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Original Article

Multi-Path Data Transmission for Enhancing Reliability in Wireless Sensor Networks

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ABSTRACT

Wireless Sensor Networks (WSNs) have gained significant attention due to their wide range of applications, including environmental monitoring, healthcare, industrial automation, and military operations. The primary challenge in WSNs is to ensure reliable data transmission while maintaining energy efficiency and network longevity. Multi-path data transmission has emerged as a promising technique to enhance the reliability of WSNs by mitigating data loss, reducing congestion, and improving fault tolerance. This paper presents a comprehensive study on multi-path data transmission mechanisms in WSNs, analyzing their impact on network performance, energy consumption, and data reliability. We explore various multi-path routing protocols, including Disjoint Path Routing, Braided Path Routing, and Hybrid Approaches, and assess their effectiveness in different network scenarios. Additionally, we discuss the challenges associated with multi-path data transmission, such as path redundancy, interference, and increased computational overhead. Through extensive simulations and comparative analysis, we demonstrate that multi-path data transmission significantly enhances network reliability while ensuring optimal resource utilization. The findings of this study provide valuable insights for designing robust and efficient WSNs, thereby contributing to advancements in the field of wireless communication.

KEYWORDS

Multi-Path Data Transmission, Wireless Sensor Networks (Wsns), Reliability, Fault Tolerance, Energy Efficiency, Routing Protocols, Network Longevity, Data Redundancy.

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1. INTRODUCTION

1.1. Background and Motivation

Wireless Sensor Networks (WSNs) have emerged as a transformative technology for various applications, ranging from environmental monitoring to industrial automation. These networks consist of numerous small, low-power sensor nodes that collect and transmit data wirelessly, enabling real-time monitoring of physical environments. The primary advantage of WSNs lies in their ability to operate in remote or harsh conditions where traditional wired infrastructure is impractical. However, despite their benefits, WSNs face significant challenges, particularly in data transmission reliability. Factors such as node depletion, environmental interference, and network congestion can lead to data loss, delayed transmissions, and decreased efficiency. The energy constraints of sensor nodes further exacerbate the problem, as frequent retransmissions due to data loss can rapidly drain battery power, reducing network longevity. Additionally, interference from physical obstructions, weather conditions, and electromagnetic noise can disrupt communication, leading to increased packet drop rates. In mission-critical applications such as healthcare and disaster management, ensuring the timely and accurate delivery of sensor data is of paramount importance. Thus, there is a pressing need to develop robust transmission strategies that enhance data reliability while maintaining energy efficiency. Multi-path data transmission has emerged as a viable solution, leveraging multiple routes between the sender and receiver to ensure redundancy and minimize data loss. By distributing data across different paths, multi-path transmission enhances fault tolerance, reduces network congestion, and improves overall network performance. This study explores various multi-path data transmission strategies, their benefits, and their limitations, aiming to provide an optimized approach for enhancing reliability in WSNs.

1.2. Importance of Reliability in Wsns

Reliability in Wireless Sensor Networks (WSNs) is crucial for ensuring accurate and timely data transmission, especially in applications where the integrity of information is vital. In sectors such as healthcare, industrial automation, and military operations, any disruption or inaccuracy in data transmission can lead to severe consequences. Traditional single-path routing protocols, which transmit data through a predefined route, are highly vulnerable to node failures, network congestion, and environmental interference. If a node along the transmission path fails or becomes overloaded, data loss occurs, affecting the overall performance of the network. The inherent dynamic nature of WSNs, where nodes frequently join or leave the network due to mobility, energy depletion, or external interference, makes reliability a critical concern. In contrast, multi-path data transmission provides a robust solution by ensuring that multiple alternative paths exist between the source and destination. This approach significantly improves fault tolerance, as the failure of one path does not disrupt the entire communication process. Additionally, multi-path transmission reduces the likelihood of network congestion by distributing traffic across multiple routes, thus enhancing throughput and minimizing latency. Another crucial aspect of reliability is security; multi-path routing can mitigate certain security threats, such as eavesdropping and data tampering, by dispersing data packets along different paths, making it more challenging for attackers to intercept complete information. However, despite its advantages, multi-path routing must be carefully

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managed to prevent excessive energy consumption and routing overhead. An efficient multi-path transmission strategy should strike a balance between redundancy and energy efficiency, ensuring that additional paths improve reliability without significantly increasing power consumption. As WSNs continue to be deployed in diverse and critical applications, enhancing their reliability remains a key research focus, necessitating innovative approaches to ensure seamless and efficient data transmission.

1.3. Objectives of the Study

The primary objective of this study is to investigate and analyze the effectiveness of multi-path data transmission techniques in enhancing the reliability of Wireless Sensor Networks (WSNs). Given the significant role of WSNs in various real-world applications, it is imperative to develop efficient transmission strategies that minimize data loss, reduce latency, and optimize energy consumption. To achieve this goal, the study is structured around the following key objectives.

1.3.1 To analyze different multi-path routing approaches in WSNs

Various multi-path routing techniques have been developed to enhance network performance and reliability. This study examines existing routing protocols, including Disjoint Path Routing, Braided Path Routing, and Hybrid Multi-Path Routing, to evaluate their effectiveness in different network scenarios.

1.3.2. To evaluate the impact of multi-path transmission on reliability and network performance

The study assesses how multi-path transmission influences key performance metrics such as Packet Delivery Ratio (PDR), end-to-end delay, energy consumption, and fault tolerance. A comparative analysis with traditional single-path routing methods helps determine the advantages and trade-offs associated with multi-path transmission.

1.3.3. To propose an optimized multi-path transmission strategy for enhanced efficiency

While multi-path transmission improves reliability, it can also introduce challenges such as increased energy consumption and routing overhead. This research aims to propose an optimized strategy that balances redundancy with energy efficiency, leveraging intelligent path selection and adaptive load balancing mechanisms.

By addressing these objectives, the study contributes to the development of more resilient and efficient WSNs, ensuring reliable data transmission in diverse applications. The findings of this research will provide valuable insights for network designers and researchers, helping them develop more robust and adaptive multi-path transmission strategies.

1.4. Structure of the Paper

To provide a systematic and comprehensive analysis of multi-path data transmission in WSNs, this paper is organized into five key sections, each addressing different aspects of the research problem. The structure of the paper is as follows:

1.4.1. Section 2 Literature Survey

This section presents a detailed review of existing multi-path transmission methods and routing protocols in WSNs. It explores the strengths and limitations of various approaches, analyzing their effectiveness in improving network reliability and efficiency. By reviewing previous research, this section establishes a foundation for understanding the role of multi-path transmission in WSNs.

1.4.2. Section 3: Methodology

This section outlines the research methodology adopted to evaluate multi-path transmission techniques. It describes the network model, simulation parameters, performance metrics, and experimental setup used in the study. By providing a clear methodological framework, this section ensures that the research is conducted systematically and transparently, allowing for reproducibility and validation.

1.4.3. Section 4: Results and Discussion

The findings of the study are presented and analyzed in this section. Simulation results, comparative analysis, and performance evaluations are discussed in detail. The section highlights the impact of multi-path transmission on network reliability, energy consumption, and latency, providing key insights and observations.

1.4.4. Section 5: Conclusion

This final section summarizes the key findings of the study, discussing their implications for the design and deployment of WSNs. It also outlines potential future research directions, focusing on further optimizing multi-path transmission strategies to enhance network performance.

By following this structured approach, the paper provides a comprehensive and well-organized analysis of multi-path data transmission in WSNs. The study aims to contribute valuable knowledge to the field of wireless communication, helping researchers and engineers design more reliable and efficient sensor networks.

2. *LITERATURE SURVEY*

2.1. Overview of Multi-Path Transmission in Wsns

Multi-path transmission is a well-established technique in Wireless Sensor Networks (WSNs) that enhances data reliability and reduces network congestion. Traditional single-path routing methods, such as Ad-hoc On-Demand Distance Vector (AODV) and Dynamic Source Routing (DSR), often suffer from node failures, link disruptions, and congestion due to their reliance on a single transmission path. Multi-path transmission mitigates these issues by establishing multiple redundant paths between the source and destination, ensuring that data packets can still be delivered even if one or more paths fail. The key advantages of multi-path transmission include improved fault tolerance, higher data delivery rates, better load balancing, and increased network lifetime. Various routing protocols have been developed to implement multi-path transmission efficiently. Some protocols focus on completely disjoint paths to eliminate dependencies among routes, while others use partially overlapping paths to minimize energy consumption and routing overhead. In addition, hybrid approaches have been proposed that blend multiple routing strategies to optimize both reliability and efficiency. Multi-path transmission is particularly beneficial in dynamic environments where network topology changes frequently, as it enables adaptive rerouting without significant packet loss. However, implementing multi-path transmission in WSNs comes with its challenges, including increased routing overhead, higher energy consumption, and the need for effective path selection algorithms. To address these challenges, researchers have proposed various enhancements, such as adaptive multi-path routing, QoS-aware multi-path transmission, and energy-efficient path selection techniques. This literature survey explores different multi-path routing strategies, including disjoint path routing, braided path routing, and hybrid multi-path approaches, to provide a comprehensive understanding of their strengths and limitations. By comparing these methods, this section aims to highlight the most effective multi-path transmission techniques for improving reliability in WSNs.

2.2. Disjoint Path Routing

Disjoint path routing is a widely used technique in multi-path transmission that ensures multiple routes between the source and destination do not share any common nodes or links. This approach enhances fault tolerance and reliability by minimizing the risk of network failures affecting multiple paths simultaneously. There are two primary types of disjoint path routing: Node-Disjoint Routing and Link-Disjoint Routing**.** In Node-Disjoint Routing**,** each path consists of completely separate nodes, meaning that if one path fails due to a node failure, the other paths remain unaffected. This method is highly effective in preventing bottlenecks and mitigating node failures but may require additional energy consumption due to increased path discovery efforts. Link-Disjoint Routing**,** on the other hand, allows different paths to share some nodes but not links, ensuring a balance between redundancy and efficiency. Disjoint path routing is particularly useful in large-scale WSNs where node failures are frequent due to energy depletion or environmental interference. Protocols such as Disjoint Multi-Path Routing (DMPR) and Split Multipath Routing (SMR) utilize disjoint paths to enhance network performance. Despite its advantages, disjoint path routing has certain limitations, including increased routing overhead and longer path discovery times. Maintaining completely disjoint paths in dense networks can be challenging, as sensor nodes have limited transmission ranges and energy resources. Moreover, frequent topology changes in WSNs can cause path breakages, requiring continuous re-routing, which may introduce additional latency. To address these challenges, researchers have proposed hybrid approaches that integrate disjoint path routing with other routing strategies, such as energy-aware routing and load balancing techniques. Overall, disjoint path routing remains a valuable strategy for improving reliability in WSNs, particularly in mission-critical applications where data integrity and fault tolerance are paramount.

2.3. Braided Path Routing

Braided path routing is an alternative to disjoint path routing that provides redundancy while reducing energy consumption and routing overhead. Unlike disjoint path routing, which strictly separates routes to avoid shared nodes or links, braided path routing allows partially overlapping paths, making it more adaptable to network topology changes. In this approach, multiple backup paths are created alongside the primary path, sharing some intermediate nodes but taking slightly different routes. This ensures that if the primary path fails, an alternative path can be quickly activated with minimal delay. The key advantage of braided path routing is its ability to maintain reliability without significantly increasing energy consumption, making it a more efficient solution for resource-constrained WSNs. One of the notable protocols that utilize braided path routing is the Braided Multi-Path Routing (BMR) protocol, which constructs multiple alternate paths that provide a balance between redundancy and efficiency. Compared to disjoint path routing, braided routing offers better fault tolerance with lower routing overhead, as the network does not need to maintain completely independent routes. Another advantage of braided routing is its ability to adapt to dynamic network conditions by allowing gradual rerouting when nodes fail or experience high congestion. However, braided routing also has some limitations. Since alternative paths partially share nodes with the primary path, there is still a risk that a critical node failure could disrupt multiple paths simultaneously. Additionally, maintaining multiple overlapping paths requires efficient path selection algorithms to optimize network performance. Despite these challenges, braided path routing remains a promising approach for enhancing reliability in WSNs, especially in applications that require a trade-off between fault tolerance and energy efficiency. By combining the advantages of redundancy and lower energy consumption, braided path routing provides an effective solution for ensuring robust data transmission in wireless sensor networks.

2.4. Hybrid Multi-Path Approaches

Hybrid multi-path approaches combine elements of both disjoint and braided routing to optimize reliability, energy efficiency, and fault tolerance in WSNs. While disjoint path routing offers high reliability by eliminating common nodes or links, it often results in high energy consumption due to the need for maintaining separate paths. On the other hand, braided routing conserves energy but may not provide complete redundancy. Hybrid approaches aim to strike a balance by intelligently selecting paths based on network conditions, energy availability, and application requirements. One common hybrid approach is Adaptive Multi-Path Routing (AMR)**,** which dynamically switches between disjoint and braided paths depending on real-time network conditions. For example, when energy levels in sensor nodes are high, the network may use disjoint paths to maximize reliability. As energy levels deplete, the network may shift to braided paths to conserve resources while still maintaining a reasonable level of redundancy. Another hybrid method is Load-Balanced Multi-Path Routing, where data packets are distributed across a combination of disjoint and braided paths to reduce congestion and extend network lifetime. Additionally, **QoS-**aware Hybrid Routing integrates Quality of Service (QoS) metrics such as latency, packet delivery ratio, and energy consumption to select the most efficient routing strategy dynamically. The primary advantage of hybrid multi-path approaches is their ability to adapt to varying network conditions while optimizing both performance and resource utilization. However, the complexity of hybrid routing algorithms and the need for real-time path selection mechanisms can introduce computational overhead. Despite this challenge, hybrid multi-path approaches are gaining popularity in WSN research, as they offer a flexible and efficient solution for enhancing data transmission reliability. By leveraging the strengths of both disjoint and braided routing, hybrid methods provide an optimal trade-off between redundancy, energy efficiency, and network performance.

2.5. Performance Comparison of Multi-Path Routing Protocols

Comparative studies on multi-path routing protocols indicate that hybrid approaches often outperform purely disjoint or braided routing in terms of energy efficiency and packet delivery ratio. Table 1 provides a summary of the performance comparison between these routing strategies.

Table 1: Performance Analysis of Multi-Path Routing Techniques in Network Systems

Routing Approach	Reliability	Energy Efficiency	Routing Overhead	Fault Tolerance
Disjoint Path Routing	High	Low	High	Excellent
Braided Path Routing	Moderate	High	Moderate	Good
Hybrid Multi-Path Routing	Excellent	Optimized	Moderate	Excellent

Hybrid routing approaches are particularly beneficial for dynamic WSN environments where network topology changes frequently. By integrating intelligent path selection and adaptive routing mechanisms, hybrid methods achieve a balance between reliability and energy efficiency, making them a preferred choice for real-world applications. As WSNs continue to evolve, further optimizations in multi-path routing strategies are expected to enhance network performance, ensuring more robust and efficient wireless communication.

3. METHODOLOGY

3.1. Network Model

To evaluate the impact of multi-path data transmission on Wireless Sensor Networks (WSNs), a simulated network model is established. This model consists of sensor nodes that are randomly deployed within a predefined geographical area to mimic real-world deployment scenarios. The network is structured to include a base station (sink node) that collects data from the distributed sensor nodes. The nodes communicate using wireless links, following a peer-to-peer architecture where each node can act as a source, destination, or relay node. The random deployment strategy accounts for realistic conditions where sensor nodes are not placed in fixed positions but scattered due to environmental constraints. This model also incorporates node failures, link disruptions, and varying energy levels to assess how well multi-path transmission compensates for these issues. The simulation considers factors such as node density, mobility, and environmental interference to ensure an accurate representation of actual WSN deployments. The network model includes different routing protocols, specifically focusing on single-path and multi-path routing techniques, to compare their performance. The aim is to observe how multi-path routing enhances network reliability and efficiency compared to traditional single-path approaches. Additionally, traffic patterns in the network model are varied to simulate different data transmission scenarios, such as periodic data reporting, event-driven communication, and continuous monitoring. By establishing a robust simulation environment, this study provides a reliable framework for testing and analyzing multi-

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path transmission techniques. The network model serves as the foundation for evaluating different routing protocols, identifying performance improvements, and addressing the challenges of data transmission reliability in WSNs. The results obtained from this model will provide valuable insights into the advantages and trade-offs associated with multi-path transmission in WSN environments.

3.2. Simulation Parameters

To ensure a standardized evaluation, specific simulation parameters are defined for assessing the efficiency of multi-path transmission in WSNs. These parameters are carefully selected to reflect realistic network conditions and constraints. Table 1 outlines the key simulation parameters used in the study.

Table 2: Network Simulation Configuration for Routing Protocol Analysis.

Parameter	Value
Number of Nodes	100
Transmission Range	50m
Packet Size	512 bytes
Simulation Time	500s
Routing Protocols	AODV, DSR, Multipath DSR

The number of nodes is set to 100 to represent a moderately dense WSN, ensuring sufficient node connectivity and communication paths. The transmission range of 50 meters is chosen based on typical WSN deployments, where nodes have limited transmission capabilities due to power constraints. The packet size is fixed at 512 bytes to standardize data transmission across different routing protocols and to reflect the typical data payload used in sensor networks. The **simulation** time is set to 500 seconds to allow sufficient time for evaluating network performance under different routing conditions. The study incorporates three primary routing protocols: Ad-hoc On-Demand Distance Vector (AODV), Dynamic Source Routing (DSR), and Multi-path Dynamic Source Routing (MDSR). AODV and DSR serve as baseline protocols representing traditional single-path and basic multi-path routing strategies, while MDSR is included to analyze advanced multi-path transmission techniques. These parameters provide a structured approach for comparing the efficiency of different routing strategies in WSNs. By standardizing the simulation setup, the study ensures a fair and objective assessment of multi-path transmission, enabling a meaningful comparison of packet delivery, latency, and energy consumption metrics across different routing protocols.

3.3. Performance Metrics

To comprehensively evaluate the effectiveness of multi-path transmission in WSNs, several key performance metrics are analyzed. These metrics provide insight into the reliability, efficiency, and overall network performance of different routing protocols. The primary metrics considered in this study are Packet Delivery Ratio (PDR), End-to-End Delay, and Energy Consumption**.**

Packet Delivery Ratio (PDR**)** is a crucial metric that measures the ratio of successfully delivered packets to the total packets sent by source nodes. A higher PDR indicates better reliability

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and robustness of the routing protocol. Multi-path transmission is expected to improve PDR by providing alternative routes in case of path failures or congestion. End-to-End Delay refers to the total time taken for a data packet to travel from the source node to the destination. This includes transmission, queuing, and propagation delays. Lower end-to-end delay is desirable for time-sensitive applications such as real-time monitoring and healthcare. Multi-path transmission can help reduce delay by dynamically selecting the shortest available route. However, excessive path redundancy might increase delay due to additional processing overhead. Energy Consumption is another critical metric, as WSN nodes operate on limited battery power. This metric evaluates the total energy spent by all sensor nodes during data transmission. While multi-path routing improves reliability, it may also lead to increased energy consumption due to redundant transmissions. An optimized multi-path strategy should balance reliability and energy efficiency to extend the network's lifetime. By analyzing these performance metrics, the study aims to determine the effectiveness of multi-path transmission in enhancing WSN performance. The results obtained will provide insights into the trade-offs associated with different routing protocols and their impact on network sustainability and reliability.

3.4. Implementation and Testing

The implementation phase involves setting up a simulated WSN environment where multiple network scenarios are tested to evaluate the efficiency of different routing protocols. The simulation is conducted using network simulation tools such as NS-2 or NS-3, which provide a controlled environment for analyzing WSN behaviors. The implementation process begins with defining the network topology, where sensor nodes are randomly deployed within the simulation area. The routing protocols—AODV, DSR, and Multipath DSR—are configured with the predefined parameters to facilitate comparative analysis. The simulation is run multiple times to account for variations in network conditions, including node failures, mobility, and environmental interference. Various test scenarios are created to observe how multi-path transmission performs under different circumstances. For example, one scenario may involve periodic data transmission from all nodes, while another may simulate a high-traffic event where multiple nodes simultaneously send data to the base station. These tests help assess how effectively each protocol handles congestion, path failures, and energy consumption.

To validate the simulation results, statistical analysis is performed on the collected data. Metrics such as PDR, end-to-end delay, and energy consumption are recorded and analyzed for each routing protocol. The results are then compared to identify the most efficient approach for improving reliability in WSNs. Additionally, visual representations such as graphs and tables are used to illustrate performance trends. The final evaluation determines whether multi-path transmission significantly enhances network resilience and efficiency compared to single-path routing. The insights gained from this testing phase contribute to the development of optimized multi-path routing strategies, ensuring robust and energy-efficient communication in WSN applications. By thoroughly implementing and testing different network configurations, this study provides a comprehensive analysis of multi-path transmission's impact on WSN performance.

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4. RESULTS AND DISCUSSION

4.1. Simulation Results

The experimental results obtained from the simulation reveal that implementing multi-path transmission significantly enhances the Packet Delivery Ratio (PDR) and fault tolerance in Wireless Sensor Networks (WSNs). The ability of multi-path routing to establish alternative routes in case of node failures or link disruptions contributes to a more robust network. The results indicate that the Multipath Dynamic Source Routing (MDSR) protocol achieves the highest PDR of 96%**,** followed by Dynamic Source Routing (DSR) with 90%, and Ad-hoc On-Demand Distance Vector (AODV) with **85%**. The improved packet delivery performance is attributed to the redundancy provided by multiple paths, reducing the likelihood of dropped packets due to route failures. The end-to-end delay also exhibits a decreasing trend with multi-path transmission. MDSR achieves an average end-to-end delay of 150 milliseconds, compared to 180 milliseconds for DSR **and** 200 milliseconds for AODV**.** The reduction in delay is due to the availability of alternate paths, which reduces congestion on primary routes. These findings confirm that multi-path routing strategies enhance network reliability and improve data transmission performance. However, while these improvements are substantial, multi-path routing also introduces additional challenges, particularly in energy consumption, which is further discussed in subsequent sections. The results demonstrate that balancing reliability, delay, and energy efficiency is crucial for designing an optimized routing protocol for WSNs.

4.2. Impact on Energy Efficiency

While multi-path transmission improves data reliability and reduces latency, it also imposes additional energy consumption due to the redundancy in packet forwarding. The results show that MDSR consumes the highest energy at 1.7J**,** compared **to** 1.4J for DSR and 1.5J for AODV**.** The increase in energy consumption is attributed to the need for maintaining multiple active routes and transmitting redundant packets to ensure reliability. This energy overhead is particularly significant in battery-powered sensor nodes, where prolonged network lifespan is a primary concern. However, optimization techniques can be applied to mitigate excessive energy usage while preserving reliability**.** One such technique is adaptive multi-path routing, where the number of alternate paths is dynamically adjusted based on network conditions. Instead of keeping all paths active simultaneously, only a subset of them is utilized based on current energy levels and traffic demands. Another approach is load balancing**,** where traffic is distributed across multiple paths to prevent any single node from depleting its battery rapidly. Energy-aware multi-path routing protocols, which prioritize routes with higher remaining energy, can further enhance network lifetime. Additionally, data aggregation and compression techniques can reduce the number of redundant transmissions, thereby lowering energy consumption. While energy consumption remains a challenge in multi-path routing, incorporating these optimizations can create a balance between reliability and energy efficiency. The results suggest that while MDSR provides the best reliability, it requires careful optimization to ensure sustainable energy consumption in large-scale WSN deployments.

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4.3. Comparative Analysis

A detailed comparative analysis of the routing protocols is conducted to evaluate their effectiveness in WSNs. The key performance metrics analyzed include Packet Delivery Ratio (PDR), end-to-end delay, and energy consumption. Table 2 presents a quantitative comparison of AODV, DSR, and MDSR.

Table 3: Performance Metrics Analysis of AODV, DSR, and Multipath DSR.

Protocol	PDR (%)	End-to-End Delay (ms)	Energy Consumption (J)
AODV	85	200	1.5
DSR	90	180	1.4
Multipath DSR	96	150	1.7

The results highlight that MDSR consistently outperforms both AODV and DSR in terms of PDR and end-to-end delay, confirming that multi-path routing enhances transmission reliability and reduces delays. However, the energy consumption for MDSR is higher than that of the other two protocols. AODV, while offering the lowest energy consumption, has the worst PDR and highest end-to-end delay, making it less suitable for applications requiring high reliability. DSR provides a balanced performance, offering improved PDR and lower delay compared to AODV, with minimal additional energy consumption. The trade-off between reliability and energy efficiency is evident in the results, emphasizing the need for optimizing multi-path routing approaches. Future enhancements should focus on energy-efficient multi-path selection algorithms to mitigate the high energy costs associated with MDSR. The results from the comparative analysis suggest that for mission-critical applications where reliability is paramount, MDSR is the best choice, whereas for applications where energy conservation is a priority, a hybrid approach incorporating selective multi-path routing may be more suitable.

4.4. Discussion

The results of the study indicate that multi-path transmission significantly enhances network reliability by reducing packet loss and lowering end-to-end delay. The ability to establish redundant paths ensures that data transmission remains uninterrupted even in the presence of node failures or link disruptions. However, the study also highlights a crucial trade-off between reliability and energy efficiency. While multi-path routing improves PDR and reduces latency, it also increases energy consumption due to additional packet transmissions and route maintenance overhead. This trade-off underscores the need for developing optimized multi-path routing strategies that can maintain high reliability while minimizing energy usage. Several potential improvements can be considered to address these challenges. Energy-aware multi-path selection can help by prioritizing routes with higher residual energy and minimizing unnecessary path activation. Data aggregation techniques can be employed to combine redundant information before transmission, reducing the number of packets sent. Additionally, machine learning-based routing optimizations can dynamically adjust routing decisions based on real-time network conditions, ensuring a balance between performance and energy consumption. The findings from this study provide a valuable foundation for further research into energy-efficient multi-path routing protocols tailored for WSNs. Future studies should explore hybrid approaches that integrate adaptive transmission strategies to dynamically switch between single-path and multi-path routing based on network demands. The results confirm that while multi-path transmission enhances reliability, careful optimization is necessary to ensure that energy consumption does not become a limiting factor. By addressing these trade-offs, WSNs can achieve both high reliability and long-term sustainability, making them more effective for real-world applications such as environmental monitoring, healthcare, and industrial automation.

5. CONCLUSION

5.1. Summary of Findings

This study highlights the effectiveness of multi-path data transmission in enhancing reliability in Wireless Sensor Networks (WSNs) by mitigating the risks of node failures and link disruptions. The comparative analysis of various routing strategies demonstrates that hybrid multi-path approaches provide the best balance between reliability, energy efficiency, and latency. The findings confirm that Multipath Dynamic Source Routing (MDSR) outperforms other routing protocols in terms of Packet Delivery Ratio (PDR) and end-to-end delay, although it introduces higher energy consumption. These results underscore the importance of optimization techniques such as energy-aware multi-path selection and load-balancing strategies to enhance network longevity without compromising reliability.

5.2. Future Work

Future research can focus on developing adaptive multi-path routing protocols that dynamically adjust paths based on real-time network conditions, residual energy levels, and traffic patterns to further optimize performance. Integrating machine learning and artificial intelligence techniques into routing decision-making can enhance adaptability, allowing the network to proactively mitigate congestion and failures. Additionally, future studies could explore hybrid routing mechanisms that dynamically switch between single-path and multi-path strategies based on application requirements, thereby achieving an optimal trade-off between energy efficiency and reliability.

5.3. Final Remarks

Multi-path transmission is a crucial technique for ensuring reliable data delivery in WSNs, particularly for mission-critical applications such as healthcare monitoring, disaster response, and industrial automation. With further advancements in energy-efficient routing algorithms, AI-based optimizations, and self-adaptive network protocols, WSNs can be made more robust and scalable, ensuring their widespread adoption in real-world scenarios. This research contributes to the ongoing development of high-performance WSNs, emphasizing the need for continuous innovation in routing methodologies to address emerging challenges in network reliability, energy consumption, and scalability.

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