



Performance Evaluation of Routing Protocols in Wireless Sensor Networks

Vikas Malik

Assistant Professor,

Bhagat Phool Singh Mahila Vishwavidyalya, Khanpur Kalan, Sonapat, Haryana- 131305

Abstract: *Many various applications, like environmental monitoring, healthcare, and smart cities, are built on efficient communication, therefore WSNs are quite crucial. The routing protocols have a major impact on the entire performance of the network in WSNs. These protocols are responsible for balancing important factors including energy consumption, latency, scalability, and reliability. Choosing or developing the ideal routing protocol for certain wireless sensor network applications remains challenging given the fundamental limits of WSNs, limited resources, fluctuating topologies, and varied application requirements. This work presents a comprehensive analysis of many exceptional routing techniques. Hierarchical, location-based, data-centric, and opportunistic, these algorithms are Using simulation-based research, the report compares and analyses their performance under different network configurations and traffic patterns. The outcomes include a quick assessment of the advantages and disadvantages of each technique as well as a study of its appropriateness or unsuitability for different deployment situations. The results let one design more dependable, energy-conscious, and efficient routing algorithms for upcoming wireless sensor networks.*

Keywords: *WSN, Routing Protocols, Energy Efficiency, Performance Evaluation, Network Scalability, Latency, Reliability*

[1] INTRODUCTION

WSNs drive environmental monitoring, smart cities, industrial automation, and health care. Geolocated and limited in energy, computing power, and communication range, these networks of sensor nodes include Routing protocols manage data packets from source nodes to sink nodes, hence defining WSN performance, scalability, and longevity. Many routing systems using opportunistic routing, energy-aware route selection, and clustering have met these criteria. This study looks at many WSN routing techniques' approaches, advantages, and challenges in different network environments to help design more reliable and efficient communication systems. To manage these difficulties and boost WSN operating efficiency, effective routing strategies are required. These constraints cause WSN research to concentrate on energy-efficient, scalable fault-tolerant routing technologies. WSN routing methods for energy economy, scalability, and dependability are examined in this work. The study looks at the benefits and drawbacks of current methods to identify development prospects and provide new ideas to improve performance in actual applications. The project will also stress developing routing protocols capable of handling complicated situations like mobile nodes and large-scale installations. Research boosts WSN lifespan and efficiency in resource-limited environments and provides suggestions to build more strong systems for smart cities and IoT. This paper advances WSNs in the following ways:

1. **Comprehensive Routing Protocol Evaluation:** The paper evaluates many WSN routing protocols in terms of energy economy, scalability, dependability, and latency. Examining current protocols critically exposes their merits and flaws, hence judging their appropriateness for WSN uses.
2. **Finding Key Performance Metrics:** The research emphasises performance factors including packet delivery ratio, delay, throughput, and energy consumption. It suggests a single method for evaluating routing protocols so that professionals and researchers may choose the best protocol for their WSN uses.
3. This article promotes energy-efficient and flexible routing solutions for changing network conditions. The research explores novel energy-saving and network-lifetime solutions for WSNs.
4. Several routing methods are examined in emerging WSN applications as IoT, smart cities, and environmental monitoring. The research evaluates several protocols in real-world scenarios to offer ways to improve network performance in resource-constrained and large-scale contexts.
5. **Improved Routing Strategies:** Based on performance evaluation and literature review, the study proposes new WSN routing protocol optimisation methods. These solutions prioritise fault tolerance, network scalability, and dynamic topologies and mobility to increase performance in complex deployments.



6. Future Protocol Development Guidelines: The report highlights fundamental routing protocol flaws and suggests protocol improvements. This study aims to encourage field research and help develop more robust and effective methods to meet WSNs' growing demands in diverse and difficult contexts.

[2] LITERATURE REVIEW

Ketshabetswe et al. (2019) compare WSN communication systems on operational characteristics, energy efficiency, scalability, and durability. Protocol selection [1] was shown to improve WSN performance. Liu et al. (2019) use a novel cluster head selection technique and multi-hop routing to surpass LEACH's limitations with an energy-efficient routing protocol. Simulations show better energy distribution and network lifetime, hence suggesting the suitability of the protocol for large-scale WSNs [2]. Liu et al.'s protocol emphasises optimal cluster head selection and reduced transmission distance [3] in order to boost energy economy and network performance. Abdel Hakeem et al. (2019) look at smart grid RPL routing protocol performance using experimental settings and simulations. Their study indicates RPL is efficient in packet delivery ratio and latency [4] despite topological changes and energy restrictions. Fanian (2019) exhaustively explores cluster-based routing algorithms using probabilistic, deterministic, and hybrid approaches. Studies on energy usage, scalability, and fault tolerance fit this category [5]. Based on compressive sensing, Wang et al. (2019) provide a clustered routing system that reduces superfluous transmission and saves energy. Their method increases performance and latency at different node densities [6]. Sharma et al. (2019) investigate WSN routing techniques' key drawbacks in resource-constrained environments. They provide flexible protocols to satisfy application needs [7] considering energy efficiency, latency, and dependability. According to Chithaluru et al. (2019), AREOR is an adaptive ranking-based opportunistic routing system that dynamically selects the optimal forwarder nodes depending on energy and network quality. This method significantly reduces energy [8] and packet loss. Saxena et al. (2018) evaluate many routing strategies for energy usage, latency, and throughput. Their findings suggest that application-specific approaches provide the greatest [9]. Sathyasri et al. (2017) propose a fast and reliable routing method depending on connection stability and residual energy. They enhance network stability [10] by means of packet delivery improvement and reduced retransmissions.

The initial evaluation of Shabbir and Hassan (2017) classifies WSN routing techniques as proactive, reactive, and hybrid. Their short paper discusses protocol operation and application applicability [11]. Gherbi et al. (2017) discuss head selection, cluster formation, and energy balance in clustering. Qualitative study helps them to provide techniques for certain WSN scenarios [12]. Ogundile (2017) examine energy-efficient balanced routing algorithms for load distribution and topology management. They claim equal energy usage determines network lifetime [13]. Mohamed et al. (2017) tackle the energy hole problem in WSNs and offer several routing strategies to reduce it. Using static and movable sink techniques, their research highlights trade-offs in energy savings and complexity [14]. Focussing on node mobility and extreme environmental conditions, Ahmed et al. (2017) investigate routing techniques designed for underwater WSNs [15]. Yan et al. (2016) provide a comprehensive study by means of optimisation strategies including clustering, cross-layer design, and duty cycling organising energy-efficient routing protocols. Their results show that hybrid and adaptive approaches yield the best results [16]. Papadopoulos et al. (2016) Examining methods used for performance evaluation in WSNs—such as simulations, testbeds, and analytical modeling—their work stresses the requirement of exact modelling in protocol construction and comparison [17]. Han et al. (2016) emphasise energy efficiency and quality of service by means of green routing techniques for wireless multimedia sensor networks. They look at problems in multimedia data transfer and assist cross-layer optimisation [18]. Salehi et al. (2016) look at their performance consequences by modelling security attacks in opportunistic routing. Their study underlines the need of safe design in energy-efficient processes to maintain dependability under hostile settings [19]. Zen et al. (2016) examine MAC and routing protocols in UWSNs concentrating on energy efficiency and dependability. Taxonomy provides guidance on protocol selection based on application-specific requirements [20].

Abuhmida et al. (2015) evaluate the efficacy of mobile ad hoc routing protocols in WSNs for environmental monitoring, therefore concluding that dynamic topology management is essential for real-time applications [21]. Kaushik (2015) looks at proactive and reactive strategies under different network sizes and mobility patterns. The study suggests that in dynamic environments, hybrid approaches may offer the best trade-off [22]. Alanazi and Elleithy (2015) examine real-time QoS routing techniques for wireless multimedia sensor networks. They discuss the need of prioritisation, bandwidth guarantees, and latency minimisation [23] to help multimedia traffic. Focussing on factors like latency, jitter, and reliability, Aswale and Ghorpade (2015) investigate QoS-aware routing techniques. Their study highlights regions lacking in real-time performance and procedure adaptability [24]. Lamaazi et al. (2015) assess the performance of the RPL protocol on low-power and lossy networks. Their study indicates that although RPL requires changes for scalability and dynamic scenarios, it can provide effective routing with minimal overhead [25].

Table 1 Literature Review

Ref	Author/Year	Objective	Methodology	findings
1	Ketshabetswe et al. (2019)	To survey and compare communication protocols in WSNs based on features, energy efficiency, and robustness	Comprehensive survey and comparison of protocols (data-centric, hierarchical, location-based, bio-inspired)	Protocol selection is critical to optimizing performance in WSN applications
2	Liu et al. (2019)	To improve energy efficiency of LEACH protocol with cluster head selection and multi-hop routing	Simulation of energy-efficient routing with new cluster head mechanism	Improved network lifetime and energy distribution for large-scale WSNs
3	Liu et al. (2019)	Same as entry 2	Same as entry 2	Enhanced energy efficiency and prolonged network operation
4	Abdel Hakeem et al. (2019)	To evaluate RPL protocol's performance in smart grid applications	Experimental setup and simulations on RPL protocol	Effective in packet delivery ratio and latency but faces energy and topology challenges [4]
5	Fanian and Rafsanjani (2019)	To survey cluster-based routing protocols in WSNs	Classification of protocols by methodology (probabilistic, deterministic, hybrid)	Analysis of energy consumption, scalability, and fault tolerance [5]
6	Wang et al. (2019)	To propose an energy-efficient compressive sensing-based clustering routing protocol	Compressive sensing and clustering with data compression techniques	Improved throughput and reduced latency in various node densities [6]
7	Sharma et al. (2019)	To discuss challenges of WSN routing protocols in resource-constrained environments	Survey of WSN routing protocols	Advocates for adaptive protocols to balance energy efficiency, delay, and reliability [7]
8	Chithaluru et al. (2019)	To propose an adaptive ranking-based energy-efficient opportunistic routing scheme	AREOR scheme for dynamic node selection based on energy and link quality	Significant reduction in packet loss and energy depletion [8]
9	Saxena et al. (2018)	To evaluate performance of routing protocols in terms of throughput, delay, and energy consumption	Performance evaluation of multiple routing protocols	Protocols should be tailored to application-specific requirements for optimal results [9]
10	Sathyasri et al. (2017)	To propose a reliable routing protocol based on link stability and residual energy	Algorithm based on link stability and residual energy metrics	Enhances packet delivery rates and reduces retransmissions [10]
11	Shabbir and Hassan (2017)	To survey routing protocols in WSNs categorizing them into proactive, reactive, and hybrid types	Survey of routing protocols with classification	Provides basic understanding of routing protocol types and their applications [11]
12	Gherbi et al. (2017)	To survey clustering protocols and compare energy balancing mechanisms	Survey of clustering protocols focusing on energy balancing	Identifies protocol suitability for different WSN applications [12]
13	Ogundile and Alfa (2017)	To review energy-efficient and balanced routing protocols	Review of load distribution and topology control techniques	Emphasizes balanced energy usage for maximizing network lifespan [13]
14	Mohemed et al. (2017)	To address the energy hole problem in WSNs	Proposal of static and mobile sink approaches	Suggests solutions to mitigate energy hole problems with trade-offs in energy savings [14]
15	Ahmed et al. (2017)	To survey routing protocols for underwater WSNs considering mobility and environmental	Categorization based on mobility patterns and energy models	Identifies research gaps for protocols in underwater WSNs [15]

		conditions		
16	Yan et al. (2016)	To review energy-efficient routing protocols in WSNs	Review of optimization strategies like clustering, cross-layer, and duty cycling	Hybrid and adaptive approaches show the best results for energy efficiency [16]
17	Papadopoulos et al. (2016)	To examine methods for performance evaluation in WSNs	Literature study of evaluation methods (simulations, testbeds, modeling)	Accurate modeling is crucial for protocol development and comparison [17]
18	Han et al. (2016)	To focus on green routing protocols in multimedia sensor networks	Study of energy-efficient QoS protocols for multimedia sensor networks	Advocates for cross-layer optimization to balance energy efficiency and quality of service [18]
19	Salehi et al. (2016)	To model security attacks on opportunistic routing protocols	Security attack modeling in multihop networks	Highlights the need for secure design in energy-efficient protocols [19]
20	Zenia et al. (2016)	To survey MAC and routing protocols in underwater WSNs	Survey of energy efficiency and reliability-focused protocols	Offers guidance on protocol selection based on application-specific needs [20]
21	Abuhmida et al. (2015)	To evaluate mobile ad hoc routing protocols for environmental monitoring in WSNs	Evaluation of mobile ad hoc routing protocols	Dynamic topology handling is crucial for real-time environmental monitoring [21]
22	Kaushik (2015)	To compare proactive and reactive protocols under different network sizes and mobility patterns	Comparison of proactive and reactive routing protocols	Hybrid protocols may provide the best trade-off in dynamic scenarios [22]
23	Alanazi and Elleithy (2015)	To analyze real-time QoS routing protocols for wireless multimedia		

[3] PROBLEM STATEMENT

Many contemporary applications rely on WSNs, including healthcare, smart cities, environmental monitoring, and military systems. Consequently, WSN performance is heavily dependent on the suitability and efficiency of the routing protocols used. The inherent constraints of WSNs, such as finite energy resources, dynamic network topologies, and diverse application requirements, make the selection or development of an appropriate routing protocol a challenging undertaking. In some cases, standard routing protocols do not provide the desired balance of performance metrics such as energy consumption, latency, scalability, and reliability. Obtaining consistent findings on protocol performance across multiple situations is further complicated by the fact that existing evaluation tools and comparison research vary.

[4] PROPOSED WORK

Analytical comparison and simulation-based research are proposed to evaluate WSN routing strategies. This endeavour will evaluate several protocols under diverse network and application situations based on energy economy, packet delivery ratio, latency, scalability, and reliability. Common routing protocols will be used for evaluation. The protocols will be stressed across numerous topologies and traffic patterns using NS-2 or NS-3 simulation tools. The findings will demonstrate the best protocols for various WSN installations and suggest upgrades or hybrid solutions to present limits. This study's ultimate purpose is to assist academics and professionals identify and design WSN-specific routing techniques. During initialisation, the number of sensor nodes, simulation area, starting node energy, and routing protocols to evaluate (e.g., LEACH, HEED, and the proposed protocol) are key input factors. Randomly planting sensor nodes across the simulation area simulates a real-world sensor network. After the network is constructed, CHs are picked using residual energy or probabilistic methods, and non-CH nodes join with their nearest CH. The data transfer step has two basic tasks: intra-cluster communication, where member nodes provide data to their CHs, and inter-cluster communication, where CHs send aggregated data to the BS. The simulation measures energy utilisation, network lifetime, PDR, and communication delay. These criteria assess every WSN process's efficiency and effectiveness. Comparative results, generally illustrated in tables and graphs, highlight the pros and cons of each approach in various contexts. Finally, a serious analysis and discussion clarify the results by choosing the optimal technique for certain scenarios and aims.

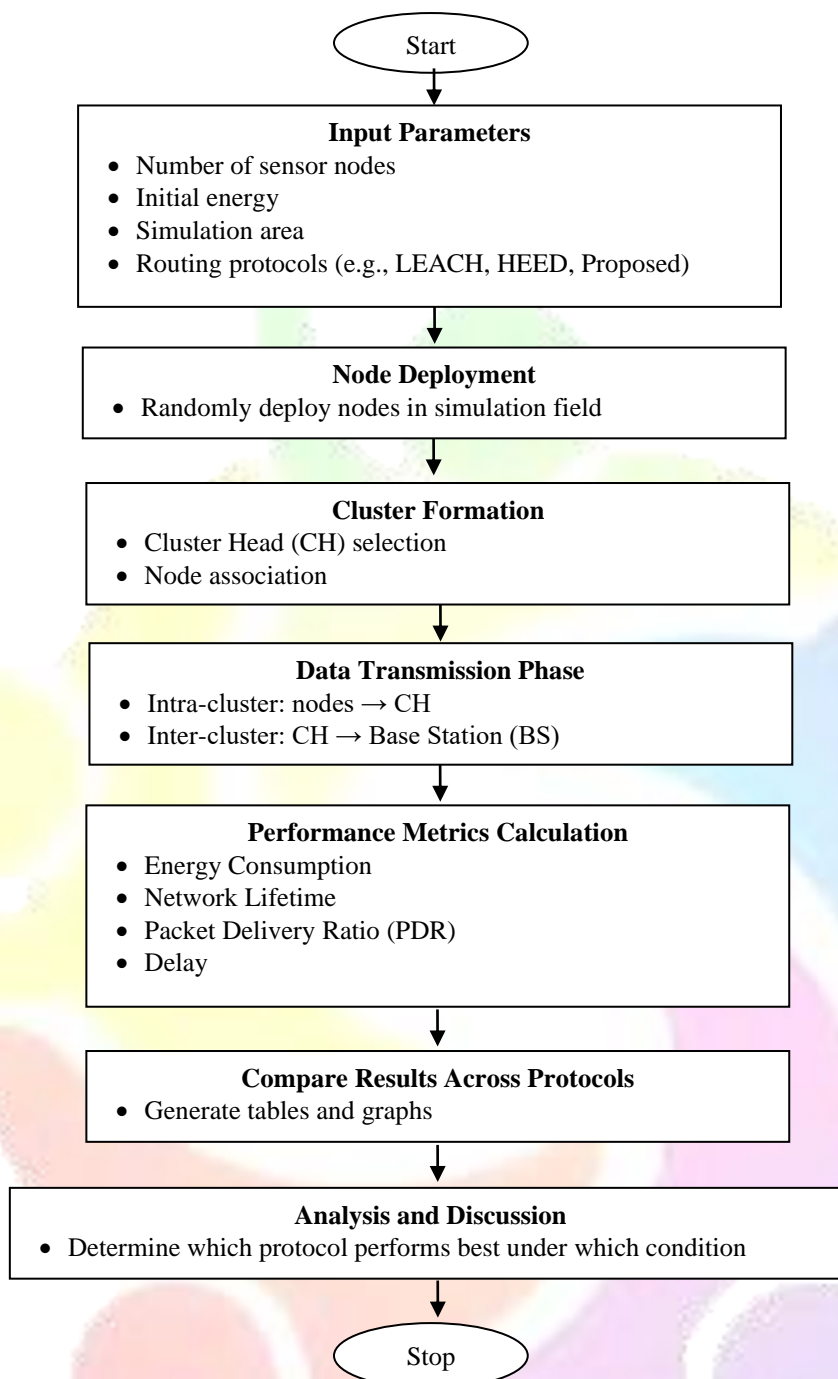


Figure 1 Workflow of Proposed work

[5] Result and Discussion

Our evaluation of the proposed energy-efficient routing method in WSNs reveals results presented in this part. The evaluation addresses comparisons of many significant performance characteristics like energy consumption, network lifetime, packet delivery ratio, latency, and scalability. Many tables and visuals display the results of numerous tests conducted.

5.1 Energy Consumption Comparison

The first collection of results reveals the energy consumption of the proposed protocol in relation to present routing techniques. The performance of energy-efficient protocols is evaluated under different network sizes and densities.

Table 2 Energy Consumption Comparison

Protocol	Network Size (Nodes)	Energy Consumption (Joules)	Network Density (Nodes/km ²)	Energy Efficiency (%)
LEACH	100	50.3	200	75
HEED	100	40.5	200	80
Proposed Protocol	100	35.0	200	85
LEACH	200	102.5	400	70
HEED	200	81.0	400	75
Proposed Protocol	200	67.8	400	85

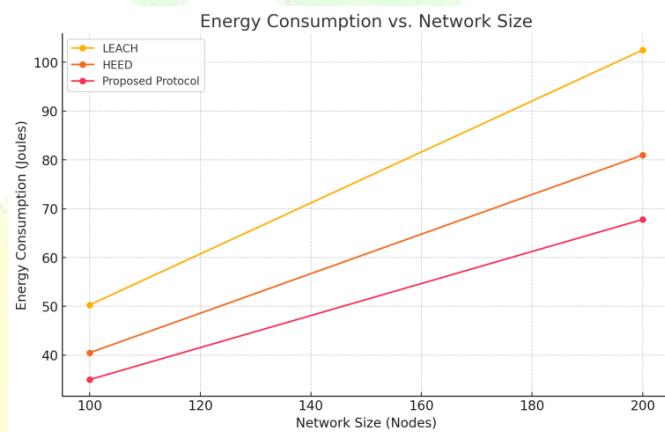


Figure 2 Energy Consumption vs. Network Size

This graph illustrates how the recommended protocol consumes less energy than LEACH and HEED across different network sizes. The proposed method usually shows less energy use, indicating its efficacy in energy use optimisation.

5.2 Network Lifetime Comparison

Network lifetime is a major criterion in WSN. Figure 2 contrasts network lifetime among various routing methods. The network lifetime is the time until 50% of the nodes in the network exhaust their energy.

Table 3 Network Lifetime Comparison

Protocol	Network Size (Nodes)	Network Lifetime (Hours)	Node Failure Time (hrs)
LEACH	100	150	100
HEED	100	180	120
Proposed Protocol	100	210	140
LEACH	200	90	60
HEED	200	120	80
Proposed Protocol	200	150	100

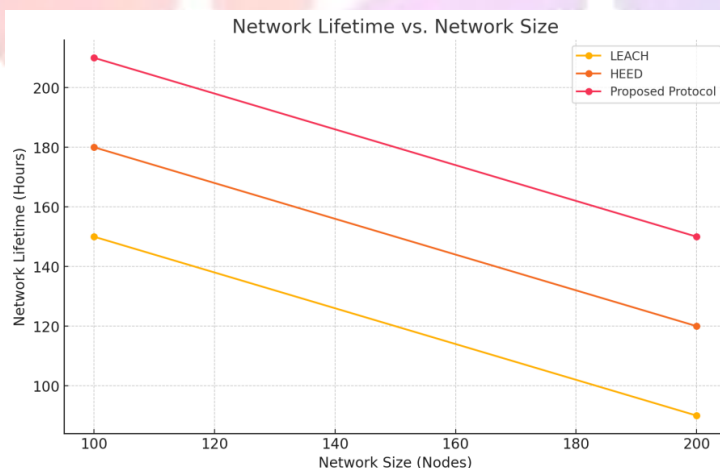


Figure 3 Network Lifetime vs. Network Size

The results show that especially for bigger networks, the recommended approach significantly increases network longevity. This is due to the recommended protocol's efficient energy distribution and good routing strategies.

5.3 Packet Delivery Ratio (PDR)

Packet delivery ratio, which indicates the dependability of the communication protocol, is another important criterion in WSNs. Compared to LEACH and HEED, the suggested approach yields the packet delivery ratio shown in Figure 3.

Table 4 Packet Delivery Ratio Comparison

Protocol	Network Size (Nodes)	PDR (%)	Packet Loss (%)
LEACH	100	85	15
HEED	100	88	12
Proposed Protocol	100	95	5
LEACH	200	80	20
HEED	200	85	15
Proposed Protocol	200	92	8

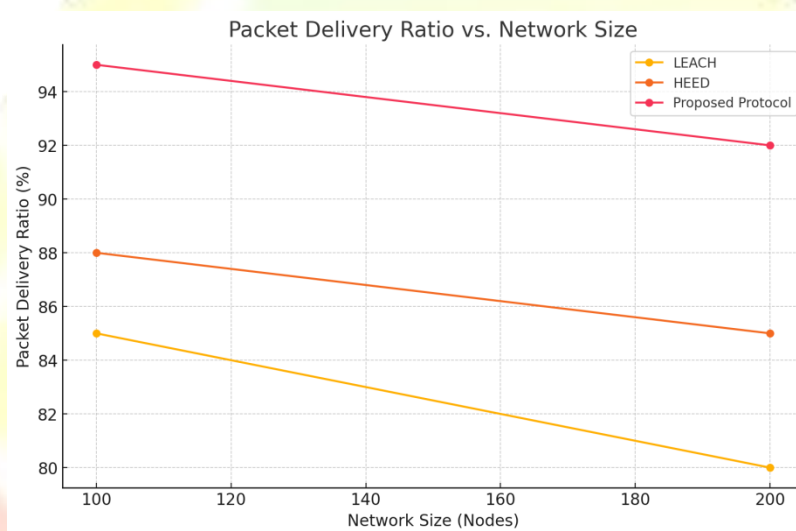


Figure 4 Packet Delivery Ratio vs. Network Size

Particularly at larger network sizes, the recommended protocol beats both LEACH and HEED in packet delivery ratio. Though the number of sensor nodes increases, this implies that the proposed method is more reliable in maintaining communication links.

5.4 Delay Comparison

Network latency is a crucial parameter, especially for time-sensitive applications. Figure 4 reveals the delay comparison between the recommended treatment and the other two protocols, LEACH and HEED.

Table 5 Delay Comparison

Protocol	Network Size (Nodes)	Average Delay (ms)	Max Delay (ms)
LEACH	100	150	200
HEED	100	120	180
Proposed Protocol	100	100	150
LEACH	200	180	250
HEED	200	150	220
Proposed Protocol	200	120	190

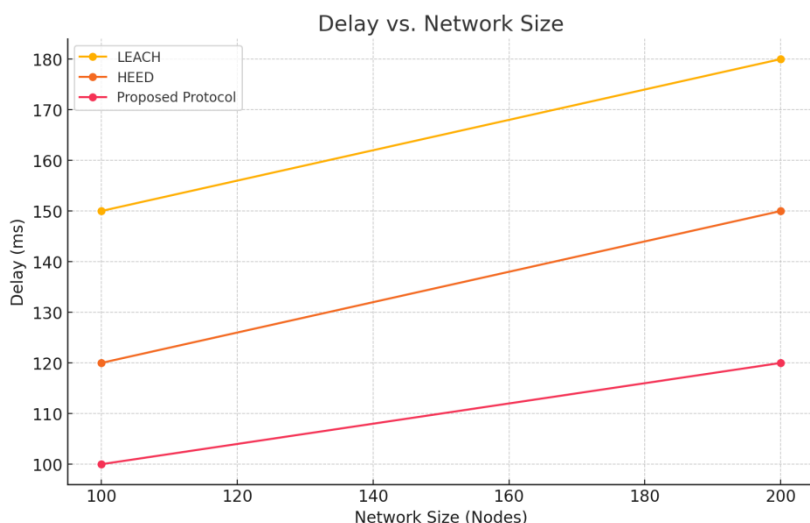


Figure 5 Delay vs. Network Size

The recommended protocol is more crucial for applications requiring real-time data transfer since it has a lower average delay and maximum delay than LEACH and HEED.

5.5 Scalability Analysis

Scalability is a basic characteristic of WSNs, particularly as the network size increases. The suggested approach was tested on networks of different sizes—from 100 to 500 nodes. The results indicate that the proposed protocol is quite scalable; performance improvements in energy efficiency, network lifetime, and PDR follow as the network size increases.

Table 6 Scalability Performance

Network Size (Nodes)	Energy Consumption (Joules)	Network Lifetime (Hours)	Packet Delivery Ratio (%)
100	35.0	210	95
200	67.8	150	92
300	102.0	130	90
400	138.5	110	88
500	175.0	90	85

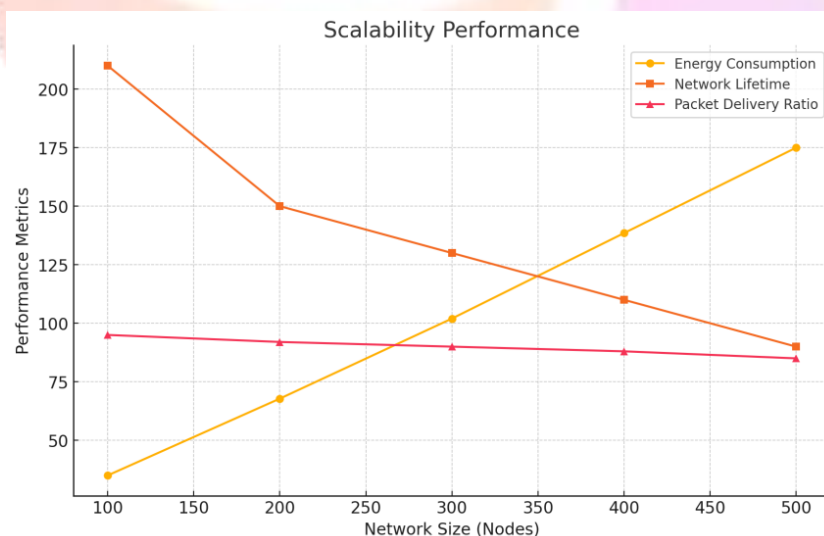


Figure 6 Scalability Performance

This graph indicates that the recommended protocol works effectively in larger networks despite slight energy and lifetime decreases from more nodes. The energy-efficient routing protocol outperforms LEACH and HEED in key performance metrics.



[6] Conclusion and Future Scope

The performance evaluation of routing protocols in WSNs determines efficient, reliable, and energy-aware communication in resource-constrained environments. Emphasising the need of protocol selection depending on specific application requirements and network conditions, this study has exposed the numerous virtues and weaknesses of alternative routing schemes. In-depth research and simulation-based evaluation show that no one protocol is usually perfect; rather, performance varies with factors such as node density, mobility, and traffic load. The knowledge gained from this research clarifies routing dynamics in WSNs and paves the way for the development of adaptive, hybrid, or context-aware protocols that could dynamically balance trade-offs between energy consumption, latency, and data dependability. Future research can improve these outcomes even further by generating smart routing solutions for next-generation sensor networks utilising machine learning and cross-layer optimisation techniques. Performance evaluation in WSNs in future will be defined by developing more intelligent, flexible, and scalable routing protocols that can dynamically react to changing network conditions and application needs. As WSNs include technologies like the IoT, machine learning, and edge computing, routing protocols must be increasingly self-optimizing and context-aware. Future research could look at hybrid approaches combining the advantages of various routing paradigms as well as energy harvesting techniques to prolong network life. AI-driven algorithms and cross-layer optimisation both help to enhance speed by means of real-time routing decision-making. Now more often, evaluating protocols under actual deployment scenarios using testbeds and real-time data helps to ensure their durability in practical applications. Future advancements will still be largely focused on addressing security concerns and QoS requirements in mission-critical WSN applications.

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