

Energy-Efficient Routing in Wireless Sensor Networks: A Review of Classical and Intelligent Routing Techniques

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Abstract

Wireless Sensor Networks (WSNs) have emerged as an essential technology for monitoring and data collection in applications such as environmental surveillance, healthcare, industrial automation, agriculture, and smart cities. Since sensor nodes operate with limited battery resources and are often deployed in inaccessible environments, energy efficiency remains one of the most critical challenges in WSN design. Routing protocols play a significant role in determining network performance because communication consumes a major portion of node energy. This paper presents a comprehensive study of energy-efficient routing techniques in Wireless Sensor Networks. Various routing protocols, including flat, hierarchical, location-based, hybrid, multipath, query-based, negotiation-based, and Quality of Service (QoS)-based approaches, are discussed and theoretically classified. The study also reviews prominent protocols such as LEACH, PEGASIS, TEEN, HEED, DEEC, GEAR, and SPIN, highlighting their characteristics, advantages, limitations, and energy conservation capabilities. Furthermore, recent advancements in Artificial Intelligence, Machine Learning, Fuzzy Logic, Particle Swarm Optimization, and Ant Colony Optimization-based routing techniques are examined. Comparative analysis indicates that intelligent and adaptive routing approaches provide superior energy efficiency, scalability, load balancing, and network lifetime, making them promising solutions for future WSN and Internet of Things (IoT) applications.

Keywords

Wireless Sensor Networks (WSNs), Energy-Efficient Routing, LEACH, PEGASIS, TEEN, Hierarchical Routing, Location-Based Routing, Artificial Intelligence, Machine Learning, O.

Introduction

1. Energy Efficient Routing in Wireless Sensor Networks (WSNs)

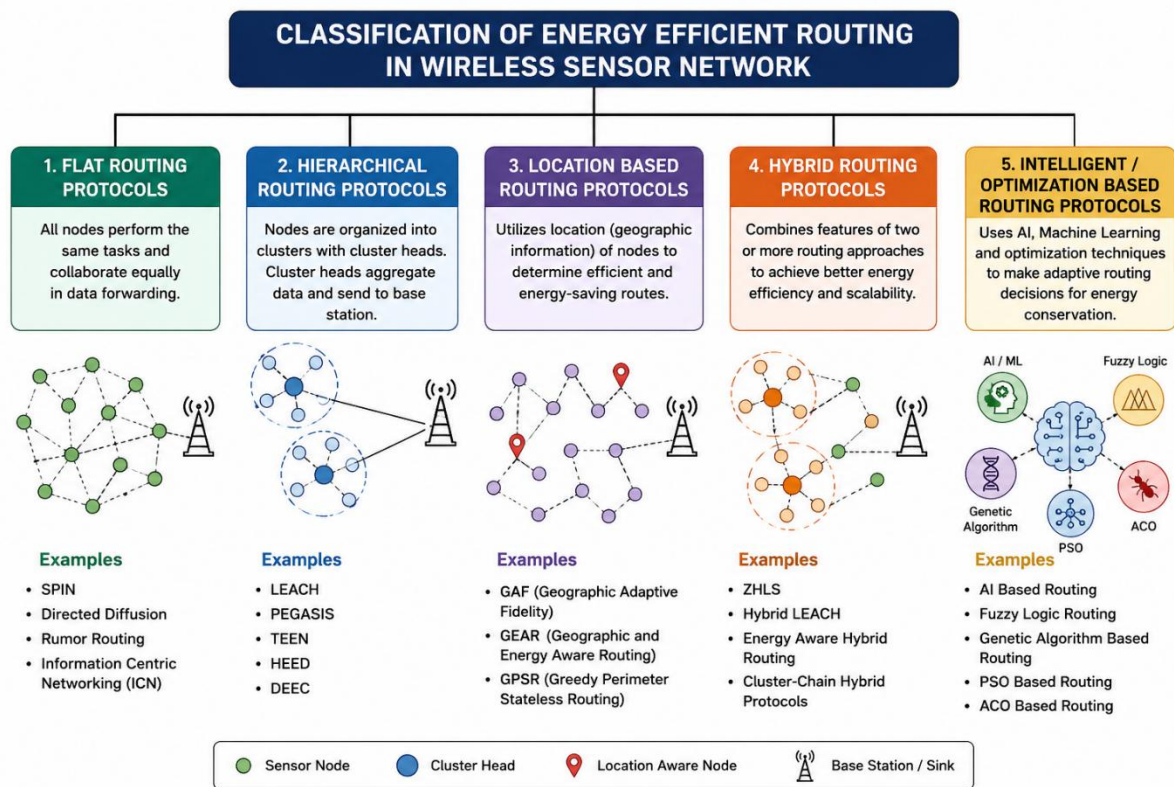
Wireless Sensor Networks (WSNs) have emerged as one of the most significant technologies in the field of wireless communication and embedded systems. A Wireless Sensor Network consists of a large number of tiny sensor nodes that are deployed in a physical environment to monitor environmental conditions such as temperature, humidity, pressure, vibration, sound, and motion. These sensor nodes communicate wirelessly and collaboratively transmit the collected information to a central base station or sink node for further processing and analysis. Due to their wide applicability in military surveillance, healthcare monitoring, environmental observation, industrial automation, agriculture, and smart cities, WSNs have gained enormous attention from researchers and industries across the world.

A typical sensor node in a WSN is composed of sensing units, microcontrollers, memory units, wireless transceivers, and power supply components. Among all these components, the energy source or battery plays a critical role because sensor nodes are generally deployed in remote or inaccessible areas where battery replacement or recharging is extremely difficult. Therefore, energy efficiency becomes one of the most important design challenges in Wireless Sensor Networks. Since communication operations consume more energy than sensing or processing operations, the routing mechanism used for transmitting data significantly affects the overall network lifetime.

Routing in WSN refers to the process of selecting efficient communication paths between sensor nodes and the base station. Traditional routing protocols designed for conventional wireless networks are not suitable for WSNs because sensor networks have unique characteristics such as limited power resources, dense deployment, dynamic topology, low bandwidth, and data redundancy. Hence, specialized energy-efficient routing protocols are required to optimize power consumption while maintaining reliable data transmission.

The primary objective of energy-efficient routing is to minimize energy consumption during communication and maximize the operational lifetime of the network. Efficient routing protocols attempt to reduce unnecessary transmissions, balance energy usage among nodes, avoid network congestion, and minimize packet loss. In WSNs, if certain nodes consume energy faster than others, network partitioning may occur, leading to communication failures and reduced network performance. Therefore, routing protocols must distribute energy consumption uniformly across the network.

1.1 Classification of Routing protocols



1.2 Theoretical Classification of Energy Efficient Routing in Wireless Sensor Networks (WSNs)

Energy-efficient routing protocols in Wireless Sensor Networks (WSNs) are classified on the basis of network structure, communication model, routing strategy, and energy conservation techniques. The primary objective of these routing protocols is to reduce energy consumption, improve communication efficiency, and extend the operational lifetime of the network. The theoretical classification of energy-efficient routing protocols is explained below:

12.1. Flat Routing Protocols (Data-Centric Routing)

In flat routing protocols, all sensor nodes perform the same role and possess equal functionality. There is no hierarchical organization among nodes. Communication occurs through collaboration between nodes, and data is transmitted based on queries or data attributes rather than node addresses.

1.2.2 Characteristics

- All nodes have equal importance.
- Data-centric communication is used.
- Suitable for small-scale networks.
- Reduces redundant data transmission.

1.2.3 Advantages

- Simple architecture.
- Efficient for homogeneous networks.
- Reduces communication overhead.

1.2.4 Disadvantages

- Not suitable for large-scale networks.
- Increased delay due to flooding mechanisms.

1.2.5 Examples

- SPIN (Sensor Protocols for Information via Negotiation)
- Directed Diffusion
- Rumor Routing

2. Hierarchical Routing Protocols (Cluster-Based Routing)

Hierarchical routing protocols organize sensor nodes into clusters. Each cluster contains a Cluster Head (CH) responsible for collecting, aggregating, and forwarding data to the base station. These protocols are highly energy-efficient because they reduce long-distance communication.

2.1 Characteristics

- Nodes are grouped into clusters.
- Cluster Heads manage communication.
- Data aggregation is performed.
- Reduces transmission energy.

2.2 Advantages

- Enhances scalability.
- Balances energy consumption.
- Extends network lifetime.

2.3 Disadvantages

- Cluster Head failure affects communication.
- Cluster formation creates additional overhead.

2.4 Examples

- LEACH (Low-Energy Adaptive Clustering Hierarchy)
- PEGASIS
- TEEN
- HEED
- DEEC

3. Location-Based Routing Protocols (Geographic Routing)

Location-based routing protocols utilize the geographical positions of sensor nodes to determine routing paths. Sensor nodes use GPS or localization algorithms to identify their positions and select energy-efficient routes.

3.1 Characteristics

- Routing decisions are based on node location.
- Reduces unnecessary data transmission.
- Optimizes communication distance.

3.2 Advantages

- Saves energy through shortest-path routing.
- Improves routing efficiency.
- Reduces communication delay.

3.3 Disadvantages

- Requires localization hardware or algorithms.
- GPS implementation may increase cost.

3.4 Examples

- GAF (Geographic Adaptive Fidelity)
- GEAR (Geographic and Energy Aware Routing)
- GPSR (Greedy Perimeter Stateless Routing)

4. Hybrid Routing Protocols

Hybrid routing protocols combine the features of two or more routing techniques to achieve better performance and energy efficiency. These protocols adapt according to network conditions and application requirements.

4.1 Characteristics

- Combines hierarchical and flat routing approaches.
- Adaptive communication mechanisms.
- Provides better scalability and flexibility.

4.2 Advantages

- Improved energy conservation.
- Better load balancing.
- Increased reliability.

4.3 Disadvantages

- Complex implementation.
- Higher computational overhead.

4.4 Examples

- Hybrid LEACH
- ZHLS (Zone-Based Hierarchical Link State Routing)
- Energy-Aware Hybrid Routing

5. Multipath Routing Protocols

Multipath routing protocols establish multiple communication paths between source and destination nodes. If one path fails, another path is used for data transmission, improving reliability and fault tolerance.

5.1 Characteristics

- Multiple paths are maintained.
- Provides backup communication routes.
- Supports load balancing.

5.2 Advantages

- Increases reliability.
- Reduces packet loss.
- Enhances fault tolerance.

5.3 Disadvantages

- More routing overhead.
- Increased energy consumption due to maintaining multiple paths.

5.4 Examples

- N-to-1 Multipath Routing
- Braided Multipath Routing

6. Query-Based Routing Protocols

In query-based routing, the sink node sends queries to sensor nodes requesting specific information. Nodes with relevant data respond to the query.

6.1 Characteristics

- Communication is query-driven.
- Data transmission occurs only when requested.
- Reduces unnecessary communication.

6.2 Advantages

- Energy-efficient communication.
- Reduces redundant transmissions.

6.3 Disadvantages

- Delay may occur during query processing.
- Less efficient for continuous monitoring systems.

6.4 Examples

- Directed Diffusion
- ACQUIRE

7. Negotiation-Based Routing Protocols

Negotiation-based routing protocols use negotiation mechanisms to eliminate redundant data transmission. Nodes exchange metadata information before actual data transmission.

7.1 Characteristics

- Uses metadata negotiation.
- Prevents duplicate transmissions.
- Conserves energy.

7.2 Advantages

- Efficient bandwidth utilization.
- Reduces unnecessary communication.

7.3 Disadvantages

- Metadata exchange introduces overhead.
- May increase communication delay.

7.4 Examples

- SPIN Protocol Family

8. QoS-Based Routing Protocols (Quality of Service Routing)

QoS-based routing protocols focus on maintaining Quality of Service parameters such as delay, bandwidth, reliability, and energy efficiency.

8.1 Characteristics

- Supports real-time communication.
- Balances QoS and energy consumption.
- Prioritizes critical data.

8.2 Advantages

- Suitable for multimedia and healthcare applications.
- Ensures reliable communication.

8.3 Disadvantages

- Complex routing mechanisms.
- Increased energy consumption for QoS maintenance.

8.4 Examples

- SAR (Sequential Assignment Routing)
- SPEED Protocol

9. Coherent and Non-Coherent Routing Protocols

This classification is based on data processing methods before transmission.

(a) Coherent Routing

In coherent routing, minimal processing is performed at sensor nodes before data transmission.

Advantages

- Low processing overhead.
- Faster communication.

Disadvantages

- Increased communication load.

(b) Non-Coherent Routing

In non-coherent routing, significant data processing and aggregation are performed before transmission.

Advantages

- Reduces communication energy.
- Eliminates redundant data.

Disadvantages

- Higher processing complexity.

Chapter 2

Literature Survey

Wireless Sensor Networks (WSNs) have become a major research area due to their wide applications in environmental monitoring, healthcare systems, industrial automation, military surveillance, and smart cities. Since sensor nodes operate with limited battery power, energy-efficient routing has emerged as one of the most critical challenges in WSNs. Researchers have proposed numerous routing protocols and optimization techniques to improve network lifetime, reduce energy consumption, and enhance communication efficiency. The following literature survey presents significant research contributions related to energy-efficient routing in Wireless Sensor Networks.

1. Akyildiz et al.

Wireless Sensor Networks researchers Ian F. Akyildiz, Weilian Su, Yogesh Sankarasubramaniam, and Erdal Cayirci presented one of the earliest comprehensive surveys on Wireless Sensor Networks. The study discussed the architecture, communication protocols, challenges, and applications of WSNs. The authors identified energy conservation as one of the primary research concerns because sensor nodes are battery-operated and often deployed in inaccessible locations. The paper emphasized the importance of designing energy-efficient routing protocols to extend network lifetime and improve communication reliability.

2. Heinzelman et al. – LEACH Protocol

Heinzelman et al. proposed the LEACH (Low-Energy Adaptive Clustering Hierarchy) protocol, which became one of the most widely used hierarchical routing protocols in WSNs. LEACH introduced a clustering mechanism where sensor nodes are grouped into clusters, and cluster heads are selected randomly to distribute energy consumption evenly among nodes. The protocol also performs data aggregation at cluster heads before transmission to the base station, thereby reducing communication overhead and conserving energy. The study demonstrated significant improvements in network lifetime compared to traditional routing approaches. Later studies highlighted that LEACH suffers from limitations such as random cluster head selection and uneven cluster distribution. Nevertheless, LEACH laid the foundation for many advanced energy-efficient clustering protocols.

3. Lindsey and Raghavendra

Lindsey and Raghavendra proposed PEGASIS (Power-Efficient Gathering in Sensor Information Systems), which improves energy efficiency by organizing sensor nodes into chains instead of clusters. In PEGASIS, each node communicates only with its nearest neighbor, and one node in the chain transmits aggregated data to the base station. This approach significantly reduces communication distance and energy consumption. The authors showed that PEGASIS achieves better network lifetime than LEACH because it minimizes the number of long-distance transmissions. However, PEGASIS introduces higher communication delay due to sequential data forwarding among nodes.

4. Manjeshwar and Agrawal – TEEN Protocol

Manjeshwar and Agrawal developed TEEN (Threshold-sensitive Energy Efficient sensor Network protocol), which is specifically designed for time-critical applications. TEEN uses hierarchical clustering and introduces Hard Threshold (HT) and Soft Threshold (ST) mechanisms to control data transmission. Sensor nodes transmit data only when sensed values exceed predefined thresholds. The protocol significantly reduces unnecessary data transmission and conserves energy. TEEN is highly suitable for applications such as fire detection and emergency monitoring where immediate response is required. However, the protocol may not be suitable for applications requiring continuous data monitoring.

5. Nakas et al. (2020)

Christos Nakas, Dionisis Kandris, and Georgios Visvardis presented a comprehensive survey on energy-efficient routing protocols in Wireless Sensor Networks. The study classified routing protocols into different categories including flat routing, hierarchical routing, location-based routing, QoS-based routing, and multipath routing. The authors compared

various protocols based on performance metrics such as energy consumption, scalability, packet delivery ratio, and network lifetime. The survey concluded that hierarchical routing protocols and intelligent optimization techniques provide better energy conservation and scalability for modern WSN applications. The paper also highlighted future research challenges such as security, fault tolerance, mobility support, and integration with Internet of Things (IoT) systems.

6. Zagrouba and Kardi (2021)

Rachid Zagrouba and Amine Kardi conducted a comparative study of energy-efficient routing techniques in Wireless Sensor Networks. The researchers proposed a new taxonomy for routing protocols based on parameters such as network architecture, communication initiation, delivery mode, topology, and application type. The study analysed protocols including LEACH, Mod-LEACH, iLEACH, E-DEEC, PEGASIS, and M-GEAR using NS3 simulation tools. The authors concluded that intelligent and adaptive routing techniques based on Artificial Intelligence and optimization algorithms are highly effective in enhancing network lifetime and improving sensing area coverage.

7. Jain and Goel (2018)

Abhilasha Jain and Ashok Kumar Goel reviewed various energy-efficient routing algorithms in Wireless Sensor Networks. Their research emphasized the problem of limited battery power and uneven energy depletion among sensor nodes. The authors discussed heterogeneous routing approaches where nodes with different energy levels are utilized to improve network lifetime. The study compared several routing algorithms based on parameters such as throughput, scalability, fault tolerance, and energy consumption. The researchers suggested that clustering and intelligent routing mechanisms significantly improve network performance and energy efficiency.

8. Patel and Soni (2015)

Ashish D. Patel and Honey A. Soni presented a survey on energy-efficient routing protocols with special emphasis on hierarchical routing techniques such as LEACH, PEGASIS, and TEEN. The authors highlighted that energy is the most valuable resource in Wireless Sensor Networks and routing protocols must minimize energy wastage during communication. Their study concluded that clustering-based protocols are more efficient than flat routing approaches because they reduce communication overhead and support data aggregation. The paper also discussed the importance of balancing energy consumption among sensor nodes to prevent early node failures.

9. Al-Karaki and Kamal

Al-Karaki and Kamal reviewed routing techniques in Wireless Sensor Networks and classified routing protocols into flat, hierarchical, and location-based categories. The authors discussed several design challenges such as fault tolerance, scalability, data aggregation, and Quality of Service (QoS). The study emphasized that routing protocols should focus on minimizing communication energy because wireless transmission consumes significantly more power than sensing and processing operations. The researchers also identified the need for adaptive routing protocols capable of handling dynamic network conditions.

10. Soft Computing and AI-Based Routing Approaches

Recent research has focused on Artificial Intelligence (AI), Fuzzy Logic, Genetic Algorithms, Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) for energy-efficient routing in WSNs. These intelligent techniques dynamically optimize routing decisions based on network conditions, residual energy, communication cost, and node reliability. Soft computing-based routing protocols improve load balancing, fault tolerance, and network lifetime. Researchers have shown that AI-based routing mechanisms outperform traditional routing protocols in dynamic and large-scale sensor networks.

Comparison Table of Energy Efficient Routing Protocols in Wireless Sensor Networks (WSNs)

Protocol	Type of Routing	Main Technique Used	Energy Efficiency	Scalability	Advantages	Limitations
LEACH (Low-Energy Adaptive Clustering Hierarchy)	Hierarchical / Cluster-Based	Randomized Cluster Head Selection	High	Good	Reduces communication overhead and balances energy consumption	Random cluster head selection may reduce efficiency
PEGASIS (Power-Efficient)	Chain-Based Hierarchical	Chain Formation Between	Very High	Moderate	Minimizes communication distance	High transmission delay due to

Protocol	Type of Routing	Main Technique Used	Energy Efficiency	Scalability	Advantages	Limitations
Gathering in Sensor Information Systems)		Nodes			and increases network lifetime	chain communication
TEEN (Threshold-sensitive Energy Efficient Network)	Hierarchical Reactive Routing	Threshold-Based Data Transmission	Very High	Good	Suitable for time-critical applications and reduces unnecessary transmissions	Not suitable for continuous monitoring applications
APTEEN (Adaptive Periodic TEEN)	Hybrid Routing	Combines Periodic and Threshold-Based Transmission	High	Good	Supports both periodic and event-driven communication	Increased complexity and overhead
HEED (Hybrid Energy-Efficient Distributed Clustering)	Hierarchical Routing	Residual Energy-Based Cluster Head Selection	High	Very Good	Better cluster formation and balanced energy usage	Additional communication overhead during clustering

Protocol	Type of Routing	Main Technique Used	Energy Efficiency	Scalability	Advantages	Limitations
SPIN (Sensor Protocols for Information via Negotiation)	Flat/Data-Centric Routing	Metadata Negotiation	Moderate	Limited	Eliminates redundant data transmission	Delivery of data is not guaranteed
Directed Diffusion	Data-Centric Routing	Interest-Based Communication	High	Moderate	Reduces redundant transmissions and supports in-network aggregation	Not suitable for continuous data delivery
GAF (Geographic Adaptive Fidelity)	Location-Based Routing	Geographic Information Utilization	Moderate	Good	Conserves energy by turning off unnecessary nodes	Requires accurate location information
GEAR (Geographic and Energy Aware Routing)	Location-Based Routing	Geographic and Residual Energy Information	High	Good	Efficient route selection and energy conservation	Increased routing complexity

Protocol	Type of Routing	Main Technique Used	Energy Efficiency	Scalability	Advantages	Limitations
DEEC (Distributed Energy Efficient Clustering)	Hierarchical Heterogeneous Routing	Residual Energy-Based CH Selection	Very High	Very Good	Suitable for heterogeneous sensor networks	Complex energy calculations
SEP (Stable Election Protocol)	Hierarchical Routing	Weighted Cluster Head Election	High	Good	Improves network stability period	Limited adaptability in dynamic networks
Rumor Routing	Flat Routing	Event-Based Communication	Moderate	Moderate	Reduces flooding overhead	May increase delay in large networks
SAR (Sequential Assignment Routing)	QoS-Based Routing	QoS and Energy Balancing	Moderate	Moderate	Supports fault tolerance and QoS requirements	High routing overhead
SPEED Protocol	QoS-Based Routing	Delay-Aware Routing	Moderate	Good	Provides real-time communication support	Increased energy consumption
ACO-Based Routing	Intelligent Optimization Routing	Ant Colony Optimization	Very High	Very Good	Finds optimal energy-efficient paths dynamically	Higher computational complexity

Protocol	Type of Routing	Main Technique Used	Energy Efficiency	Scalability	Advantages	Limitations
PSO-Based Routing	AI-Based Routing	Particle Swarm Optimization	Very High	Very Good	Improves load balancing and network lifetime	Requires optimization processing
Fuzzy Logic Routing	Intelligent Routing	Fuzzy Decision-Making	High	Good	Handles uncertainty and dynamic network conditions	Complex rule management
Machine Learning-Based Routing	AI/ML Routing	Predictive and Adaptive Routing	Very High	Excellent	Adaptive decision-making and improved energy efficiency	High computational and training requirements

Performance Comparison Summary

Parameter	Best Performing Protocols
Maximum Energy Efficiency	PEGASIS, DEEC, ACO-Based Routing
Best Scalability	HEED, DEEC, Machine Learning-Based Routing
Lowest Communication Delay	LEACH, TEEN
Best Fault Tolerance	Multipath and AI-Based Routing
Best for Time-Critical Applications	TEEN, SPEED

Parameter	Best Performing Protocols
Best for Heterogeneous Networks	DEEC, SEP
Best Intelligent Optimization	ACO, PSO, Machine Learning Routing

Key Observations

1. **Hierarchical routing protocols** such as LEACH, PEGASIS, TEEN, and HEED are widely used because they significantly reduce communication energy through clustering and data aggregation.
2. **Location-based routing protocols** improve routing efficiency by using geographic information to minimize communication distance.
3. **Flat routing protocols** are simple but less scalable for large sensor networks.
4. **AI and optimization-based routing techniques** provide the best overall energy efficiency and adaptability in dynamic environments.
5. **Hybrid routing protocols** combine multiple routing approaches and provide better scalability, reliability, and load balancing.
6. Modern research mainly focuses on integrating **Artificial Intelligence, Machine Learning, IoT, and optimization algorithms** with routing protocols to further improve network lifetime and energy conservation.

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