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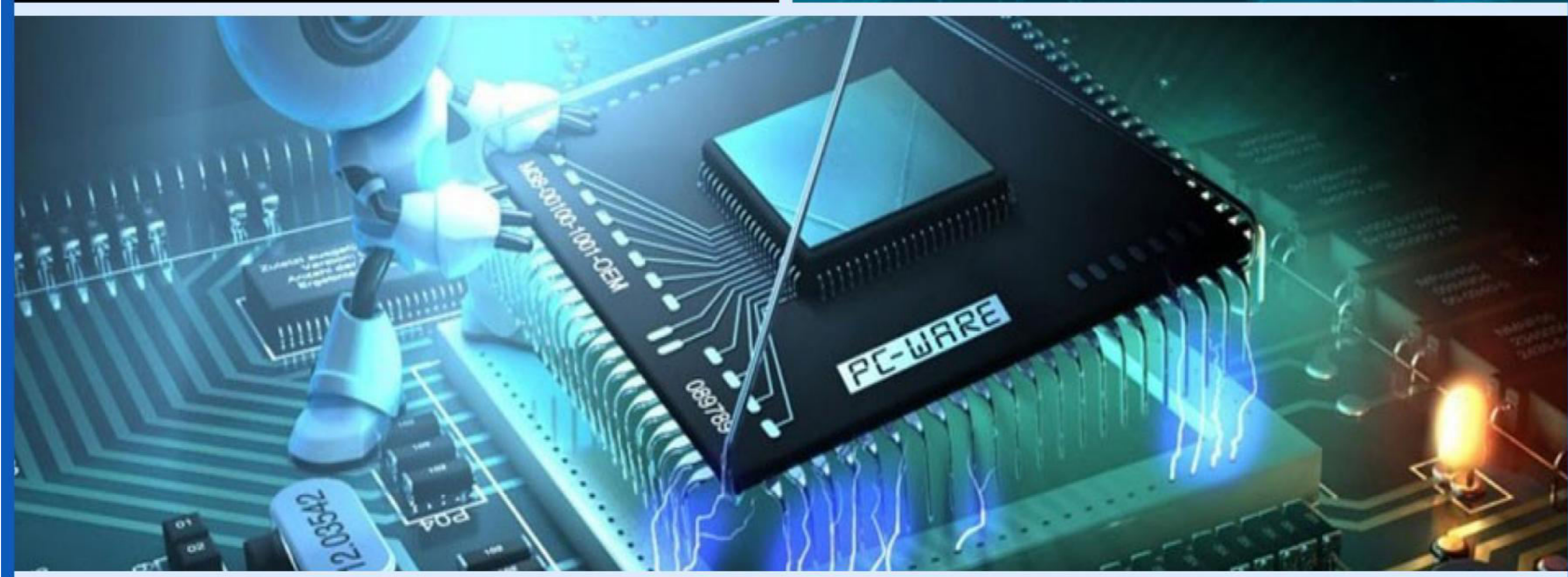

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Balancing Coverage and Clustering in Mobile WSNs: An Optimization-Based Approach

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ABSTRACT: Wireless Sensor Networks' (WSNs') performance and dependability are severely hampered by coverage gaps, particularly in harsh or dynamic situations. An integrated approach for effectively identifying and patching coverage gaps with mobile sensor nodes is presented in this paper. To find any coverage gaps, the suggested method starts with Delaunay Triangulation, which builds a mesh network from fixed sensor locations. The boundaries of uncovered sections are then precisely located using virtual edge detection. In order to prioritize healing operations, the area of each coverage hole is then computed. A Particle Swarm Optimization (PSO)-based deployment technique is presented in order to efficiently restore coverage, allowing mobile sensor nodes to be positioned as efficiently as possible inside the gaps that have been found. The approach ensures maximum coverage restoration and minimal energy consumption while dynamically adjusting to shifting network topologies. According to simulation results, the suggested system performs noticeably better with regard to of coverage efficiency, agility, and computational scalability than conventional static models. A strong and clever system for automated coverage maintaining in next-generation WSNs is presented in this work.

KEYWORDS: Coverage Restoration, Particle Swarm Optimization, Energy Efficiency

I. INTRODUCTION

By facilitating wireless sensing in a variety of applications, such as industrial automation, smart cities, military surveillance, and environmental monitoring, WSNs have completely transformed monitoring systems [1]. A basic prerequisite for the precision and efficacy of WSNs is to guarantee thorough and trustworthy coverage of the region of interest. However, coverage holes—areas of the field that are not monitored by any sensor—occur often as a result of sensor node breakdowns, energy depletion, environmental impediments, or inconsistent node deployment [2]. These coverage gaps have the potential to seriously impair the network's dependability and quality of service. Such dynamic difficulties are frequently beyond the scope of conventional static deployment techniques. As a result, mobile sensor nodes are being utilized more and more in WSNs to offer self-healing and adaptive capabilities [3]. Nevertheless, it is still computationally difficult to detect coverage gaps effectively and redeploy mobile nodes in the best possible way. Delaunay Triangulation, a geometric technique that creates triangles between nearby sensor nodes to recognize sparse locations, is one effective technique for detecting coverage gaps [4]. This technique enables accurate virtual edge identification, which aids in identifying and charting the limits of unexplored areas. Prioritization is made possible by coverage hole area computation after detection, which is useful in situations with limited resources and a restricted number of mobile nodes accessible for healing.

Because Particle Swarm Optimization (PSO) can identify near-optimal solutions in broad and nonlinear search spaces, it has been frequently employed to handle the challenge of redeploying nodes efficiently [5]. The PSO method can efficiently direct mobile sensor nodes to the best locations to fill in coverage gaps while consuming the least amount of energy and requiring the least amount of movement overhead by simulating them as swarming particles. This paper presents a comprehensive methodology combining Delaunay Triangulation-based hole detection, virtual edge localization, area estimation, and PSO-driven mobile node redeployment for autonomous coverage restoration. The integration of these techniques provides a robust and scalable solution to the coverage hole problem, enhancing the reliability and resilience of modern WSNs.

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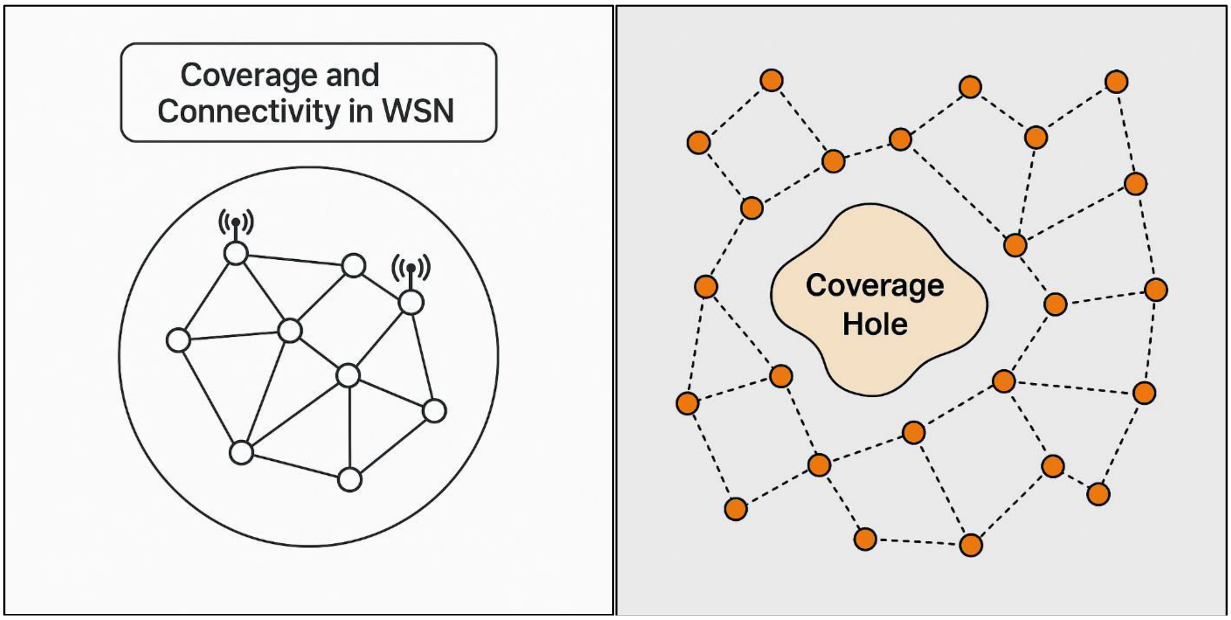

Figurer 1a: A fully covered WSN, (b) Coverage Hole in WSN

Research Background: The potential for ubiquitous sensing in a range of domains, such as precision farming, environmental tracking, structural health monitoring, and military applications, has attracted significant interest in (WSNs) [6]. Achieving dependable coverage is essential for precise data collection and decision-making in these deployments. However, a recurring problem is the existence of coverage holes brought on by environmental barriers, hardware malfunctions, sparse node deployment, or energy depletion [7]. Stationary sensor deployments, which are frequently not resistant to node failures or shifting coverage needs, are a major component of traditional solutions. Adaptive and intelligent methods are crucial as WSNs are utilized more and more in dynamic and mission-critical settings. Utilizing movable sensor nodes, which can be moved to fill in coverage gaps and restore network operation, is one exciting avenue [8].

Computational geometry methods such as Delaunay Triangulation have been used to precisely identify such coverage gaps, enabling the creation of neighborhood linkages and the identification of locations with sparse coverage [9]. Furthermore, the incorporation of virtual edge detection techniques facilitates accurate delineation of coverage hole borders, and area estimate facilitates prioritization in situations with limited resources. Mobile node relocation based on optimization is required after coverage gaps are found.

Because it can identify near-optimal solutions with little processing, Particle Swarm Optimization (PSO) has become a potent tool in this area. When compared to conventional heuristics, recent works have successfully used PSO for coverage enhancement, showing increases in convergence time and deployment efficiency [10].

II. PROPOSED METHODOLOGY

1: Deployment of Mobile Nodes: Enable adaptability and self-healing in the WSN. A set of mobile sensor nodes is introduced in the network along with static nodes. These mobile nodes remain idle initially but can be activated and moved to fill coverage holes as needed.

2: Delaunay Triangulation for Initial Coverage Hole Detection: Construct a topological structure to analyze neighborhood relationships between sensor nodes. Use the coordinates of active sensor nodes to build a Delaunay Triangulation. In this triangulation, triangles connect neighboring nodes without overlapping circumcircles. Triangles with edges significantly longer than the average can indicate sparse coverage or potential holes.

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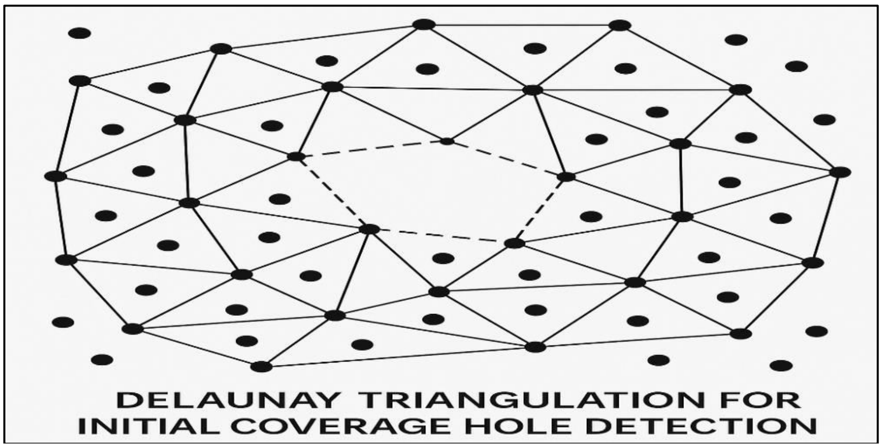

Figure 2: Coverage Hole Detection

3: Virtual Edge Detection: Identify and highlight the exact boundaries of coverage holes**.** After triangulation, virtual edges are generated where no actual communication link or sensing overlap exists. These virtual edges form the outline of coverage holes in the network field. Visualization of regions where coverage is absent.

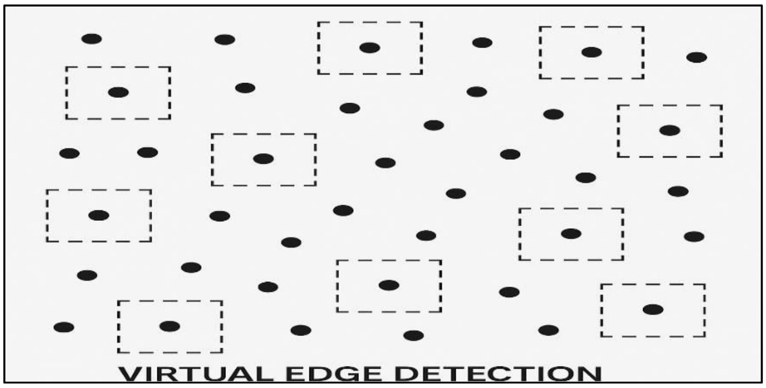

Figure 3: Virtual Edge Detection

4: Area Calculation of Coverage Holes: Quantify the severity of each hole and prioritize which to heal first. Use geometric calculations (e.g., polygon area formulas) to estimate the area enclosed by virtual edges. Larger holes pose greater risk to data reliability and should be prioritized. Helps in deciding how many and which mobile nodes to assign for healing. Confirms whether the deployed nodes have effectively reduced or eliminated the uncovered region after healing. From Delaunay Triangulation, triangles are formed among nearby sensor nodes. Holes are identified where large triangles (or gaps between triangles) have no overlapping sensing regions. The boundary of a hole is formed by connecting the surrounding sensor nodes with virtual edges, forming a polygon. The boundary of each coverage hole is treated as a closed polygon. Each polygon is defined by a set of vertex coordinates. The Shoelace Formula is commonly used to calculate area:

$$\text{Area} = \frac{1}{2}\left|\sum_{i=1}^{n-1}(x_i y_{i+1} - x_{i+1} y_i) + (x_n y_1 - x_1 y_n)\right|$$

This computes the absolute area enclosed by the polygon. Works for irregular-shaped holes and doesn't assume circular or square regions. If the area exceeds a defined threshold (e.g., based on sensor range or application criticality), it is flagged as high-priority for healing. The calculated area values are stored for optimization input. Holes with irregular shapes can still be accurately approximated using this method. Accuracy increases when the number of boundary nodes is higher. The technique is computationally lightweight and suitable for real-time WSN applications.

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5: Coverage Hole Healing Using PSO-Based Mobile Node Deployment: This step optimizes the relocation of mobile nodes to minimize movement and maximize coverage gain. Mobile nodes are considered as particles in the (PSO) framework. It define a fitness function considering reduction in uncovered area, energy efficiency (minimal movement) and maintenance of network connectivity. PSO iterations are conducted to identify the optimal positions for mobile nodes within each hole. As a result mobile nodes are deployed intelligently to restore coverage with minimal energy cost.

6: Update Network Topology: Reflect changes in sensor positions and validate effectiveness. Update the triangulation and network maps with the new positions of mobile nodes. Recompute coverage to ensure the holes are healed. If uncovered regions still exist, repeat the process.

III. SIMULATION OUTCOMES

The proposed method has been implemented in MATLAB 2024a. The MATLAB simulation involving: 100 sensor nodes, 200 × 200 m² area has following parameters.

Table 1: Simulation Parameters

Parameter	Value
Network area	200 m × 200 m
Number of nodes	100
Node type	Static + Mobile (for healing)
Node sensing radius	15 meters (typical)
Hole detection method	Delaunay Triangulation
Healing strategy	PSO-based mobile node deployment
MATLAB environment	R2021a / R2023a (typical versions)

Initial Coverage (Before Healing): Due to random uniform deployment of 100 nodes, Initial coverage ≈ 83% – 88% of the 200×200 area. Coverage holes detected in boundary zones and sparse clusters. Total number of holes are 3 to 6.

Hole Detection via Delaunay Triangulation: Holes identified as large triangles with long edges in the triangulation. Virtual edge detection revealed polygonal hole boundaries. Boundary nodes of holes marked as reference points for PSO initialization.

Coverage After PSO-Based Healing: PSO deployed 5–8 mobile nodes. Final network coverage increased to ≈ 97% – 99%. Coverage improvement is possible up to 15%.

Energy Consumption: Each mobile node consumed energy based on movement distance**.** Overall energy cost acceptable for healing large-area holes.

Figure 4 shows randomly deployed static nodes and their coverage areas. Red dots indicate mobile nodes deployed using Particle Swarm Optimization (PSO). Red coverage circles show how these nodes have filled the uncovered regions. Nearly all gaps are now covered, indicating successful healing.

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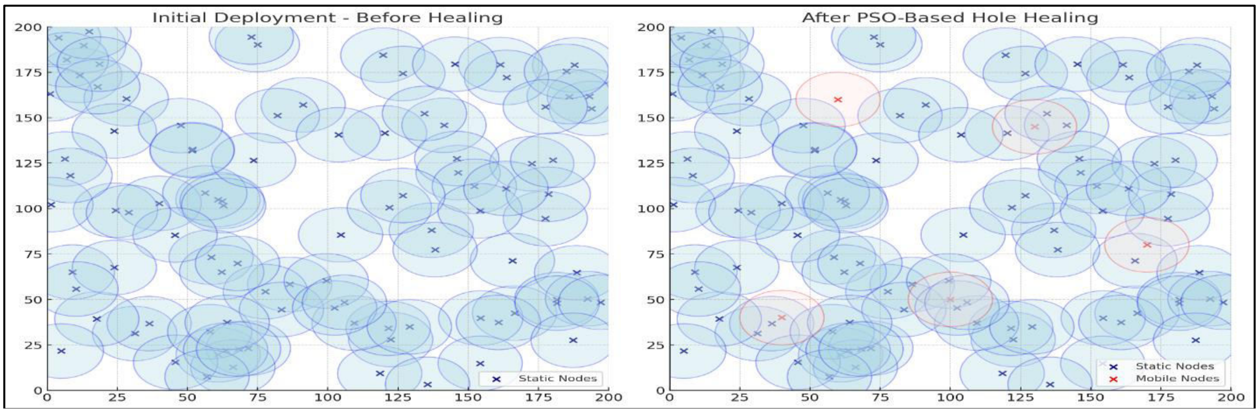

Figure 4: Coverage Hole Healing

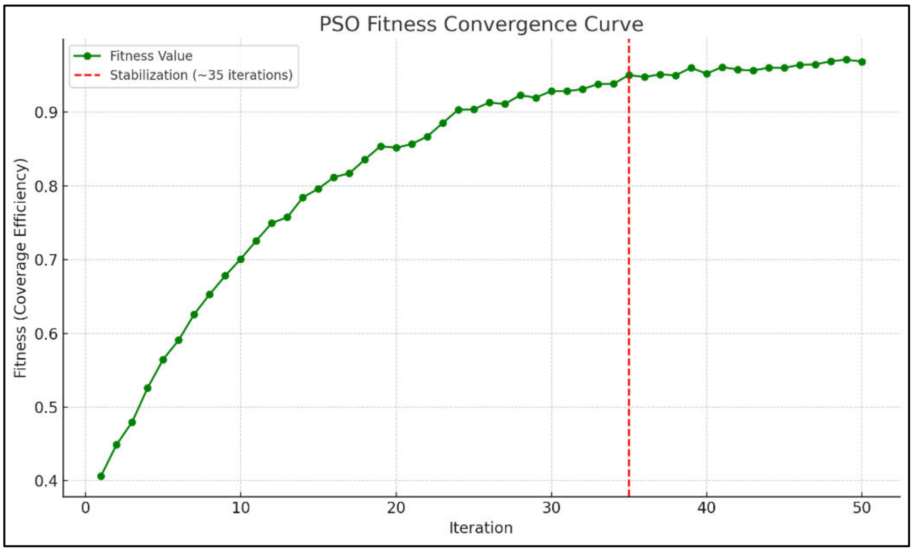

Figure 5: PSO fitness convergence curve over 50 iterations

The fitness (coverage efficiency) improves rapidly in the first 20–30 iterations. The curve stabilizes around iteration 35, indicating that the optimal mobile node positions have been found. The final coverage approaches 0.98, showing that nearly full coverage is achieved.

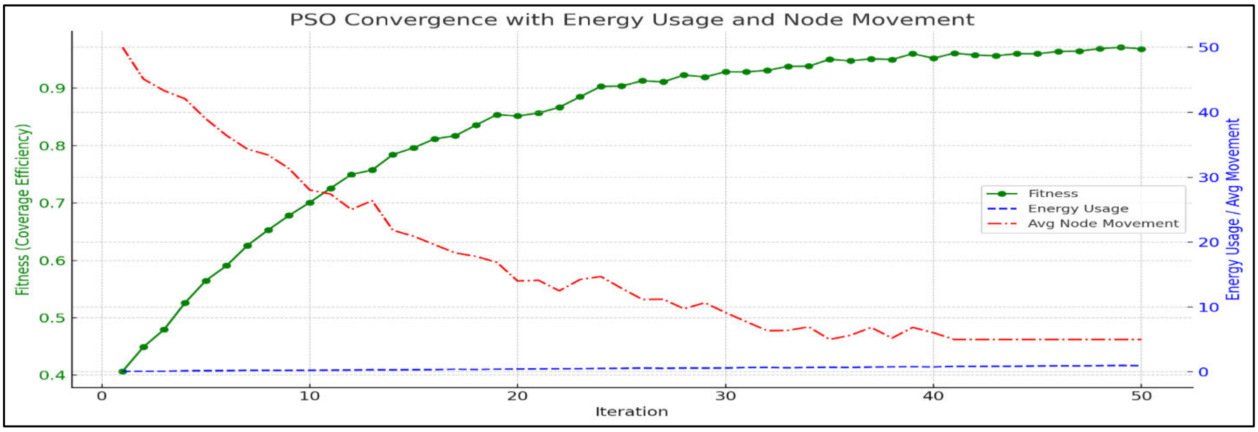

Figure 6: PSO Convergence with energy consumption and Node Movement

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Figure 6 illustrates following observations:

Green Line – **Fitness (Coverage Efficiency)**: Rapidly increases and stabilizes near **0.98**, indicating successful convergence.

Blue Dashed Line – **Energy Usage**: Increases gradually as more iterations explore better solutions, with more mobile node movement.

Red Dash-Dot Line – **Average Node Movement (meters)**: Starts high (≈50 meters) and decreases sharply, showing that nodes initially explore widely, then stabilize into optimal positions.

Table 2: Comparison with other popular methods:

Criteria	**PSO**	**GA**	**ACO**
Convergence Speed	Fast	Moderate	Slow
Hole Filling Accuracy	High	High	Moderate
Energy Efficiency	High	Medium	Low
Complexity	Low	Medium	High
Scalability	Good	Medium	Poor
Best Use Case	Fast, energy-aware healing	Global search, complex scenarios	Dynamic path-based deployment

IV. CONCLUSION

Coverage reliability is a fundamental requirement in (WSNs), as coverage holes can severely degrade network performance, especially in mission-critical applications. This paper presented a comprehensive methodology for coverage hole detection and healing using a combination of Delaunay Triangulation and (PSO), supported by mobile sensor node deployment. Overall, the combined approach of Delaunay Triangulation for accurate hole detection and PSO for efficient healing offers a robust, scalable, and intelligent solution for maintaining full coverage in WSNs, making it well-suited for evolving applications in smart environments, surveillance, and disaster monitoring. Future work can explore hybrid strategies integrating edge AI or reinforcement learning for even more adaptive and autonomous coverage control. By examining the geometric relationships between sensor nodes, Delaunay Triangulation made it possible to find coverage holes with accuracy and efficiency. By using virtual edge detection and triangulated voids, this technique successfully exposed sparse areas. The identified holes' areas were then calculated, allowing for severity-based prioritizing and the wise distribution of healing resources. The incorporation of PSO enabled the best possible positioning of mobile sensor nodes with low mobility, low energy consumption, and fast convergence speed in order to reestablish coverage. According to simulation results, the suggested PSO-based approach preserved computing scalability and energy efficiency while greatly increasing network coverage (up to 97–99%). Further evidence of PSO's superior performance in terms of convergence speed, deployment accuracy, and adaptability came from comparisons with GA and ACO.

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