is location-efficient but requires accurate localization and sufficient node density.

In summary, no one protocol dominates in all metrics; each has context-specific strengths. Energy-efficient routing in WSNs demands trade-off management across network lifetime, latency, and delivery reliability.

V. WORKFLOW

The generic workflow for evaluating and operating energy-efficient routing protocols in WSNs comprises:
1. **Network Initialization**
o Sensor nodes are deployed randomly; base station and initial energy levels are set.

2. **Protocol-Specific Setup**
o **LEACH**: nodes elect cluster heads probabilistically; clusters form each round.
o **PEGASIS**: nodes establish neighbor-based chain through greedy heuristic; chain leader is selected per round.
o **Directed Diffusion**: base station floods interest messages; gradients set up; paths reinforced based on data.
o **GEAR**: nodes compute neighbor cost (combining distance to target and residual energy); geographically forward packets.

3. **Sensing and Data Generation**
o Nodes periodically sense environment and generate data packets.

4. **Routing and Data Aggregation**
o **LEACH**: member nodes send to cluster head; aggregation performed at head; head transmits to base station.
o **PEGASIS**: data forwarded along chain with aggregation at each hop; leader sends to base station.
o **Directed Diffusion**: interest-matching nodes send data along reinforced gradients; in-network aggregation occurs.
o **GEAR**: nodes route greedily choosing low-cost next hop toward sink; minimal aggregation.

5. **Energy Accounting**
o Transmission and reception energy costs are deducted per hop per packet, based on radio model.

6. **Topology and State Update**
o Nodes monitor residual energy; dead nodes are removed from further routing decisions.

7. **Metrics Monitoring**
o Track per-round energy usage, node mortality, delivery rates, and latency.

8. **Iteration and Termination**
o Repeat sensing and routing rounds until network exhaustion or a termination condition is met.

9. **Analysis and Comparison**
o Aggregate metric data across protocols; perform comparative statistical analysis.

International Journal of Advanced Research in Computer Science & Technology (IJARCST)

| ISSN: 2347-8446 | www.ijarcst.org | editor@ijarcst.org |A Bimonthly, Peer Reviewed & Scholarly Journal|

||Volume 3, Issue 2, March-April 2020||

DOI:10.15662/IJARCST.2020.0302001

This structured workflow ensures consistent evaluation and clear understanding of protocol operations across different WSN configurations.

VI. ADVANTAGES AND DISADVANTAGES

LEACH

- *Advantages*: Low overhead, energy load balancing via cluster head rotation, simplicity.
- *Disadvantages*: Cluster formation overhead, single-hop cluster head communication cost, poor scalability.

PEGASIS

- *Advantages*: Minimal communication energy, even distribution through chain structure, improved network lifetime.
- *Disadvantages*: Increased latency, chain maintenance overhead, vulnerability to chain breaks.

Directed Diffusion

- *Advantages*: Data-centric, supports in-network aggregation, adaptable to queries, resilient to topology changes.
- *Disadvantages*: High control overhead from interest flooding, requires state maintenance, not ideal for continuous data streams.

GEAR (Geographic Routing)

- *Advantages*: Low overhead in dense networks, location-aware energy balancing, low latency.
- *Disadvantages*: Requires localization, poor performance in sparse networks, geographic holes can hinder routing.

VII. RESULTS AND DISCUSSION

Simulation results confirm that each protocol is suited to different WSN scenarios. **PEGASIS**' chain-based design dramatically reduces energy consumption and extends network lifetime, making it ideal for applications where latency is non-critical (e.g., environmental monitoring). **LEACH** balances energy and delay, especially in moderate-size deployments requiring periodic reporting. **Directed Diffusion** offers flexibility and query-driven adaptability, beneficial for event-based sensing tasks, though at the cost of greater control message overhead. **GEAR** excels in applications needing low-latency geographic forwarding, provided accurate localization and sufficient node density.

Trade-offs abound: optimizing for energy efficiency often sacrifices latency or increases complexity. For example, PEGASIS's low energy comes with high path length; Directed Diffusion's adaptability demands more messaging. Moreover, real-world challenges such as asynchronous clocks, node failure, and changing topology warrant further protocol resilience not always captured in simulation.

Therefore, protocol selection must align with application demands—network size, energy constraints, latency sensitivity, and environmental dynamics.

VIII. CONCLUSION

Energy-efficient routing in wireless sensor networks remains a critical design area. Pre-2019 protocols such as LEACH, PEGASIS, Directed Diffusion, and GEAR each contribute unique strategies—clustering, chain-based aggregation, data-centric queries, and geographic forwarding—to conserve energy and extend network lifetime. Our comparative analysis shows that, while no protocol is universally optimal, each excels under specific conditions. Progress in hybrid strategies that combine stacking elements—e.g., cluster-based chains or geographic-aware clustering—promises to yield balanced performances. Future sensor network deployments must carefully consider trade-offs between energy consumption, latency, delivery reliability, and complexity.

IX. FUTURE WORK

Building on pre-2019 protocols, enhancements for the future include:

- **Hybrid Protocols**: Combine clustering with chain or geographic routing for synergistic benefits.
- **Energy-Harvesting Awareness**: Incorporate dynamic energy availability (e.g., solar or vibrational harvesting) into routing decisions.

| ISSN: 2347-8446 | www.ijarcst.org | editor@ijarcst.org |A Bimonthly, Peer Reviewed & Scholarly Journal|

||Volume 3, Issue 2, March-April 2020||

DOI:10.15662/IJARCST.2020.0302001

- **Machine Learning for Cluster Head Selection**: Use reinforcement learning to adaptively choose cluster heads based on residual energy, node centrality, and traffic.
- **Mobility-Aware Routing**: Design protocols that adapt to mobile nodes or moving sinks.
- **Localization-Free Geographic Routing**: Develop routing strategies that approximate location without GPS, reducing hardware overhead.
- **Fault Tolerance**: Introduce self-healing mechanisms to detect and recover from failed nodes or broken chains.

These directions aim to create more robust, adaptive, and efficient routing suitable for dynamic, real-world WSN deployments.

REFERENCES

1. Heinzelman, W. B., Chandrakasan, A., & Balakrishnan, H. (2000). Energy-efficient communication protocol for wireless microsensor networks. *Proceedings of the 33rd Annual Hawaii International Conference on System Sciences (HICSS)*.
2. Lindsey, S., & Raghavendra, C. S. (2002). PEGASIS: Power-efficient gathering in sensor information systems. *IEEE Aerospace Conference Proceedings*.
3. Intanagonwiwat, C., Govindan, R., & Estrin, D. (2003). Directed diffusion: A scalable and robust communication paradigm for sensor networks. *Proceedings of the 6th Annual International Conference on Mobile Computing and Networking (MobiCom)*.
4. Xu, Y., Heidemann, J., & Estrin, D. (2001). Geography-Informed Energy Conservation for Ad Hoc Routing. *Proceedings of the 7th Annual International Conference on Mobile Computing and Networking (MobiCom)*.
5. Yu, Y., Govindan, R., & Estrin, D. (2001). Geographical and Energy Aware Routing: A Recursive Data Dissemination Protocol for Wireless Sensor Networks. *UCLA Technical Report*.
6. Younis, O., & Fahmy, S. (2004). HEED: A hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks. *IEEE Transactions on Mobile Computing*, 3(4), 366–379.
7. Ganesan, D., Krishnamurthy, S. V., Woo, A., et al. (2002). Complex Behavior at Scale: An Experimental Study of Low-Power Wireless Sensor Networks. *Technical Report*, UCLA.
8. Potdar, V., Sharif, K., & Chang, E. (2009). Wireless sensor networks: A survey. *Proceedings of the 2009 International Conference on Advanced Information Networking and Applications Workshops (WAINA)*.