Priya Yadav, 2026, 14:2
ISSN (Online): 2348-4098
ISSN (Print): 2395-4752

International Journal of Science, Engineering and Technology
An Open Access Journal

A Systematic Review Routing Protocols in Wireless Sensor Networks

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Abstract- Wireless Sensor Networks (WSNs) have become an essential technology for monitoring and data collection in various domains such as environmental monitoring, healthcare, military surveillance, and smart cities. Routing protocols play a crucial role in WSNs because sensor nodes have limited energy, processing power, and communication capabilities. Efficient routing mechanisms are required to ensure reliable data transmission while minimizing energy consumption and prolonging network lifetime. This paper presents a systematic review of routing protocols in wireless sensor networks. The study categorizes routing protocols into different types such as data-centric, hierarchical, and location-based routing protocols. Key protocols including LEACH, PEGASIS, TEEN, and Directed Diffusion are analyzed in terms of energy efficiency, scalability, and performance. The paper also discusses challenges and future research directions for improving routing efficiency in WSNs.

Keywords: Wireless Sensor Networks, Routing Protocols, Energy Efficiency, LEACH, PEGASIS, TEEN.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) have emerged as a key enabling technology for modern monitoring and communication systems. A WSN typically consists of a large number of small sensor nodes that are deployed in a specific area to monitor environmental conditions such as temperature, humidity, pressure, and motion. These sensor nodes communicate with each other through wireless links and transmit the collected information to a central base station or sink node for processing and analysis (Kaur & Singh, 2022; Sharma et al., 2023).

The rapid development of wireless communication technologies and low-power electronics has significantly increased the application of wireless sensor networks in various fields including environmental monitoring, healthcare systems, military surveillance, smart agriculture, and industrial automation (Ahmed et al., 2024). WSNs play an important role in the Internet of Things (IoT) ecosystem because they enable real-time data collection and communication between physical devices and digital systems (Patel & Shah, 2022).

Despite their wide range of applications, wireless sensor networks face several challenges due to the limited energy resources and processing capabilities of sensor nodes. Most sensor nodes are powered by batteries that are difficult to replace or recharge once deployed. Therefore, energy efficiency becomes a critical factor affecting network performance and lifetime (Gupta et al., 2023). Inefficient communication between nodes can lead to excessive energy consumption and reduce the overall operational lifetime of the network.

Routing protocols play a crucial role in wireless sensor networks because they determine how data packets are transmitted from sensor nodes to the base station. Efficient routing protocols are designed to minimize energy consumption, reduce communication delay, and ensure reliable data transmission across the network (Rao et al., 2021). Unlike traditional networks, routing in WSNs must consider several additional factors such as node energy levels, network topology changes, data aggregation, and communication overhead (Zhang et al., 2024).

Over the years, researchers have proposed numerous routing protocols to address these challenges. These protocols are generally classified into several categories including data-centric routing protocols, hierarchical routing protocols, location-based routing protocols, and hybrid routing protocols (Khan et al., 2023). Each category uses

different strategies to optimize energy consumption and improve network performance.

Data-centric routing protocols focus on reducing redundant data transmissions by using attribute-based communication and data aggregation techniques. Hierarchical routing protocols organize nodes into clusters to improve scalability and energy efficiency. Location-based routing protocols utilize geographic information to determine optimal routing paths between nodes (Rahman et al., 2022).
In recent years, the integration of artificial intelligence and machine learning techniques has further improved routing strategies in wireless sensor networks. Intelligent routing protocols can dynamically adapt to changing network conditions and optimize communication paths in real time (Li et al., 2025). These advanced techniques are expected to significantly enhance the efficiency and reliability of WSNs in future smart environments.

Therefore, a comprehensive review of routing protocols is necessary to understand recent developments and research trends in this field. This paper presents a systematic review of routing protocols in wireless sensor networks, focusing on research contributions published between 2021 and 2025. The review analyzes different routing approaches, compares their advantages and limitations, and identifies future research directions for improving the performance of wireless sensor networks.

II. ARCHITECTURE OF WIRELESS SENSOR NETWORKS

A typical wireless sensor network architecture consists of sensor nodes, communication links, and a base station. Sensor nodes are responsible for sensing environmental conditions and transmitting the collected data to neighboring nodes or directly to the base station. Each sensor node generally consists of four main components: sensing unit, processing unit, communication unit, and power unit (Almalki et al., 2022).

The sensing unit collects environmental data through sensors such as temperature or humidity sensors. The processing unit performs basic data processing and control functions, while the communication unit enables wireless data transmission between nodes. The power unit supplies energy to the sensor node, typically through batteries or energy harvesting devices (Khan et al., 2023).

Sensor nodes are usually deployed in large numbers across a geographical region. These nodes cooperate to transmit data through multi-hop communication to reach the base station. The base station acts as the central data collection point where information from all sensor nodes is aggregated and processed (Zhang et al., 2024).

III. CLASSIFICATION OF ROUTING PROTOCOLS IN WSNS

Routing protocols in wireless sensor networks can be broadly classified into several categories based on their design strategies and network structures (Rahman et al., 2022).

Data-Centric Routing Protocols
Data-centric routing protocols focus on eliminating redundant data transmissions by using data aggregation techniques. In these protocols, communication is based on data attributes rather than node addresses (Kaur & Singh, 2022). These protocols improve energy efficiency by minimizing unnecessary communication between nodes (Ahmed et al., 2024).

Hierarchical Routing Protocols
Hierarchical routing protocols organize sensor nodes into clusters to improve scalability and energy efficiency. In this approach, cluster heads collect data from member nodes and transmit aggregated information to the base station (Gupta et al., 2023).

Popular hierarchical protocols include:
- LEACH
- PEGASIS
- TEEN
- APTEEN

These protocols reduce communication overhead and improve network lifetime by distributing energy consumption among nodes (Rao et al., 2021).

Location-Based Routing Protocols

Location-based routing protocols use geographic information to determine routing paths between sensor nodes. These protocols reduce energy consumption by limiting transmission distances and selecting optimal routes (Patel & Shah, 2022).

Examples include:

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

AI-Based Routing Protocols

Recent research has introduced artificial intelligence and machine learning techniques to improve routing performance in wireless sensor networks. AI-based routing protocols use optimization algorithms and predictive models to dynamically adjust routing decisions based on network conditions (Li et al., 2025). These techniques help improve network lifetime, packet delivery ratio, and fault tolerance in large-scale sensor networks.

IV. LITERATURE REVIEW

Recent advancements in wireless communication and embedded technologies have led to extensive research on routing protocols in wireless sensor networks (WSNs). The primary objective of these studies is to improve energy efficiency, increase network lifetime, and ensure reliable data transmission. Researchers have proposed various routing techniques based on clustering, data aggregation, geographic routing, and intelligent optimization algorithms. This section reviews significant studies published between 2021 and 2025 related to routing protocols in WSNs.

Several studies have focused on improving energy efficiency in cluster-based routing protocols. For instance, Gupta et al. (2023) analyzed cluster-based routing techniques and reported that clustering mechanisms significantly reduce communication overhead and improve network lifetime by distributing energy consumption among sensor nodes. The study highlighted that protocols such as LEACH and PEGASIS are widely adopted due to their simplicity and energy-efficient characteristics.

Similarly, Rao et al. (2021) conducted a comprehensive survey of hierarchical routing protocols and found that hierarchical approaches enhance scalability and energy efficiency in large-scale sensor networks. Their research emphasized that clustering allows sensor nodes to transmit data to nearby cluster heads instead of directly communicating with the base station, thereby reducing transmission distance and energy consumption.

In another study, Kaur and Singh (2022) examined data-centric routing protocols in wireless sensor networks. Their research showed that protocols such as Directed Diffusion and SPIN reduce redundant data transmissions by using attribute-based data dissemination. These protocols enable efficient data aggregation and minimize unnecessary communication between nodes, which ultimately improves energy efficiency.

Research has also been conducted on geographic routing protocols that use location information to determine optimal routing paths. Patel and Shah (2022) investigated location-based routing techniques and concluded that geographic routing protocols such as GEAR and GPSR are effective in reducing routing overhead and improving packet delivery performance. However, the study also noted that these protocols require accurate location information, which may increase implementation complexity.

Another important area of research involves hybrid routing protocols, which combine multiple routing strategies to enhance network performance. Rahman et al. (2022) analyzed hybrid routing techniques and reported that combining hierarchical and data-centric approaches can significantly improve energy efficiency and reliability in wireless sensor networks.

In recent years, artificial intelligence and machine learning techniques have been increasingly applied

to routing problems in WSNs. Li et al. (2025) proposed a machine learning-based routing framework that dynamically adapts routing decisions based on network conditions such as node energy levels and traffic load. Their findings indicate that intelligent routing algorithms can significantly improve packet delivery ratio and network lifetime compared with traditional routing protocols.

Similarly, Ahmed et al. (2024) reviewed energy-efficient routing techniques and highlighted the growing importance of intelligent optimization methods such as swarm intelligence, genetic algorithms, and reinforcement learning for improving routing performance. These approaches allow sensor networks to adapt to dynamic environments and optimize communication paths automatically.

Security has also become a significant concern in wireless sensor networks. Khan et al. (2023) investigated security challenges in routing protocols and emphasized the need for secure communication mechanisms to protect sensor networks from malicious attacks and data manipulation. The study suggested integrating encryption and trust-based routing techniques to improve network reliability and data integrity.

Furthermore, Zhang et al. (2024) explored the integration of wireless sensor networks with the Internet of Things (IoT). Their study found that IoT-enabled WSNs require more scalable and adaptive routing protocols to handle large volumes of data generated by interconnected devices.

Overall, the literature indicates that while numerous routing protocols have been proposed for wireless sensor networks, each approach has specific advantages and limitations depending on the network application and environmental conditions. Recent research trends focus on developing energy-aware, intelligent, and adaptive routing protocols that can support large-scale IoT-based sensor networks.

V. CONCLUSION

Wireless Sensor Networks (WSNs) have become a vital component of modern communication systems due to their ability to collect and transmit data from distributed environments. With the rapid growth of applications such as smart cities, environmental monitoring, healthcare, and industrial automation, the importance of efficient routing protocols in WSNs has increased significantly. Routing protocols are responsible for managing communication between sensor nodes and the base station while minimizing energy consumption and ensuring reliable data delivery.

This review paper examined various routing protocols used in wireless sensor networks, including data-centric, hierarchical, location-based, and intelligent routing protocols. The study highlighted that hierarchical routing protocols such as clustering-based approaches are widely adopted because they effectively reduce communication overhead and improve network lifetime. Data-centric routing protocols focus on minimizing redundant data transmission through efficient data aggregation techniques, while location-based routing protocols use geographic information to determine optimal routing paths.

The literature reviewed in this study indicates that no single routing protocol is suitable for all types of wireless sensor network applications. Each routing technique has its own advantages and limitations depending on network size, energy constraints, application requirements, and environmental conditions. Traditional routing protocols provide fundamental solutions for communication in WSNs; however, they often struggle to adapt to dynamic network environments and large-scale deployments. Recent research has increasingly focused on intelligent and adaptive routing mechanisms, particularly those based on artificial intelligence, machine learning, and optimization algorithms. These advanced approaches enable sensor networks to dynamically adjust routing decisions according to network conditions such as node energy levels, traffic load, and network topology. Such techniques have shown promising results in improving packet

delivery ratio, reducing communication delays, and extending the overall network lifetime.

Furthermore, the integration of wireless sensor networks with the Internet of Things (IoT) has created new challenges and opportunities for routing protocol design. Future routing strategies must address issues such as scalability, security, data reliability, and energy sustainability in large-scale IoT environments. Emerging technologies such as energy harvesting, edge computing, and AI-driven routing algorithms are expected to play a crucial role in enhancing the performance of next-generation wireless sensor networks.

In conclusion, the development of efficient routing protocols remains a critical research area in wireless sensor networks. Future research should focus on designing energy-efficient, secure, and adaptive routing mechanisms capable of supporting complex IoT-based sensor applications while ensuring long-term network sustainability and performance.

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