International Journal of Innovative Research in Engineering
Volume 7, Issue 2 (March - April 2026), PP: 390-395.
www.theijire.com **ISSN No: 2582-8746**

A Survey on Coverage Enhancement Strategies in WSN

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How to cite this paper:
Chetan[1], Preeti [2] "A Survey on Coverage Enhancement Strategies in WSN", IJIRE-V7I2-390-395.

Abstract: *Wireless Sensor Networks (WSNs) play a vital role in applications such as environmental monitoring, smart cities, healthcare, and military surveillance, where reliable sensing coverage is essential. However, due to random deployment, node failures, energy depletion, and environmental constraints, coverage holes in regions that remain unmonitored often arise, significantly degrading network performance. This survey paper provides a comprehensive review of coverage hole detection, localization, and healing techniques in WSNs. It categorizes existing approaches into geometric methods (e.g., Voronoi diagrams and Delaunay triangulation), grid-based techniques, and optimization-based methods, including metaheuristic algorithms such as Particle Swarm Optimization (PSO), Genetic Algorithms (GA), and Ant Colony Optimization (ACO). A comparative analysis of various techniques is presented based on performance parameters, including coverage efficiency, computational complexity, energy consumption, and scalability. The paper also highlights current challenges and emerging research directions in coverage optimization.*

Keywords: *Coverage Hole Detection, Coverage Hole Healing, Network Reliability.*

I.INTRODUCTION

Wireless Sensor Networks (WSNs) have gained significant attention in recent years due to their wide range of applications in environmental monitoring, industrial automation, healthcare, and military surveillance. A WSN consists of a large number of spatially distributed sensor nodes that collaboratively monitor physical or environmental conditions. One of the most critical performance metrics in WSNs is coverage, which determines how effectively the network can observe a region of interest. However, due to random deployment, node failures, limited energy resources, and environmental constraints, coverage holes—regions not monitored by any sensor often arise, thereby degrading the network's reliability and effectiveness of the network [1].

To address the coverage hole problem, a variety of techniques have been proposed in the literature. Early research focused on geometric and cooperative covering models, where optimal placement strategies were derived to maximize coverage. For instance, cooperative coverage problems in planar and network-based environments have been extensively studied by [2], who formulated coverage as a location optimization problem and analyzed efficient placement strategies to maximize coverage efficiency. These foundational works established the theoretical basis for coverage optimization in distributed systems.

With advances of computational intelligence, researchers have increasingly explored optimization-based approaches to improve coverage in WSNs. Metaheuristic algorithms such as Particle Swarm Optimization (PSO) have shown promising results in handling thenonlinearity and multi-objectivity of coverage problems. For example, in [3], a multi-objective PSO was applied to simultaneously maximize coverage and network lifetime, demonstrating the effectiveness of swarm intelligence in optimizing sensor deployment. Similarly, hybrid approaches have been proposed to further enhance coverage efficiency. The authors in [4] introduced an optimized bidding-based algorithm for hybrid WSNs, which improves coverage by intelligently selecting and repositioning sensor nodes based on network conditions.

Despite these advancements, the coverage hole problem remains a challenging issue due to trade-offs between coverage, energy consumption, computational complexity, and scalability. Moreover, emerging concepts such as K-coverage, which ensures that each point in the sensing area is covered by multiple sensors, have introduced new dimensions to coverage analysis by enhancing network robustness and fault tolerance. Therefore, a comprehensive understanding of existing techniques is essential for designing efficient and reliable WSNs.

In this survey paper, we provide a detailed review of coverage hole detection, localization, and healing techniques in wireless sensor networks. The study categorizes existing approaches into geometric, grid-based, and optimization-driven methods, and presents a comparative analysis based on key performance metrics. Additionally, the survey highlights recent trends, challenges, and future research directions in coverage optimization, aiming to guide researchers toward developing more efficient and intelligent WSN solutions.

II.RESEARCH BACKGROUND

Several research efforts have addressed the problem of coverage hole detection and recovery in wireless sensor networks (WSNs). The authors in [5] proposed a method for detecting boundary nodes and identifying coverage holes by analyzing network topology. Their approach focuses on distinguishing boundary nodes to accurately locate hole regions, improving detection efficiency without requiring precise location information. Similarly, authors in [6] introduced a combined detection and recovery mechanism in which coverage holes are first identified and then repaired using node-movement strategies. Their work highlights the importance of integrating both detection and healing processes to enhance network performance.

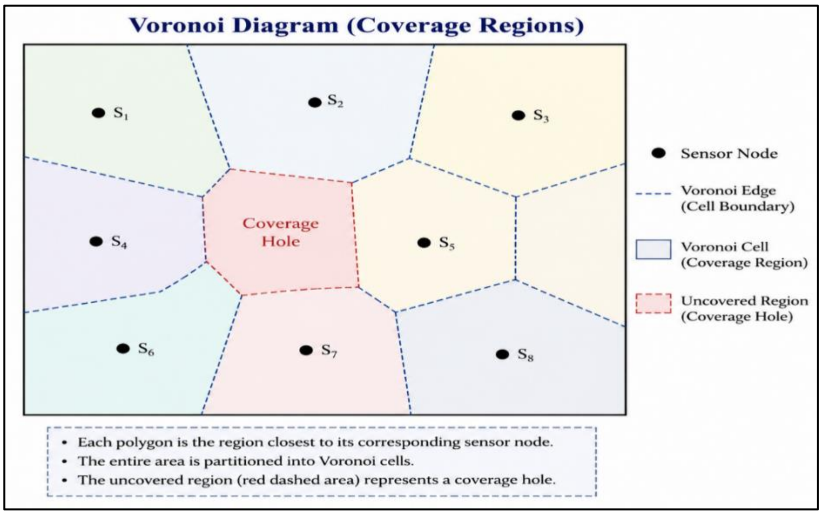
To improve monitoring efficiency, the authors in [7] explored optimal path-planning strategies for mobile nodes to address coverage holes. Their approach focuses on efficient traversal of uncovered regions, ensuring that mobile sensors can dynamically monitor and reduce holes over time. In another study [8], a clustering-based coverage hole detection method was proposed. By grouping nodes into clusters, their approach reduces computational complexity and improves scalability, making it suitable for large-scale WSN deployments.

Further advancements in hole detection were presented by [9], who developed techniques for detecting and measuring the size of coverage holes. Their work not only identifies holes but also quantifies their dimensions, enabling more precise recovery strategies. Additionally, authors in [10] introduced a dynamic cluster-based routing approach for WSN-IoT environments that integrates coverage hole detection and recovery. This method enhances both routing efficiency and coverage performance by adapting to network changes and node mobility. Overall, the reviewed literature demonstrates that coverage hole problems have been addressed through various approaches, including topology-based methods, clustering techniques, path planning strategies, and integrated detection-recovery frameworks. While these methods improve coverage and network efficiency, challenges such as energy consumption, scalability, and real-time adaptability remain open research issues, motivating the need for more advanced optimization-based solutions.

III.GEOMETRIC METHODS FOR COVERAGE HOLE DETECTION

Geometric and topological approaches form the foundation of many coverage hole detection techniques in wireless sensor networks (WSNs), providing accurate, mathematically grounded solutions. Among geometric methods, Voronoi diagrams and Delaunay triangulation are widely used to analyze spatial relationships between sensor nodes. In Voronoi-based methods, the sensing field is partitioned into regions, each corresponding to the area closest to a particular sensor node; large Voronoi cells or uncovered vertices often indicate potential coverage holes. Similarly, the Delaunay triangulation connects neighboring sensor nodes to form triangles, and the circumcircles of these triangles are examined to detect uncovered regions.

These methods provide precise hole localization but typically require accurate node position information. Complementing geometric approaches, topology-based methods aim to detect coverage holes without relying on exact coordinates. For instance, Li and Wu (2016) [11] proposed a tree-based coverage hole detection and healing method that uses network connectivity information to identify holes and guide recovery through a structured node organization. Likewise, Dhanapala and Jayasumana (2013) [12] introduced topology-preserving maps, which extract the layout of WSNs from virtual coordinates, enabling hole detection even when physical locations are unknown. More recently, Sharma and Singh (2022) [13] applied these concepts in wireless underground sensor networks, combining topology-aware strategies with healing mechanisms to address challenging deployment environments. Although geometric methods offer high accuracy and topology-based approaches provide flexibility and reduced dependency on location information, both face limitations in scalability, computational complexity, and dynamic network conditions, motivating the use of optimization-based techniques in modern research.



- Each polygon is the region closest to its corresponding sensor node.
- The entire area is partitioned into Voronoi cells.
- The uncovered region (red dashed area) represents a coverage hole.

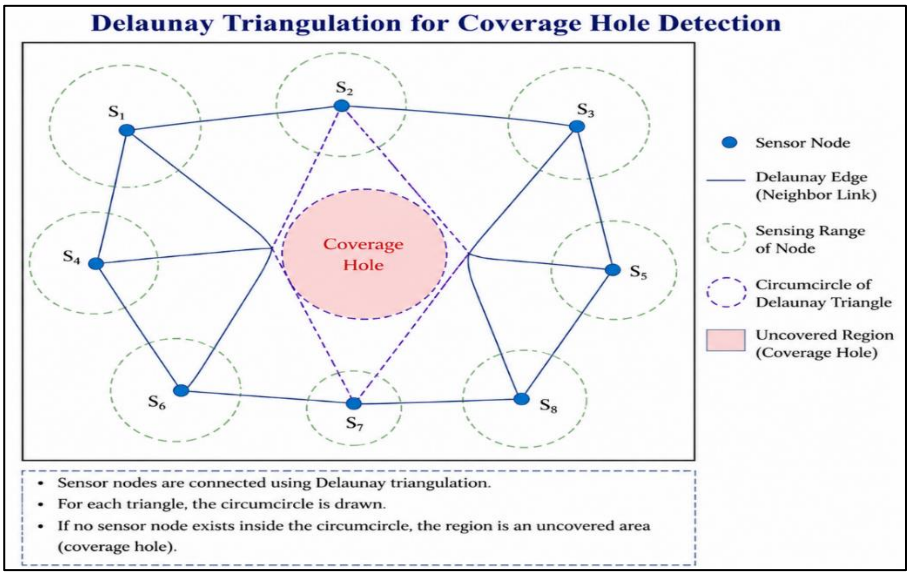
Figure 1: Geometric Method of Coverage Hole Detection

Figure 1 illustrates a Voronoi diagram used for coverage analysis in a WSN. The sensing area is divided into multiple polygonal regions, called Voronoi cells, where each cell corresponds to the area closest to a particular sensor node (S_1–S_8). The dashed lines indicate the boundaries between neighboring cells, forming the Voronoi structure. The red-highlighted region in the center represents a coverage hole, which occurs when a region is not adequately covered by any nearby sensor node. This typically happens when sensors are unevenly distributed or spaced too far apart. Thus, the diagram helps in identifying weak coverage areas by analyzing the size and shape of Voronoi cells, making it a useful geometric tool for detecting and addressing coverage holes in WSNs.

Figure 2 illustrates how Delaunay Triangulation is used to detect coverage holes in a wireless sensor network (WSN). The blue points (S_1–S_8) represent sensor nodes, and the solid lines connecting them form Delaunay triangles that show the neighbor relationships between nodes. Around each node, the dashed green circles indicate the sensing range. For each triangle formed, a circumcircle (shown with dashed purple lines) is drawn. The key idea is that if the circumcircle of a triangle contains an area that is not covered by any sensor's sensing range, then that region is identified as a coverage hole. In the figure, the central shaded red region represents such a hole, indicating that the sensors are too far apart to fully cover that area. Thus, Delaunay triangulation helps detect coverage gaps by analyzing the geometric relationships between neighboring nodes, making it an effective method for identifying uncovered regions in WSNs.

IV.GRID-BASED COVERAGE TECHNIQUES IN WSNS

Grid-based techniques are widely used for coverage hole detection in (WSNs) due to their simplicity and computational efficiency. In this approach, the sensing area is divided into a uniform grid of small cells or points. Each grid point is then evaluated to determine whether it lies within the sensing range of at least one sensor node. This is typically done by calculating the distance between the grid point and all sensor nodes; if the distance is less than or equal to the sensing radius of any node, the point is marked as covered, otherwise it is identified as a coverage hole.

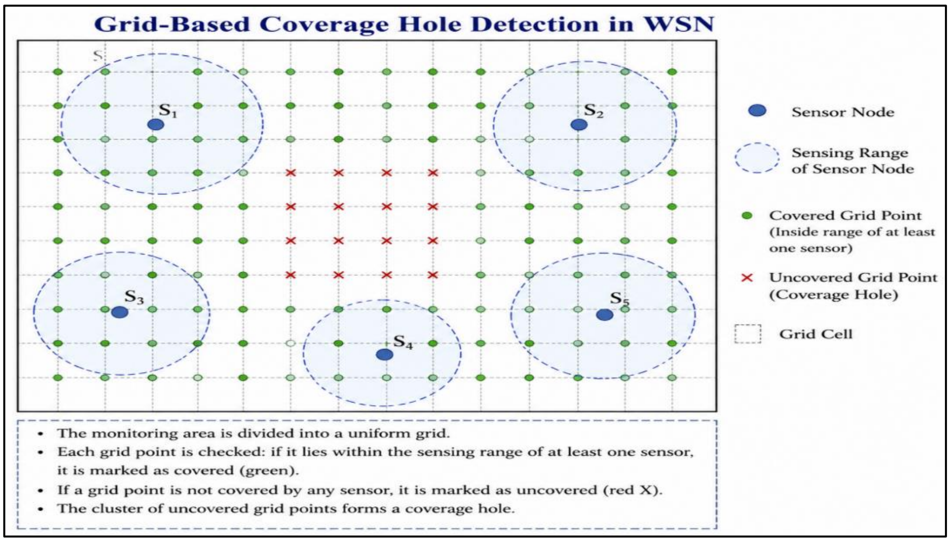

Delaunay Triangulation for Coverage Hole Detection

- Sensor nodes are connected using Delaunay triangulation.
- For each triangle, the circumcircle is drawn.
- If no sensor node exists inside the circumcircle, the region is an uncovered area (coverage hole).

Figure 2: Delaunay Triangulation for Coverage Hole in WSN

Unlike geometric methods such as Voronoi diagrams and Delaunay triangulation, grid-based approaches do not require complex computations or strict geometric constraints, making them highly suitable for large-scale, dynamic networks [14]. These methods also provide a straightforward way to compute the coverage ratio, defined as the proportion of covered grid points to the total number of grid points. Furthermore, grid-based techniques can be easily integrated with optimization algorithms such as Particle Swarm Optimization (PSO), in which uncovered grid points guide the movement of sensor nodes to improve coverage. However, the accuracy of grid-based methods depends on the grid resolution: finer grids provide more accurate hole detection but increase computational cost, while coarser grids reduce computation at the expense of precision [15-16]. Despite this trade-off, grid-based methods remain one of the most practical and widely adopted approaches for coverage analysis and hole detection in WSNs.

Figure 3 illustrates the grid-based coverage hole detection method in a WSN. The entire sensing area is divided into a uniform grid, where each small point represents a grid location to be evaluated. The blue circles denote sensor nodes, and the dashed circles around them represent their sensing range. Each grid point is checked to determine whether it lies within the sensing radius of at least one sensor. If it is covered, it is marked with a green dot; otherwise, it is marked with a red "X", indicating an uncovered point (coverage hole). In the center of the figure, a cluster of red X marks indicates a coverage hole, where no sensor can detect events due to insufficient overlap of sensing ranges. This method clearly visualizes coverage performance and enables easy identification of uncovered areas, which can then guide optimization algorithms (such as PSO) to reposition nodes and improve overall coverage.

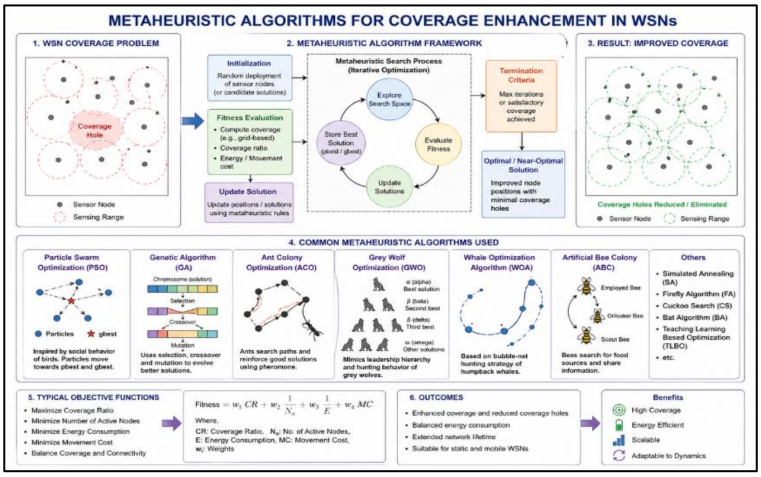


- The monitoring area is divided into a uniform grid.
- Each grid point is checked: if it lies within the sensing range of at least one sensor, it is marked as covered (green).
- If a grid point is not covered by any sensor, it is marked as uncovered (red X).
- The cluster of uncovered grid points forms a coverage hole.

Figure 3: Grid-based coverage hole detection

V.METAHEURISTIC ALGORITHMS COVERAGE TECHNIQUES IN WSNS

Metaheuristic algorithms have become one of the most effective approaches for solving the coverage hole problem in WSNs due to their ability to handle complex, non-linear, and multi-objective optimization problems. In WSNs, coverage optimization involves determining the optimal placement or movement of sensor nodes to maximize coverage while minimizing energy consumption and movement cost. Traditional deterministic and geometric methods often struggle with scalability and dynamic environments, whereas metaheuristic algorithms offer flexible, adaptive solutions. Among the most widely used techniques, Particle Swarm Optimization (PSO) is a popular swarm intelligence-based method that models the social behavior of birds. In PSO, each particle represents a possible configuration of sensor node positions, and the algorithm iteratively updates these positions based on personal best (*pbest*) and global best (*gbest*) solutions. This enables efficient exploration of the search space and helps in reducing coverage holes by guiding nodes toward uncovered regions [17]. Similarly, Genetic Algorithms (GA) use evolutionary principles such as selection, crossover, and mutation to evolve optimal sensor placements over successive generations, making themsuitable for large-scale coverage optimization problems. Other metaheuristic approaches include Ant Colony Optimization (ACO), where artificial ants search for optimal paths or node placements based on pheromone trails, and Grey Wolf Optimization (GWO), which mimics the leadership hierarchy and hunting behavior of wolves to find optimal solutions. Additionally, algorithms such as the Whale Optimization Algorithm (WOA) and the Artificial Bee Colony (ABC) have been applied to improve coverage and energy efficiency in WSNs. Recent research focuses on hybrid metaheuristic models that combine multiple algorithms (e.g., PSO-GA, GA-WOA) to enhance convergence speed and solution quality[18-19]. Despite their advantages, metaheuristic techniques face challenges such as parameter tuning, computational overhead, and the risk of local optima. However, their ability to adapt to dynamic environments and optimize multiple objectives simultaneously makes them highly suitable for modern WSN applications. As a result, metaheuristic algorithms continue to play a crucial role in advancing coverage hole detection and healing strategies.



Random deployment of sensor nodes (or candidate solutions)

- Compute coverage (e.g., grid-based)
- Coverage ratio
- Energy / Movement cost

Update positions / solutions using metaheuristic rules

Max iterations or satisfactory coverage achieved

Improved node positions with minimal coverage holes

Inspired by social behavior of birds. Particles move towards pbest and gbest.

Uses selection, crossover and mutation to evolve better solutions.

Ants search paths and reinforce good solutions using pheromone.

Mimics leadership hierarchy and hunting behavior of grey wolves.

Based on bubble-net hunting strategy of humpback whales.

Bees search for food sources and share information.

- Simulated Annealing (SA)
- Firefly Algorithm (FA)
- Cuckoo Search (CS)
- Bat Algorithm (BA)
- Teaching Learning Based Optimization (TLBO)
- etc.

- Maximize Coverage Ratio
- Minimize Number of Active Nodes
- Minimize Energy Consumption
- Minimize Movement Cost
- Balance Coverage and Connectivity

$$\text{Fitness} = w_1\,CR + w_2\,\frac{1}{N_a} + w_3\,\frac{1}{E} + w_4\,MC$$

Where,
CR: Coverage Ratio, N_a: No. of Active Nodes,
E: Energy Consumption, MC: Movement Cost,
w_i: Weights

- Enhanced coverage and reduced coverage holes
- Balanced energy consumption
- Extended network lifetime
- Suitable for static and mobile WSNs

Figure 4: Metaheuristic algorithms coverage techniques in WSNs

Figure 4 illustrates how metaheuristic algorithms are applied to improve coverage in (WSNs) through an optimization-based framework. It begins with the coverage problem, where sensor nodes are randomly deployed, leading to coverage holes due to insufficient overlap of sensing ranges. To address this, a metaheuristic optimization process is applied. Initially, candidate solutions (sensor positions) are generated, and a fitness function evaluates their performance based on parameters such as coverage ratio, energy consumption, and movement cost. The algorithm then iteratively improves solutions by updating node positions using mechanisms inspired by natural behaviors (e.g., swarm intelligence or evolution). During this process, the best solutions (pbest and gbest in PSO) are stored and used to guide future updates. The optimization continues until a stopping criterion is met, such as reaching the maximum number of iterations or achieving satisfactory coverage.

Criteria	**Geometric Methods (Voronoi, Delaunay)**	**Grid-Based Techniques**	**Metaheuristic Algorithms (PSO, GA, ACO, etc.)**
Basic Idea	Use geometric structures to detect holes based on node positions	Divide the area into grid points and check coverage	Optimize node placement using intelligent search algorithms
Input Requirement	Requires accurate node location (coordinates)	Requires sensing radius + grid resolution	Requires initial node positions + objective function
Coverage Hole Detection	High accuracy using Voronoi vertices or Delaunay triangles	Moderate to high accuracy, depending on grid resolution	Indirect (detect + optimize simultaneously)
Computational Complexity	High (complex geometric calculations)	Low to moderate	High (iterative optimization process)
Scalability	Limited for large-scale networks	Good scalability	Moderate (depends on algorithm & iterations)
Adaptability (Dynamic Networks)	Poor	Moderate	High (adaptive and flexible)
Energy Efficiency	Not considered directly	Limited consideration	Optimized (can include energy in fitness function)
Node Movement / Healing	Only detection (needs extra method for healing)	Detection only (needs optimization for healing)	Detection + healing (integrated optimization)
Accuracy	Very high (precise hole localization)	Depends on grid size (resolution dependent)	High (near-optimal solutions)
Implementation Complexity	Complex	Simple	Complex
Real-Time Application	Difficult	Possible	Challenging but feasible
Best Use Case	Static networks with known node positions	Large-scale networks with simple analysis	Dynamic networks requiring optimization and healing
Examples	Voronoi Diagram, Delaunay Triangulation	Grid sampling, pixel-based coverage	PSO, GA, ACO, GWO, WOA

Table 1: Comparative Analysis of Coverage Hole Detection Technique

VI.CONCLUSION

This survey paper presented a comprehensive review of coverage hole detection and healing techniques in WSNs, highlighting the importance of maintaining effective sensing coverage for reliable network performance. Various approaches, including geometric methods, grid-based techniques, and metaheuristic algorithms, were analyzed and compared based on their efficiency, accuracy, computational complexity, and adaptability. Geometric methods such as Voronoi diagrams and Delaunay triangulation provide highly accurate detection of coverage holes, but their reliance on precise location information and computational overhead limits their applicability in large-scale or dynamic environments.

Grid-based techniques offer a simple, scalable solution, enabling straightforward identification of uncovered regions at relatively low computational cost; however, their accuracy depends on the grid resolution. In contrast, metaheuristic algorithms, including Particle Swarm Optimization, Genetic Algorithms, and other swarm intelligence techniques, demonstrate superior performance by integrating both detection and healing processes, enabling adaptive optimization of sensor placement to minimize coverage holes while considering additional constraints such as energy consumption and movement cost. Despite significant advancements, several challenges remain, including balancing coverage optimization with energy efficiency, ensuring scalability for large deployments, and handling dynamic network conditions. Future research directions may focus on developing hybrid approaches that combine the strengths of geometric, grid-based, and optimization techniques, and on incorporating intelligent, learning-based methods for real-time coverage management.

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