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ISSN (Online) 2394-6849

International Journal of Engineering Research in Electronics and Communication Engineering (IJERECE)

Vol 9, Issue 6, June 2022

WSN Coverage Holes Healing by Novel Chaotic Slime Mould Optimization

[1] Rohit Chugh,* [2] Prachi Chaudhary

[1] [2] ECE Department, DCRUST Murthal, India.
Corresponding Author Email: [1] rrohhitchhugh@gmail.com, [2] prachi.ece@dcrustm.org

Abstract*— WSN nodes can't run for longer timeframes because of a lack of energy. In the case that certain nodes die more quickly than others, the network's coverage may be compromised by a communication gap. In order to transport a data packet from one node ID to another, the node must consume more energy because of a gap in the network's coverage. Using a novel hybrid optimization method, we were able to fill this gap in our work. We have a global optimization method thanks to the Slime Mould optimization and chaotic mapping. Using auxiliary nodes that had previously been missed by existing technology, gaps were detected and fixed. The Delaunay triangulation approach used an improved algebraic methodology to determine the number of holes. In order to confirm the findings, a variety of node sensing ranges and densities were evaluated in-depth. According to our understanding, this method looks to outperform current alternatives. Increases in the number of redundant nodes may also help us cover more ground.

I. INTRODUCTION

The wireless sensor network (WSN) is an emerging technology with a wide range of potential applications. One of the key challenges in WSN is to design an efficient and effective routing protocol to ensure that data is reliably delivered from the sensor nodes to the base station. Many routing protocols have been proposed for WSN, but they all suffer from the same problem: the so-called coverage hole. A coverage hole is an area in the sensor field where the sensor nodes are not able to communicate with each other or with the base station. This results in a loss of data and can lead to the failure of the entire network. A possible solution to the coverage hole problem is the use of a hole healing approach. In this approach, the base station broadcasts a special hole healing packet that is received by the sensor nodes in the coverage hole. The sensor nodes then use this packet to establish communication with each other and with the base station. This approach has the advantage of being simple and effective, but it has the disadvantage of being energy-intensive.

There have been numerous work available on the hole coverage in WSN. However, the method proposed in [23] used the geometrical approach and random mobility model but it was not suitable for specific applications. The method proposed in [2] used the RSSI approach for the detection of coverage holes and provided the solution for the restoration of holes. However, an error occurred in the RSSI based approach for the animal monitoring applications. In [4] a DVOC method was proposed for the detection of K-coverage holes but it was not suitable for the moving nodes. In [5] the author used a tree and a graph approach for the identification of sensor holes. In [7] the author used the Delaunay triangulation approach to the graph formation and identified the coverage holes. However, it was not suitable for the moving nodes. In [8] the author used a hybrid optimization algorithm SAPSO which was suitable for circular holes only. In [9] a contour model-based approach was used for the coverage holes detection. In [10] a DVHD and GCHD algorithm proposed for the detection of coverage holes. However, it was not suitable for specific applications. In [11] a CHDR algorithm was proposed for the detection of coverage holes. In [12] the author used the PSO and time cumulative probability curves for the deployment of static sensors. In [13] the author used the Monte Carlo simulation for the deployment of static sensors. In [14] the author used the residual energy concept for the detection of coverage holes. In [16] the author proposed a method for the detection of both coverage and routing hole detection. In [17] the author used the RMSD for the detection of coverage holes. In [19] the author used the WHD algorithm for the detection of coverage holes. In [20] the author used the Delaunay triangulation approach for the detection of coverage holes. In [21] the author used the CSO-WT approach for the detection of coverage holes. In [22] the author used the Voronoi and Delaunay triangulation approach for the detection of coverage holes.

It can be validated in previous works that hole detection algorithms based on geometric approaches are good enough to achieve a high accuracy. Though the hole healing approaches are divided into several algorithms. Most of them are relying on evolutionary optimization algorithms. These optimization algorithms solve the hole healing approach by moving the auxiliary nodes at the place of coverage hole. These algorithms have the challenge of falling into local minima which project the optimal auxiliary nodes location as the best solution. However, these doesn't guarantee the avoiding the trap of local minima. This challenge motivates the development of new hybrid global optimization algorithm.

The proposed method combined the sensor node movement and the hybrid optimization algorithm chaotic

ISSN (Online) 2394-6849
International Journal of Engineering Research in Electronics and Communication Engineering (IJERECE)
Vol 9, Issue 6, June 2022

slime mould optimization algorithm (CSMO). The proposed method provided the solution for the moving nodes. The above-mentioned methods were not suitable for the moving nodes. The proposed method combines the sensor node movement and CSMO to overcome the problem of moving nodes. The proposed method provides the solution for the moving nodes.

The suggested contribution is divided into the following steps:

- Sensor nodes deployment phase: The proposed method uses the random placement of the nodes.
- Coverage hole detection phase: The proposed method uses the Delaunay Triangulation approach to detect the coverage holes.
- Coverage hole restoration phase: The proposed method uses the CSMO algorithm to move the auxiliary sensor node and provides the solution for the restoration of coverage holes.

The article is further divided into the hole detection approach discussion in section 2 and the hole healing approach is discussed in 3rd section. Results are discussed in section 4th section which is concluded in 5th section.

II. DELAUNAY HOLE DETECTION APPROACH

We propose a method to detect coverage holes using Delaunay triangulation. The idea is to use a Voronoi diagram based on the Delaunay triangulation to obtain the coverage holes. The Voronoi diagram is a partitioning of a plane into regions based on the distance to points in a specific subset of the plane. The Delaunay triangulation for a set of points P in the plane is a triangulation $DT(P)$ such that no point in P is inside the circumscribed circle of any triangle in $DT(P)$. A Voronoi diagram is a partitioning of a plane into regions based on distance to points in a specific subset of the plane. The Voronoi diagram of a set of points P is a subdivision of the plane into Polygons such that each polygon is associated with a point in P and each point in P is associated with a polygon. The Voronoi diagram is constructed by connecting the points in P by straight lines. The points in P are the vertices of the Voronoi diagram and the straight lines are the edges.

The Voronoi diagram can be used to detect coverage holes. A coverage hole is a region in the plane where there are no points in P. The coverage holes are the regions of the plane that are not associated with any point in P. We can use the Voronoi diagram to find the coverage holes by finding the regions of the plane that are not associated with any point in P. We can do this by finding the Voronoi cells that do not contain any points in P. The Voronoi cells that do not contain any points in P are the coverage holes.

Let P be a set of points in the plane. A Delaunay triangulation for P is a triangulation $DT(P)$ such that no point in P is inside the circumcircle of any triangle in $DT(P)$. For each triangle $\Delta abc \in DT(P)$, let $R_{\Delta abc}$ be the circumcircle of Δabc. The coverage hole of Δabc is the set of points $p \in P$ such that p is inside $R_{\Delta abc}$ but not inside any other circumcircle of triangles in $DT(P)$. The coverage hole detection problem is to find all coverage holes in the Delaunay triangulation $DT(P)$.

The hole detection algorithm is implemented to find the isolated empty circle (IsEC) area. The algorithm is based on the circumradius of the triangle. The triangle is formed with the three vertices, the nodes in the network. The three nodes form the triangle and have a common side. The side is greater than the twice of R_s. If the side is greater than the twice of R_s, then hole exists there. The hole is circular in nature. The hole's radius is the difference of sensing range of the nodes and the triangle's circumradius. The algorithm is implemented to find out the area of the hole. The algorithm is based on the circumradius of the triangle. The triangle is formed with the three vertices, the nodes in the network. The three nodes form the triangle and have a common side. The side is greater than the twice of R_s . If the side is greater than the twice of R_s, then hole exists there. The hole is circular in nature. The hole's radius is the difference of sensing range of the nodes and the triangle's circumradius. The full coverage detection is conditioned as:

Suppose a triangle developed by the three nodes $(v_i, v_j \ and \ v_k) \in V$ located at point $(p_i, p_j, and \ p_k) \in P$, with inside the circumcircle no other nodes available. The Euclidean distance among the nodes $v_i \ and \ v_j$ reflected as d_{ij} with the same distance from the other nodes. The acute triangle is completely covered if the equation 2 condition is satisfied;

$$R_S \geq \frac{d_{ij}d_{jk}d_{ik}}{\sqrt{\left(d_{ij}^2+d_{jk}^2+d_{ik}^2\right)^2-2(d_{ij}^4+d_{jk}^4+d_{ik}^4)}} \quad (1)$$

In the obtuse triangle case, the fully covered condition is derived in equation 2

$$R_s \geq max\left\{\frac{d_{ij}^2 d_{jk}}{d_{ij}^2+d_{jk}^2-d_{ik}^2}, \frac{d_{ik}^2 d_{jk}}{d_{ik}^2+d_{jk}^2-d_{ij}^2}\right\} \quad (2)$$

Algorithm 1 shows the pseudo-code for the coverage hole detection.

Input: WSN sensor nodes $\Longrightarrow \boldsymbol{V_n}$, $\boldsymbol{sensing\ range} \Longrightarrow \boldsymbol{R_s}$

Output: number of holes $\Longrightarrow \boldsymbol{N_{hole}}$, IsEC radius $\Longrightarrow \boldsymbol{R_e}$

1. Initialize $\boldsymbol{N_{hole} = 0}$
2. Deployed the nodes in an area by Gaussian distribution $\boldsymbol{f(x|\mu,\sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(x-\mu)^2}{2\sigma^2}}}$
3. Formulate the Delaunay triangle for deployed nodes $\boldsymbol{D_n}$.
4. For $\boldsymbol{i = 1: D_n - 1}$
5. For $\boldsymbol{j = i + 1: D_n}$
6. If ($\boldsymbol{D_i}$, $\boldsymbol{D_j}$ are neighbors) && ($\boldsymbol{D_{i_{\overline{ab}}} \equiv D_{j_{\overline{ab}}}}$)
7. Calculate the length of the common side $\boldsymbol{D_{i_{\overline{ab}}}} \Longrightarrow (\boldsymbol{d_{i_{\overline{ab}}}})$

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            If d_{i_ab} > 2 * R_s
                N_hole = N_hole + 1
                R_{e,ij} = R_s − D_{i,j,circumradius}
            End if
        End if
    End for
End for
```

III. COVERAGE HOLE DETECTION USING IMPROVED PSO

The proposed DT managed to get the coverage hole area with a number of holes. The mitigation of these sensor nodes considered the auxiliary nodes [1] which remain idle or in sleep mode while other sensor mates work. These auxiliary nodes add to vertices of sensor tree as a new subset $V_d \in v_{1d}, v_{2d}, \ldots\ldots, v_{kd}$, to mitigate or reduce the coverage holes. We assumed these nodes have the moving capability and change the WSN graph dynamically to get optimal positions. This paper is focused on the mitigation of holes only. V_ds are optimally deployed to ensure we get maximum coverage.

We adapted the swarm optimization method to deploy the V_d optimally to cover up holes. A hybrid Particle Swarm Optimization Algorithm is proposed for this purpose. We formulated the objective function as

$$argmin(w_1 \times N_{hole} + w_2 \times \sum_{i\in(1,N)} A_{hole,i}) \quad (3)$$

Here w_1, w_2 are random weights $\in (0,1)$.

The proposed chaotic Slime Mould optimization (CSMO) algorithm is used to deploy the auxiliary nodes for a given WSN graph. The WSN graph is partitioned into a set of overlapping subgraphs. The CSMO algorithm is then used to find the optimal placement of the auxiliary nodes in each subgraph. The placement of the auxiliary nodes are evaluated using the coverage hole area and the number of holes.

The algorithm works by simulating the behavior of slime moulds. The slime moulds are placed on a two-dimensional grid. Each slime mould has a certain amount of energy. The slime moulds move around the grid and when they encounter an obstacle, they use their energy to overcome it. The slime moulds will continue to move around the grid until they find an area of the grid that is free of obstacles. The CSMO is developed on the framework of SMO. To discuss the SCMO, a brief about the SMO is discussed in the next subsection.

3.1 Slime Mould optimization (SMO)

Slime mould optimization algorithm is a relatively new optimization technique that has shown great promise in a variety of different fields. The algorithm is inspired by the behaviour of a type of slime mould called Physarum polycephalum. This slime mould is capable of finding the shortest path between two points by growing and shrinking its body in a process known as plasmodium.

The slime mould algorithm can be applied to a wide range of problems including the Travelling Salesman Problem (TSP), vehicle routing and resource allocation. The algorithm has been shown to outperform more traditional methods such as evolutionary algorithms and ant colony optimization.

The slime mould algorithm works by creating a network of potential solutions. Each solution is represented by a node in the network. The nodes are connected by edges which represent the cost of moving from one solution to another. The cost can be anything from a distance between two points in the TSP to the amount of resources required to move from one location to another in a resource allocation problem. The algorithm begins by growing the slime mould in the network of solutions.

The mould will grow towards the nodes that represent the most promising solutions. As the mould grows, it will leave behind a trail of edges. These edges represent the path that the slime mould has taken and the cost of moving from one solution to another. Once the slime mould has reached a node, it will begin to shrink. The process of shrinking is known as plasmodium. During this stage, the slime mould will remove any edges that are not part of the shortest path to the goal. The final path that is left behind is the solution to the problem.

The algorithm works as follows:

- Initialize a population of solutions.
- For each solution in the population, evaluate its fitness.
- Select the fittest solution and move it to the next generation.
- mutate and crossover the remaining solutions to create new solutions.
- Repeat steps 2-5 until a stopping criterion is met.

The main advantage of SMOA is its simplicity. The algorithm is easy to implement and does not require much parameter tuning. Additionally, SMOA is a population-based algorithm, which means it is less likely to get stuck in local optima. One potential drawback of SMOA is that it can be slow to converge to the global optimum.

This algorithm is based on the principle of stigmergy, which is a form of communication between organisms in which they leave trails in their environment that can be followed by other organisms. The slime mould optimization algorithm is divided into two parts:

- the first part is the search phase, in which the slime mould explores the environment in order to find the food source;
- the second part is the navigation phase, in which the slime mould follows the trails left by the other slime moulds in order to reach the food source.

The position update of SMA is mathematically formulated as (for more detailed information, readers are suggested to read [35]):

3.1.1 Position update of Slime Mould

The slime mould can approach food according to the odour in the air. To express its approaching behavior in mathematical formulae, the following formulae are proposed to imitate the contraction mode:

$$\overline{X(t+1)} = \begin{cases} \overrightarrow{X_b(t)} + \overrightarrow{vb}\left(\overrightarrow{W}.\overrightarrow{X_A(t)} - \overrightarrow{X_B(t)}\right), & r < p \\ \overrightarrow{vc}.\overrightarrow{X(t)}, & r \geq p \end{cases}$$

(4)

Here $\vec{X}$ represents the current location of slime mould, $\overrightarrow{X_a(t)}$ and $\overrightarrow{X_b(t)}$ are randomly selected positions from the group of slim moulds. t is the current iteration and $\overrightarrow{vc}, \overrightarrow{vb}$ are two constants which lie in range of $[-b, b]$ and $[-a, a]$.. p is a constant which is the position update condition and can be calculated as:

$$p = \tanh |s_{i\in 1,2,..n} - DF| \quad (5)$$

Figure 1 indicates the position update phenomena [35].

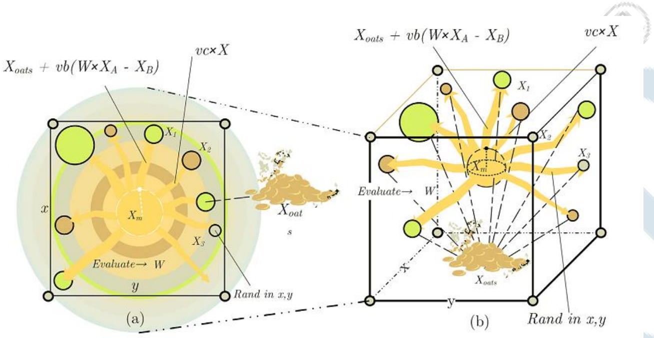


Figure 1: Position update of slime mould as per equation 4 in 2 and 3 dimensions

3.2 Chaotic Slime Mould algorithm optimization

Following the similar line of action as SMA, the randomness in the update step is reduced to get the certain and better results. The logistic chaotic map is used to update the exploration step of the SMA. The equation 4 can be rewritten as:

$$\overline{X(t+1)} = \begin{cases} \overrightarrow{X_b(t)} + \overrightarrow{C_{v_b}}\left(\overrightarrow{W}.\overrightarrow{X_A(t)} - \overrightarrow{X_B(t)}\right), & r < p \\ \overrightarrow{C_{v_c}}.\overrightarrow{X(t)}, & r \geq p \end{cases}$$

(6)

Where $\overrightarrow{C_{v_b}}$ and $\overrightarrow{C_{v_c}}$ are chaotic updated constant which are calculated by logistic mapping. It is formulated as:

$$x_n = r x_n(1 - x_n), n \in d \quad (7)$$

$$\overrightarrow{C_{v_b}} = \overrightarrow{vb} \times x_n \quad (8)$$

$$\overrightarrow{C_{v_c}} = \overrightarrow{vc} \times x_n \quad (9)$$

The r is a system parameter (0,4], $x_n \epsilon [0,1]$ and d is the search space dimension. The equation 7 is logistic mapping linear equation. The complete algorithm is also shown as flow chart in figure 2.

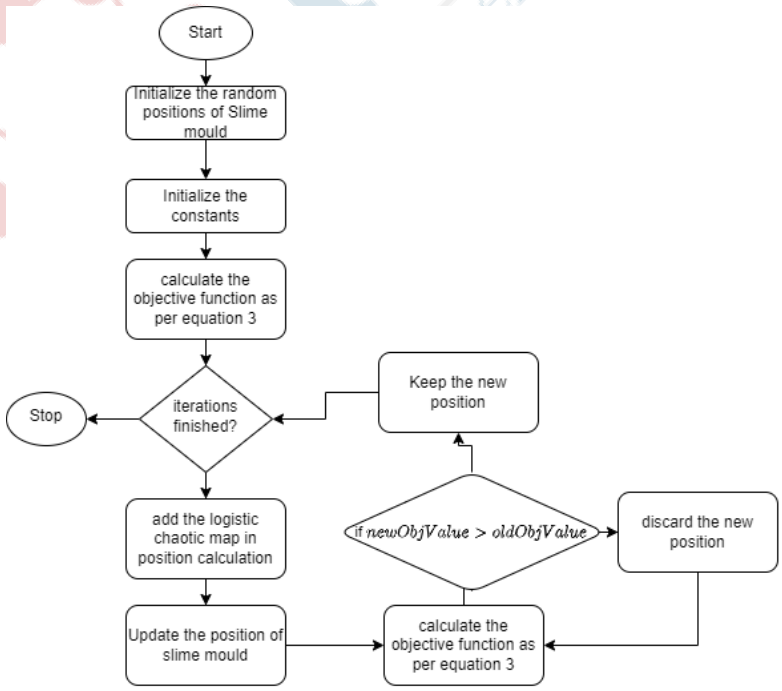


Figure 2: Flow chart of the proposed chaotic Slime Mould Optimization Algorithm

IV. EXPERIMENTAL ANALYSIS

The algorithm is implemented in the ns-3 simulator. The MATLAB is used to simulate the wireless sensor network. The wireless sensor network is simulated with 50 nodes. The nodes are placed on a two-dimensional grid. The nodes transmit data to the sink node. The sink node collects the data from the nodes. The Chaotic Slime Mould optimization algorithm is used to find the best placement of the nodes in the wireless sensor network to reduce the coverage hole. The placement of the nodes is optimized so that the nodes can cover the maximum area. The algorithm is tested with a different number of nodes. The results show that the algorithm is able to find the best placement of the nodes in the wireless sensor network.

A varied number of auxiliary nodes are used for each test. We looked at the number of holes and the area covered by the holes to determine the outcomes. As a result, results are compared to the most advanced algorithm as in [36] and SMA. Figure 3 shows the deployment of the nodes without the use of coverage hole repair.

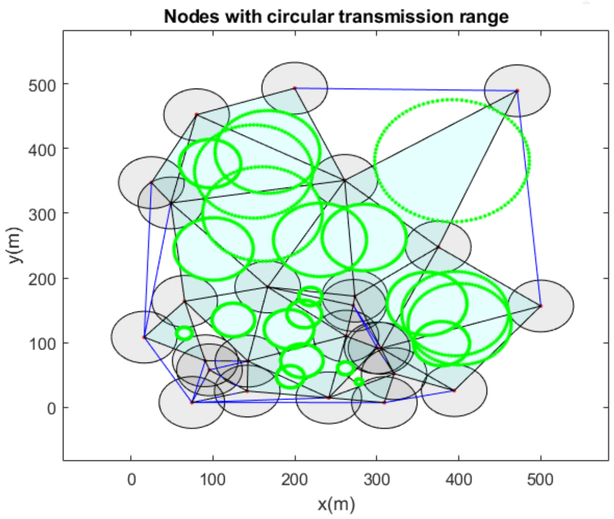
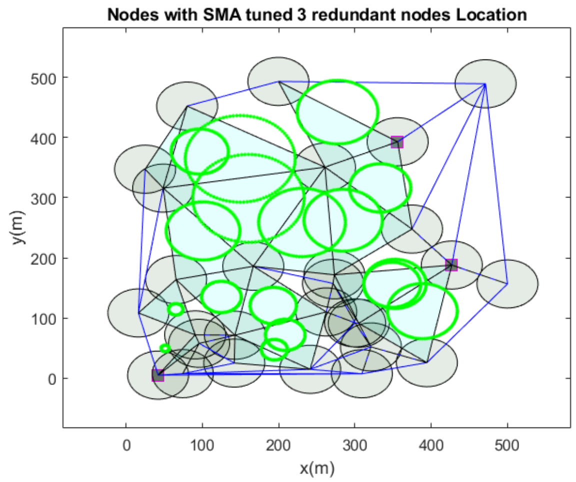
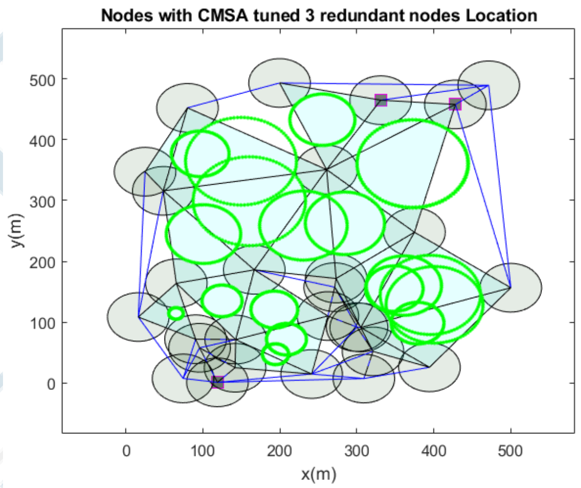


Figure3: WSN nodes with circular holes in green color

Because auxiliary nodes are initially inactive, they are only activated when a mending of the coverage hole is needed. The three auxiliary nodes have been taken into account for proposed optimization procedures. The nodes shown with a square box in the diagram are auxiliary. The green circle in figure 4 depicts the circular hole left after auxiliary nodes have been positioned.



(a)



(b)

Figure 4: Auxiliary nodes' placements in the network to heal the coverage hole for (a) SMA (b) chaotic SMA optimization

Figure 4(a) has a larger surface area of holes than 4(b). Premature termination is to blame for this since MSA cannot find the best location for auxiliary nodes. Figure 4(b) shows that the hole area has decreased, but the number of holes has remained the same. As seen in Figure 4, the suggested strategy has eliminated these drawbacks while also reducing the overall size and number of holes.

These two methods were compared to each other in our study as well. When the curve is at its lowest point, the equation 3 minimization convention is validated. As may be seen in Figure 5, the convergence curves are compared. The convergence curve shows that our optimization strategy is effective. To improve optimization, a saturation value should be hit as soon as possible. Our ultimate goal is to have fewer tiny holes, but we also want to lessen the size of those holes. Figure 5 depicts the ordinate of Equation 3's target function. The convergence point has been reduced by incorporating chaotic disturbances into hybrid optimization.

ISSN (Online) 2394-6849

International Journal of Engineering Research in Electronics and Communication Engineering (IJERECE)

Vol 9, Issue 6, June 2022

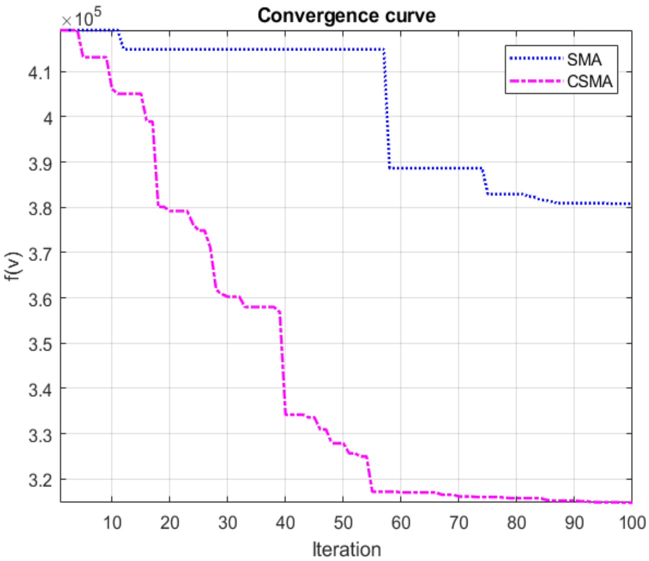


Figure 5: Convergence curve for the hole healing approach using proposed CSMA and state-of-the-art SMA

Table 1 depicts the number of holes and the area each hole covers in this situation, as well as the total number of holes. Because CSMA covers a larger region, SMA's coverage is less than that of CSMA. SMA had a coverage area of 17.34% less than the proposed optimization strategy, respectively. The proposed work has also shown an improvement of 12.85% more coverage than the state-of-the-art work [36].

Table 1: Comparative analysis of detected coverage holes and coverage area after hole mitigation

	Without healing	SMA	CSMA	PSOCGSA[36]
Number of holes (N_{hole})	21	19	17	19
Hole coverage area (A_{hole}).	924607.88	761604.94	629492.0	722358.08

V. CONCLUSION & FUTURE SCOPE

In our work, we've resolved the problem of locating and patching coverage holes in WSN. Using a new hybrid optimization technique, the damaged area will be restored. As a result, we've opted to install redundant nodes in the uncovered zone using a stochastic strategy. Slime Mould is now considerably more effective thanks to the logistic map. A logistics map is updated during the SMA's exploitation phase. The suggested plan's coverage area would have been 17.34% larger with SMA and 12.85% more than the state-of-the-art scheme.

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