# Improve Data Transmission Efficiency for Wireless Sensor Networks Through Routing Protocols

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Abstract: Wireless Sensor Networks (WSNs) are fundamental components of Internet of Things (IoT) applications, including environmental monitoring, healthcare, industrial automation, and smart cities. However, limited battery capacity, routing overhead, transmission delay, and dynamic topology changes remain major challenges that reduce network lifetime and communication reliability. Therefore, the development of energy-efficient and scalable routing protocols has become a critical research issue in modern WSN environments. This study presents a systematic review and comparative analysis of recent routing protocols for WSNs published between 2020 and 2025. A PRISMA-based review methodology was adopted to identify and evaluate relevant studies from major scientific databases, including IEEE Xplore, ScienceDirect, Springer, MDPI, and Google Scholar. Initially, 120 studies were collected, and after applying inclusion and exclusion criteria, 34 high-quality studies were selected for detailed analysis. The reviewed protocols are classified according to network structure, routing strategy, optimization mechanism, and intelligent decision-making approaches. In addition, this review provides comparative benchmarking using key performance metrics, including energy consumption, scalability, routing overhead, latency, throughput, packet delivery ratio, reliability, and network lifetime. Particular attention is given to intelligent routing approaches based on machine learning, deep reinforcement learning, fuzzy systems, and metaheuristic optimization algorithms. The analysis shows that hybrid intelligent routing approaches significantly improve energy efficiency and routing adaptability in dynamic WSN environments. However, challenges related to scalability, computational complexity, real-time adaptability, and lightweight AI integration remain unresolved. Finally, this study highlights current research gaps and proposes future directions for developing intelligent and energy-efficient routing frameworks for next-generation WSN applications.

## 1 INTRODUCTION

Wireless Sensor Networks (WSNs) have become one of the most important enabling technologies for modern Internet of Things (IoT) applications [1], [2]. A WSN typically consists of a large number of low-power sensor nodes that cooperatively monitor physical or environmental conditions and transmit collected data to a base station or cloud infrastructure [3]. Owing to their flexibility, low deployment cost, and self-organizing capability, WSNs are widely applied in environmental monitoring, healthcare systems, industrial automation, smart agriculture, and smart city infrastructures [4], [5].

Despite their advantages, WSNs still face several critical technical challenges that directly affect communication efficiency and network sustainability. Sensor nodes are generally powered by limited-capacity batteries and are often deployed in remote environments where battery replacement is difficult or impossible [6]. Consequently, energy efficiency has become one of the primary design objectives in WSN communication systems. Data transmission and routing operations consume the largest portion of node energy, making routing protocol design a fundamental research issue in WSNs [7], [8].

Traditional routing protocols are often unable to efficiently manage dynamic topology changes, communication overhead, packet loss, latency, and scalability requirements in large-scale IoT environments [9]. Therefore, recent research has increasingly focused on adaptive and intelligent routing approaches capable of improving transmission efficiency while extending network lifetime. Modern routing strategies employ clustering techniques, fuzzy systems, machine learning models, deep reinforcement learning, and metaheuristic optimization algorithms to optimize routing decisions and balance energy consumption among sensor nodes [10]–[14].

Several recent review studies have discussed energy-efficient routing methods in WSNs [1], [2], [7], [8]. However, many existing surveys suffer from important limitations, including insufficient comparative benchmarking, limited taxonomy structures, and lack of systematic review methodologies. In addition, rapid developments in AI-driven routing optimization between 2020 and 2025 have created the need for an updated and comprehensive review integrating intelligent routing mechanisms with modern WSN communication requirements.

To address these gaps, this study presents a systematic review and comparative benchmarking of recent routing protocols for WSNs. A PRISMA-based methodology was adopted to identify, filter, and evaluate relevant studies published between 2020 and 2025. The selected routing approaches are classified according to network architecture, routing strategy, optimization mechanism, and intelligent decision-making techniques. Furthermore, this study compares routing protocols using critical performance metrics, including energy consumption, scalability, routing overhead, latency, throughput, packet delivery ratio, reliability, and network lifetime.

The main contributions of this study are summarized as follows:

1) A systematic PRISMA-based review of recent WSN routing protocols published between 2020 and 2025.
2) A comprehensive taxonomy of routing approaches based on routing architecture and intelligent optimization methods.
3) Comparative benchmarking using key network performance metrics.
4) Critical analysis of current research gaps and unresolved technical challenges.
5) A future research framework for AI-enabled and energy-efficient WSN routing systems.

The remainder of this paper is organized as follows. Section 2 presents the systematic review methodology and PRISMA process. Section 3 introduces the taxonomy of routing protocols in WSNs. Section 4 provides comparative benchmarking and performance evaluation. Section 5 discusses current research gaps and future research directions. Finally, Section 6 concludes the study.

## 2 RELATED WORKS

### 2.1 Energy-Efficient Routing Protocols

Energy-efficient routing remains one of the most important research areas in WSNs because communication operations consume the majority of node energy. Several recent studies focused on minimizing transmission power while improving network lifetime and routing reliability. Liu et al. [20] proposed the LEACH-D protocol for industrial IoT environments to reduce transmission delay and improve energy efficiency. Similarly, Bairagi et al. [22] introduced an energy-aware geographic forwarding mechanism to optimize multi-hop communication and prolong network lifetime. Pathak and Yadav [24] improved residual-energy scheduling mechanisms to balance node energy consumption and reduce premature node failures.

Although these approaches improve energy conservation, most traditional energy-aware routing methods still suffer from scalability limitations and reduced adaptability in highly dynamic network environments.

### 2.2 Clustering-Based Routing Approaches

Clustering techniques are widely adopted in WSN routing because they reduce communication overhead and support scalable data aggregation. Recent studies have focused on intelligent cluster-head selection mechanisms to improve network stability and transmission efficiency. Gopalan et al. [11] integrated optimized cluster-head selection with the CORP routing protocol to reduce routing overhead and improve packet delivery ratio. Hu et al. [30] proposed a clustering and routing framework based on Quantum Particle Swarm Optimization and fuzzy logic to improve routing adaptability and energy balancing.

Despite their advantages, clustering-based methods often introduce additional computational overhead and may suffer from uneven cluster formation in large-scale deployments.

## 2.3 Metaheuristic Optimization-Based Routing

Metaheuristic optimization algorithms have recently attracted considerable attention for solving routing optimization problems in WSNs. Saemi and Goodarzian [9] proposed a hybrid Local Search and Global Search algorithm for underwater WSN routing optimization. Janarthanan and Srinivasan [13] introduced a multi-objective routing framework based on Bee Colony Optimization and Border Collie Optimization to reduce delay and energy consumption. [27] demonstrated the effectiveness of Particle Swarm Optimization (PSO) for selecting optimal cluster heads in WSNs, showing improved energy balancing and network lifetime compared to conventional LEACH-based approaches. Rajkumar et al. Similarly, Rajkumar et al. [28] used evolutionary algorithms for optimal shortest-path selection.

These optimization approaches provide improved routing efficiency; however, many of them require high computational complexity, which limits their applicability in resource-constrained sensor nodes.

## 2.4 AI- and Machine Learning-Based Routing

Artificial intelligence and machine learning techniques are increasingly used to improve adaptive routing decisions in dynamic WSN environments. Suresh et al. [16] proposed a federated deep reinforcement learning framework for intelligent routing optimization in IoT-enabled WSNs. Surenther et al. [31] integrated artificial neural networks with fuzzy logic to improve data transmission efficiency and reduce network latency. Furthermore, fuzzy logic-based routing protocols such as E-FLZSEPFCH [12] demonstrated improved reliability and multipath routing performance.

Although AI-driven routing approaches significantly improve adaptability and decision-making, lightweight implementation and real-time processing remain major challenges for low-power WSN environments.

## 2.5 Hybrid Intelligent Routing Frameworks

Recent studies increasingly combine multiple optimization mechanisms to improve routing efficiency and network reliability. Almuzaini et al. [15] combined fuzzy logic with bee colony optimization for mobile WSN routing optimization. Elhoseny et al. [29] proposed a hybrid optimization routing framework that improved packet delivery ratio and network lifetime simultaneously. Hybrid approaches generally achieve better trade-offs between routing efficiency, scalability, and energy consumption compared with traditional routing methods.

However, many hybrid frameworks still lack standardized benchmarking and real-world deployment validation.

## 2.6 Research Gaps

Despite significant progress in energy-efficient routing protocols, several important challenges remain unresolved. First, many existing studies focus primarily on energy reduction while insufficiently addressing scalability and routing overhead in large-scale IoT environments. Second, AI-based routing methods often require high computational resources that exceed the capabilities of lightweight sensor nodes. Third, most routing protocols are evaluated only in simulation environments without real-world validation. Finally, there is still a lack of unified benchmarking frameworks for comparing intelligent routing approaches using standardized performance metrics.

Therefore, future research should focus on lightweight AI-driven routing systems, adaptive cross-layer optimization, real-time routing intelligence, and scalable energy-aware communication architectures for next-generation WSNs.

# 3 RESEARCH METHODOLOGY

## 3.1 Review Methodology

This study adopted a systematic literature review methodology based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to identify, evaluate, and analyze recent routing protocols for Wireless Sensor Networks (WSNs). The objective of this review is to provide a comprehensive comparative analysis of energy-efficient and intelligent routing approaches proposed between 2020 and 2025.

The review process consisted of four major phases: literature identification, screening, eligibility assessment, and final study selection. The overall review methodology is illustrated in Figure 1.

## 3.2 Search Strategy

Relevant studies were collected from major scientific databases, including IEEE Xplore, ScienceDirect, SpringerLink, MDPI, Scopus-indexed journals, and Google Scholar. The literature search was conducted using combinations of the following keywords:

- "Wireless Sensor Networks"
- "WSN Routing Protocols"
- "Energy-Efficient Routing"
- "IoT-based WSN"
- "Machine Learning Routing"
- "Metaheuristic Routing Optimization"
- "Cluster-based Routing"
- "Intelligent Routing in WSN"

Boolean operators such as AND and OR were used to refine the search results and improve relevance.

## 3.3 Inclusion and Exclusion Criteria

To ensure the quality and relevance of the selected studies, predefined inclusion and exclusion criteria were applied.

### 3.3.1 Inclusion Criteria

The selected studies were required to:

- focus on routing protocols in WSNs;
- address energy efficiency, routing optimization, or intelligent routing;
- be published between 2020 and 2025;
- be indexed in recognized scientific databases;
- include experimental, simulation, or comparative evaluation results.

### 3.3.2 Exclusion Criteria

Studies were excluded if they:

- were duplicated across databases;
- lacked sufficient technical details;
- focused on unrelated networking topics;
- were short abstracts, tutorials, or non-peer-reviewed publications;
- did not evaluate routing performance metrics.

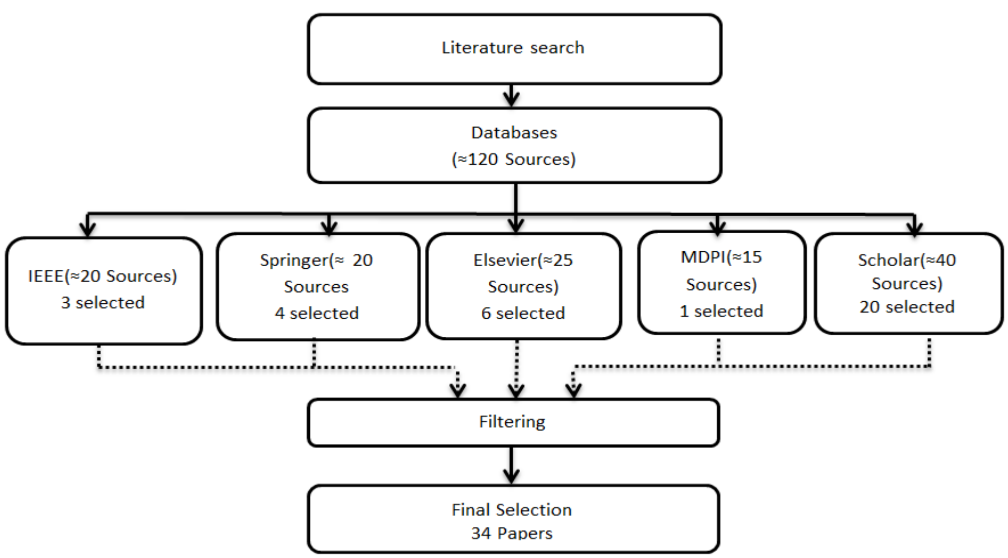


Figure 1: Display literatures selection process.

### 3.4 Study Selection Process

Initially, approximately 120 research articles were identified from the selected databases. After removing duplicate and irrelevant studies, 68 papers remained for preliminary screening. Subsequently, full-text eligibility assessment was performed according to the predefined selection criteria. Finally, 34 high-quality studies were selected for detailed comparative analysis.

The PRISMA-based study selection process is presented in Figure 1.

### 3.5 Data Extraction and Comparative Analysis

The selected studies were systematically analyzed using several technical and performance criteria, including:

- routing architecture;
- clustering strategy;
- optimization mechanism;
- machine learning integration;
- scalability;
- routing overhead;
- energy consumption;
- packet delivery ratio;
- latency;
- throughput;
- network lifetime.

The reviewed routing protocols were further classified into several categories, including energy-aware routing, clustering-based routing, metaheuristic optimization methods, machine learning-based routing, and hybrid intelligent routing approaches.

A comparative benchmarking framework was developed to evaluate the strengths and limitations of each routing strategy according to the selected performance metrics.

### 3.6 Limitations of the Review

Although this review provides a comprehensive analysis of recent routing protocols in WSNs, several limitations should be acknowledged. First, only studies published between 2020 and 2025 were considered. Second, the analysis primarily focused on peer-reviewed English-language publications. Third, some routing approaches were evaluated using different simulation environments and performance settings, which may affect direct comparison between studies.

Despite these limitations, the review provides a structured and up-to-date overview of recent advances in intelligent and energy-efficient routing protocols for WSN applications.

## 4 COMPARATIVE ANALYSIS AND DISCUSSION

### 4.1 Taxonomy of Routing Protocols

Based on the reviewed studies, recent routing protocols for WSNs can be classified into five major categories:

1) Energy-aware routing protocols
2) Clustering-based routing approaches
3) Metaheuristic optimization-based routing methods
4) Machine learning and AI-based routing techniques
5) Hybrid intelligent routing frameworks

Energy-aware routing protocols mainly focus on minimizing transmission energy and extending network lifetime through optimized path selection. Clustering-based methods improve scalability and reduce communication overhead by organizing sensor nodes into hierarchical structures. Metaheuristic approaches employ optimization algorithms such as Particle Swarm Optimization (PSO), Bee Colony Optimization (BCO), Genetic Algorithms (GA), and Harris Hawks Optimization (HHO) to improve routing efficiency. AI-based routing methods utilize machine learning, deep reinforcement learning, fuzzy systems, and neural networks for adaptive routing decisions in dynamic environments. Hybrid intelligent frameworks combine multiple optimization mechanisms to achieve better trade-offs between energy efficiency, reliability, and scalability.

### 4.2 Comparative Benchmarking of Routing Protocols

The reviewed studies used different performance metrics to evaluate routing efficiency and network

performance. The most frequently used metrics include:
- energy consumption;
- packet delivery ratio (PDR);
- throughput;
- latency;
- routing overhead;
- scalability;
- reliability;
- network lifetime.

Table 1 summarizes the comparative benchmarking of recent routing approaches.

Traditional energy-aware routing protocols demonstrated lower computational complexity and stable performance in static network environments. However, their adaptability decreases significantly in highly dynamic topologies. In contrast, AI-driven routing methods achieved improved routing adaptability and better packet delivery performance but introduced additional computational overhead and processing complexity.

Hybrid optimization approaches generally achieved the best balance between network lifetime, routing reliability, and scalability because they integrate intelligent optimization with adaptive routing mechanisms.

## 4.3 Scalability Analysis

Scalability remains a critical challenge in large-scale WSN deployments. Many traditional routing protocols experience increased routing overhead and communication delay as the number of sensor nodes grows. Clustering-based routing protocols improve scalability by reducing direct communication between sensor nodes and the base station.

AI-based routing methods further enhance scalability through adaptive decision-making and dynamic topology management. However, lightweight implementation remains difficult because many machine learning models require significant computational and memory resources.

Hybrid routing frameworks demonstrated improved scalability compared with traditional approaches by combining hierarchical communication with intelligent optimization techniques.

## 4.4 Energy Consumption Analysis

Energy consumption is the most important evaluation metric in WSN routing because communication operations consume a large proportion of node energy. The reviewed studies indicate that intelligent routing strategies significantly improve energy balancing among sensor nodes and reduce premature node failures.

Metaheuristic optimization methods such as PSO, Bee Colony Optimization, and Genetic Algorithms achieved considerable improvements in path optimization and energy efficiency. Similarly, clustering-based routing protocols reduced communication distance and transmission overhead through efficient cluster-head selection mechanisms.

Table 1: Present data routing protocols and metrics.

| References | Methods Used | Metrics Evaluated |
|---|---|---|
| [16] | Deep Reinforcement Learning | PDR, Delay, Throughput, Energy Consumption |
| [14] | MAC Protocol Optimization | Throughput, Delay, Energy Efficiency |
| [10] | Data Compression-based Routing | Energy Consumption, Throughput |
| [9], [26] | Underwater Routing + Metaheuristic | Delay, Reliability, Energy Efficiency |
| [22], [24] | Geographic / Energy-aware Routing | Energy Consumption, Network Lifetime |
| [21] | Energy-aware Scheduling | Energy Efficiency, Network Lifetime |
| [17] | Data aggregation with routing support | Energy Consumption, Throughput |
| [31] | Evolutionary Algorithm-based Routing | Shortest Path, Energy Consumption |
| [1], [2], [6], [7], [8] | Review-based Routing Studies | General Metrics (PDR, Delay, Energy, Lifetime) |
| [18] | Underwater WSN Routing (IEEE Conference) | Reliability, Packet Delivery |
| [19] | Multipath fault-tolerant routing | Reliability, Fault Tolerance |
| [23] | QoS-based Routing | Throughput, Delay, QoS Performance |
| [25] | Path planning-based communication | Energy Efficiency, Distance Optimization |

Machine learning-based routing approaches improved adaptive energy management in dynamic environments; however, excessive computational complexity may increase processing energy consumption in resource-constrained sensor nodes.

### 4.5 Routing Overhead and Latency Analysis

Routing overhead and transmission latency strongly affect the reliability and responsiveness of WSN communication systems. Traditional routing protocols often generate excessive control packets during route establishment and maintenance processes, leading to increased communication overhead.

Adaptive routing mechanisms and intelligent path selection approaches significantly reduced retransmissions and improved routing stability. Deep reinforcement learning and fuzzy logic-based methods demonstrated improved latency performance by dynamically selecting optimal transmission paths according to real-time network conditions.

However, some AI-based routing frameworks still suffer from long training times and increased computational overhead, particularly in highly dynamic environments.

### 4.6 AI-Based vs Heuristic Routing Approaches

Recent studies increasingly compare AI-driven routing methods with conventional heuristic optimization techniques. Heuristic methods such as PSO, Genetic Algorithms, and Bee Colony Optimization provide efficient path optimization with relatively low implementation complexity. However, these approaches often lack real-time adaptability in dynamic network environments.

In contrast, AI-based routing techniques offer improved learning capability, adaptive routing decisions, and better handling of topology changes. Deep reinforcement learning and neural-network-based methods demonstrated higher packet delivery ratios and lower latency in dynamic scenarios.

Nevertheless, AI-based approaches still face important challenges related to computational complexity, training requirements, memory consumption, and lightweight implementation for low-power sensor nodes.

### 4.7 Critical Research Gaps

Despite significant progress in intelligent routing optimization, several important research gaps remain unresolved:

- Lack of standardized benchmarking frameworks for routing evaluation;
- Limited real-world deployment and experimental validation;
- High computational complexity of AI-based routing models;
- Insufficient focus on lightweight AI integration;
- Limited support for real-time adaptive routing;
- Security and privacy challenges in intelligent WSN routing;
- Scalability limitations in ultra-dense IoT environments.

Future research should focus on developing lightweight intelligent routing frameworks that integrate energy-aware optimization, adaptive clustering, edge intelligence, and real-time routing analytics for next-generation WSN applications.

## 5 CONCLUSIONS

This study presented a systematic review and comparative analysis of recent energy-efficient routing protocols for Wireless Sensor Networks (WSNs). The review focused on recent studies published between 2020 and 2025 and analyzed routing approaches designed to improve data transmission efficiency, reduce energy consumption, and enhance communication reliability in IoT-enabled WSN environments.

Using a PRISMA-based review methodology, 34 high-quality studies were selected from an initial collection of 120 research articles. The reviewed routing protocols were classified into several major categories, including energy-aware routing, clustering-based routing, metaheuristic optimization methods, machine learning-based routing, and hybrid intelligent routing frameworks. Furthermore, comparative benchmarking was conducted using important network performance metrics such as energy consumption, packet delivery ratio, throughput, latency, scalability, routing overhead, reliability, and network lifetime.

The analysis demonstrated that intelligent and hybrid routing approaches significantly improve routing adaptability and energy efficiency compared with traditional routing methods. In particular, machine learning and metaheuristic optimization techniques showed strong potential for adaptive path selection and energy balancing in dynamic network environments. However, several challenges remain unresolved, including scalability limitations, computational complexity, routing overhead, and real-time adaptability in resource-constrained sensor nodes.

Overall, this review provides a comprehensive overview of recent advances in WSN routing protocols and highlights the growing importance of intelligent optimization techniques for next-generation IoT communication systems.

# 6 FUTURE WORK

Despite recent advances in energy-efficient routing protocols, several challenges still affect the performance and reliability of WSNs, particularly in dynamic and large-scale IoT environments. Future research should focus on developing adaptive, scalable, and lightweight intelligent routing frameworks for resource-constrained sensor nodes.

Artificial intelligence and machine learning techniques are expected to play an important role in improving routing decisions, energy balancing, and real-time adaptability. In addition, hybrid optimization methods that combine metaheuristic algorithms with intelligent learning mechanisms can further enhance routing efficiency and network reliability.

Future routing protocols should also support dynamic topology management, low routing overhead, secure communication, and scalable network architectures. Furthermore, standardized benchmarking frameworks and real-world experimental validation are needed to improve the reliability and reproducibility of routing performance evaluation.

Overall, integrating AI-driven optimization, lightweight intelligent systems, and adaptive communication strategies will be essential for next-generation WSN and IoT applications.

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