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Research Article

Optimal Deployment for Hybrid Sensor Networks Based on Efficient Node Configuration

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Hybrid sensor networks, which contain mobile nodes and stationary nodes, are being used more and more widely. The second deployment of mobile nodes is a key problem to be solved, and the deployment performance of the network directly affects the monitoring effect of the network. Optimizing the configuration ratio of the two nodes can effectively reduce the network cost. In this paper, under the premise of knowing the coverage of the required monitoring area, the impact of sensor devices on node configuration is studied through parameter analysis, and the number and types of sensors that should be deployed in the hybrid sensor network are deduced, which can be conveniently and accurately used to design the actual hybrid sensor network. At the same time, for the secondary deployment of mobile nodes, this paper proposes a new mobile coverage method BS-CCP (box search and concentric circle positioning) to improve the coverage of the hybrid sensor network and maximize the coverage of the target area with the specified sensor types and numbers. Compared with existing work, the method in this paper reduces the number of iterations and reduces the number of required nodes. Comparing BS-CCP with the existing network mobile coverage algorithm, the experimental results show that the coverage obtained by this method is larger and more efficient.

1. Introduction

Wireless sensor networks (WSNs) is an ad hoc network composed of a large number of miniature sensor nodes deployed in the monitoring area [1]. With the continuous development of semiconductor technology and sensor technology, the perception, calculation, and communication capabilities of wireless sensor network technology have been comprehensively improved. As a promising technology, WSNs have been maturely used in military [2, 3], health [4, 5], animals and plants [6, 7], industry [8, 9], urban areas [10, 11], etc. Extensive monitoring, tracking, and surveillance provide a variety of services; some aspects are still in the initial stage of development, such as being applied to emerging fields like intelligent communication [12], smart home [13], and smart city [14] in recent years.

When WSNs are deployed in harsh ecological environments, they may face challenges such as random deployment, sensor damage, and node energy depletion, which can result in coverage gaps within the network [15]. In addition, large-scale redundant deployment of sensor nodes will cause high cost and technical difficulties. Due to the autonomous operation of sensor nodes in the ecological environment, the computing, communication, and sensing capabilities have certain limitations, and these nodes are unattended, so minor malfunctions will lead to a host of trouble [16]. Coverage control is one of the important research directions in the application of WSNs. It is to optimize the allocation of limited resources in WSNs, including sensor node energy, network communication bandwidth, and computing processing capacity. This optimization is achieved through strategic node deployment and other effective approaches. By efficiently managing these constrained resources, the aim is to enhance various quality of services, such as perception, monitoring, and communication capabilities within the network [17]. For large-scale monitoring areas, deploying static sensors through deterministic deployment can be time-consuming and labor-intensive. On the other hand, uniform random deployment makes it difficult to find an appropriate number of sensors to cover the entire area. If the quantity of sensors is very limited, coverage gaps may occur, while having too many sensors would result in high costs. If only mobile sensors are deployed, it can ensure high coverage rates. However, due to the movement of nodes, it results in excessive energy consumption and accelerates network failure.

Compared to WSNs that deploy only one type of node, deploying hybrid wireless sensor networks (HWSNs) can better integrate various factors [18]. Nowadays, many researchers are studying coverage algorithms for HWSNs. These algorithms involve randomly deploying both mobile nodes and static nodes and then moving the mobile nodes to the final target position determined by the algorithm, so as to improve the coverage of the network.

For the hybrid sensor network coverage algorithm, it can be mainly divided into two ways: swarm intelligence optimization algorithm and computational geometry. Since the coverage problem in WSNs is an NP-complete problem, there is no polynomial time efficient algorithm, and an approximate optimal solution can only be obtained by an approximate algorithm [19]. In recent years, with the emergence of more and more swarm intelligent optimization algorithms, a variety of swarm intelligent optimization algorithms have been applied to the coverage problem of wireless sensor networks, most of which are improved. Chen et al. proposed an improved Ant Lion optimizer (IALO) to solve the coverage optimization problem in WSNs [20]. They compared IALO with the original Ant Lion optimizer (ALO) and other algorithms on nine benchmark functions to verify its effectiveness. Finally, IALO is applied to the coverage optimization of wireless sensor networks. Simulation results show that compared with previous work, IALO provides higher coverage, makes the sensor distribution more uniform, and effectively reduces the deployment cost. Wang et al. proposed a coverage algorithm of wireless sensor networks based on an improved meta-heuristic algorithm [21]. By establishing the sensor deployment coverage model, they transformed the sensor network coverage problem into a high-dimensional multimodal function optimization problem. Then, the reverse expansion of the initial population was applied to enhance the global search capability and search scope of the algorithm. Also, the firefly principle was finally introduced to reduce the local constraint of sparrows and avoid local optimization problems in the search process of the population. In tests with different monitoring ranges and number of nodes, the proposed EFSSA algorithm demonstrated higher coverage than other algorithms. The results show that EFSSA algorithm can effectively enhance the coverage of sensor deployment. Dongliang proposed a hole repair algorithm based on fish swarm optimization (HRFSO) in wireless sensor networks [22]. In the algorithm, the network coverage is used as the objective function, and the biological behavior of artificial fish is used to simulate the node movement. In addition to foraging, rear-ending, and grouping, new moves for jumping and survival of the fittest have been defined to improve the convergence of optimization. The faulty hole was repaired by moving the sensor node with the shortest distance. The simulation results show that the algorithm has better repair effect, faster convergence speed, higher accuracy, efficiency, and robustness, prolonging the network life by increasing the coverage of WSN. Yao et al. proposed the VF-IMFO algorithm to repair coverage holes and reduce energy consumption during sensor node deployment [23]. The path is optimized by adaptive inertia weight and variable spiral position updating strategy, and by analyzing the attraction of uncovered grid points, the virtual force between adjacent sensor nodes and the repulsive force of the boundary, and using the joint force as the disturbance factor of moth position updating. Moth search is used to guide nodes to move to the area with coverage holes to achieve coverage optimization. In different deployment environments, VF-IMFO algorithm maintains significant performance advantages. Jiao et al. proposed a coverage optimization strategy based on flower pollination algorithm (FPA) [24]. First, an improved FPA is proposed in view of the shortcomings of classical FPA in convergence and accuracy. Then, the network deployment optimization problem is modeled as a multiobjective optimization problem to ensure the coverage of target points and the connectivity of the network, while minimizing the energy consumption of moving sensor nodes. By utilizing the improved FPA, sensor nodes are selected and moved to the appropriate position to minimize the energy consumption of sensor motion and guarantee coverage and connectivity. The test results show that compared with other evolutionary algorithms, the improved FPA has good convergence speed and accuracy, and the proposed algorithm meets the coverage requirements while ensuring the network connectivity and reduces the energy consumption of sensor motion.

Regarding the application of computational geometry to optimize hybrid sensor network coverage, Singh and Chen proposed a string-based sensor coverage hole repair method called the chord-based hole covering (CBHC) [25]. This approach provides comprehensive network coverage by reducing the overlap between sensor coverage areas and minimizing the number of sensors used. So et al. proposed a new distributed deployment algorithm for coverage hole repair called coverage hole-healing algorithm (CHHA), aiming at maximizing area coverage and minimizing the total sensor moving distance [26]. CHHA detects coverage holes by applying Delaunay-based triangulation and utilizes virtual forces to determine the movement of mobile sensors to fix coverage holes. Wu proposed a method to add mobile sensor nodes at optimal locations by exchanging information between single-hop neighbor border nodes [27]. This approach is simpler and easier to understand than constructing nodes in the form of Bornoy polygons to identify and recover coverage holes. Vatankhah and Babaie proposed an algorithm based on optimized bidding to identify coverage holes after deploying fixed sensor nodes and adjust the sensing radius of nodes based on Delaunay triangulation [28]. In addition, the algorithm also fills coverage holes and reduces overlapping areas by relocating some mobile nodes. Combined with the triangular structure, the algorithm is validated by extensive simulations in terms of coverage, number of mobile nodes, number of active nodes, and moving average of nodes.

Previous hybrid sensor network coverage algorithms have high computational complexity and require a long time and a large number of iterations. If an algorithm can be found to directly calculate the target position of the mobile node based on the existing static sensor position, the deployment will be simpler and more efficient.

For the problem of node configuration in hybrid sensor networks, Farsi et al. gave a detailed review of wireless sensor network coverage, where they emphasized the importance of the minimum number of nodes in randomly deployed wireless sensor networks [29]. Ghosh proposed a cooperative coverage enhancement algorithm (COVEN) [30]. The algorithm uses the Voronoi diagram to deterministically estimate the exact number of coverage holes under random deployment and utilizes static nodes for cooperative estimation to determine the need to deploy and relocate to the optimal the number of additional mobile nodes at optimal locations to maximize coverage. Maksimović and Milošević studied how to use the minimum number of nodes to achieve full area coverage and long life of sensor nodes and optimize the deployment of sensor nodes [31]. Liu et al. introduced the WSNs redundant node coverage algorithm (VSGCA) based on the virtual square grid. This algorithm achieves acceptable coverage and connectivity with the least number of sensor nodes, and its running time is short and the effect is good [32]. Qi et al. proposed a new mobile coverage scheme, which aims to improve the coverage and lifetime of hybrid sensor networks and completely cover the target area using the minimum number of mobile sensor nodes while reducing the energy consumption of hybrid sensor networks [33]. Compared with existing work, the minimum number of mobile sensor nodes required by the scheme significantly reduced, which means that the moving distance and energy consumption of mobile nodes are reduced.

At present, for the node configuration problem of hybrid sensor network, most papers are studying the coverage with fewer mobile sensor nodes, and there is no specific calculation standard. If a specific relationship between the coverage rate and the configuration ratio of mobile and static sensor nodes can be derived, configuration of nodes according to actual needs can be chosen before deploying sensors. In this way, it is necessary to first determine the ratio of mobile nodes to static nodes based on factors such as the environment and sensor characteristics and then deploy the sensors in the area. This analysis can serve as the initial part of designing networks of any given size and requirements. Considering that each sensor node has limited energy, communication range, and sensing range and is subjected to environmental factors such as obstacles and noise in the propagation path, choosing a perception model that comprehensively considers these factors is particularly important. Subsequently, using the derived model, an empirical formula can be further derived, which will serve as an essential parameter for future WSNs design, meeting the requirements of any WSNs design. On the one hand, it can avoid the second deployment if the number of sensors is not enough. On the other hand, it can reduce the redundancy of nodes and make full use of the sensing ability of each sensor node.

This paper aims to address two aspects in the coverage control problem of wireless sensor networks: algorithm complexity and unclear node configuration. At the coverage algorithm level, this study explores a method that directly calculates based on random deployment, eliminating the need for a large number of intelligent optimization algorithm iterations and saving the energy consumed by each node in this aspect. At the node configuration level, this study aims to obtain the relationship between network coverage rate and the proportion of hybrid nodes under the minimum number of sensor nodes required to completely cover the target area. Also, an empirical formula is derived, which can serve as a quality-of-service design parameter. Before deployment, the optimal ratio of mobile and static nodes is calculated, and then random deployment is carried out. The algorithm is used for the secondary deployment of mobile nodes to achieve the desired coverage in any practical HWSNs system. This approach is convenient for practical applications, as it helps to avoid sensor resource waste caused by erroneous estimation of the monitoring area or insufficient initial deployment of sensors leading to a need for secondary deployment.

The main contributions of this paper can be summarized as follows:

(i) A new secondary deployment algorithm for hybrid sensor networks is proposed. After the initial random deployment, mobile nodes are scheduled to supplement the coverage gaps. This method is simpler and more efficient than the existing methods.

(ii) The function relationship between coverage rate and ratio of dynamic and static nodes in hybrid sensor networks is derived, which can be used for researchers to design hybrid sensor networks in advance before deployment, so as to reduce network cost.

The rest of this paper is structured as follows. Section 2 builds the model of the hybrid sensor network. Section 3 gives the BS-CCP algorithm of HWSNs and the configuration method of nodes. Section 4 evaluates our algorithm. Finally, Section 5 summarizes the full text.

2. Hybrid Sensor Network Model Establishment

2.1. Sensing Model. In this paper, a simulation environment is constructed in a two-dimensional unobstructed space. The simulation setting assumes an area with an area of 100×100, in which sensor nodes with a sensing radius of both are uniformly and randomly deployed in the area.

This article uses a Boolean sensing model, also known as a 0-1 sensing model. If the monitoring node can cover the target area, it is 1, otherwise it is 0. As shown in Figure 1, the sensing radius of sensor nodes in the network is R_s, and the probability that any spatial point in the sensing area can be sensed and covered by sensor nodes is

$$f(d(s,z)) = \begin{cases} 1, & d(s,z) \le R_s, \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

Among them, $d(s,z)$ represents the Euclidean distance between the sensor node s and the spatial target point z. The Boolean sensing model can reduce the difficulty of solving the coverage problem and facilitate the in-depth study of the problem.

2.2. Coverage Model. This paper considers a hybrid sensor network consisting of two types of sensor nodes, namely, static nodes and mobile nodes. Static nodes cannot be moved after deployment, while mobile nodes will move according to the mobile coverage scheme. It is assumed that the node set $S = \{s_1, s_2, \cdots s_n\}$ of the hybrid wireless sensor network includes n mobile nodes and m static nodes, which are randomly and uniformly distributed in a rectangular area. Due to the randomness of network deployment, the coverage of the network does not meet the expected requirements, and n mobile nodes need to be redeployed. For the sake of discussion, the following assumptions are made for WSNs:

1. Each sensor node can obtain its own location information through positioning
2. Each sensor node has the same sensing radius R_s
3. The energy of the mobile node is sufficient to support the redeployment of its location

In order to calculate the coverage degree of the network, we divide the area into $N \times N$ grids, and the degree of grid center point is covered to represent the degree of grid coverage. Let the coordinates of the center point of the grid g be (x_g, y_g), and the coordinates of the sensor nodes s_i be (x_i, y_i), then the distance between the grid g and the node s_i is

$$\mathrm{d}(s_i, g) = \sqrt{\left(x_i - x_g\right)^2 + \left(y_i - y_g\right)^2}. \tag{2}$$

The probability that grid g is covered by sensor node s_i is

$$P\_\mathrm{COV}(s_i, g) = \begin{cases} 1, & d(s_i, g) \le R_s, \\ 0, & \text{otherwise.} \end{cases} \tag{3}$$

2.3. Sensor Price Regulation. Mathur et al. compare the application of mobile nodes and static nodes in wireless sensor networks, and they think that one mobile node is equal to five static nodes [34]. Johnson et al. stipulates that the cost of a static node is about \$100 [35], and according to Mathur's analysis, a mobile node has additional peripherals (motors and wheels) for actuation, and the entire sensor node requires additional packaging to accommodate peripherals. The cost of the mobile node was set at \$150 by taking into account the additional cost of the sensor's peripherals and packaging.

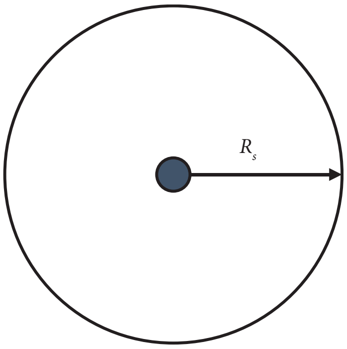


Figure 1: Boolean sensing model.

3. Hybrid Sensor Network Node Configuration Method

3.1. Determination of the Total Number of Sensors. To maximize the rational use of sensor resources, this paper will use the proposed HWSNs coverage optimization algorithm to determine the target position of the mobile node through the coordinates of all static nodes and the size of the rectangular area without adding additional sensors. It is to cover and monitor the area as large as possible. Before deployment, it is necessary to determine the total number of sensors covering a certain area.

As for the minimum number of sensor nodes, with the continuous research of researchers, the results have been given. The authors in [36] mathematically deduce in detail how many circles with known radius can completely cover a rectangle. In the field of WSNs, through people's continuous experiments and summarization, the minimum number of circles in the coverage area was finally obtained as follows [33, 37, 38]:

$$N = \frac{A}{3\sqrt{3}{R_s}^2/2}. \tag{4}$$

Here, N is the number of sensors, A is the total area of the region, and R_s is the sensing radius of the sensor.

3.2. Mobile Node Movement Algorithm

3.2.1. Algorithm Description. Due to the segmentation of the grid in the area by the sensor coverage model, there will be multiple blank areas, and these blank areas are composed of grids one by one. Through this algorithm, we first select a relatively large-scale area for sensor filling. Figure 2 is an example of deleting mobile nodes in the monitoring area and only retaining the distribution of static nodes, and Figure 3 is a schematic diagram of finding large-scale uncovered areas in the area.

To maximize the rational use of sensor resources, the nodes with inferior mobile sensor locations are redeployed

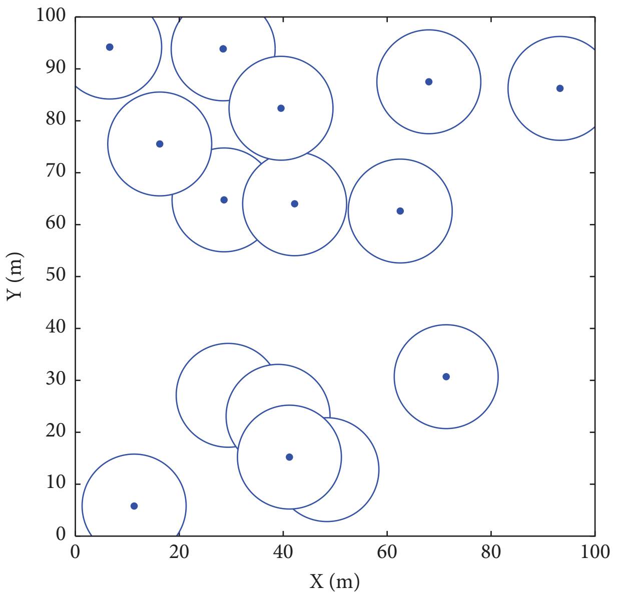


Figure 2: Static node distribution.

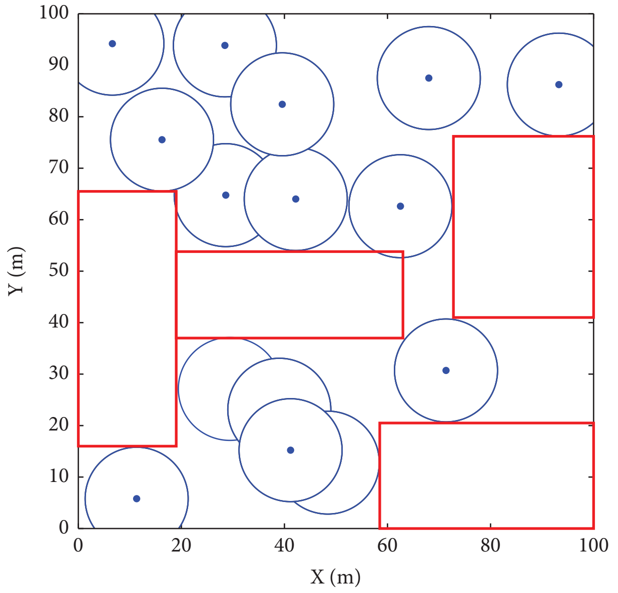


Figure 3: Large uncovered area search.

without changing the number of sensors. Hybrid WSN coverage optimization algorithm based on box search and concentric circle positioning (BS-CCP) proposed in this paper is described as follows:

Input: The current set of static node coordinates

Output: Optimal deployment position of mobile nodes

Step 1 Determine whether all the grids have been covered, marked as 1 if covered, and 0 if not covered.

Step 2 Arrange all the grids marked 0 according to the dimension of the row, accumulate the adjacent grids marked 0, and record the cumulative length as l_1. If $l_1 > 2R_s$, record the grids that satisfy each row into the set P.

Step 3 Accumulate the grid in the dimension of the column, and the accumulated length is l_2. If $l_2 > 2R_s$, keep it in P, otherwise delete it.

Step 4 Obtain a large uncovered area drawn in a rectangular shape through steps 2 and 3, as shown in Figure 3, it starts from the lower left vertex of the rectangle, then translate a distance of a sensing radius to the right and upward, and record it as the target coordinate of the mobile node.

Step 5 Repeat steps 1, 2, and 3 in turn, and end the process when the target node position can no longer be found or the iteration stop condition is satisfied.

Step 6 Determine the number of remaining mobile nodes to be deployed.

Step 7 Traverse all the grid nodes in the area not covered by the sensor, take all the nodes as the center of the circle, the width of the grid is the initial radius and make concentric circles outward, and the maximum radius of the concentric circle is the communication distance of the sensor.

Step 8 When the concentric circle coincides with the original sensor coverage area, stopping radius increases, and the center position and radius of the circle at this time are recorded.

Step 9 Let $Q = \{q_1, q_2, \ldots q_m\}$ be the set of concentric circles of all grid nodes not covered by the sensor, and find the circle with the largest radius in the set (if the maximum radius is the same, take the circle with the smaller sum of the horizontal and vertical coordinates of the center position, to keep it close to the lower left of the area), record the size of the node and radius of the circle at this time, and merge the area where the circle is located at this time into the sensor coverage area.

Step 10 Repeat steps 7, 8, and 9 in turn. When the number of determined circles is equal to N, the process ends.

At this time, the position of the center of the circle determined sequentially is the position of the target node.

The pseudo code of the algorithm is as follows:

3.2.2. Algorithm Time Complexity Analysis. Suppose the population size of the algorithm is N, the dimensionality of the search space is D, the maximum number of iterations is T, for the swarm intelligence optimization algorithm, its time complexity is $O(NDT)$, for algorithm BS-CCP, its time complexity analysis is as follows:

(1) The first part of the algorithm is about searching in a rectangular area, excluding the number of populations, and the maximum number of iterations is the number of mobile nodes. The value is set to e, $e \ll T$, so the time complexity of the algorithm required for this part is $O(De)$.

```
Input: current static node coordinates
for the total number of mobile nodes
    while can find a suitable location do
        Calculate grid coverage according to formula (3)
        Calculate large uncovered areas in both $x$ and $y$ dimensions from all uncovered grids
        Place sensor nodes based on area size to cover holes
    end while
    Calculate the number $K$ of remaining mobile nodes to be deployed
    for $i = 1, 2, \ldots, K$ do
        Make a concentric circle with all the grids as the center and the grid width as the initial radius, and increase the radius until it coincides with the coverage area of the existing sensor nodes, $r_{\max} \leq 2R_s$.
        Find the circle with the largest radius and merge its area into the sensor coverage area.
    end for
end for
Output the final coordinates of all mobile nodes.
```

Algorithm 1: BS-CCP.

(2) The second part of the algorithm about concentric circle positioning does not include population number, and the number of grids is M, $M < T$, so the time complexity of the algorithm required for this part is $O(\mathrm{DM})$.

Due to $M > e$, the time complexity of the BS-CCP algorithm composed of the two strategies is $O(De) + O(\mathrm{DM}) = O(\mathrm{DM})$. To sum up, the time complexity of the BS-CCP algorithm is less than that of each group intelligent optimization algorithm.

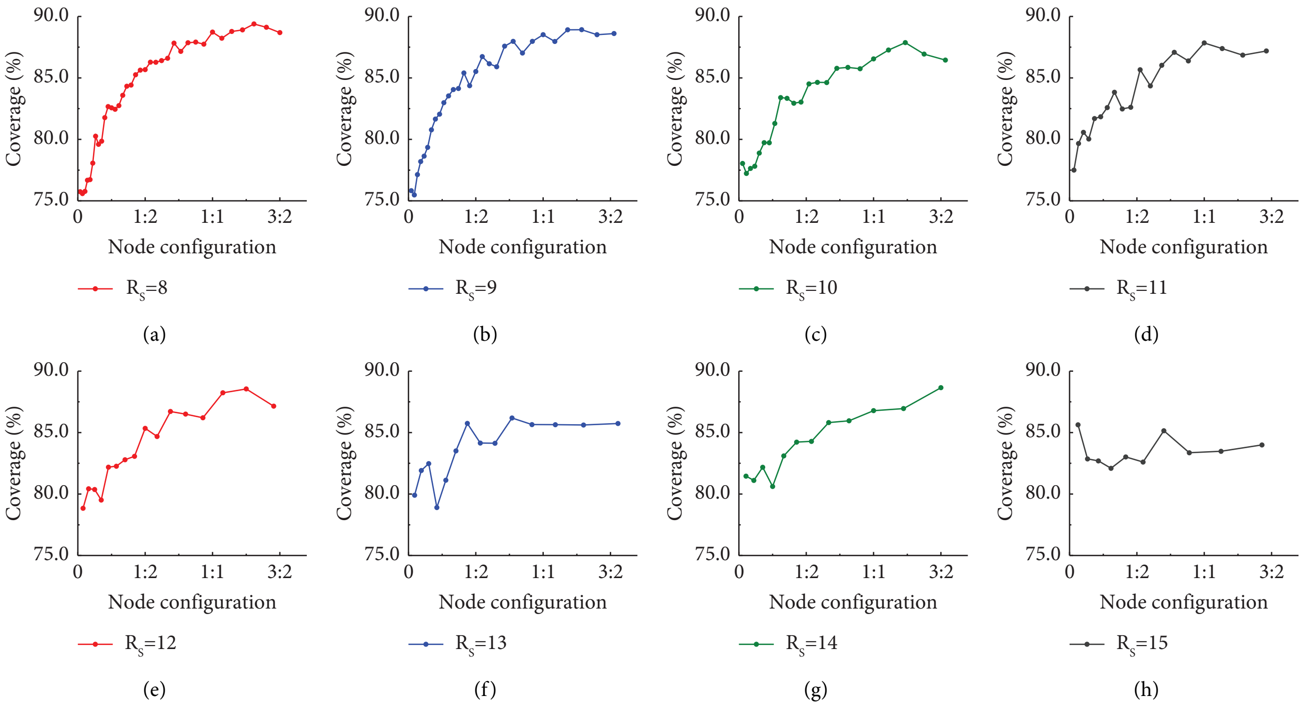
3.3. Mobile and Static Node Ratio Configuration. When deploying sensors in a certain area, the minimum number of sensor nodes required and the method of determining the final position of the mobile nodes are known, and the coverage of different mobile and static node ratios can be tested to obtain the network coverage for different configurations. Then, curve fitting is performed with the coverage rate as the independent variable and the node configuration as the dependent variable to obtain the formula. This formula can be used to select the node configuration according to the desired coverage before deploying the area.

Note that the ratio of the side length of the area to the sensing radius of the sensor is L: R_s; if the value is too large, the total number of sensors required will be more, the coverage of a single sensor is smaller than that of the entire area, and network coverage can only reach the average level after the mobile nodes were redeployment. Assuming that the value is too small, the number of sensors required will be small, and even a single-digit sensor can completely cover the area, which loses the meaning of finding the configuration of mobile and static nodes. Assuming that the proportion of mobile nodes in the node configuration is too high, more energy will be consumed to allocate mobile node positions and schedule mobile nodes. At the same time, it will waste more economic cost, which is not worth it for the small part of coverage improved. Therefore, before doing the above experiments, it is necessary to consider the range of sensor sensing radius and node configuration to meet actual needs.

For the abovementioned analysis, this study conducted experiments on the coverage of the region with a side length of 100 m and different sensing radius. Under a certain sensing radius, the area is covered by changing the node configuration to obtain a trend graph of coverage. It can be seen from Figure 4 that when L: $R_s < 100$: 12, due to the increase of the sensing radius, the total number of sensors required became less and less, and the relationship between node configuration and coverage became less and less obvious. This means that the sensor nodes do not need to be configured at this time, and all of them are static nodes or increasing the proportion of mobile nodes will not cause too much deviation to the coverage. The reduction of the number of sensors caused by the increase of the sensor radius is the direct cause of the abovementioned results.

When L: $R_s > 100$: 7, as shown in Figure 5, the total number of sensors is increasing at this time, especially when the number of mobile nodes increases, the fluctuation of the obtained coverage becomes violent and irregular. Also, under this sensing radius, the maximum network coverage cannot reach 85%, which is not applicable in the actual environment.

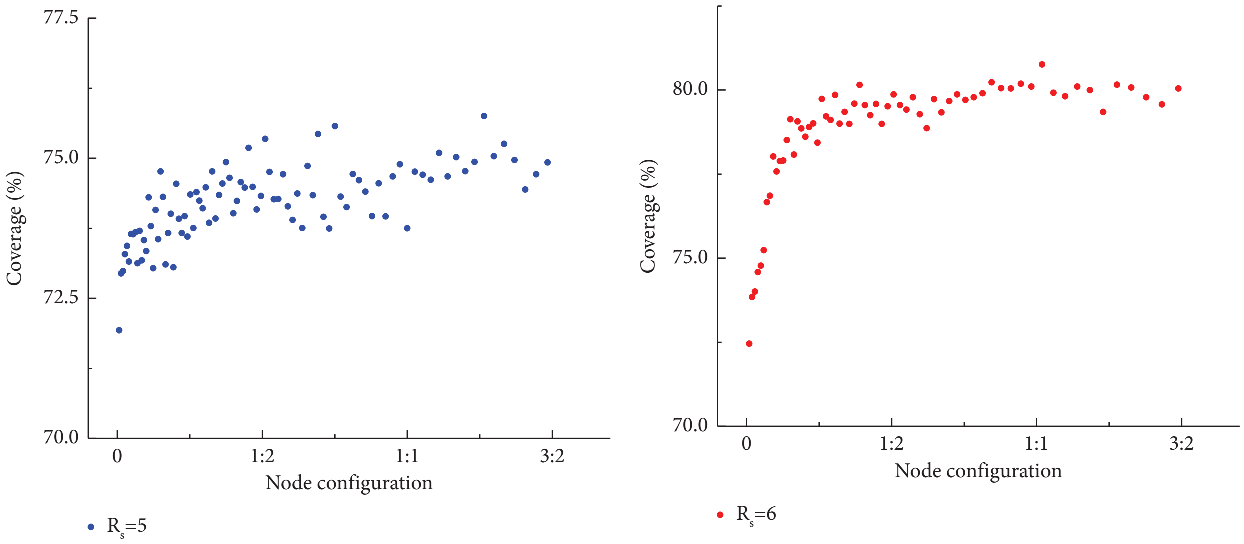
When selecting the range of sensor configurations, this study considers starting with one mobile node in all nodes, increasing the number of mobile nodes one by one to conduct experiments. From the perspective of cost, mobile nodes are more expensive than static nodes, so mobile nodes should not be too many. Aiming at the problem of cost, this paper compares the coverage rate of hybrid sensors after moving using the algorithm in Section 3.2, and the coverage rate is obtained by using pure static nodes for random deployment under the same cost conditions, as shown in Figure 6. Under the same cost conditions, the coverage obtained by using hybrid sensor deployment areas is higher than that obtained by random deployment of pure static nodes. In addition, it can also be seen from Figure 6 that when the ratio of mobile and static nodes reaches 3 : 2, the range covered by the hybrid sensor basically tends to be stable. Therefore, in subsequent experiments, the maximum



(a) (b) (c) (d)

(e) (f) (g) (h)

Figure 4: The relationship between node configuration and coverage under different radii. (a) $R_s = 8$. (b) $R_s = 9$. (c) $R_s = 10$. (d) $R_s = 11$. (e) $R_s = 12$. (f) $R_s = 13$. (g) $R_s = 14$. (h) $R_s = 15$.

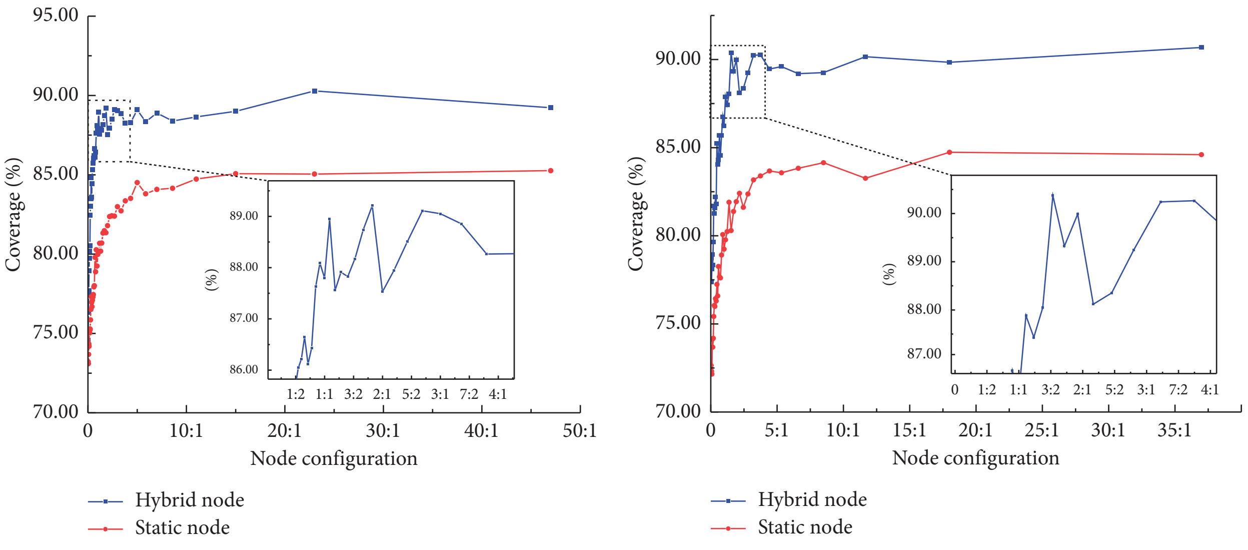


(a) (b)

Figure 5: Scatter diagram of coverage and node configuration. (a) $R_s = 5$. (b) $R_s = 6$.

limit of node configuration can be set to the number of mobile nodes: the number of static nodes = 3 : 2.

After the abovementioned discussion, this study controls the ratio of the area side length to the sensor radius between 100 : 11 and 100 : 7, and this ratio is applicable to the side lengths of other area. The range of node configurations is limited to a mobile-static ratio of 3 : 2. Afterwards, experiments were carried out under different sensing radius. For example, when the radius is R_s, different coverage ratios can be obtained by changing the node configuration. The method is the same as when selecting the node configuration range. To increase the number of mobile nodes from 1 until the ratio of mobile and static reaches the specified upper limit of 3 : 2, the area coverage is recorded for each configuration. Also, the experiments in all radius cases are completed accordingly.



(a) (b)

Figure 6: Comparison of coverage achieved by hybrid nodes and static nodes at the same cost. (a) $R_s = 9$. (b) $R_s = 10$.

In this way, the corresponding table of node configuration and coverage under different sensing radius is obtained. With the coverage rate as the independent variable and the node configuration as the dependent variable, using the least squares method to perform curve fitting on the obtained data to obtain the respective coverage rate-configuration function relationships of different sensing radius, as shown in Figure 7.

Finally, the relationship between coverage rate and node configuration is obtained as follows:

$$P = \sum_{i=1}^{4}\left[\sum_{j=1}^{5} a_{ij}\left(\frac{L}{R_s}\right)^{j-1}\right]x^{i-1}, \tag{5}$$

where the coefficient a_{ij} is as follows:

$$a = \begin{bmatrix} -269755.885 & 96953.57324 & -12909.38564 & 754.16138 & -16.33079 \\ 953666.9321 & -343215.4416 & 45760.41602 & -2676.64795 & 58.03019 \\ -1.116277e+6 & 402347.1227 & -53726.45729 & 3147.07419 & -68.32178 \\ 432025.2715 & -155993.0515 & 20867.23236 & -1224.32895 & 26.6213 \end{bmatrix}. \tag{6}$$

Here, P is the ratio of mobile dynamic and static nodes, x is the required coverage, L is the side length of the monitoring area, and r is the sensing radius of the sensor.

4. Result Analyses

In order to evaluate the performance of the node location algorithm and the performance analysis of node configuration presented in this paper, simulations were conducted on a PC with Windows 11 operating system using MATLAB 2019a. The PC used for the simulations was equipped with a 13th Gen Intel (R) Core (TM) i5-13500H (2.60 GHz) chip.

4.1. Performance Analysis of Node Location Algorithm. The simulation scene is a rectangular area with a size of $100m \times 100m$, as shown in Figure 8. In the comparison experiment, in order to reduce the contingency of the experiment, 30 independent experiments using different algorithms were carried out on 25, 35, and 45 sensor nodes; the average coverage rate obtained by each algorithm was taken. The average coverage comparison of the five algorithms BS-CCP, PSO [39], BOA [40], SOA [41], WOA [42], and BES [43] under different node numbers is shown in Figure 9.

It can be seen from Figure 9 that the BS-CCP algorithm achieves the best coverage in the case of 35 and 45 sensor nodes, and its average final coverage is 88.72% and 96.04%, respectively; however, when the number of sensors is 25, that is, the number is small, our algorithm is basically the same as the BES algorithm. This shows that the coverage of BS-CCP algorithm continues to increase and gradually outperforms other algorithms as the number of sensor nodes increases. Also, from 3.2.2 algorithm time complexity analysis, the time complexity of BS-CCP algorithm is relatively small. Overall, the BS-CCP algorithm outperforms the other five algorithms.

In Figure 8, sensor nodes are randomly deployed in a rectangular area, including static and mobile sensor nodes. The circle is marked as the sensing area of the sensor node, and the mobile and static sensor nodes have the same

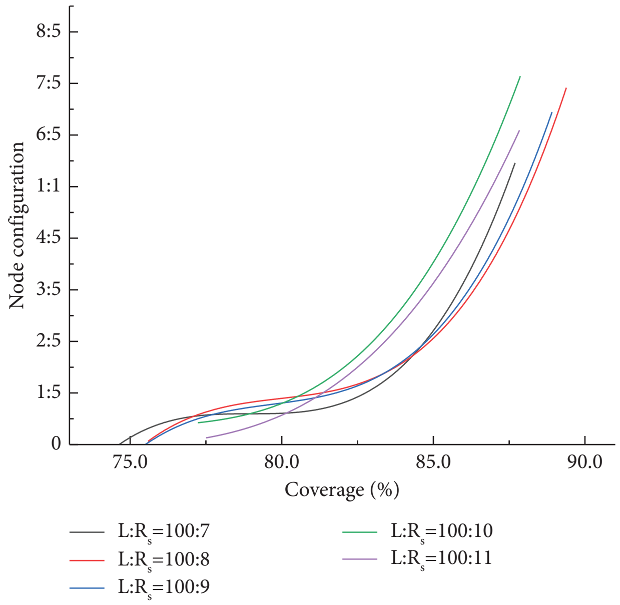
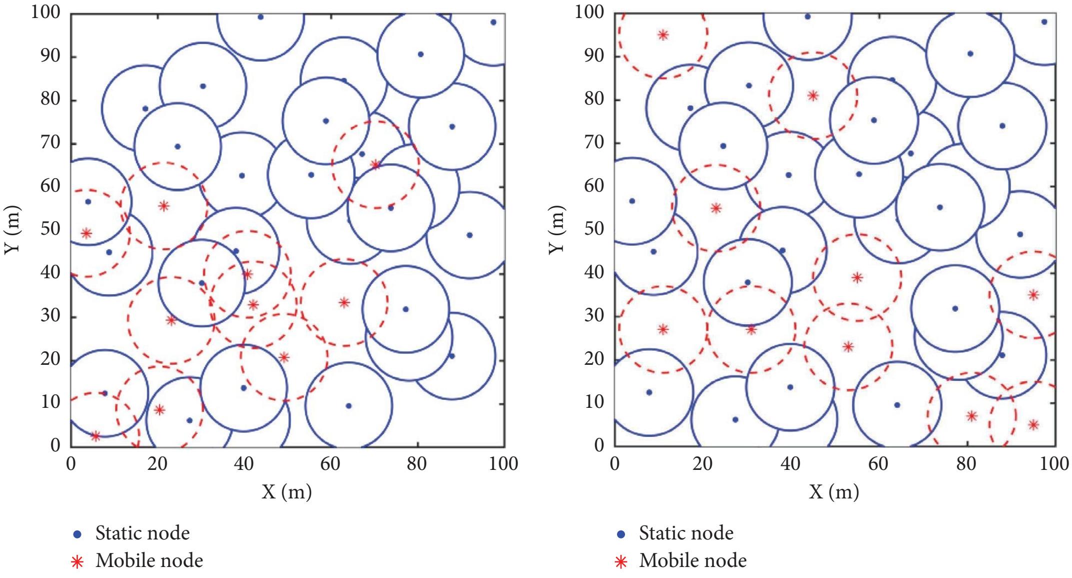


Figure 7: Coverage and node configuration relationship diagram.



(a)

(b)

Figure 8: Coverage comparison chart before and after node movement. (a) Initial state coverage = 75.77%. (b) Finial state coverage = 85.28%.

sensing radius. The blue circle with the blue point as the center represents the static sensor node, and the red dotted circle with the red asterisk as the center represents the mobile sensor node. Figure 8(a) shows the random deployment of sensors, and the coverage rate is 75.77%; Figure 8(b) shows the redeployment of mobile sensors, and the coverage rate is 85.28% after deployment.

It can be seen intuitively from Figure 8(b) that the red mobile sensor nodes have been moved to a more suitable monitoring position after being processed by the algorithm. Since all nodes are initially placed by random deployment, the distance between the sensors in Figure 8(a) is relatively short, resulting in the incomplete utilization of the coverage capabilities of the sensors. After executing the algorithm, the mobile node is redeployed to patch the coverage gap as much as possible.

4.2. Performance Analysis of Node Configuration. Initially considering the scattered trend, an attempt was made to fit using an exponential function. However, due to the "explosive" growth of the exponential function, it was found that only a few curves could be fitted, and the error of the rest

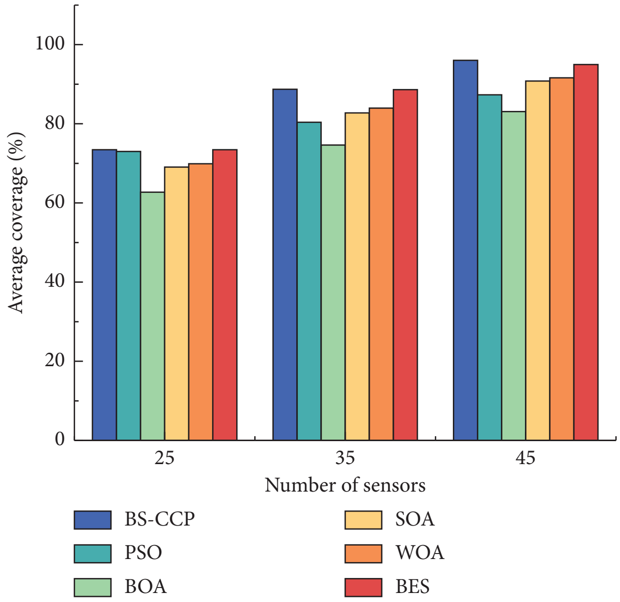


Figure 9: Comparison of average coverage under different number of nodes.

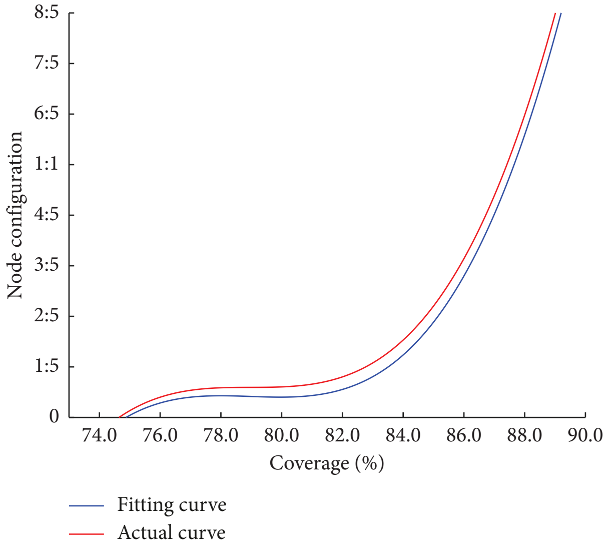


Figure 10: Effect diagram of node configuration formula.

of the curves was too large. Subsequently, a polynomial function is used for fitting. In order to describe the relationship between the coverage rate and the configuration ratio more precisely, a cubic polynomial and a quartic polynomial are considered. But the quartic polynomial also has an excessive error. The cubic polynomial, on the other hand, demonstrated a good fitting performance with a consistent trend and a close fit. The obtained formula contains three variables: area side length, sensor sensing radius, and required coverage rate, which can meet the requirements of node configuration in most cases. Also, it can be known from Figure 6 that the cost saving effect can be achieved by adopting such a hybrid node configuration method.

Figure 10 is a comparison chart of the curve calculated by the formula and the curve of the original experimental data. It can be seen that the fitting effect of the cubic polynomial is better.

This paper uses the proposed formula (5) to plan the types and numbers of sensor nodes before network deployment, which can effectively reduce the economic cost of network deployment. Compared with the sensing radius adaptive coverage control (SRACC) algorithm proposed by Wang et al. [44], known for achieving a certain coverage rate at a given cost, under the same monitoring area and sensor sensing radius, we utilize formula (5) to calculate the types and quantities of sensors required, assessing the economic cost, and employ the BS-CCP algorithm for deployment within the region.

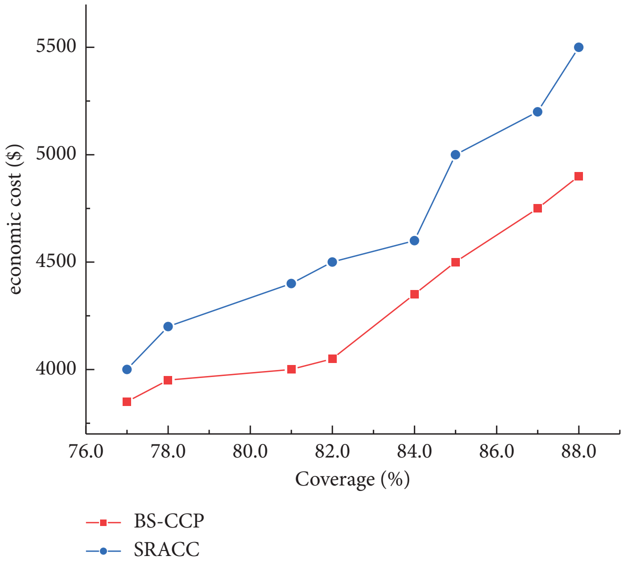


Figure 11: Cost comparison chart under the same coverage.

Comparing the sensor cost required by the SRACC algorithm to achieve the same coverage rate, as shown in Figure 11, the formula proposed in this paper can save a certain economic cost, which is lower than the sensor cost required by the SRACC algorithm to achieve the same coverage rate.

5. Conclusion

In this paper, we propose a mobile coverage adjustment scheme, BS-CCP, for hybrid wireless sensor networks based on computational geometry principles. The BS-CCP algorithm achieves efficient coverage using the minimum number of sensor nodes, significantly reducing the time complexity and computational costs. Extensive experiments demonstrate its superiority over existing simulation schemes in terms of time and iterations while achieving comparable coverage. Moreover, our parameter analysis using the Boolean sensing model yields an empirical formula that accurately calculates the ratio of mobile and static nodes for achieving the required coverage in initially randomly deployed monitoring areas. The economic cost of the sensors calculated using this formula is shown to be lower than that of existing algorithms for achieving the same network coverage. However, our proposed scheme has limitations, particularly in the number of sensors selected for the experiment, which is based on the minimum number required to achieve complete coverage in the area. To improve coverage further, increasing the total number of sensors could be considered, though it would come at an increased economic cost. In addition, future research can explore different perception models to derive more practical formulas for node deployment decisions. In summary, our proposed BS-CCP scheme demonstrates efficient coverage performance with reduced costs, making it a promising approach for hybrid wireless sensor networks. Further improvements and considerations of different models offer opportunities for enhancing network coverage and economic efficiency.

Data Availability

The data used to support the study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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