Proactive Routing to Avoid Holes in Wireless Sensor Networks

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Abstract

Wireless Sensor Networks (WSNs) are important for many uses, from environmental monitoring to smart cities, because they can collect and send data on their own. However, holes forming in the network, where nodes are either missing or not working, is a big problem that affects network performance and reliability. This study explores proactive routing strategies to prevent and reduce these holes in WSNs. The study examines the causes of holes, including physical damage, energy depletion, and poor node placement. The proposed study demonstrates the different proactive routing methods like energy-efficient protocols, geographic routing, and load balancing, which are essential for keeping the network working well. The study also look at hole detection methods and prediction tools that help find and stop holes early and finally, discusses the challenges and future work in the field, highlighting the need for solutions that can grow and use new technologies. This comprehensive review emphasizes how important proactive routing is for making WSNs work better and last longer.

Keywords: Wireless Sensor Networks (WSNs), Proactive Routing, Network Holes, Energy-Efficient Protocols, Geographic Routing, Load Balancing, Hole Detection, Predictive Models, Network Performance.

1. Introduction

Wireless Sensor Networks (WSNs) have become very important in technology, useful for many applications from environmental monitoring to smart cities. These networks consist

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of distributed, independent sensors that monitor conditions like temperature, sound, or pressure, and work together to send their data to a central hub. As WSNs keep growing, the efficiency and reliability of data transmission become essential. One big challenge in WSNs is holes areas in the network where data transmission is broken due to various factors. This study explores proactive routing strategies aimed at avoiding and reducing these holes, making WSNs perform better and more reliable [11].

1.1 Wireless Sensor Networks (WSNs)

Wireless Sensor Networks (WSNs) are made up of many small, low-cost, low-power sensor nodes that communicate wirelessly to monitor and collect data about environmental conditions or other specified parameters. These nodes usually have a microcontroller, sensors, and a wireless communication interface. The collected data is sent wirelessly to a central hub, where it can be used. WSNs are used in different areas like environmental monitoring, healthcare, industrial automation, and military applications. They provide real-time data and are flexible to deploy, making them very useful where wired connections are not possible.

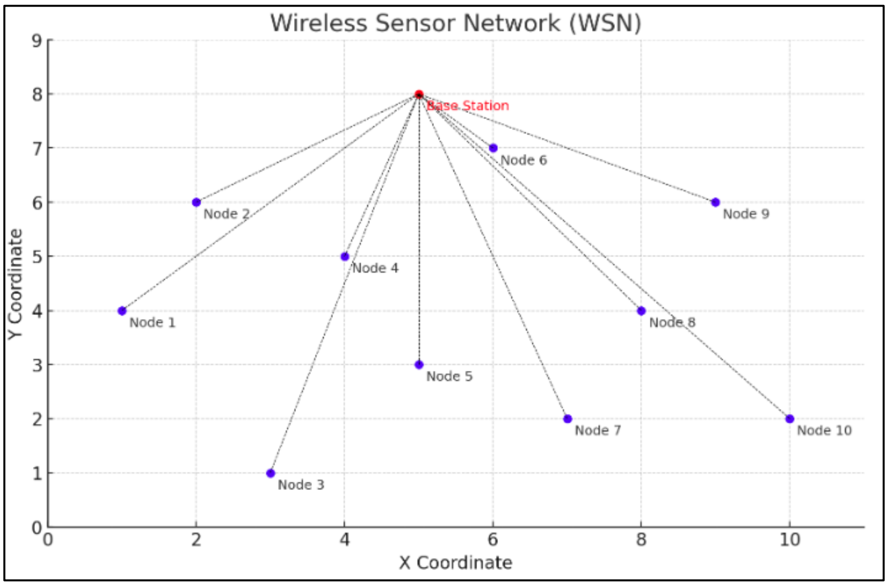

Figure 1. Sensor Nodes Distributed Across an Area

From Figure 1. blue colour indicates the sensor nodes, red colour indicates the base station, dashed lines indicate the data transmission paths from each sensor node to the base station [12].

1.2 Importance of Efficient Routing in WSNs

Efficient routing in WSNs is important for a few reasons. First, it ensures that data collected by the sensor nodes is sent accurately and timely to the central hub. Efficient routing protocols help in saving energy, which is essential since sensor nodes are usually battery-powered and replacing batteries can be hard or even impossible in some environments. Moreover, efficient routing makes the network more reliable and long-lasting by preventing node failures and ensuring balanced energy use across the network. This balance helps in keeping the network connected and prevents parts from becoming isolated when nodes run out of energy. Efficient routing protocols also help WSNs grow, allowing them to support more nodes without a big drop in performance.

1.3 Concept of Holes in WSNs

Holes in WSNs are areas in the network where data transmission is broken. These disruptions can happen due to several reasons:

Physical Causes: Nodes might fail due to bad weather or physical damage.

Energy Depletion: Nodes can run out of energy, especially if they are involved in frequent data transmission or are located in areas with high traffic, leading to uneven energy use.

Deployment Issues: Poor initial placement of nodes can lead to areas with insufficient coverage, creating gaps in the network.

These holes can severely impact the network's performance by causing data loss, increasing latency, and reducing overall network reliability. They can also lead to more energy use as nodes try to find alternative routes, making the problem worse. Therefore, fixing holes with proactive routing is essential for maintaining the functionality and efficiency of WSNs.

2. Related Study

[1] Proposes a novel distributed clustering approach for long-lived ad-hoc sensor networks, called Hybrid Energy-Efficient Distributed Clustering (HEED). The protocol selects cluster heads based on node residual energy and secondary parameters like proximity or degree. HEED terminates in O(1) iterations, incurs low message overhead, and achieves uniform

distribution across the network. Simulation results show HEED prolongs network lifetime and supports scalable data aggregation. [2] Explores the use of multiple mobile sinks in wireless sensor networks, focusing on the scenario of two sinks traveling in the same or divided regions, analyzing network lifetime, data delivery delay, and performance comparisons.

[3] This study addresses the problem of k-coverage in wireless sensor networks (WSNs) by studying sensor dutycycling strategies for generating k-coverage configurations. It models the k-coverage problem, derives a sufficient condition for sensor spatial density, and provides a relationship between communication and sensing ranges. The authors propose four configuration protocols to solve k-coverage in WSNs, proving they select a minimum number of sensors for full coverage while guaranteeing connectivity. Simulation results show these protocols outperform existing distributed k-coverage configuration protocols. [5] Analyzes Wireless Sensor Networks (WSNs) are used to monitor real-time environmental conditions; however, design is difficult due to energy limits. This study examines commercial and research prototypes of existing WSNs and proposes future research paths in this field, taking into account various criteria for each application. Autonomous and semi-autonomous mobile multirobot systems require a wireless communication network for collaborative tasks. A self-forming, self-healing, and self-organizing multihop network is ideal for these systems in unpredictable environments.

However, critical node failures can cause network partitions. To achieve fault-tolerant configurations, simple algorithms are proposed for biconnectivity, a basic graph theoretic metric. These algorithms can be formulated as linear programs for one-dimensional networks and efficient heuristic approaches for two-dimensional networks. Simulations are used to compare performance of these algorithms. [6] This study surveys recent routing protocols for wireless sensor networks, categorizing them into data-centric, hierarchical, and location-based approaches. It discusses each protocols appropriate category, contemporary methodologies like network flow and quality of service modeling, and concludes with open research issues.[7]

The study proposes LEACH (Low-Energy Adaptive Clustering Hierarchy), a clustering based protocol for wireless distributed microsensor systems. It uses randomized rotation of local cluster base stations to evenly distribute energy load among sensors. LEACH achieves a factor of 8 reduction in energy dissipation compared to conventional routing protocols and doubles the useful system lifetime for simulated networks. It also incorporates data fusion for reduced information transmission.[8] Advances in micro-sensor and radio technology will enable smart sensors for environmental monitoring applications. To reduce communication overhead and improve network longevity, efficient data-centric routing mechanisms are needed. This study describes and evaluates Rumor Routing, a tunable scheme that delivers queries to network events, allowing tradeoffs between setup overhead and delivery reliability. It is intended for situations where geographic routing criteria are not applicable.[9] Advances in technology enable small, cheap nodes to communicate, communicate, and compute, enabling networks to coordinate for distributed sensing of environmental phenomena. This study explores the directed diffusion paradigm, which is data-centric, energy-saving, and evaluated for a simple remote-surveillance sensor network.[10]

3. Proactive Routing in WSNs

Proactive routing in WSNs involves establishing routes between sensor nodes in advance of data transmission. This protocol maintains routing information continuously, ensuring that routes are always available when data needs to be transmitted. This contrasts with reactive protocols, which establish routes only when needed.

Nodes in proactive routing periodically exchange routing information to maintain up-to-date knowledge of the network topology. This proactive exchange ensures that nodes are aware of potential routes and can quickly adapt to changes in network conditions. Since routes are pre-established, proactive routing tends to have lower latency compared to reactive routing protocols, where the route discovery process introduces additional delay. One well-known proactive routing protocol is the Optimized Link State Routing (OLSR) protocol, which uses a periodic exchange of control messages to maintain routing tables. Another example is the Destination-Sequenced Distance Vector (DSDV) protocol, which relies on periodic updates and sequence numbers to ensure routing table consistency.

Proactive routing protocols (Figure 2) often consume more energy compared to reactive protocols because of the continuous exchange of control messages and maintenance of routing tables. This is an important consideration in WSNs where energy efficiency is critical. Proactive routing is suitable in scenarios where nodes have relatively stable mobility patterns or where nodes are deployed in a static manner. It ensures that routes are always available without the delay associated with route discovery in reactive protocols.

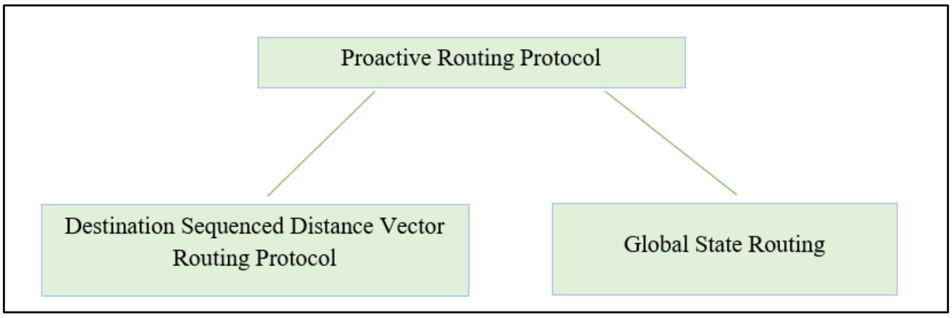

Figure 2. Types of Proactive Routing Protocol

DSDV: It is a proactive routing protocol designed to facilitate efficient and reliable communication in MANETs and WSNs. It enhances the traditional distance vector routing by incorporating sequence numbers to ensure that the routes are valid and prevent routing loops.

GSR: It aims to maintain up-to-date routing information to ensure efficient data transmission across the network.

4. Causes of Holes in WSNs

Holes in Wireless Sensor Networks (WSNs) refer to areas within the network where sensor nodes are either absent or non-functional, leading to gaps in coverage and communication. The primary causes of these holes can be categorized into

- Physical Cause
- Node Failures due to Environmental Factors
- Hardware Malfunctions

Table 1. lists various causes of holes in WSNs and their corresponding effects on the network and the Figure 3 illustrates the flowchart of node hole.

Table 1. Factors that Cause Holes in WSN

Causes	Description	Effect on Network
Node Failure	Hardware malfunctions or software issues leading to node failure	Loss of connectivity, data loss, reduced coverage
Energy Depletion	Nodes running out of battery power	Creation of dead zones, disrupted communication

Physical Damage	Damage from environmental factors (e.g., weather, animals)	Loss of node functionality, coverage gaps
Environmental Interference	Electromagnetic interference or physical obstacles blocking signals	Communication disruption, increased data latency
Hardware Malfunctions	Defects or aging components causing node failures	Inconsistent performance, node outages
Electromagnetic Interference	Disruption from other electronic devices or natural sources	Unreliable communication, increased error rates
Obstacles	Physical barriers (e.g., buildings, trees) obstructing signal paths	Reduced network range, communication gaps
Security Attacks	Deliberate attacks on nodes (e.g., DoS attacks, tampering)	Network vulnerabilities, data breaches
Software Bugs	Errors in node software causing malfunctions	Unpredictable node behavior, potential network collapse
Load Imbalance	Nodes overburdened with traffic leading to quicker energy depletion	Uneven network performance, isolated failures

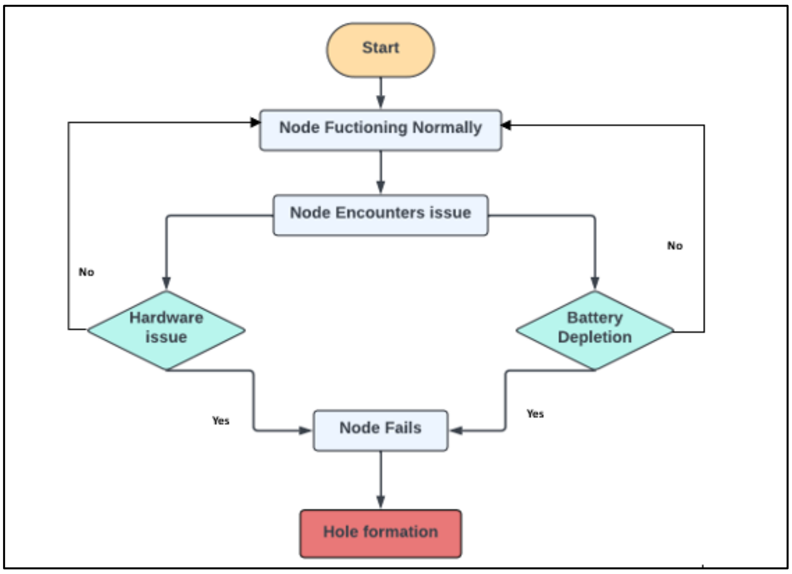

Figure 3. Flowchart of Node Hole

5. Strategies for Proactive Routing to Avoid Holes

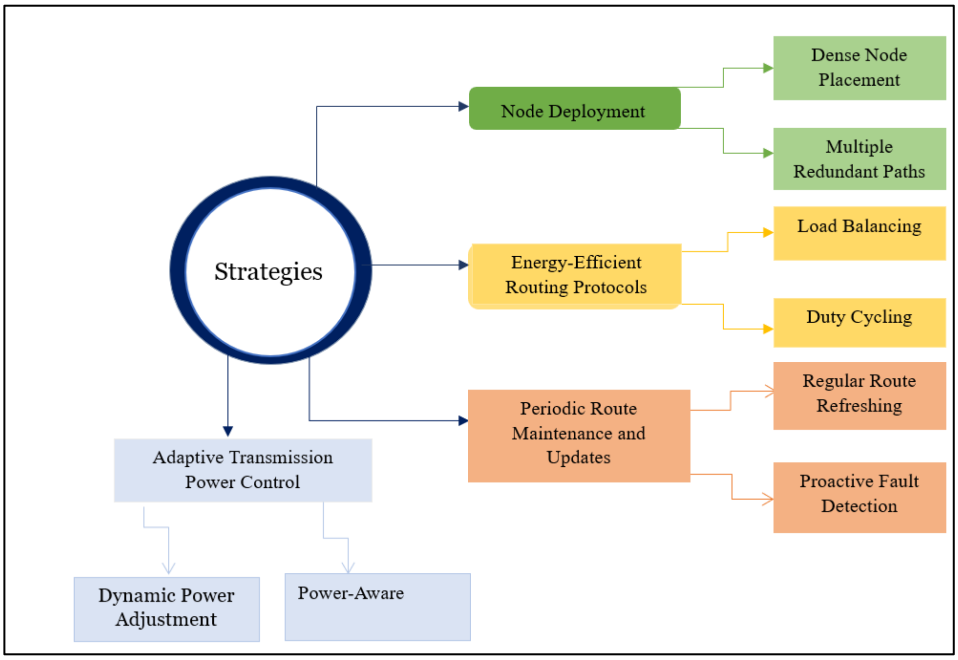

Figure 4. Strategies to Avoid Holes in Proactive Routing

5.1 Node Deployment

In a wireless sensor network, node deployment is the process of arranging and placing sensor nodes in a certain target area. Inadequate node distribution can result in communication holes, which are areas where sensor nodes are either non-existent or unable to relay data because of obstructions, low battery life, or node failure. Therefore, efficient deployment is essential for guaranteeing full coverage, connection, and network dependability.

Node deployment strategies are important when discussing proactive routing to prevent gaps in WSNs because they define the structure of the network and affect the path taken by data packets as they travel from sensor nodes to the sink (central node). Ensuring that the deployment is optimized lowers the chance of node failures and prevents situations where the network's connectivity is compromised.

In proactive routing, node deployment plays a dual role:

1. Facilitating consistent network coverage for data collection.
2. Maintaining robust connectivity to enable seamless packet transmission from source nodes to the sink or base station.

Key strategies in node deployment, such as dense node placement and multiple redundant paths, can drastically reduce the occurrence of holes and enhance network resilience. These strategies ensure that even if some nodes fail, alternate communication routes are available, preventing disruption in data transmission.

5.1.1 Dense Node Placement: Ensuring Coverage and Connectivity

Dense node placement refers to deploying sensor nodes in close proximity to each other, ensuring there are no coverage gaps or unconnected regions in the network.

5.1.2 Multiple Redundant Paths: Guaranteeing Communication in Dynamic Networks

Another essential aspect of node deployment in proactive routing strategies is the creation of multiple redundant paths between source and destination nodes. Redundant paths allow the network to avoid routing holes by offering several alternatives for packet transmission, ensuring that even if one path becomes unavailable, others remain operational.

5.2 Energy Efficient Routing Protocol

Energy-efficient routing protocols are essential in Wireless Sensor Networks (WSNs) due to the limited energy resources of sensor nodes. Since each sensor node is battery-powered, optimizing energy consumption directly impacts the network's longevity, reliability, and the ability to maintain consistent connectivity, which is essential for avoiding communication holes. Routing holes often occur due to nodes depleting their energy too quickly, leading to gaps in the network's communication infrastructure.

To proactively avoid such holes, energy-efficient routing protocols are designed to minimize energy usage while maintaining optimal routing paths, ensuring that nodes remain operational for longer periods and holes are less likely to form. Two key techniques that play a significant role in these protocols are load balancing and duty cycling.

5.2.1 Load Balancing: Distributing Energy Consumption

Load balancing is a technique that ensures the network's energy consumption is distributed evenly among nodes, preventing any single node or group of nodes from depleting their energy resources too quickly. In the context of proactive routing, load balancing helps avoid the formation of holes by preventing the overuse of specific nodes that are frequently involved in data transmission.

5.2.2 Duty Cycling: Minimizing Energy Consumption

Duty cycling is another technique used in energy-efficient routing protocols, where nodes alternate between active and sleep states to conserve energy. Since most sensor nodes don’t need to be active all the time, duty cycling helps reduce unnecessary energy expenditure, especially in idle periods.

5.3 Periodic Route Maintenance and Updates in WSN

Periodic route maintenance and updates are essential components of Wireless Sensor Networks (WSNs) that guarantee network stability and stop communication gaps from forming. The routes between sensor nodes are routinely checked and refreshed as part of these operations, and routing data is updated to account for network changes brought about by node failures, energy depletion, or environmental changes. Periodic maintenance aims to prevent communication breakdowns by proactively managing the network's routing patterns and keeping them updated. Figure 5 illustrates the performance of different methods.

Proactive routing solutions necessitate periodic route maintenance and upgrades because they enable WSNs to detect and address possible problems before they lead to crucial communication failures. Proactive fault detection and routine route refreshing are two important components in this situation.

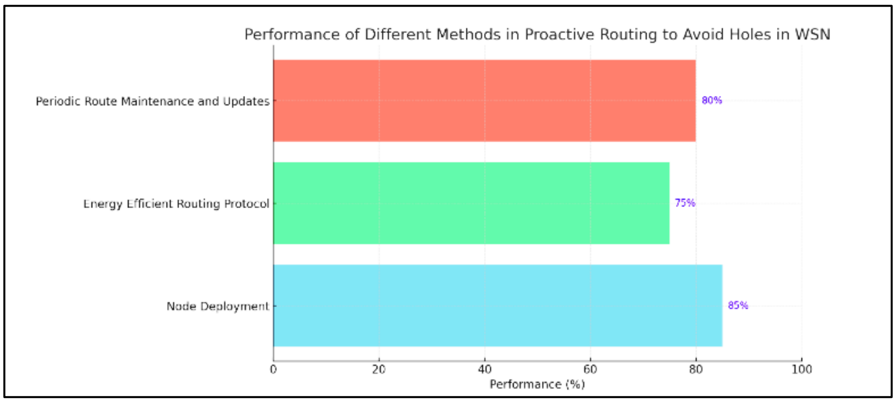

Figure 5. Performance of Different Methods

5.3.1 Regular Route Refreshing: Ensuring Up-to-Date Connectivity

Regular route refreshing refers to the periodic updating of routing tables and paths to ensure that the network always uses the most efficient and reliable routes. Since sensor nodes in WSNs can experience failures, deplete energy, or face physical obstacles, the network's topology can change over time. Regular refreshing helps the network adapt to these changes and prevent routing holes from developing.

5.3.2 Proactive Fault Detection: Identifying and Addressing Failures Early

Proactive fault detection is the process of continuously monitoring the network for potential issues and addressing them before they lead to major disruptions. This involves detecting faults in nodes or links early and rerouting traffic to prevent communication holes from forming.

5.4 Adaptive Transmission Power Control in WSN

Adaptive Transmission Power Control (ATPC) is a critical technique in Wireless Sensor Networks (WSNs) aimed at optimizing energy consumption, enhancing communication reliability, and preventing communication holes. ATPC involves dynamically adjusting the transmission power of sensor nodes based on network conditions, node locations, or energy levels. By controlling the amount of power used to transmit data, the network can efficiently manage energy resources, reduce interference, and avoid unnecessary energy wastage that might lead to node failures and routing holes.

In the context of proactive routing, adaptive transmission power control is essential because it helps maintain robust communication paths and ensures that sensor nodes remain operational for longer periods, preventing energy depletion that could cause holes in the network.

5.4.1 Dynamic Power Adjustments: Balancing Energy Use and Connectivity

Dynamic power adjustments involve modifying the transmission power of each sensor node based on the current communication needs and network conditions. Instead of transmitting at a fixed power level, nodes adjust their power dynamically to achieve efficient communication while conserving energy.

5.4.2 Power-Aware Routing: Optimizing Routes Based on Energy Levels

Power-aware routing complements adaptive transmission power control by selecting communication routes based on the energy levels of the nodes involved. This approach ensures that nodes with low energy are not overburdened with communication tasks, which could lead to early node failures and routing holes.

6. Discussion

The use of energy-efficient routing protocols and adaptive transmission power control helps conserve energy across sensor nodes, extending their operational lifespan. This reduces the likelihood of node failures caused by energy depletion, thus enhancing the overall longevity of the network. Dense node deployment and the creation of multiple redundant paths ensure that communication paths remain available even when nodes fail. This redundancy makes the network resilient to failures and proactively prevents communication holes. By utilizing load balancing techniques within energy-efficient routing protocols, the communication load is evenly distributed across nodes, preventing any single node from being overburdened. This reduces the risk of early node exhaustion and the formation of holes. Periodic route maintenance and updates combined with proactive fault detection ensure that potential issues are identified early. This enables the network to reroute data before any failures lead to the formation of holes, maintaining seamless communication.

Adaptive transmission power control allows for real-time adjustments based on current network conditions, improving communication efficiency and ensuring that the right amount of energy is used for each transmission. This adaptability reduces the chances of unnecessary energy depletion and enhances the overall robustness of the network. The combination of periodic route updates and energy-aware metrics ensures that the most reliable and energy-efficient paths are always used for data transmission. This enhances the reliability of the network by preventing the formation of inefficient or broken routes.

While dense node deployment enhances network redundancy, it also leads to higher energy consumption as more nodes are active and communicating simultaneously. This may result in faster depletion of node batteries if not properly managed, potentially leading to node failures. Periodic route maintenance and updates can introduce significant communication overhead, especially in large-scale networks. Frequent updates require additional energy for transmitting route information, potentially leading to higher overall energy consumption and reduced network lifetime. Duty cycling in energy-efficient protocols, where nodes alternate between active and sleep states, can introduce latency in data transmission. In time-sensitive applications, this delay may hinder real-time communication, affecting the performance of the network.

Strategies like adaptive transmission power control and power-aware routing require real-time monitoring of network conditions and energy levels. Implementing these dynamic, adaptive strategies in large-scale WSNs can be complex and resource-intensive, requiring advanced algorithms and control systems. There is often a trade-off between energy savings and performance. For example, reducing transmission power to conserve energy can sometimes lead to weaker signal strength, which might affect the quality of communication or increase the risk of data loss. As WSNs scale up in size, the effectiveness of these strategies can diminish. For instance, maintaining periodic updates and managing adaptive power control for a large number of nodes can become impractical and increase the complexity of network management. In large deployments, these strategies may need to be optimized or simplified to remain efficient. Adjusting transmission power dynamically in densely populated networks can lead to interference if many nodes increase their power levels simultaneously. This could degrade the overall communication quality, resulting in packet loss or decreased network performance.

7. Conclusion

In Wireless Sensor Networks (WSNs), preventing communication holes is essential for maintaining efficient and reliable data transmission. The strategies discussed in this article node deployment, energy-efficient routing protocols, periodic route maintenance, and adaptive transmission power control each contribute significantly to proactive routing techniques aimed at avoiding routing holes. Through dense node placement and multiple redundant paths, networks can ensure coverage and fault tolerance, while energy-efficient protocols extend node lifespan by distributing energy consumption effectively. Periodic route maintenance enhances network reliability by updating routes and detecting faults proactively, preventing the formation of holes. Moreover, adaptive transmission power control dynamically adjusts power usage based on real-time conditions, ensuring energy efficiency without compromising communication quality. Together, these techniques form a complete approach for addressing the inherent challenges of WSNs, particularly the risk of node failures and the creation of communication voids. the strategies also face challenges related to energy consumption, communication overhead, and implementation complexity, particularly in large-scale deployments. Addressing these limitations while optimizing the balance between energy efficiency and network performance remains an ongoing area of research.

8. Future Enhancement

Integrating machine learning (ML) algorithms into routing protocols could allow WSNs to learn from historical network behavior and predict potential faults or failures. ML could also help optimize routing decisions based on dynamic network conditions, further improving energy efficiency and reducing the risk of routing holes. Incorporating energy harvesting technologies, such as solar or environmental energy, could enhance the sustainability of sensor nodes, reducing the risk of energy depletion and node failure. Coupling energy harvesting with energy-efficient routing protocols can significantly extend the operational lifetime of the network. Future protocols could explore hybrid approaches, combining the strengths of proactive and reactive routing. This could involve on-demand route updates in low-energy scenarios while maintaining proactive fault detection to avoid holes. Such hybrid methods may balance energy consumption with reliability. Enhancing adaptive transmission power control through collaborative techniques could further optimize energy usage across nodes. Nodes could share real-time energy and signal strength information with neighbouring nodes, dynamically adjusting transmission power while avoiding interference or network instability.

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