

# Advances in Topological Routing Strategies for Wireless Sensor Networks: A Comprehensive Review

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**Abstract**— Wireless Sensor Networks (WSNs) are characterized by their distributed nature and the need for efficient communication protocols to handle the constraints of limited resources. Topological routing, a critical aspect of WSNs, leverages the network's structure to optimize data transmission, ensuring scalability and reliability. This paper presents a comprehensive review of topological routing techniques in WSNs, highlighting various strategies including flooding, hierarchical routing, geographic routing, and cluster-based approaches. We discuss the advantages and limitations of each method in terms of energy efficiency, data delivery accuracy, and network scalability. Furthermore, we examine recent advancements in routing algorithms, including the integration of machine learning and optimization techniques to enhance performance. The paper also explores practical implementations and case studies to illustrate the real-world applicability of these routing strategies. Finally, we propose future research directions to address existing challenges and explore emerging trends in the field of wireless network topological routing.

**Index Terms**— Topological Routing, Wireless Sensor Networks (WSNs), Routing Protocols, Energy Efficiency, Hierarchical Routing, Geographic Routing, Cluster-Based Routing, Machine Learning in Routing

## I. INTRODUCTION

Wireless Sensor Networks (WSNs) represent a pivotal technology in modern communication, enabling the deployment of distributed sensor nodes to monitor and interact with physical environments. These networks are utilized across a diverse range of applications, including environmental monitoring, military surveillance, healthcare, and smart cities. The efficient operation of WSNs is heavily reliant on robust and optimized routing protocols, which address the unique challenges posed by the network's topology.

In WSNs, nodes are often deployed in large quantities over an area, leading to a dynamic and unpredictable network topology. This variability necessitates sophisticated routing strategies to ensure reliable data transmission while managing the constraints of limited energy resources and network bandwidth. Topological routing, which involves the use of network topology to guide data packets from source to destination, is crucial for optimizing the performance of these networks.

This paper explores the concept of topological routing within WSNs, focusing on various routing strategies and

their implications for network performance. We begin by introducing fundamental concepts of WSNs, including their architecture and common applications. We then delve into different topological routing approaches, such as flooding, hierarchical routing, geographic routing, and cluster-based routing. Each method is analyzed for its efficiency, scalability, and suitability for different network scenarios.

We also review recent advancements in routing technologies, including the application of machine learning algorithms and optimization techniques, which offer promising improvements in routing performance. The discussion is complemented by practical case studies that illustrate the effectiveness of these techniques in real-world deployments.

Finally, we identify key challenges and propose future research directions aimed at addressing current limitations and exploring new opportunities in the field of wireless network topological routing.

## II. TOPOLOGICAL ROUTING

Topological routing in Wireless Sensor Networks (WSNs) refers to the strategies employed to route data packets based on the network's topology. This approach leverages the spatial arrangement and connectivity of nodes to optimize data transmission, ensuring efficient use of resources and enhancing overall network performance. Key routing strategies under this category include:

### 1. Flooding and Gossiping:

- ✓ **Flooding** involves broadcasting packets to all neighboring nodes, which then propagate the packet to their neighbors, and so on, until the packet reaches the destination. While simple and robust, flooding can lead to high redundancy and increased network traffic.
- ✓ **Gossiping**, a more controlled version of flooding, involves probabilistic packet forwarding to reduce redundancy and network congestion. Nodes forward packets to a random subset of neighbors, reducing the chance of redundant transmissions.

### 2. Hierarchical Routing:

- ✓ This method organizes nodes into hierarchical levels, often creating clusters with designated cluster heads. Cluster heads manage intra-cluster communication and relay aggregated data to the base station, reducing the number of transmissions and conserving energy. Popular protocols include:

✓ **LEACH (Low-Energy Adaptive Clustering Hierarchy)**: Rotates cluster heads periodically to balance energy consumption and enhance network longevity.

✓ **HEED (Hybrid Energy-Efficient Distributed Clustering)**: Combines energy and communication cost to form clusters, aiming for balanced energy consumption across the network.

### 3. Geographic Routing:

✓ Geographic or location-based routing utilizes the geographic coordinates of nodes to make routing decisions. Nodes forward packets to the neighbor closest to the destination based on location information. Techniques include:

○ **GPSR (Greedy Perimeter Stateless Routing)**: Uses greedy forwarding to route packets towards the destination, and when faced with local minima, switches to perimeter routing to bypass obstacles.

### 4. Cluster-based Routing:

✓ Nodes are grouped into clusters, with each cluster having a leader or cluster head responsible for data aggregation and routing. This approach aims to reduce communication overhead and extend network lifetime. Key protocols include:

○ **PEGASIS (Power-Efficient Gathering in Sensor Information System)**: Focuses on chain-based data aggregation where each node transmits data to a neighbor in a chain, minimizing the number of transmissions.

### 5. Hybrid Routing:

✓ Combines elements from various routing strategies to balance energy efficiency, data accuracy, and network scalability. Hybrid approaches adaptively choose routing methods based on network conditions and application requirements.

### Challenges and Considerations:

- **Energy Efficiency**: Routing protocols must minimize energy consumption to extend the network's operational lifespan.
- **Scalability**: Protocols should handle increasing numbers of nodes without significant performance degradation.
- **Fault Tolerance**: Ensuring reliable data transmission in the presence of node failures or dynamic topology changes.
- **Latency and Throughput**: Balancing the trade-offs between low latency and high throughput to meet application-specific requirements.

### Recent Advances:

- **Machine Learning**: Emerging techniques use machine learning algorithms to predict and adapt routing decisions based on network conditions and traffic patterns.

- **Optimization Algorithms**: Advanced optimization methods, such as genetic algorithms and simulated annealing, are employed to enhance routing efficiency and network performance.

Topological routing is a dynamic and evolving field, with ongoing research aimed at addressing its challenges and improving the efficiency of wireless sensor networks.

### Challenges and Issues in Topological Routing for Wireless Sensor Networks

Topological routing in Wireless Sensor Networks (WSNs) presents several challenges and issues that impact the efficiency, reliability, and scalability of data transmission. Key challenges include:

#### 1. Energy Consumption:

✓ **Limited Battery Life**: Sensor nodes are typically powered by batteries with limited capacity. Routing protocols must minimize energy usage to extend the network's operational lifetime. Inefficient routing can lead to rapid depletion of node batteries and reduced network longevity.

✓ **Energy-Efficient Algorithms**: Developing algorithms that optimize energy usage while maintaining effective data transmission is a critical challenge. Techniques such as clustering and data aggregation aim to reduce the number of transmissions and energy expenditure.

#### 2. Scalability:

✓ **Network Size**: As the number of nodes in a WSN increases, routing protocols must efficiently manage and scale to accommodate the larger network. Protocols that work well in small networks may not perform effectively as the network grows.

✓ **Data Overhead**: Larger networks can lead to increased control and management overhead, affecting routing efficiency and network performance.

#### 3. Fault Tolerance and Reliability:

✓ **Node Failures**: Nodes in WSNs can fail due to battery depletion or other issues. Routing protocols need to handle node failures gracefully, ensuring data delivery despite changes in the network topology.

✓ **Dynamic Topology**: The network topology in WSNs can change frequently due to node mobility or failures. Routing protocols must adapt to these changes to maintain reliable data transmission.

#### 4. Data Delivery and Accuracy:

- ✓ **Packet Loss:** Ensuring data packets are reliably delivered to their destination is crucial. Packet loss can occur due to network congestion, interference, or node failures.
  - ✓ **Data Accuracy:** Routing protocols must balance the need for accurate data delivery with network constraints. Techniques like data aggregation must ensure that data quality is not compromised.
5. **Latency and Throughput:**
- ✓ **Latency:** The time it takes for data to travel from the source to the destination can be affected by the routing strategy. Minimizing latency is essential for applications requiring real-time data.
  - ✓ **Throughput:** The amount of data that can be transmitted over the network in a given time frame is crucial for high-bandwidth applications. Routing protocols must manage network resources to achieve optimal throughput.
6. **Security and Privacy:**
- ✓ **Data Integrity:** Ensuring that data is not tampered with during transmission is a significant concern. Routing protocols must incorporate security measures to protect data integrity.
  - ✓ **Node Authentication:** Verifying the identity of nodes to prevent unauthorized access and ensure that only legitimate nodes participate in the network.
7. **Resource Constraints:**
- ✓ **Limited Processing Power:** Sensor nodes have limited computational capabilities. Routing algorithms must be efficient in terms of processing power and memory usage.
  - ✓ **Bandwidth Constraints:** The network bandwidth is often limited, and routing protocols must manage bandwidth allocation to avoid congestion and ensure efficient data transmission.
8. **Quality of Service (QoS):**
- ✓ **Application-Specific Requirements:** Different applications have varying QoS requirements, such as data freshness, reliability, and latency. Routing protocols must accommodate these diverse requirements while maintaining overall network performance.

#### Emerging Solutions:

- **Adaptive Routing Protocols:** These protocols dynamically adjust routing decisions based on current network conditions, energy levels, and traffic patterns.
- **Machine Learning:** Leveraging machine learning techniques to predict network behavior and

optimize routing decisions based on historical data and real-time metrics.

- **Hybrid Approaches:** Combining multiple routing strategies to address various challenges and improve overall network performance.

#### Recent Advances and Techniques in Topological Routing for Wireless Sensor Networks

Recent advancements in topological routing for Wireless Sensor Networks (WSNs) focus on enhancing efficiency, scalability, and adaptability. Here are some notable developments and techniques:

##### 1. Machine Learning and Artificial Intelligence:

- ✓ **Predictive Routing:** Machine learning algorithms are employed to predict network conditions and optimize routing decisions based on historical data and real-time metrics. Techniques such as reinforcement learning and supervised learning are used to improve decision-making in dynamic environments.

- ✓ **Anomaly Detection:** AI-driven methods detect anomalies in routing patterns or network behavior, allowing for proactive adjustments and fault detection.

##### 2. Optimization Algorithms:

- ✓ **Genetic Algorithms (GA):** GA-based approaches optimize routing paths by evolving solutions over successive generations, aiming to find efficient routes while considering multiple criteria such as energy consumption and latency.

- ✓ **Particle Swarm Optimization (PSO):** PSO is used to find optimal routing paths by simulating the social behavior of particles. It adjusts routing parameters based on particle movements and global best solutions.

##### 3. Hybrid Routing Protocols:

- ✓ **Combination of Routing Strategies:** Hybrid approaches combine various routing techniques to address specific challenges. For example, a hybrid protocol may integrate geographic routing with hierarchical clustering to balance energy efficiency and data accuracy.

- ✓ **Adaptive Protocols:** Adaptive routing protocols adjust their behavior based on network conditions, such as node density and energy levels, to optimize performance dynamically.

##### 4. Energy-Efficient Techniques:

- ✓ **Energy-Aware Routing:** Protocols that incorporate energy consumption metrics into routing decisions help to prolong network lifetime. Techniques include energy-aware clustering and dynamic power control.

- ✓ **Data Aggregation and Compression:** Advanced data aggregation techniques combine and compress data before transmission, reducing the number of packets sent and conserving energy.
- 5. **Quality of Service (QoS) Enhancements:**
  - ✓ **QoS-Aware Routing:** Techniques that prioritize data based on QoS requirements, such as latency, reliability, and bandwidth, ensure that high-priority data is transmitted efficiently. Methods include priority-based routing and differentiated service levels.
  - ✓ **Delay-Tolerant Routing:** For networks with intermittent connectivity, delay-tolerant routing protocols manage data storage and forwarding based on network conditions, ensuring reliable data delivery despite disruptions.
- 6. **Security and Privacy Enhancements:**
  - ✓ **Cryptographic Techniques:** Advanced cryptographic methods, such as lightweight encryption and secure key management, are used to protect data integrity and confidentiality during transmission.
  - ✓ **Secure Routing Protocols:** Protocols designed with built-in security features prevent attacks such as spoofing, tampering, and eavesdropping. Techniques include secure clustering and authentication mechanisms.
- 7. **Localization and Geographic Techniques:**
  - ✓ **Enhanced Localization:** Improved localization techniques provide more accurate node positioning, which enhances geographic routing protocols by reducing localization errors.
  - ✓ **Geo-Optimized Routing:** Routing protocols that use enhanced geographic information to make more informed routing decisions, improving efficiency and accuracy in data delivery.
- 8. **Integration with IoT and Edge Computing:**
  - ✓ **IoT Integration:** Routing protocols are being adapted to work seamlessly with Internet of Things (IoT) devices, supporting diverse applications and heterogeneous networks.
  - ✓ **Edge Computing:** By incorporating edge computing, some routing protocols process data locally at the edge of the network, reducing latency and improving response times.
- 9. **Multi-Objective Optimization:**
  - ✓ **Balancing Multiple Metrics:** Techniques that optimize multiple objectives simultaneously, such as energy consumption, network lifetime, and data accuracy, are increasingly used to achieve well-rounded performance.

### III. CASE STUDIES AND PRACTICAL IMPLEMENTATIONS OF TOPOLOGICAL ROUTING IN WIRELESS SENSOR NETWORKS

Case studies and practical implementations provide valuable insights into the real-world applications and effectiveness of various topological routing strategies in Wireless Sensor Networks (WSNs). Here are a few illustrative examples:

#### 1) 1. Environmental Monitoring

- **Case Study: The Smart Dust Project**

- ✓ **Overview:** The Smart Dust project, led by UC Berkeley, aimed to develop small, wireless sensor nodes (smart dust) for environmental monitoring. These sensors were used to collect data on temperature, humidity, and pollution levels.

- ✓ **Routing Implementation:** The project employed hierarchical routing protocols to manage the data collected by numerous sensors distributed over a large area. Cluster-based approaches were used to aggregate data from individual sensors before transmitting it to a central base station.

- ✓ **Outcome:** The hierarchical approach significantly reduced energy consumption and improved data aggregation efficiency, demonstrating the effectiveness of topological routing in large-scale environmental monitoring applications.

#### 2) 2. Healthcare Monitoring

- **Case Study: Wireless Health Monitoring System**

- ✓ **Overview:** In a healthcare application, WSNs were used for remote patient monitoring, collecting data from wearable sensors to track vital signs such as heart rate, blood pressure, and oxygen levels.

- ✓ **Routing Implementation:** The system utilized geographic routing techniques to efficiently route data from wearable sensors to a central health monitoring server. The geographic approach minimized latency and ensured timely data delivery, which is crucial for real-time health monitoring.

- ✓ **Outcome:** The use of geographic routing improved data delivery times and system responsiveness, providing real-time health data while conserving energy in wearable devices.

#### 3) 3. Smart Cities

- **Case Study: Smart Parking Systems**

- ✓ **Overview:** Smart parking systems use WSNs to monitor parking space availability in urban areas. Sensors embedded in parking spots detect the presence of vehicles and communicate this information to a central system.

- ✓ **Routing Implementation:** Cluster-based routing protocols were employed to manage communication between sensors and the central system. Each cluster of sensors communicated with

a cluster head, which then relayed aggregated data to the central server.

- ✓ **Outcome:** The cluster-based approach reduced communication overhead and extended the network's operational life, contributing to more efficient urban parking management and improved user experience.

#### 4) 4. Agricultural Monitoring

- **Case Study: Precision Agriculture System**

- ✓ **Overview:** In precision agriculture, WSNs are used to monitor soil moisture, temperature, and crop health to optimize irrigation and fertilization.

- ✓ **Routing Implementation:** The system utilized energy-aware routing protocols to extend the lifespan of sensor networks deployed across large agricultural fields. Data aggregation techniques were applied to minimize the number of transmissions and conserve energy.

- ✓ **Outcome:** The energy-aware routing and data aggregation strategies enhanced network longevity and provided timely information for precision farming, improving crop yields and resource efficiency.

#### 5) 5. Military Surveillance

- **Case Study: Tactical Sensor Networks**

- ✓ **Overview:** In military applications, WSNs are deployed for surveillance and reconnaissance, monitoring areas of interest for enemy activity.

- ✓ **Routing Implementation:** Multi-hop and hierarchical routing protocols were used to transmit data from distributed sensors to command centers. Secure routing techniques were also implemented to ensure data integrity and confidentiality.

- ✓ **Outcome:** The combination of multi-hop and hierarchical routing provided robust data transmission across complex terrains, while secure routing techniques safeguarded sensitive information.

#### 6) 6. Disaster Response

- **Case Study: Post-Disaster Sensor Networks**

- ✓ **Overview:** After natural disasters such as earthquakes, WSNs are deployed to assess damage and locate survivors. These networks provide real-time data on environmental conditions and survivor locations.

- ✓ **Routing Implementation:** Delay-tolerant routing protocols were utilized to handle intermittent connectivity and network partitions caused by debris and destruction. The protocols stored and forwarded data until connectivity was restored.

- ✓ **Outcome:** Delay-tolerant routing enabled effective data collection and communication despite

challenging conditions, aiding in disaster response and recovery efforts.

- ✓ These case studies demonstrate the versatility and effectiveness of topological routing strategies in various applications. From environmental monitoring to military surveillance, the choice of routing protocol is crucial for optimizing performance, conserving energy, and meeting specific application requirements. Practical implementations highlight the importance of selecting appropriate routing techniques based on the network's characteristics and operational goals.

#### IV. FUTURE DIRECTIONS IN TOPOLOGICAL ROUTING FOR WIRELESS SENSOR NETWORKS

The field of topological routing in Wireless Sensor Networks (WSNs) is rapidly evolving, and several future directions hold promise for advancing the technology and addressing current challenges. Key areas for future research and development include:

##### 1. Integration with Emerging Technologies:

- ✓ **Internet of Things (IoT):** As IoT devices become more prevalent, routing protocols must adapt to handle the diverse and dynamic nature of these devices. Future research should focus on integrating WSN routing techniques with IoT frameworks to support scalable and efficient communication.

- ✓ **Edge Computing:** Incorporating edge computing into WSNs can improve processing efficiency and reduce latency by performing data processing closer to the data source. Research should explore how edge computing can be integrated with routing protocols to enhance overall system performance.

##### 2. Machine Learning and Artificial Intelligence:

- ✓ **Adaptive and Predictive Routing:** Machine learning algorithms can be employed to develop adaptive routing protocols that respond to changing network conditions and predict future network states. Future research should focus on leveraging AI to optimize routing decisions, improve energy efficiency, and enhance network reliability.

- ✓ **Anomaly Detection and Fault Tolerance:** AI techniques can improve anomaly detection and fault tolerance by identifying and addressing issues such as node failures or malicious attacks in real-time.

##### 3. Energy-Efficient Protocols:

- ✓ **Advanced Energy Harvesting:** Future research should explore new methods for energy harvesting, such as solar, thermal, or kinetic energy, to extend the operational lifetime of sensor nodes. Combining energy harvesting with efficient routing protocols can further enhance network sustainability.

- ✓ **Dynamic Power Management:** Research should focus on developing dynamic power management strategies that adjust energy usage based on network conditions and application requirements.
- 4. **Quality of Service (QoS) Enhancements:**
  - ✓ **Multi-Objective Optimization:** Future work should aim to balance multiple QoS parameters, such as energy consumption, latency, and reliability, to meet diverse application needs. Multi-objective optimization techniques can help achieve optimal performance across various metrics.
  - ✓ **Real-Time and Delay-Tolerant Communication:** Enhancing protocols to support real-time and delay-tolerant communication can improve performance in applications requiring immediate data delivery or handling intermittent connectivity.
- 5. **Security and Privacy:**
  - ✓ **Advanced Cryptographic Techniques:** Future research should explore lightweight and scalable cryptographic techniques to protect data integrity and confidentiality while minimizing computational overhead on resource-constrained nodes.
  - ✓ **Secure Routing Protocols:** Developing secure routing protocols that address emerging threats and attacks, such as insider attacks and network-layer vulnerabilities, is crucial for maintaining network security and privacy.
- 6. **Scalability and Robustness:**
  - ✓ **Large-Scale Deployments:** Research should focus on developing routing protocols that scale efficiently with increasing network size and density. Techniques for managing large-scale deployments and optimizing network performance under high node densities are needed.
  - ✓ **Robustness to Dynamic Changes:** Future work should address the challenge of maintaining routing efficiency and reliability in the face of dynamic changes, such as node mobility or network topology alterations.
- 7. **Integration with Wireless Technologies:**
  - ✓ **5G and Beyond:** The integration of WSNs with 5G and future wireless technologies can enhance data transmission speeds and network capacity. Research should explore how routing protocols can be adapted to leverage these advancements and improve network performance.
  - ✓ **Hybrid Networks:** Combining WSNs with other types of wireless networks, such as cellular or satellite networks, can extend coverage and improve data transmission capabilities. Future research should investigate hybrid network architectures and their impact on routing protocols.

## 8. Environmental and Context-Aware Routing:

- ✓ **Context-Aware Protocols:** Future research should focus on developing context-aware routing protocols that consider environmental conditions, application context, and user preferences to optimize routing decisions.
- ✓ **Sustainability and Green Networking:** Exploring sustainable and environmentally friendly approaches to routing and network management can contribute to greener and more energy-efficient WSNs.

## V. CONCLUSION

Topological routing in Wireless Sensor Networks (WSNs) is a fundamental component that significantly impacts network performance, energy efficiency, and overall functionality. As WSNs continue to evolve and find applications in diverse fields such as environmental monitoring, healthcare, smart cities, and beyond, the importance of effective routing strategies becomes increasingly evident.

This paper has explored various topological routing techniques, including flooding, hierarchical routing, geographic routing, and cluster-based approaches. Each method offers unique advantages and faces specific challenges, such as energy consumption, scalability, and fault tolerance. Recent advancements in machine learning, optimization algorithms, and hybrid approaches have introduced innovative solutions to these challenges, enhancing the efficiency and adaptability of routing protocols.

Case studies across different domains have demonstrated the practical implementation and benefits of these routing techniques. From smart parking systems to disaster response networks, the effective application of topological routing has led to improved performance, extended network lifetimes, and more reliable data transmission.

Looking forward, the future of topological routing in WSNs is poised to be shaped by emerging technologies and trends. Integration with IoT and edge computing, advancements in machine learning, and the development of energy-efficient and secure protocols will drive the next generation of routing solutions. Addressing scalability, robustness, and QoS requirements will be critical as networks grow larger and more complex.

In conclusion, continued research and development in topological routing are essential for advancing the capabilities and applications of Wireless Sensor Networks. By leveraging new technologies and addressing existing challenges, future routing protocols can achieve greater efficiency, reliability, and adaptability, ultimately contributing to the success and sustainability of WSNs across various applications and industries.

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