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Energy-Efficient Routing Protocols in Wireless Sensor Networks: A Comprehensive Review

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ABSTRACT

Emerging as a vital technology in many uses including environmental monitoring, healthcare, and industrial automation are wireless sensor networks (WSNs). The lifetime and efficiency of these networks are greatly challenged, nevertheless, by sensor nodes' finite energy resources. Emphasizing energy-efficient routing techniques in WSNs, this thorough study investigates their design ideas, performance criteria, and general application under several conditions. We examine and contrast several types of routing systems: data-centric, location-based, and hierarchical ones. Furthermore included in the paper are current developments in energy-efficient routing including cross-layer optimization methods based on machine learning. At last, we highlight open research questions and future prospects in this subject, therefore offering insightful analysis for practitioners and academics engaged in WSN implementations.

Keywords: Wireless Sensor Networks, Energy-Efficient Routing, Hierarchical Protocols, Location-Based Protocols, Data-Centric Protocols, Machine Learning

1. Introduction

Environmental sensing, healthcare, industrial automation, and smart cities among other fields have transformed data collecting and monitoring via wireless sensor networks (WSNs [1]. These networks comprise spatially dispersed autonomous sensors that collaboratively monitor physical or environmental variables and relay data via the network to a central point [2]. A WSN consists mostly in sensor nodes, sink nodes (or base stations), and the wireless communication infrastructure.

Notwithstanding their many benefits, WSNs provide major difficulties mostly related to the restricted energy resources of sensor nodes [3]. Since these nodes are sometimes placed in far-off or inaccessible locations, it is either expensive or impossible to replace or recharge their batteries. Consequently, especially in routing protocols, energy efficiency has grown to be a major consideration in the design and execution of WSNs [4].

While considering elements like energy consumption, network lifetime, and data delivery dependability, routing procedures in WSNs are in charge of building effective paths for data transmission from source nodes to the sink [5]. Many energy-efficient routing systems have been proposed over the past two decades to solve these problems, each with special method and trade-off.

With an emphasis on their design concepts, performance criteria, and applicability over several scenarios, this work offers a thorough evaluation of energy-efficient routing protocols in WSNs. We classify and examine several routing techniques, including data-centric, location-based, and hierarchical, hierarchical, We also discuss latest developments in the field including cross-layer optimization methods and machine learning-based routing.

This paper is structured as follows generally: An introduction of WSN architecture and energy consumption models is given in Section 2. Section 3 addresses energy-efficient routing protocol classification. Sections 4, 5, and 6 explore, respectively hierarchical, location-based, and data-centric protocols. Section 7 investigates most current developments in energy-efficient routing. Section 8 offers a comparison of the examined protocols. Section 9 points out areas of open study difficulty and future directions. Section 10 closes the paper at last.

2. WSN Architecture and Energy Consumption Models

2.1 WSN Architecture

A typical WSN consists of the following components:

1. Small, low-power sensors with detecting, computation, and communication capabilities abound in sensor nodes. Data collection from the surroundings and distribution to the sink node falls to them.
2. Acting as an interface between the sensor network and the end-user, sink nodes—base stations—are more potent nodes. Before transmitting it to the user, it gathers data from sensor nodes and might process or aggregate it.
3. Gateway: Under some setups, the WSN could be connected to outside networks—like the Internet—using a gateway node.
4. The end user—that is, the person or system—that examines the WSN's gathered data.

2.2 Energy Consumption Models

Development of energy-efficient routing protocols depends on an awareness of WSN energy consumption. Sensor node energy consumption mostly comes from:

- Sensing: Energy eaten by sensors gathering environmental data.
- Energy consumed in data processing and storage activities.
- Usually the most important cause of energy consumption is the effort made in transmitting and receiving data.

Many models of energy consumption have been suggested to project WSN energy consumption [6]. The first-order radio model is one often used model that takes data packet energy consumption for transmission and reception in mind. $E_{Tx}(k, d) = E_{elec} * k + \varepsilon_{amp} * k * d^n$ gives the energy used to transmit a k-bit message over a distance d.

Typically between two and four, n is the route loss exponent; E_{elec} is the energy spent per bit in the transmitter circuitry; ε_{amp} is the energy dissipated in the transmit amplifier.

Receiving a k-bit message requires $E_{Rx}(k) = E_{elec} * k$.

Knowing these energy consumption patterns facilitates the design of routing systems meant to reduce energy use and increase network lifetime.

3. Classification of Energy-Efficient Routing Protocols

Energy-efficient routing protocols in WSNs can be broadly classified into several categories based on their underlying principles and network structure. The main categories include:

1. Hierarchical Protocols
2. Location-Based Protocols
3. Data-Centric Protocols
4. QoS-Based Protocols
5. Multipath Routing Protocols

In this review, we will focus on the first three categories, as they represent the most common and widely studied approaches to energy-efficient routing in WSNs.

4. Hierarchical Routing Protocols

Hierarchical routing systems arrange the network into clusters under cluster leaders in charge of data aggregation and base station communication. By cutting the quantity of long-distance transfers, this method can greatly lower energy use.

4.1 LEACH—Low-Energy Adaptive Clustering Hierarchy

Among the trailblazing hierarchical routing systems for WSNs is LEACH [7]. It uniformly distributes the energy load among sensor nodes by means of a randomized rotation of cluster heads. The protocol runs in rounds, with a steady-state period sandwiched between a setup phase.

Important aspects of LEACH consist in:

Distribution of cluster development

Heads of clusters rotated at random

Local data fusion will help to cut the data flow to the base station.

Although LEACH has various restrictions, such the assumption of homogeneous nodes and single-hop communication to the base station, it greatly increases network lifetime compared to direct transmission or minimum transmission energy protocols.

4.2 PEGASIS, sometimes known as Power-Efficient Gathering in Sensor Information Systems

PEGASIS is a development over LEACH whereby sensor nodes create chains rather than clusters [8]. Every node takes turns broadcasting to the base station and only interacts with its closest neighbor, therefore saving data transmission's energy expenditure.

Important characteristics of PEGASIS comprise:

Data gathering based on chains

At every node, data fusion
Round of single node connection with the base station
Though the extended chain topology causes more latency, PEGASIS beats LEACH in terms of energy economy.

4.3 HEED—Hybrid Energy-Efficient Distributed Clustering—

Considered both residual energy and communication cost in the cluster head choosing process, HEED is a distributed clustering method [9]. It seeks a consistent cluster head distribution over the network.

Important aspects of HEED consist in:

Selection of distributed cluster heads
Multi-hop correspondence between the base station and cluster heads
Examining residual energy and communication cost during cluster creation
Using homogeneous nodes and single-hop communication to the base station, HEED solves some of LEACH's constraints.

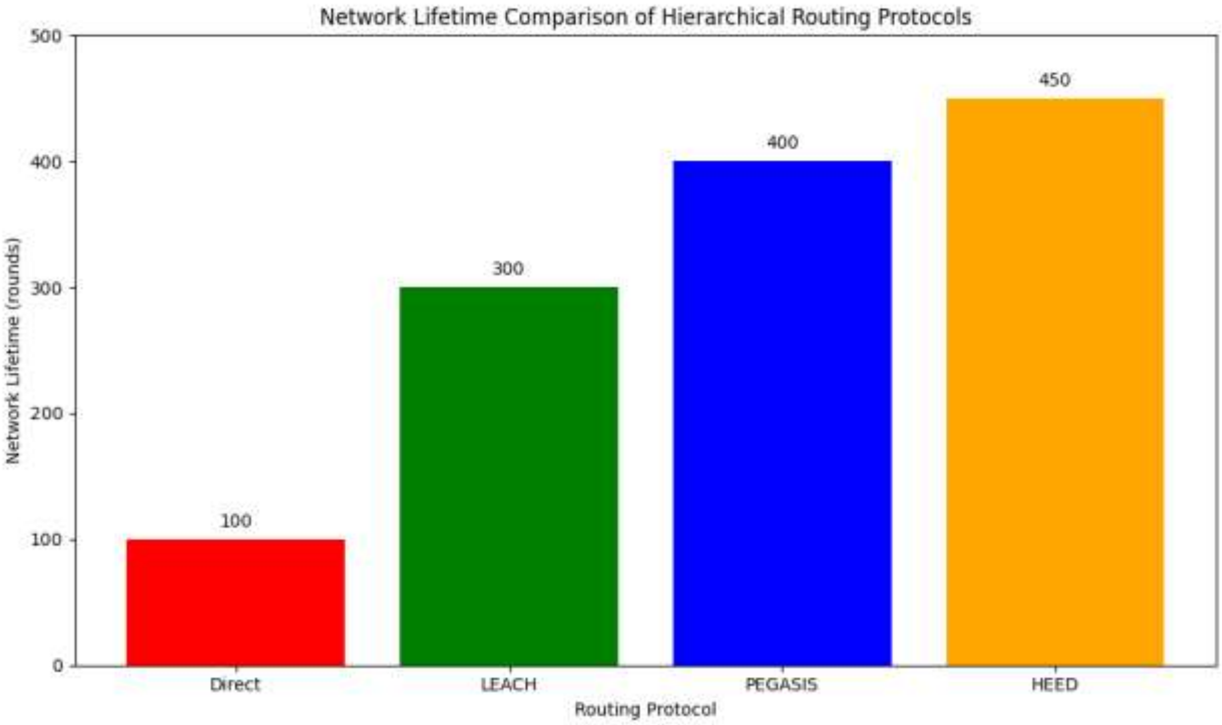

Figure 1: Network Lifetime Comparison of Hierarchical Routing Protocols

5. Location-Based Routing Protocols

Location-based routing systems create routing judgments using sensor node geographical position data. These systems minimize the amount of transmissions and maximize the routing path, therefore lowering the energy usage.

5.1 Geographic and Energy-Aware Routing

Using geologically informed and energy-aware neighbor selection heuristics, GEAR is a location-based routing system that routes packets toward the target area [10]. It seeks to lower transmission count and balance network energy usage.

- Important characteristics of Gears consist in:
- Utilizing residual energy and spatial data in neighbor choosing
- Routing based on regions
- Recursive spatial forwarding inside the target area

Particularly in uneven traffic distribution situations, GEAR displays better performance than non-location-aware protocols.
5.2 Geo-adaptive Fidelity, or GAF
Divising the network area into fixed-sized virtual grids, GAF is an energy-aware location-based routing system [11]. In terms of packet routing, nodes inside the same grid are regarded as identical, so some of them can sleep while keeping routing integrity.

- Main characteristics of GAF consist in:
- Virtual grid-based network segmentation

- Adaptive node sleeping in response to application demand
- Load balancing amongst same grid's nodes

Reducing the number of active nodes while preserving connectivity helps GAF greatly prolong network longevity.

5.3 MECN—Minimal Energy Communication Network

Designed as a location-based protocol, MECN creates and preserves a minimum energy network for wireless networks [12]. It discovers a sub-network with less nodes that requires less transmission between any two nodes, therefore saving electricity.

Important aspects of MECN consist in:

- Spread computation of minimum energy pathways
- Flexible in node installations and failures
- Examining obstacle impacts helps one decide on best linkages.

When compared to networks where all nodes are used for routing, MECN can save notable energy.

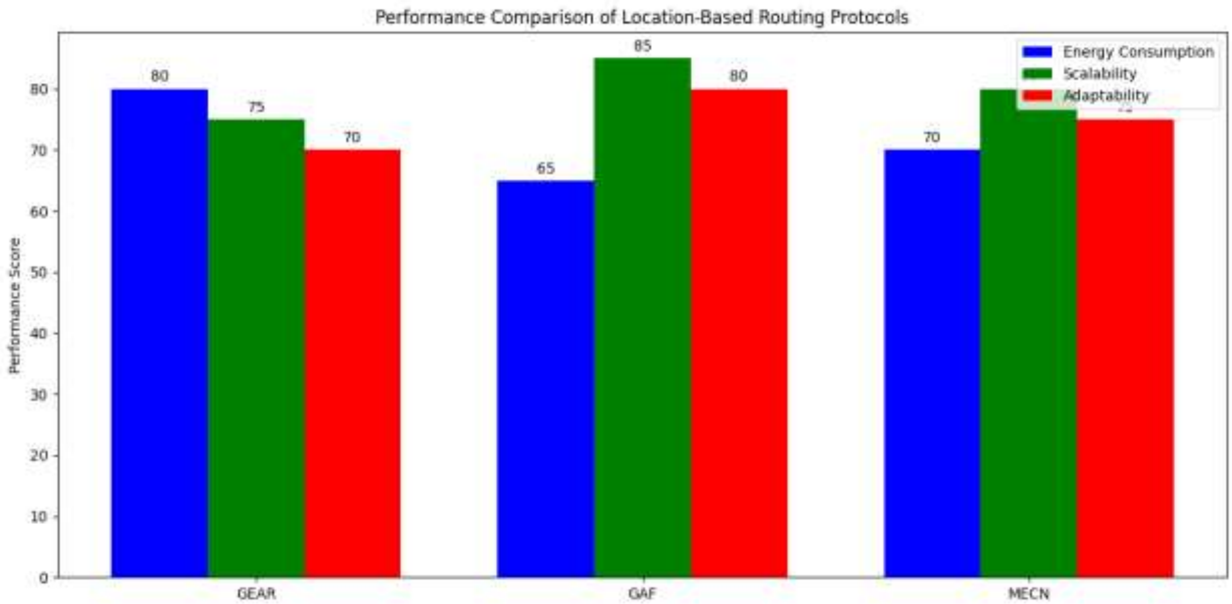

Figure 2: Performance Comparison of Location-Based Routing Protocols

6. Data-Centric Routing Protocols

Focus of data-centric routing systems is on the sensed data instead of the sensor nodes themselves. By use of data aggregation and redundant data transmissions via in-network processing, these protocols seek to lower energy usage.

6.1 SPIN—Sensor Protocols for Information via Negotiation

Within an energy-limited wireless sensor network, SPIN is a family of adaptive protocols that effectively distributes information among sensors [13]. It removes duplicate data transmission by use of meta-data negotiation and resource-adaptive algorithms.

- **Important aspects of SPIN consist in:**

- Using meta-data to characterize sensor data
- Data advertisement and request system

data transmission: resource-aware decision making

Particularly in situations involving spatially confined sensor data, SPIN achieves notable energy savings relative to flooding and gossiping techniques.

6.2 Explicit Diffusion

Directed diffusion is an application-aware, data-centric model for WSN data distribution [14]. It employs a publish-subscribed communication approach whereby the sink node broadcasts interests to all the sensors, therefore requesting data.

Important aspects of directed diffusion consist in:

- Named data based on attribute-value pairs
- Gradient building and dissemination of interest
- In-network data gathering
- Enhancement of best pathways

Data aggregation and redundant transmission elimination allow directed diffusion to save a lot of energy.

6.3 Rumor Routing
An energy-efficient method for guiding searches to nodes having seen specific events in the network is rumor routing [15]. It just preserves paths that are really used and generates paths leading to every event.
Important characteristics of Rumor Routing consist in:
- Event flooding with long-lived packets known as agents
- Query routing along known event routes.
- Agent probabilistic forwarding of searches and inquiries

Whirl rumours Routing is especially helpful in cases when flooding is too expensive and geographic routing is not practical.

7. Recent Advancements in Energy-Efficient Routing
Recent years have seen significant advancements in energy-efficient routing protocols for WSNs, incorporating techniques from machine learning, cross-layer optimization, and bio-inspired computing. Some notable developments include:

7.1 Machine Learning-Based Routing
Machine learning techniques have been applied to optimize routing decisions in WSNs, leading to improved energy efficiency and network performance [16]. These approaches can adapt to changing network conditions and learn optimal routing strategies over time.
Examples of machine learning-based routing protocols include:
- Q-Learning-based adaptive routing
- Neural network-based path selection
- Fuzzy logic-based cluster head selection

7.2 Cross-Layer Optimization
Cross-layer optimization techniques aim to improve energy efficiency by considering information from multiple layers of the network stack [17]. These approaches can lead to more informed routing decisions and better overall network performance.
Examples of cross-layer optimization in routing include:
- Joint routing and MAC layer optimization
- Energy-aware routing with topology control
- QoS-aware cross-layer routing protocols

7.3 Bio-Inspired Routing Protocols
Bio-inspired algorithms, such as ant colony optimization and particle swarm optimization, have been applied to develop energy-efficient routing protocols for WSNs [18]. These approaches mimic natural processes to find optimal routing paths and balance energy consumption across the network.
Examples of bio-inspired routing protocols include:
- Ant Colony Optimization-based routing
- Artificial Bee Colony-based clustering and routing
- Genetic Algorithm-based path optimization

8. Comparative Analysis
Table 1 presents a comparative analysis of the reviewed energy-efficient routing protocols based on various performance metrics.

Table 1: Comparative Analysis of Energy-Efficient Routing Protocols

Protocol	Energy Efficiency	Scalability	Load Balancing	Latency	Complexity
LEACH	High	Medium	Medium	Low	Low
PEGASIS	Very High	Low	High	High	Medium
HEED	High	High	High	Medium	Medium
GEAR	High	High	Medium	Low	Medium
GAF	High	High	High	Medium	Low
MECN	Very High	Medium	Medium	Low	High
SPIN	High	Medium	High	Low	Medium

Directed Diffusion	High	High	High	Medium	High
Rumor Routing	Medium	High	Medium	Medium	Low

This comparative analysis highlights the trade-offs between different routing approaches and can guide researchers and practitioners in selecting appropriate protocols for specific WSN applications.

9. Open Research Challenges and Future Directions

Even with major progress in WSN energy-efficient routing techniques, some difficulties still exist. Among the main open research topics and future orientations are some:

1. Creating routing systems capable of effectively managing networks with varied nodes, varying energy capacities, and different communication ranges will help to address heterogeneous networks.
2. Designing systems that can sustain energy efficiency and performance in vast-scale WSN installations including hundreds of millions of nodes is known as scalability.
3. Including energy-efficient security methods into routing systems helps to minimize energy overhead and guard against different kinds of threats.
4. Mobile WSNs address the difficulties of node mobility in energy-efficient routing including dynamic link quality and frequent topological changes.
5. Investigating WSN integration with upcoming technologies including edge computing, the Internet of Things (IoT), and 5G/6G networks can help to improve general performance and energy economy.
6. Creating routing systems capable of real-time adaptation to changing network circumstances, application needs, and environmental elements will help to be context-aware.
7. Including energy harvesting methods into routing systems helps to extend network lifetime and maybe attain continuous operation in specific situations.
8. Further investigating the possibility of machine learning and artificial intelligence approaches to maximize routing decisions and raise general network performance.
9. Investigating more complete cross-layer optimization techniques considering interactions across several layers of the network stack would help to attain improved energy economy.
10. Working toward standardizing energy-efficient routing protocols will help to enable interoperability and more general acceptance in commercial WSN implementations.

10. Conclusion

Focusing on hierarchical, location-based, and data-centric methods, this thorough analysis has investigated many energy-efficient routing techniques for Wireless Sensor Networks. For every category we have examined the design concepts, salient features, and performance qualities of well-known protocols. We have also looked at more recent developments in the subject like cross-layer optimization methods and machine learning-based routing.

This review's comparative analysis emphasizes the trade-offs between several routing techniques and can direct researchers and practitioners in choosing suitable protocols for certain WSN uses. Although energy-efficient routing protocols have advanced significantly, some difficulties still exist, especially with regard to scalability, security, and adaption to heterogeneous and mobile networks.

Future studies should concentrate on tackling these difficulties and investigating the integration of WSNs with newly developing technology. Maximizing network longevity and general performance depends on the development of more effective, flexible, and strong routing protocols as WSNs remain indispensable in many different applications.

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, 2002.

[2] J. Yick, B. Mukherjee, and D. Ghosal, "Wireless sensor network survey," Computer Networks, vol. 52, no. 12, pp. 2292-2330, 2008.

[3] G. Anastasi, M. Conti, M. Di Francesco, and A. Passarella, "Energy conservation in wireless sensor networks: A survey," Ad Hoc Networks, vol. 7, no. 3, pp. 537-568, 2009.

[4] J. N. Al-Karaki and A. E. Kamal, "Routing techniques in wireless sensor networks: a survey," IEEE Wireless Communications, vol. 11, no. 6, pp. 6-28, 2004.

[5] K. Akkaya and M. Younis, "A survey on routing protocols for wireless sensor networks," Ad Hoc Networks, vol. 3, no. 3, pp. 325-349, 2005.

[6] M. Lounis, A. Bounceur, A. Laga, and B. Pottier, "CPU-GPU based on parallel computing for wireless sensor networks," Journal of Network and Computer Applications, vol. 45, pp. 1-10, 2014.

[7] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in Proceedings of the 33rd Annual Hawaii International Conference on System Sciences, 2000.
[8] S. Lindsey and C. S. Raghavendra, "PEGASIS: Power-efficient gathering in sensor information systems," in Proceedings of IEEE Aerospace Conference, 2002.
[9] 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, 2004.
[10] Y. Yu, R. Govindan, and D. Estrin, "Geographical and energy aware routing: a recursive data dissemination protocol for wireless sensor networks," UCLA Computer Science Department Technical Report, 2001.
[11] Y. Xu, J. Heidemann, and D. Estrin, "Geography-informed energy conservation for ad hoc routing," in Proceedings of the 7th Annual International Conference on Mobile Computing and Networking, 2001.
[12] V. Rodoplu and T. H. Meng, "Minimum energy mobile wireless networks," IEEE Journal on Selected Areas in Communications, vol. 17, no. 8, pp. 1333-1344, 1999.
[13] J. Kulik, W. Heinzelman, and H. Balakrishnan, "Negotiation-based protocols for disseminating information in wireless sensor networks," Wireless Networks, vol. 8, no. 2/3, pp. 169-185, 2002.
[14] C. Intanagonwiwat, R. Govindan, and D. Estrin, "Directed diffusion: a scalable and robust communication paradigm for sensor networks," in Proceedings of the 6th Annual International Conference on Mobile Computing and Networking, 2000.
[15] D. Braginsky and D. Estrin, "Rumor routing algorithm for sensor networks," in Proceedings of the 1st ACM International Workshop on Wireless Sensor Networks and Applications, 2002.
[16] M. A. Alsheikh, S. Lin, D. Niyato, and H. P. Tan, "Machine learning in wireless sensor networks: Algorithms, strategies, and applications," IEEE Communications Surveys & Tutorials, vol. 16, no. 4, pp. 1996-2018, 2014.
[17] F. Foukalas, V. Gazis, and N. Alonistioti, "Cross-layer design proposals for wireless mobile networks: a survey and taxonomy," IEEE Communications Surveys & Tutorials, vol. 10, no. 1, pp. 70-85, 2008.
[18] S. P. Singh, S. C. Sharma, and M. Sharma, "Energy efficient cluster based routing protocol for WSN using butterfly optimization algorithm and ant colony optimization," Ad Hoc Networks, vol. 110, p. 102317, 2021.
[19] Onuekwusia, N.C.; Okpara, C.R. Wireless Sensor Networks (WSN): An Overview. Am. Sci. Res. J. Eng. Technol. Sci. 2020, 64, 53–63. [Google Scholar]
[20] Kandris, D.; Nakas, C.; Vomvas, D. Applications of Wireless Sensor Networks: An Up-to-Date Survey. Appl. Syst. Innov. 2022, 3, 14. [Google Scholar] [CrossRef]
[21] Tsvetanov, F.; Georgieva, I. Modeling of Energy Consumption of Sensor Nodes. In Proceedings of the 2023 43rd International Convention on Information, Communication and Electronic Technology (MIPRO), Opatija, Croatia, 28 September–2 October 2020; pp. 431–436. [Google Scholar]