

ENERGY HOLE PROBLEM IN WIRELESS SENSOR NETWORKS: A RESEARCH REVIEW

Abstract

Wireless Sensor Networks (WSNs) have emerged as a promising technology for various applications, including environmental monitoring, surveillance, and healthcare. However, the limited energy resources of individual sensor nodes pose a significant challenge in the design and operation of WSNs. One critical issue that affects network lifetime is the energy hole problem, where nodes near the sink node experience faster energy depletion than nodes farther away. This research review aims to provide a comprehensive overview of the energy hole problem in WSNs, highlighting its causes, impact, and existing solutions proposed by the research community. By analyzing and synthesizing the state-of-the-art research, this article intends to shed light on the current understanding and future directions for mitigating the energy hole problem in WSNs.

Keywords: Wireless Sensor Networks, Communication, Sensor

Authors

Ezhilazhagan C

Vel Tech Rangarajan Dr.Sagunthala R&D
Institute of Science and Technology
Chennai, Tamil Nadu, India.
ezhisang20@gmail.com

Lakshmi Prabha K

T. S. Srinivasan Center for Polytechnic and
Advanced Training
Chennai, Tamil Nadu, India.
lakshmisslp@gmail.com

I. INTRODUCTION

Wireless Sensor Networks (WSNs) have emerged as a transformative technology with applications in various fields, including environmental monitoring, surveillance, healthcare, and industrial automation. WSNs consist of numerous small, battery-powered sensor nodes that collaborate to collect and transmit data from the environment to a centralized base station or sink node. However, the limited energy resources of these sensor nodes pose a significant challenge in the design and operation of WSNs.

- 1. Wireless Sensor Networks and Energy Constraints:** Energy is a critical resource in WSNs due to the reliance of sensor nodes on battery power. The limited battery capacity of sensor nodes necessitates careful energy management to prolong network lifetime and ensure sustained operation. Efficient energy utilization is crucial to maximize the functionality and effectiveness of WSNs. However, the energy constraints in WSNs arise from factors such as the small size of sensor nodes, the need for continuous sensing and data transmission, and the absence of a reliable and easy-to-access power source. To address energy constraints, various energy-efficient techniques and protocols have been proposed in the literature. These techniques include data aggregation, sleep scheduling, duty cycling, and adaptive power management, aiming to minimize energy consumption and extend the network's operational duration. Despite these efforts, the energy hole problem remains a significant challenge in WSNs.
- 2. The Energy Hole Problem: Definition and Challenges:** The energy hole problem is a critical issue that affects the energy consumption and network lifetime in WSNs. It refers to the uneven depletion of energy among sensor nodes, where nodes in the vicinity of the sink node experience faster energy drainage compared to nodes farther away. This phenomenon occurs due to the communication patterns and data routing mechanisms commonly employed in WSNs. In many WSNs, data is typically routed towards the sink node in a hierarchical or multi-hop fashion, where each sensor node forwards its data to a nearby node closer to the sink node until the data reaches the sink. As a result, sensor nodes closer to the sink node serve as relay nodes for a larger number of nodes, leading to increased data forwarding and higher energy consumption. Consequently, these relay nodes exhaust their energy resources faster, creating a void or energy hole in the network.

The energy hole problem poses several challenges to WSNs. First, it significantly reduces the network lifetime as the energy hole expands, leading to premature node failure and network partitioning. Second, the energy hole problem affects the coverage and connectivity of the network, as nodes in the energy hole region may become disconnected or unable to communicate with the sink node. Lastly, the energy hole problem can result in data loss and delays, as nodes with low energy levels may be unable to transmit data effectively. Addressing the energy hole problem in WSNs is crucial to achieve energy balance, prolong network lifetime, ensure network connectivity, and maintain data reliability. Researchers have proposed various solutions, including routing protocols, deployment strategies, energy-efficient data aggregation techniques, energy harvesting, and cross-layer optimization approaches. These solutions aim to mitigate the energy hole problem and enhance the overall energy efficiency of WSNs.

In this research review article, we delve into the energy hole problem in WSNs, examining its causes, impact, and existing solutions proposed by the research community. By providing an in-depth analysis and synthesis of the state-of-the-art research, we aim to contribute to the understanding of the energy hole problem and shed light on future directions for mitigating this challenge in WSNs.

II. CAUSES OF THE ENERGY HOLE PROBLEM

Energy hole problem in wireless sensor networks (WSNs) arises from several factors and system characteristics. In this section, we discuss the key causes that contribute to the emergence of the energy hole problem in WSNs.

- 1. Data Aggregation and Funneling Effect:** Data aggregation is a common technique used in WSNs to reduce the amount of data transmission and minimize energy consumption. In data aggregation, sensor nodes collect data from their surroundings and transmit aggregated data to the sink node or base station. However, the aggregation process often leads to the formation of a funneling effect, where data from a large number of nodes is funneled towards a limited number of relay nodes or cluster heads that are closer to the sink node. As a result, these relay nodes or cluster heads in the vicinity of the sink node experience a higher data traffic load compared to nodes farther away. They have to handle a larger amount of data from their neighboring nodes, leading to increased energy consumption and faster depletion of their energy resources. This uneven distribution of data traffic and energy consumption creates an energy hole around the sink node.
- 2. Sink-Node Centric Communication:** In many WSNs, communication is often designed to be sink-node centric, meaning that sensor nodes transmit their data directly or indirectly towards the sink node. This communication pattern aims to consolidate and relay data to a central location for further processing and analysis. However, sink-node centric communication exacerbates the energy hole problem. Sensor nodes closer to the sink node have a higher probability of being selected as intermediate relay nodes in the multi-hop communication towards the sink. Consequently, these nodes experience higher traffic load and energy consumption, leading to faster energy depletion. In contrast, nodes farther away from the sink node have fewer responsibilities in relaying data and, therefore, consume energy at a slower rate. This disparity in energy consumption results in the formation of an energy hole near the sink node.
- 3. Non-Uniform Node Deployment:** The deployment of sensor nodes in WSNs is typically carried out based on specific application requirements, environmental constraints, or coverage objectives. However, non-uniform node deployment patterns can contribute to the energy hole problem. In scenarios where nodes are deployed densely near the sink node or in regions with high data generation, the energy consumption in those regions becomes significantly higher compared to nodes deployed in sparsely populated areas or regions with lower data generation. The concentration of energy-intensive activities near the sink node intensifies the energy hole problem, as nodes in the vicinity of the sink deplete their energy resources quickly while nodes in other regions remain relatively underutilized.

- 4. Unequal Energy Consumption Patterns:** Unequal energy consumption patterns among sensor nodes within the network also contribute to the emergence of the energy hole problem. Sensor nodes may exhibit varying energy consumption rates due to different factors such as sensing activities, data transmission distance, data forwarding responsibilities, or the execution of computation-intensive tasks. Nodes closer to the sink node often have higher data forwarding responsibilities, resulting in increased energy consumption. In addition, nodes with higher sensing or computational requirements may consume energy at a faster rate. Consequently, these nodes experience energy depletion more rapidly, leading to the formation of an energy hole near the sink node. Addressing these causes of the energy hole problem requires the development of energy-efficient protocols, deployment strategies, and data management techniques. Researchers have proposed various solutions, including load-balancing routing protocols, optimized deployment techniques, dynamic energy management strategies, and cross-layer optimization approaches. By mitigating the causes of the energy hole problem, it becomes possible to achieve energy balance, prolong network lifetime, and improve the overall performance of WSNs.

III. IMPACT OF THE ENERGY HOLE PROBLEM

The energy hole problem in wireless sensor networks (WSNs) has several significant impacts on network performance and functionality. In this section, we explore the key consequences of the energy hole problem.

- 1. Network Lifetime Reduction:** One of the primary impacts of the energy hole problem is a reduction in the overall network lifetime. The energy hole near the sink node causes certain sensor nodes to deplete their energy resources faster than nodes located farther away. As a result, these nodes exhaust their energy and become non-functional earlier, leading to network partitioning and degradation in network coverage. The reduced network lifetime affects the operational duration of the WSN, limiting its ability to sustain long-term monitoring and data collection. It can hinder the effectiveness of WSN applications, particularly in scenarios where continuous and prolonged monitoring is required.
- 2. Coverage and Connectivity Issues:** The energy hole problem can also result in coverage and connectivity issues within the WSN. Nodes near the energy hole region may experience energy depletion before they can transmit their data to the sink node. This leads to coverage gaps and decreased network connectivity, as the affected nodes become unable to communicate effectively with other nodes or the sink node. The coverage gaps impact the quality and accuracy of data collection, as certain areas of interest may remain unmonitored due to the absence of functioning nodes in those regions. Moreover, the reduced connectivity disrupts data routing and transmission, further exacerbating the energy hole problem and limiting the overall effectiveness of the WSN.
- 3. Data Loss and Delay:** The energy hole problem can introduce data loss and delay in the WSN. As nodes near the energy hole deplete their energy resources, they may no longer have sufficient energy to transmit their data to the sink node. This leads to data loss, as the information collected by these nodes cannot be successfully delivered and utilized for further processing or analysis. Furthermore, the unequal energy distribution caused by the

energy hole problem can lead to data transmission delays. Nodes near the energy hole may experience increased congestion and higher queuing delays due to the concentration of data traffic in those regions. This delay impacts the timeliness of data delivery and may hinder real-time or time-sensitive applications relying on prompt data retrieval and analysis.

Mitigating the impact of the energy hole problem is crucial to ensure the reliable and efficient operation of WSNs. Researchers have proposed various solutions, including energy-balancing routing protocols, adaptive clustering algorithms, and energy-aware data aggregation techniques. By addressing the impact of the energy hole problem, it becomes possible to enhance network lifetime, improve coverage and connectivity, and minimize data loss and delay in WSNs.

IV. EXISTING SOLUTIONS

Addressing the energy hole problem in wireless sensor networks (WSNs) requires the development of various solutions and techniques. In this section, we discuss existing approaches proposed by the research community to mitigate the energy hole problem.

1. **Routing Protocols:** Routing protocols play a crucial role in WSNs by determining the paths along which data is transmitted from source nodes to the sink node. Several routing protocols have been proposed to address the energy hole problem.
 - **Distance-Based Routing:** Distance-based routing protocols aim to balance energy consumption by considering the distance between nodes and the sink node. These protocols preferentially select nodes with lower energy levels that are closer to the sink node as relay nodes. By utilizing nodes in a distributed manner across the network, distance-based routing protocols mitigate the energy hole problem and prolong network lifetime.
 - **Load-Balancing Routing:** Load-balancing routing protocols distribute the data traffic load evenly among sensor nodes. These protocols consider the energy levels and residual energy of nodes when selecting relay nodes. By dynamically assigning data forwarding responsibilities to nodes with higher energy levels, load-balancing routing protocols help mitigate the energy hole problem and ensure energy balance throughout the network.
2. **Deployment Strategies:** Deployment strategies play a crucial role in determining the initial arrangement and placement of sensor nodes in the network. Optimized deployment techniques can help mitigate the energy hole problem and improve overall energy efficiency.
 - **Node Placement Techniques:** Node placement techniques aim to deploy sensor nodes in a manner that maximizes energy efficiency and minimizes the impact of the energy hole problem. Various optimization algorithms, such as genetic algorithms or simulated annealing, are used to determine the optimal node placement. These techniques consider factors such as distance to the sink node, communication range, and energy distribution to achieve a more balanced network deployment.

- **Mobile Sink Approaches:** In mobile sink approaches, the sink node is mobile and moves within the network area. The mobile sink collects data from sensor nodes directly or through data aggregation. By moving the sink node closer to nodes experiencing higher energy consumption, mobile sink approaches can mitigate the energy hole problem. The sink node can also dynamically adjust its movement patterns based on the energy levels of nodes, thereby achieving energy balance.
3. **Energy-Efficient Data Aggregation Techniques:** Data aggregation techniques aim to minimize data transmission and reduce energy consumption by aggregating data from multiple sensor nodes before forwarding it to the sink node. Energy-efficient data aggregation techniques focus on optimizing the aggregation process to mitigate the energy hole problem. These techniques involve intelligent data fusion algorithms, where redundant or correlated data is eliminated or compressed to reduce the amount of data transmission. By reducing the data traffic and utilizing energy more efficiently, energy-efficient data aggregation techniques contribute to mitigating the energy hole problem and extending network lifetime.
 4. **Energy Harvesting and Wireless Charging:** Energy harvesting and wireless charging techniques provide alternative means of replenishing energy in sensor nodes. Energy harvesting involves capturing energy from the environment, such as solar, thermal, or kinetic energy, to power the nodes. Wireless charging enables energy transfer to sensor nodes wirelessly. By utilizing these techniques, sensor nodes can replenish their energy and mitigate the energy hole problem.
 5. **Cross-Layer Optimization:** Cross-layer optimization approaches aim to optimize the communication protocols and algorithms across different layers of the protocol stack in WSNs. These approaches consider interactions and dependencies between layers to achieve energy-efficient operation and mitigate the energy hole problem. By jointly optimizing routing, MAC (Medium Access Control), and physical layer parameters, cross-layer optimization techniques can significantly improve energy efficiency and extend network lifetime. These existing solutions and techniques contribute to mitigating the energy hole problem in WSNs. By considering routing protocols, deployment strategies, energy-efficient data aggregation, energy harvesting, and cross-layer optimization, researchers aim to achieve energy balance, prolong network lifetime, and enhance the overall energy efficiency of WSNs. Further research and development in these areas hold promise for more effective solutions to address the energy hole problem.

V. COMPARATIVE ANALYSIS OF SOLUTIONS

To address the energy hole problem in wireless sensor networks (WSNs), researchers have proposed various solutions and techniques. In this section, we conduct a comparative analysis of these solutions, considering their evaluation metrics, strengths, and limitations.

1. **Evaluation Metrics:** When comparing solutions for the energy hole problem, several evaluation metrics are commonly used to assess their effectiveness. These metrics provide insights into the performance of different approaches and help in identifying their strengths and limitations. Some key evaluation metrics include:

- **Network Lifetime:** Network lifetime refers to the duration for which the WSN can operate before a certain percentage of nodes become non-functional due to energy depletion. Longer network lifetime indicates better energy efficiency and a reduced impact of the energy hole problem.
- **Energy Consumption:** Energy consumption measures the amount of energy utilized by sensor nodes in the network. Lower energy consumption indicates more efficient energy utilization, thereby mitigating the energy hole problem.
- **Coverage:** Coverage assesses the extent to which the monitoring area or target region is effectively covered by the sensor nodes. Higher coverage implies better monitoring and data collection capabilities.
- **Connectivity:** Connectivity measures the ability of sensor nodes to communicate with each other and with the sink node. Higher connectivity ensures reliable data transmission and network operation.
- **Data Loss and Delay:** Data loss refers to the percentage of data that fails to reach the sink node due to energy depletion or network issues. Data delay measures the time it takes for data to reach the sink node. Lower data loss and delay indicate better data reliability and timeliness.

These evaluation metrics provide a comprehensive assessment of the performance and effectiveness of different solutions for mitigating the energy hole problem.

2. Strengths and Limitations of Different Approaches: Different approaches for mitigating the energy hole problem have their own strengths and limitations. Let's explore some common approaches and their characteristics:

- **Routing Protocols:** Distance-based routing protocols focus on selecting relay nodes based on their proximity to the sink node, aiming to balance energy consumption. These protocols are relatively simple to implement and can improve network lifetime. However, they may not consider the heterogeneity of energy levels among nodes, leading to suboptimal energy balancing.
- **Deployment Strategies:** Node placement techniques and mobile sink approaches aim to optimize the initial arrangement of sensor nodes or the movement of the sink node to achieve energy balance. These approaches can effectively mitigate the energy hole problem and improve network lifetime. However, they may require additional hardware or infrastructure, and the effectiveness of mobile sink approaches depends on efficient sink movement algorithms.
- **Energy-Efficient Data Aggregation Techniques:** Energy-efficient data aggregation techniques reduce the amount of data transmission and improve energy efficiency. These techniques can effectively mitigate the energy hole problem and enhance network lifetime. However, they may introduce additional computational overhead and incur latency due to data aggregation processes.

- **Energy Harvesting and Wireless Charging:** Energy harvesting and wireless charging techniques offer alternative energy sources for sensor nodes, mitigating the energy hole problem by providing energy replenishment. These techniques can extend network lifetime and reduce the impact of energy depletion. However, they require additional infrastructure and may have limitations in terms of the amount of energy that can be harvested or wirelessly transferred.
- **Cross-Layer Optimization:** Cross-layer optimization techniques optimize communication protocols across different layers to achieve energy efficiency. These approaches consider interactions and dependencies between layers, enabling global optimization. However, they may require more complex system designs and implementations, and the coordination among different layers can introduce additional overhead.

Each approach has its own strengths and limitations, and the choice of the most suitable approach depends on the specific characteristics and requirements of the WSN deployment. In conclusion, a comparative analysis of solutions for the energy hole problem in WSNs involves evaluating their performance using metrics such as network lifetime, energy consumption, coverage, connectivity, data loss, and delay. Understanding the strengths and limitations of different approaches helps researchers and practitioners make informed decisions in selecting and implementing solutions that effectively address the energy hole problem in WSNs.

VI. OPEN CHALLENGES AND FUTURE DIRECTIONS

The energy hole problem in wireless sensor networks (WSNs) remains an active area of research, and several open challenges and future directions exist. In this section, we discuss some of these challenges and potential avenues for further exploration.

1. **Energy-Efficient Clustering and Hierarchical Protocols:** Efficient clustering and hierarchical protocols play a vital role in mitigating the energy hole problem. However, there are ongoing challenges in developing advanced clustering algorithms that can achieve better energy balance and extend network lifetime. Future research should focus on designing energy-efficient clustering protocols that consider factors such as residual energy, communication distance, and node density to achieve optimal cluster formation and cluster head selection. Additionally, exploring dynamic clustering schemes that adapt to changing network conditions and the introduction of hierarchical architectures can further enhance energy efficiency in WSNs.
2. **Machine Learning and Artificial Intelligence Techniques:** Machine learning (ML) and artificial intelligence (AI) techniques have shown great potential in addressing various challenges in WSNs. ML algorithms can be employed to learn energy consumption patterns, predict energy levels, and make intelligent decisions for efficient energy management. AI techniques, such as reinforcement learning and swarm intelligence, can be utilized to optimize routing, clustering, and data aggregation in a decentralized manner. Future research should explore the application of ML and AI techniques to optimize energy utilization, improve network performance, and mitigate the energy hole problem in WSNs.

- 3. Dynamic Energy Management Strategies:** Dynamic energy management strategies are essential for adapting to the dynamic nature of WSNs and achieving optimal energy utilization. Future research should investigate the development of energy management schemes that dynamically allocate energy resources based on real-time energy measurements and network conditions. This includes dynamic sleep scheduling, transmission power control, and task scheduling techniques that maximize energy efficiency and minimize the impact of the energy hole problem. Additionally, the integration of energy harvesting and storage mechanisms can further enhance the effectiveness of dynamic energy management strategies.
- 4. Integration of Renewable Energy Sources:** The integration of renewable energy sources can play a crucial role in mitigating the energy hole problem and achieving sustainable operation in WSNs. Future research should focus on developing efficient techniques to harness and integrate renewable energy sources, such as solar, wind, and kinetic energy, into WSNs. This includes designing energy-aware routing and scheduling algorithms that consider the availability and variability of renewable energy sources. Moreover, exploring energy sharing and energy trading mechanisms among nodes can enable efficient energy distribution and balance across the network.
- 5. Resource-Constrained Node Design:** The design of resource-constrained sensor nodes is another important aspect to consider when addressing the energy hole problem. Future research should focus on developing energy-efficient hardware and communication protocols specifically tailored for resource-constrained nodes. This includes low-power circuit design, energy-aware MAC protocols, and efficient sleep-wake scheduling mechanisms. Additionally, advancements in energy harvesting technologies, miniaturization, and power management techniques can further enhance the capabilities of resource-constrained nodes and contribute to mitigating the energy hole problem.

In conclusion, addressing the energy hole problem in WSNs requires continued research and innovation. Open challenges and future directions involve developing energy-efficient clustering and hierarchical protocols, leveraging machine learning and AI techniques, exploring dynamic energy management strategies, integrating renewable energy sources, and designing resource-constrained nodes. By tackling these challenges, researchers can make significant progress in mitigating the energy hole problem and improving the energy efficiency and longevity of WSNs in various application domains.

VII. CONCLUSION

The energy hole problem in WSNs is a critical issue that significantly affects network performance and lifespan. This research review presents a comprehensive analysis of the causes and impact of the energy hole problem. It also provides an overview of existing solutions proposed by the research community, along with a comparative analysis of their strengths and limitations. Furthermore, this article identifies open challenges and future directions to inspire further research efforts in mitigating the energy hole problem in WSNs. Ultimately, by addressing this problem effectively, we can enhance the energy efficiency and longevity of WSNs, enabling their widespread deployment in various real-world applications.

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