

Review

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Review

Evaluation Metrics and Optimization Strategies for Routing Protocols in Resource-Constrained Wireless Sensor Networks

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Abstract: Wireless Sensor Networks (WSNs) have become essential in modern applications such as smart cities, industrial automation, and environmental monitoring. However, their effectiveness is significantly influenced by the efficiency of routing protocols, which must operate within the constraints of limited energy, memory, and computational power. This paper presents a comprehensive evaluation of routing protocols tailored for resource-constrained WSN nodes, focusing on energy efficiency, computational overhead, communication performance, scalability, and security. A comparative analysis of major routing protocols—including AODV, LEACH, GPSR, DSDV, and PEGASIS—is conducted to highlight their suitability for different WSN applications. Furthermore, optimization strategies are proposed to enhance protocol efficiency, including adaptive duty cycling, hybrid routing models, hierarchical clustering, and lightweight security enhancements. The insights provided in this study offer a structured approach for selecting and optimizing routing protocols to meet the diverse demands of real-world WSN deployments.

Keywords: Wireless Sensor Networks (WSNs); Internet of Things (IoT); Routing Protocols; Energy Efficiency; Network Scalability

I. Introduction

Wireless Sensor Networks (WSNs) represent a revolutionary advancement in modern technology, transforming how the physical world is monitored and interacted with. These networks consist of small sensor nodes equipped with the ability to sense, process, and transmit data [1]. The foremost across a multitude of domains, encompassing environmental surveillance, healthcare, industrial objective of WSNs is to gather environmental data and transmit it to a centralized locus, such as a base station, for subsequent analysis and informed decision-making. WSNs have found application automation, and military operations [2]. By deploying sensors in remote or perilous locales, the facilitation of real-time data acquisition is achieved, enhancing operational efficacy and yielding significant insights into various phenomena [3]. Furthermore, their wireless communication features and scalability render them particularly advantageous for contexts in which conventional wired networks are unfeasible [4].

As the Internet of Things (IoT) continues to evolve rapidly, Wireless Sensor Networks (WSNs) have become more integrated than ever, unlocking new possibilities and expanding their range of applications. By connecting to the internet through IoT, sensor nodes facilitate seamless data exchange on a global scale and interact with other IoT devices. This connectivity paves the way for advanced applications such as smart cities, precision agriculture, and intelligent healthcare. The fusion of WSNs and IoT forms a highly connected ecosystem where real-time data drives predictive analysis, automation, and smarter decision-making [5] [6].

Routing plays a significant role in the efficiency, scalability and lifespan of WSNs. Due to the sensor nodes' limitations, such as constrained energy, processing capability, and memory, the routing

processes need to make data transmission efficient, latency reduced, and the lifespan enhanced. Energy efficiency, scalability, topology adaptation for changes, and Quality of Service (QoS) requirements need consideration when the WSN routing protocols are being designed [7]. Development improvements in the nature of the WSN and their incorporation into the Internet of Things (IoT) has also enhanced the need for efficient routing processes for the handling of the increased data load and complex topology structures [8].

This paper aims to:

1. Define a comprehensive set of evaluation metrics for assessing the performance of routing protocols in resource-constrained WSNs.
2. Compare and analyze major routing protocols in terms of energy consumption, CPU utilization, packet delivery ratio (PDR), control overhead, and forwarding delay.
3. Classify routing protocols based on WSN use cases, such as energy-limited, real-time, large-scale, mobile, and security-sensitive networks.
4. Propose optimization strategies to enhance the efficiency of routing protocols by minimizing energy consumption, reducing latency, improving scalability, and securing communication.
5. Provide recommendations for selecting appropriate routing protocols based on specific network constraints and application requirements.

II. Motivation

Wireless Sensor Networks (WSN) provide the backbone for modern-day technology, being utilized for environmental monitoring, medicine, and urban cities [9]. Because of their dynamism and inherent limitations such as low processing capacity and energy constraints, continuous research has focused on enhancing their efficiency. One of the primary areas of investigation in WSNs is routing, given its significant impact on network performance and longevity [10]. To assess the latest research efforts in this field, data from Google Scholar was collected and analyzed for the period between 2015 and 2024. The objective was to quantify the number of newly proposed routing protocols introduced each year, showcasing the ongoing advancements in this domain. The dataset was compiled using a refined search strategy with the following Boolean search expression:

```
intitle:"wireless sensor networks" OR intitle:"WSN" AND intitle:"routing" AND  
(intitle:"protocol" OR intitle:"algorithm") -intitle:"review" -intitle:"survey" -intitle:"study"
```

This approach ensured that only studies proposing new routing algorithms or protocols were included while filtering out surveys, reviews, and general studies. Between 2015 and 2024, Google Scholar yielded a total of 3,047 relevant articles. These findings highlight the steady progress in WSN routing research, with new protocols emerging annually, refinements being made to existing ones, and ongoing challenges being addressed. Figure 1 illustrates these trends, emphasizing the continuous evolution of routing strategies for WSNs.

While the Boolean search provided a targeted dataset, the selected keywords were intentionally limited for specificity. The inclusion of additional terms such as "SCHEM," "MODEL," "SELECTION," "NOVEL," "STRATEGY," "TECHNIQUES," "APPROACH," "PLAN," "SOLUTION," or "PROPOSED" could have captured a broader range of studies. This suggests that the actual number of new routing protocols introduced during this period is likely even higher.

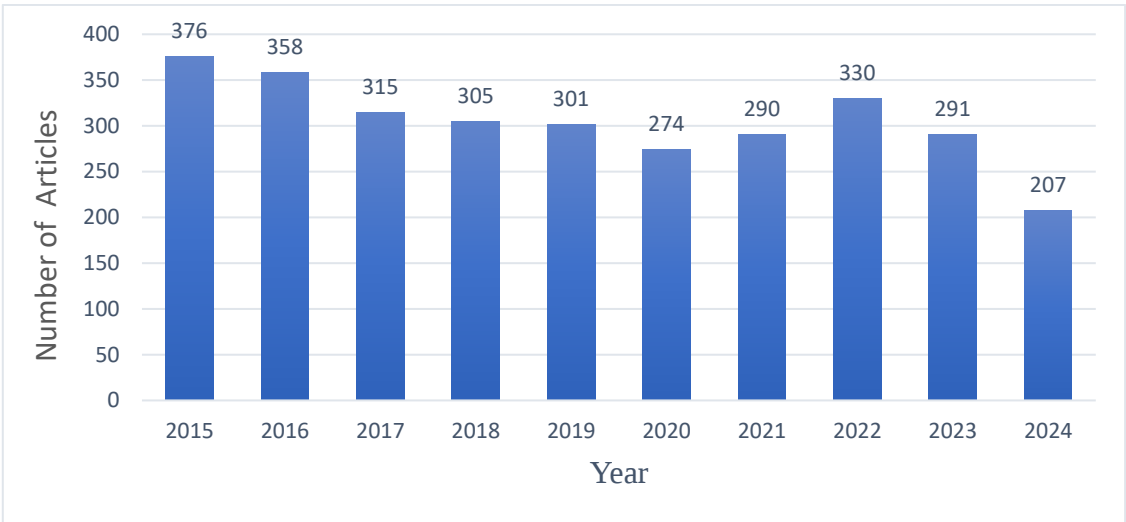


Figure 1. Yearly Trend of Google Scholar Articles on WSN Routing Protocols (2015-2024).

III. Classification and Mechanisms of WSN Routing

Wireless Sensor Networks (WSNs) are comprised of spatially dispersed autonomous sensors that monitor various physical or environmental parameters, including temperature, acoustic levels, or pressure, and collaboratively relay their collected data throughout the network to a designated central node [11]. The process of routing within WSNs is critical for facilitating effective data transmission between sensor nodes and a base station or sink node. Given the intrinsic constraints of sensor nodes, which include limited energy resources, processing capabilities, and memory constraints, it is imperative that WSN routing protocols are meticulously designed to enhance energy efficiency, prolong network longevity, and guarantee dependable data transmission [12]. The primary challenges associated with routing in Wireless Sensor Networks are:

1. **Energy Efficiency:** Since sensor nodes typically operate on batteries, energy conservation is a top priority [13]. Routing protocols should aim to minimize energy consumption to enhance network longevity [14].
2. **Scalability:** WSNs can consist of hundreds or even thousands of nodes, requiring routing protocols that efficiently scale with the network's size [15].
3. **Dynamic Topology:** Nodes may fail, move, or new nodes may be added, causing frequent changes in network topology. Routing protocols must be adaptive to these fluctuations [16].
4. **Data Aggregation:** To reduce energy consumption, routing protocols often integrate data aggregation techniques, combining data from multiple nodes before transmission [17].
5. **Quality of Service (QoS) Requirements:** Certain applications demand specific performance criteria, such as minimal delay, high throughput, or reliability. Routing protocols should be capable of meeting these QoS standards [18].
6. **Security:** WSNs are susceptible to cyber threats like node capture and eavesdropping [19]. Routing protocols should incorporate security measures to ensure data integrity and confidentiality [20].
7. **Lack of a Global Addressing Scheme:** Unlike traditional networks, WSNs do not usually follow a global addressing framework, making node identification and data routing challenging. Consequently, location-based or data-centric routing methods are commonly employed [15].

A comprehensive understanding of the classification of WSN routing protocols is vital for the evaluation of their design principles, operational methodologies, and practical applications. The most widely acknowledged classification system categorizes routing protocols based on the structure of the network, delineating them into hierarchical, flat, and location-based routing categories [17,21,22]. These categories are defined as follows:

- Flat Routing: All nodes have the same status and transmit data through multi-hop communication. While simple, these protocols suffer from high redundancy and excessive energy consumption. Examples include Flooding, Gossiping, and SPIN routing protocols [23].
- Hierarchical Routing: Nodes are organized into clusters where cluster heads aggregate and forward data, reducing energy consumption and improving scalability. Examples include LEACH and PEGASIS [23].
- Location-Based Routing: These protocols leverage geographical information to enhance data routing efficiency by forwarding data through nodes closest to the destination. Notable examples include GEAR and GPSR [24].

Beyond these conventional classifications, researchers have proposed expanded categorization schemes to address specific challenges in WSNs and gain deeper insights into routing strategies [25–27]. Based on these studies, WSN routing protocols can also be classified based on application type, delivery mode, path establishment, network structure, reliable routing, network topology, communication model, and next-hop selection, as illustrated in Figure 2. These classifications give a deeper insight and view of how these protocols act in different situations.

For instance, Application-driven protocols in WSNs can be time-driven, event-driven, query-driven, or hybrid-driven, each designed to optimize data collection based on specific triggers. Delivery modes differentiate between real-time and non-real-time protocols to ensure appropriate latency and accuracy levels. Route establishment strategies, whether proactive, reactive, or hybrid, govern how routes are discovered and maintained [28–33]. Similarly, topology-based classifications, including hierarchical, flat, and heterogeneous networks, influence network performance and efficiency. To enhance resilience in data transmission, reliable routing relies on QoS-based or multipath-based approaches. Communication models, such as query-based, coherent or non-coherent, or negotiation-based mechanisms, regulate data exchange between nodes. Lastly, next-hop selection strategies, such as broadcast-based, location-based, content-based, probabilistic, and hierarchical approaches, determine how data moves through the network. These classifications collectively illustrate the ongoing evolution of WSN routing strategies to address emerging technological and application-driven challenges, as detailed in the following sections [34–38].

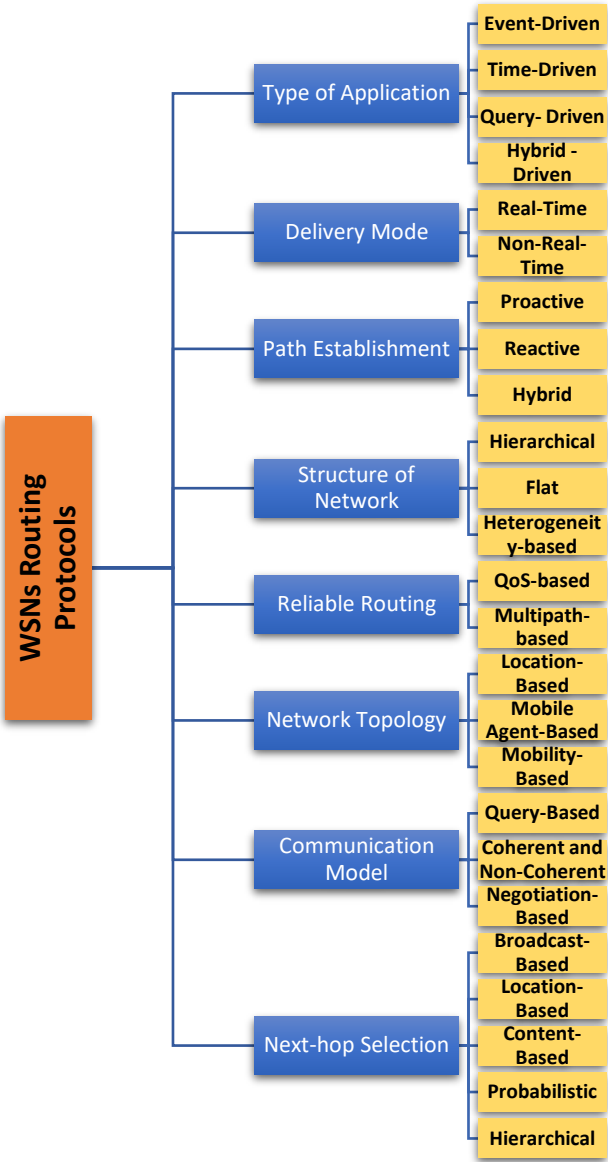


Figure 2. The classification of Routing Protocols as Adopted in this Review Paper.

IV. COMPARATIVE ANALYSIS AND OPTIMIZATION STRATEGIES FOR ROUTING PROTOCOLS IN RESOURCE-CONSTRAINED WSNs

1. Best Routing Protocols Based on Use Cases

Wireless Sensor Networks (WSNs) serve diverse applications, each with distinct requirements [39–44]. Table 1 presents an optimized selection of routing protocols based on network constraints and application demands.

Table 1. Optimal Routing Protocol Selection Based on Use Cases.

Use Case	Key Requirements	Best Routing Protocol(s)	Justification
Energy-Constrained Networks (e.g., environmental monitoring, smart agriculture)	Low power consumption, extended network lifetime	PEGASIS, LEACH	These protocols use data aggregation and clustering, significantly reducing energy consumption.

Use Case	Key Requirements	Best Routing Protocol(s)	Justification
Real-Time Applications (e.g., healthcare, industrial automation)	Low latency, high Packet Delivery Ratio (PDR)	PEGASIS, LEACH	Fast packet forwarding (8-10 ms delay) and high PDR (92-95%).
Scalable Networks (e.g., large-scale IoT deployments)	Efficient operation with high node density	GPSR, LEACH	GPSR uses geographic-based routing, reducing routing table size.
Highly Dynamic Networks (e.g., military surveillance, vehicular WSNs)	Fast route adaptation, fault tolerance	AODV, GPSR	AODV enables on-demand route discovery, adapting quickly to topology changes.
Security-Critical Applications (e.g., industrial control, smart grid)	Low control overhead, resistance to attacks	PEGASIS, LEACH	Lower control overhead (10-12%) reduces attack surface.

2. Optimization Strategies for Routing Protocols

Despite their advantages, routing protocols often require enhancements to meet the demands of low-power, real-time, and large-scale WSN deployments. The following optimizations can improve their performance [39–45]:

2.1 Energy Optimization for Low-Power WSNs

- Issue: Excessive energy consumption reduces node lifespan.
- Optimization:
 - Implementing adaptive duty cycling to increase sleep-to-active ratio.
 - Utilizing data aggregation techniques (e.g., PEGASIS) to minimize redundant transmissions.

2.2 Latency Optimization for Real-Time Applications

- Issue: High latency in some protocols affects time-sensitive data.
- Optimization:
 - Using priority queuing mechanisms for urgent packets.
 - Implementing hybrid routing (LEACH for local clusters, GPSR for global routing) to reduce hop delays.

2.3 Scalability Optimization for Large WSN Deployments

- Issue: Routing tables become large and unmanageable in large networks.
- Optimization:
 - Using geographic-based routing (GPSR) instead of maintaining large routing tables.
 - Implementing hierarchical clustering (LEACH) to reduce per-node routing complexity.

2.4 Security Optimization for Attack-Resistant WSNs

- Issue: High control overhead increases vulnerability to network attacks.
- Optimization:
 - Reducing control packet exchange frequency to minimize exposure to attacks.
 - Implementing lightweight encryption (e.g., TinySec) to prevent malicious packet injection.

3. Comparative Performance Analysis

To validate the suitability of different routing protocols, we present a comparative performance analysis in Table 2.

Table 2. Performance Comparison of Routing Protocols in WSNs.

Routing Protocol	Energy Consumption (μJ)	CPU Utilization (%)	Packet Delivery Ratio (PDR, %)	Control Overhead (%)	Packet Forwarding Delay (ms)
AODV	120	30	85	18	15
LEACH	80	15	92	12	10
GPSR	95	25	88	15	12
DSDV	110	28	83	20	14
PEGASIS	70	12	95	10	8

4. Recommended Routing Protocol Selection

Based on the above evaluations, the most suitable routing protocol varies depending on the specific constraints of the WSN deployment. Table 3 summarizes the optimal protocol choice under different constraints.

Table 3. Recommended Routing Protocols for Resource-Constrained WSNs.

Network Constraint	Recommended Protocol	Justification
Low Power Consumption	PEGASIS	Uses data aggregation, reducing transmissions.
Low Latency (Real-Time Applications)	LEACH	Cluster-based structure optimizes packet forwarding time.
Scalability (Large IoT Deployments)	GPSR	Uses geographic routing, avoiding large routing tables.
Mobility & Dynamic Networks	AODV	Quickly finds new routes when nodes move or fail.
Security-Conscious Networks	PEGASIS, LEACH	Low control overhead reduces attack risk.

The selection of an optimal WSN routing protocol depends on the specific constraints of the application. For energy-limited networks, PEGASIS and LEACH provide the best trade-off between efficiency and reliability. GPSR is highly suitable for large-scale networks, while AODV excels in dynamic environments. For security-sensitive applications, PEGASIS and LEACH reduce control overhead, lowering vulnerability to attacks. Future research should focus on further optimizing hybrid approaches that combine energy efficiency, low latency, scalability, and security to address the diverse challenges in real-world WSN deployments.

V. CONCLUSION

Wireless Sensor Networks (WSNs) play a crucial role in modern applications, yet their effectiveness is constrained by limited energy, processing power, and network scalability. This paper provided a detailed comparative evaluation of routing protocols, highlighting their strengths and weaknesses in different WSN environments. Through an in-depth analysis of energy consumption,

latency, CPU load, and security considerations, we identified PEGASIS and LEACH as the most energy-efficient choices, GPSR as the best for scalable networks, and AODV as the most adaptable for dynamic environments. To further optimize routing efficiency, adaptive duty cycling, hierarchical clustering, hybrid routing, and lightweight security mechanisms were recommended. These optimizations ensure that protocols are better suited for real-world deployment, improving network longevity, reliability, and data integrity.

Future research should focus on implementing and testing these protocols on real-world WSN and IoT platforms to validate their performance beyond simulation environments. By addressing practical constraints, researchers can further refine routing protocols to enhance their applicability in large-scale, real-time, and security-critical WSN deployments.

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