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Strategies of Coverage Hole Repair in Wireless Sensor Networks

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ABSTRACT

With the widespread application of Wireless Sensor Networks (WSNs) in daily life, enhancing the practicality and effectiveness of WSNs has gradually become an urgent demand. The issue of repairing coverage holes in WSNs has emerged as a hot research topic. Therefore, this paper aims to categorize and organize various repair strategies to provide research insights for more scientific researchers. This paper systematically categorizes and summarizes repair strategies for coverage holes in WSNs from four aspects: Adjustment of Mobile Nodes, Network Topology Optimization, Dynamic Routing Adjustment, and Adjustment of Coverage Range. It discusses the advantages and disadvantages of these strategies and the problems they address.

KEYWORDS

WSN; Coverage hole repair; Survey

1. INTRODUCTION

Wireless Sensor Networks (WSNs) are widely used and extensively researched in recent years, with research institutions worldwide showing great optimism about their prospects. One of the key features of WSNs is their ability to expand people's perception boundaries, especially in areas that are difficult or impossible for humans to reach. The deployment of WSNs nodes through aerial scattering by aircraft results in uneven node distribution, leading to network coverage gaps that can significantly impact the overall monitoring performance of the network, deviating from the intended deployment objectives. Currently, research on WSNs mainly focuses on topology, routing protocols, sensing coverage, localization, clock synchronization, and network security. Among these, coverage is a primary concern for WSNs as it reflects the monitoring coverage status of a specific area within the network. Establishing a robust network coverage monitoring model is a prerequisite for sensor nodes to effectively perceive and monitor objects.

Individual sensor nodes have limited sensing coverage range, and a large number of sensor nodes are randomly deployed in the monitoring area to observe the target region. Typically, the deployment environment for nodes is harsh, and nodes rely on limited onboard power sources as the feasibility of secondary power replacement is minimal. Designing an effective, low-power, and robust coverage model is crucial for extending the network's lifespan and ensuring that the deployment area is effectively monitored for an extended period. Therefore, to guarantee long-term effective coverage of the monitoring area and promptly address network coverage gaps, modeling the void regions and designing efficient node coverage repair algorithms have become hot topics in WSNs research. This paper aims to compile and summarize strategies for repairing node coverage gaps in WSNs, facilitating more researchers to contribute to the field of node coverage repair.

2. ADJUSTMENT OF MOBILE NODES

The strategy of adjusting mobile nodes involves relocating a subset of nodes within a wireless sensor network to optimize coverage and fill in coverage gaps. By strategically moving nodes to specific locations, the overall monitoring coverage of the network can be enhanced, leading to improved data collection and analysis capabilities. This dynamic adjustment of node positions is crucial for maintaining effective surveillance over the monitoring area and ensuring that critical data is captured efficiently. Through careful planning and coordination, the adjustment of mobile nodes can effectively address coverage deficiencies and enhance the overall performance of the network in terms of monitoring and data acquisition.

In their study, Wang Shan propose a mobile node-based coverage hole repair algorithm called the Joint Patch Method [1]. This algorithm stitches the required mobile nodes together according to a pre-designed patching scheme, forming a large "fabric" to directly repair the coverage holes. The algorithm allows for flexible selection of repair strategies based on specific needs, requiring a minimal number of mobile nodes while achieving high node coverage and low redundancy.

Existing solutions for coverage hole repair often face challenges like high energy consumption and reliance on additional nodes. To address these issues, a novel distributed self-healing algorithm, DHDR, is introduced [2]. This algorithm efficiently detects and repairs coverage holes using existing network nodes, optimizing coverage and minimizing energy consumption. Simulation results demonstrate that DHDR outperforms existing algorithms in terms of enhanced coverage, improved connectivity, and reduced energy usage.

3. NETWORK TOPOLOGY OPTIMIZATION

Network Topology Optimization is a strategic approach aimed at enhancing the efficiency and performance of a network by optimizing its topology. This process involves analyzing and adjusting the arrangement of network components, such as nodes and links, to improve key network metrics like throughput, latency, and reliability. By strategically optimizing the network topology, researchers and engineers can achieve better resource utilization, increased scalability, and enhanced overall network functionality.

In Wang, S.’s research, a novel topology optimization strategy for wireless sensor networks, focusing on coverage and network reliability in complex industrial settings, is proposed based on the wolf pack algorithm [3]. This approach combines the wireless sensor network topology structure with the wolf pack algorithm to redefine group behavior and introduce a head wolf mutation strategy. This strategy enhances search capabilities, improves distribution uniformity, and accelerates calculations. By evenly distributing energy consumption and optimizing cluster member data distribution, the algorithm achieves balanced network coverage.

Fu, X. introduces a sink-oriented cascading model for wireless sensor networks (WSNs) and proposes the memetic algorithm MA-TOSCA for enhancing network robustness through topology optimization [4]. By leveraging a new network balancing metric, "sink-oriented betweenness entropy," the algorithm efficiently identifies more robust network topologies compared to existing methods. The study showcases the model's ability to accurately depict WSN cascading processes and highlights the robustness of networks with an "onion-grid topology structure." Additionally, it reveals positive correlations between network communication efficiency, modularity, clustering coefficient, and network robustness, while noting a negative relationship with average shortest path length.

4. DYNAMIC ROUTING ADJUSTMENT

Dynamic routing adjustment is a strategic approach in network management where routing paths are continuously optimized and modified based on real-time network conditions. This strategy involves the dynamic adaptation of routing protocols to enhance network performance, reliability, and efficiency. By adjusting routing paths in response to changing network dynamics such as traffic congestion, link failures, or varying quality of service requirements, dynamic routing adjustment aims to maximize data transmission efficiency and minimize latency. This proactive approach ensures that network resources are utilized optimally, leading to improved overall network performance and responsiveness.

Jain, J. K.'s research introduces a bi-layered Wireless Sensor Network (WSN) architecture designed for dynamic clustering-based routing and coverage hole detection and recovery [5]. The proposed method involves cluster formation, cluster head selection, coverage hole detection and recovery, and routing. Clusters are established using the K-means algorithm, with cluster head selection based on a Determined Weight (DW) metric derived from residual energy and distance considerations. Cluster maintenance techniques such as splitting and merging are explored for improved clustering efficiency. Coverage hole detection targets three locations: within the cluster, among clusters, and at the network edge. A hole manager (HM) employing fuzzy logic aids in identifying nodes capable of recovering coverage holes. The Multi-objective Emperor Penguin Optimization Algorithm (MO-EPO) is utilized to determine the optimal multi-hop route for transmission. The proposed approach is applied to Agriculture Applications in WSN with IoT integration. Performance evaluation includes metrics like energy consumption, network lifetime, number of active nodes, and packet delivery ratio, with simulations conducted using the NS3.26 simulator.

Chanak, P. addresses the issue of network failures in Wireless Sensor Networks (WSNs) caused by environmental hazards and internal faults in sensor nodes [6]. The proposed solution involves a novel clustering algorithm, Distributed Energy Efficient Heterogeneous Clustering (DEEHC), which selects cluster heads based on residual energy levels and a secondary timer. Sensor nodes establish k-vertex disjoint paths to cluster heads during clustering, depending on neighbor node energy levels. A k-Vertex Disjoint Path Routing (kVDPR) algorithm is introduced for cluster heads to find paths to the base station and relay data. Additionally, a Route Maintenance Mechanism (RMM) is proposed to repair paths during monitoring sessions, making the WSN tolerant to k-1 failures. Extensive testing demonstrates the effectiveness of the scheme compared to existing approaches.

5. ADJUSTMENT OF COVERAGE RANGE

The strategy of Coverage Range Adjustment involves optimizing the transmission range of wireless sensor nodes to enhance network coverage and performance. By adjusting the coverage range, the network can achieve better connectivity, improved data collection efficiency, and reduced energy consumption. This strategy aims to balance the trade-off between coverage area and energy consumption, ultimately improving the overall effectiveness and reliability of the wireless sensor network.

Cardei, M. focuses on addressing the target coverage issue in wireless sensor networks through the utilization of sensors with adjustable sensing ranges [7]. By organizing sensors into sets that are activated sequentially, energy resources can be conserved effectively, thus extending the network's lifetime. The Adjustable Range Set Covers (AR-SC) problem is introduced, aiming to maximize the number of set covers while ensuring each sensor set covers all targets within energy constraints. The study presents mathematical models and efficient heuristics for solving this problem and includes simulation results to validate the proposed approaches.

Jia, J. introduces a novel coverage control scheme for wireless sensor networks, focusing on maintaining sensing coverage with minimal active sensor nodes and energy consumption [8]. Unlike previous uniform sensing models, the study considers sensors with adjustable sensing radii randomly deployed in a target area. The proposed scheme utilizes an elitist non-dominated sorting genetic algorithm (NSGA-II) in a heterogeneous sensor network, implemented in a distributed manner through a cluster-based architecture. An improved binary coding method is used to represent both sensing radius adjustment and sensor selection. Numerical and simulation results demonstrate the effectiveness and efficiency of the algorithm in achieving an optimal balance between maximum coverage rate, minimal energy consumption, and a reduced number of active nodes.

6. CONCLUSION

Undoubtedly, with the development and advancement of science and technology, Wireless Sensor Networks (WSNs) are becoming increasingly efficient, convenient, intelligent, and economically practical. All of these achievements are inseparable from the relentless efforts and dedication of scientific and technological talents in this field.

This paper systematically summarizes four strategies for repairing coverage holes in WSNs. It is evident that moving mobile nodes dynamically to fill coverage gaps can adapt to changing network conditions and optimize coverage effectively. However, the mobility of nodes may introduce additional energy consumption and communication overhead, increasing network complexity and potentially causing connectivity issues. Optimizing network topology can strategically redistribute sensor nodes to enhance coverage and connectivity, improving overall network performance. Nevertheless, this approach may require significant computational resources and communication overhead to reconfigure network topology, potentially leading to delays and affecting real-time applications. Dynamic routing adjustment can help reroute data packets to avoid coverage holes and maintain network connectivity in real-time. However, continuous routing adjustments may introduce latency and network overhead, affecting data transmission efficiency and potentially causing network congestion. Adjusting sensor nodes' coverage range can optimize energy consumption and coverage efficiency, prolonging network lifespan and enhancing performance. Nevertheless, fine-tuning coverage ranges may require precise calibration and monitoring, which could be resource-intensive and challenging to implement in large-scale networks. These methods have their respective advantages and limitations, warranting further in-depth research by scientific researchers to make outstanding contributions to the field of WSNs.

Of course, coverage hole repair in WSNs is not limited to the four strategies outlined in this paper. For instance, energy-efficient node deployment strategies optimize node deployment and energy management, enabling nodes to work more efficiently within the coverage area and extending network lifespan. Therefore, coverage hole repair in WSNs remains a research area worthy of exploration, as it will continue to contribute to the effectiveness and practicality of WSNs.

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