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Research Article

Monitoring Area Coverage Based on Improved Virtual Force and Multimedia Nodes Movement Data in Mobile Wireless Sensor Networks

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High-quality network coverage can quickly and accurately collect the data in the monitoring area and complete the task of target monitoring in wireless sensor networks. The existing related work focuses on improving the effect of network coverage and reducing the consumption of network resources. Aiming at the problems of coverage blind area and node redundancy in network coverage, a monitoring area coverage algorithm based on an improved virtual algorithm is proposed by improving the existing virtual force algorithm. This algorithm controls the moving direction and distance of nodes by adjusting the distance between nodes. Make the node move to a reasonable position, improve the coverage effect of the network, and reduce the moving distance of the node. The simulation results show that compared with the DNDVF algorithm and VFADP algorithm, this algorithm has a better application effect, can improve the coverage effect, and reduce the moving distance of nodes.

1. Introduction

The wireless sensor node observes physical phenomena and collects data according to the observed phenomena. The power supply device is composed of a battery to provide power for all other components in the wireless sensor node. All these units should be built into a small system with low power consumption and low production cost [1].

The wireless sensor node is designed and developed according to the needs of users and is used to collect interested data. It can be seen as a microcomputer system, which integrates microcontrol equipment and microprocessing equipment into the node, as well as microstorage equipment and microbattery into the node, so as to achieve small volume and low cost. Therefore, a wireless sensor node is a small computer system that combines microcomputing technology and automatic networking technology [2].

Wireless sensor nodes are deployed in the monitoring area, so that all nodes can monitor the targets in the monitoring area. According to the monitoring environment at that time, nodes can sleep or wake up, exit or join the network, and prolong the service time of the network. Some wireless sensor nodes can actively send signals and obtain data related to the target through the reflection or refraction of the signal after encountering the target, such as radar. On the other hand, some wireless sensor nodes do not send signals and wait for the target to actively send out the sound, image, vibration, heat, smell, radiation, and other physical quantities that can be collected by wireless sensor nodes, such as seismic sensors, sound sensors, and video sensors. Some wireless sensor nodes can be installed on mobile devices, such as mobile robots, unmanned aerial vehicles (UAV), and underwater vehicles [3].

Aiming at the problem of poor coverage effect in wireless sensor networks, an optimal coverage algorithm of monitoring area based on improved virtual force (IVF) algorithm and nodes movement distance is proposed.

The main contributions of this article are as follows:

(1) Summarize and analyze the existing algorithms
(2) Put forward the problems existing in the existing algorithm
(3) Modify and improve the existing algorithm

The article is organized as follows:

(1) Background knowledge is introduced in Section 1
(2) Related work is described in Section 2
(3) The improved virtual force (IVF) algorithm is designed in Section 3
(4) IVF algorithm is compared with other algorithms through simulation in Section 4
(5) The full article is summarized in Section 5

2. Related Work

The evaluation indexes of network coverage effect mainly include the following points.

2.1. Number of Nodes Used. Wireless sensor nodes have a small volume, simple structure, and low cost. If they can reduce the number of nodes as much as possible when completing the minimum demand of monitoring tasks, it is a research direction of wireless sensor networks [4].

2.2. Network Coverage Effect. The effect of network coverage is expressed by network coverage, which is a ratio. For point coverage, network coverage is the ratio of the number of targets that can be monitored by at least one sensor node to the total number of targets in the network. For fence coverage, network coverage is the possibility that the target in the network can be perceived when passing through the fence composed of wireless sensor nodes. For area coverage, network coverage is the ratio of the area that can be monitored by at least one sensor node to the whole area to be monitored [5].

2.3. Algorithm Complexity. More and more algorithms pay attention to the coverage effect and ignore the complexity of the algorithm. Therefore, according to the characteristics of wireless sensor nodes, designing coverage algorithms with low power consumption and low complexity is the focus of various research works. These low complexity algorithms can optimize the computing process of nodes, reduce the use of processor and memory, reduce energy consumption, and prolong the service time of the network [6].

Now, many researchers have proposed various methods to solve the problem of monitoring area coverage in wireless sensor networks [7].

Wireless sensor node deployment is one of the research problems of wireless sensor networks. It has a very important impact on the coverage effect of the network. Due to the limitation of monitoring the regional environment, node random deployment has become an important deployment method. There are many random deployment methods of nodes. Considering different network parameters, the randomly deployed network usually needs many redundant nodes, which increases the cost of the network. Reference [8] proposed a nonuniform node random deployment method to optimize the network consumption of uniform node deployment wireless sensor networks. A new concept of cost and the problems to be solved are defined. Combined with a variety of measurement standards, such as monitoring area coverage and network usage time, an optimization model is given. Through the theoretical analysis of node density and energy consumption, the network topology is determined, and the deployment method and corresponding topology control and routing strategy are given, which can be used in large-scale wireless sensor networks.

When controlling the location of wireless sensor nodes, it is usually necessary to ensure high area coverage, cover specific target points, and ensure a long monitoring time. Reference [9] established a general wireless sensor network coverage model under k-coverage considering wireless sensor network coverage and service time and adopted several improved particle swarm optimization algorithms to obtain a better optimal deployment effect. Different algorithms are used to simulate the deployment of wireless sensor nodes in different situations, such as target point coverage, area coverage, and boundary coverage.

For the target coverage problem, reference [10] proposed a wireless sensor node deployment method based on the natural heuristic algorithm, which has been used to solve various optimization problems. The wireless sensor target coverage problem is transformed into an objective function and solved by a natural heuristic algorithm, namely the bat algorithm. Although this is not the first time to use bats to solve the coverage problem, this method introduces a new concept, called the bat combination algorithm, which is composed of two bat algorithms. This method can ensure that the wireless sensor node is connected to the sink node through at least one communication path, so as to improve the network energy utilization. Different from other methods, this method considers a practical feature of wireless sensor nodes: the monitoring probability of wireless sensor nodes decreases with the increase of distance from the target. Other methods use the binary model, and the success of target monitoring depends entirely on whether the distance between the target and the wireless sensor node is within the threshold. This method uses a probability perception mathematical model instead of the binary mathematical model. This method can get the optimal solution faster than other natural heuristic algorithms. Although this method requires more computation in most network environments, the network usage time can be improved. In addition, this method has scalability and faster computing speed, especially when the area of network monitoring area is small and the number of nodes is large. In this method, the connectivity between the wireless sensor node and the sink node is considered when selecting the relay node. If the routing algorithm is comprehensively considered, a more energy-saving method can be designed.

Wireless video sensor networks are widely used in intelligent cities, intelligent transportation, industrial process control, and other fields. By using the video data collected by wireless video sensors to provide monitoring information, the practicability of wireless sensor networks can be expanded. In some application scenarios, wireless sensor network applications need high-definition images when completing the monitoring task, so the video data collected by wireless video sensors put forward higher requirements. It is important to ensure that the network can collect high-quality video data related to monitoring tasks, which can be processed by the mathematical function of the wireless video sensor. In order to solve this problem, reference [11] discussed the monitoring service quality of wireless video sensor networks when monitoring area coverage and proposed a wireless video sensor node redeployment optimization method based on greed and evolution, so as to improve the sensing effect and service quality of wireless video sensor nodes and allow flexible processing of variables. For example, the location, direction, and perspective of wireless video sensors provide flexibility for the definition of various parameters and make a significant contribution to the development of monitoring area coverage of wireless video sensor networks.

Wireless sensor networks have energy consumption in the process of data acquisition. The existing network protocols and network coverage algorithms cannot effectively reduce the energy consumption of the network system. In order to improve the service time of wireless sensor networks, reference [12] studied the routing protocol of wireless sensor networks, discussed the classical protocol from the perspective of clustering routing, analyzed its advantages and disadvantages, proposed a clustering process based on the k-means algorithm, and added a scoring function to the algorithm.

The main research content of various resource-constrained wireless sensor networks is to improve the network service time without affecting the key indicators such as network coverage effect and network node connectivity. Coverage effect and network node connectivity are two basic problems in wireless sensor networks. These problems are very important for randomly deployed wireless sensor nodes. Random deployment is a biased deployment strategy of wireless sensor nodes. After random deployment, wireless sensor nodes have some problems, such as uneven node distribution, coverage redundancy in some monitoring areas, and repeated coverage in some areas, resulting in too fast energy consumption in the network. In order to solve these problems, reference [13] proposed a coverage algorithm and node connectivity maintenance protocol for wireless sensor networks based on reinforcement learning. Wireless sensor nodes learn their optimal trajectory through the protocol also provides a mechanism, which has a good optimization effect in terms of node connectivity and system energy consumption.

Rapid coverage monitoring of ground targets using UAV is an important research hotspot, which is of great significance in the application field of mobile wireless sensor networks. Inspired by the intermolecular force, reference [14] proposed a UAV group coverage maximization deployment algorithm based on the molecular force field. Multiple UAVs are used to carry wireless sensor nodes to quickly establish wireless sensor networks in the specified coverage monitoring area. According to the requirement of minimizing the overlapping area of the UAV coverage area, the minimum number of UAV and wireless sensor nodes is determined. Using this algorithm, the wireless sensor nodes carried by UAV can cover the monitoring area to the greatest extent. By introducing the mathematical model of molecular force, the force model of UAV is more accurate. In order to reduce the influence of randomly initialized UAV position on the network coverage effect, the network coverage monitoring area is divided into multiple polygons with equal area to make the UAV position more uniform in the initial stage. Different from some algorithms that can only cover rectangular network coverage monitoring areas, this algorithm is suitable for network coverage monitoring areas with different shapes. The algorithm can maximize the coverage of the network coverage monitoring area and can still obtain a good coverage effect in an environment with too many nodes.

Many existing research work mainly focuses on the deployment optimization of wireless sensor nodes in a two-dimensional plane environment, but in various practical applications, wireless sensor nodes are often deployed in a three-dimensional environment. Reference [15] proposed a three-dimensional wireless sensor node deployment algorithm based on vertex coloring. By selecting the best deployment location of wireless sensor nodes, the optimal monitoring target coverage effect is obtained. The breadth-first search algorithm is used to determine the connectivity of wireless sensor nodes in the network. The algorithm has a better network coverage effect and node connectivity, makes the wireless sensor network fault-tolerant, and prolongs the service time of the whole network.

With the rapid increase of the demand for wireless sensor network technology in various fields, the existing research basically has the disadvantages of high energy consumption and high node cost in the network. Reference [16] proposed an efficient node deployment method based on a node probability perception mathematical model and harmonious search algorithm to achieve the balance of monitoring area coverage effect and energy consumption in heterogeneous wireless sensor networks. The harmony search algorithm can be used to optimize the deployment of nodes in heterogeneous wireless sensor networks to balance the coverage effect and resource consumption. Based on the mathematical model of node probability perception, the algorithm is used to solve the problem of monitoring area coverage overlap between wireless sensor nodes. The performance of the model is analyzed from two aspects: coverage effect and resource consumption. Compared with homogeneous wireless sensor network node deployment, a heterogeneous wireless sensor network node deployment algorithm can achieve the maximum coverage effect of the monitoring area and the minimum number of wireless sensor nodes.

An underwater sensor network needs an effective node deployment algorithm to ensure the network coverage of the underwater wireless sensor network. A distributed node deployment algorithm based on virtual force (DNDVF) is proposed to improve the network coverage effect of underwater wireless sensor networks [17]. Before designing the algorithm, as part of the research, the stress of the nodes in the dynamic marine environment was studied. In the process of node deployment, node density, residual energy, and node movement efficiency are considered to optimize the node movement process.

According to the theoretical proof, the hexagonal topology can obtain the maximum coverage under the condition of a fixed number of sensor nodes, and the goal of mobile sensor network node deployment is to form a hexagonal network topology while consuming the minimum energy. Using a virtual force algorithm to move randomly distributed nodes into the target topology is one of the widely used research methods to achieve this goal [18]. A new virtual force algorithm based on the physical laws of dusty plasma systems (VFADP) is applied to mobile sensor network deployment scenarios. The method developed is derived from the study of crystal structure in condensed matter physics and gives clear evidence as to when a regular lattice is ready. It will provide some engineering guidance by assisting in deploying in complex geometric areas or those recovering from disasters.

3. Improved Virtual Force

3.1. Node Movement Model. As shown in Figure 1, the distance between node A, node B, and node C is unreasonable. Because the distance between nodes is too close, the monitoring areas overlap each other and affect the coverage effect of the network. There are the same problems between node D and node E, resulting in the overlapping of monitoring areas, which also affects the coverage effect of the network. The distance between node F and node G is too far, and there is no problem of overlapping monitoring areas. The monitoring area of each node is not affected by neighbor nodes, and the maximum coverage is achieved.

As shown in Figure 2, when the distance between node A and node B is too close, there will be repulsion between them. This force will make the two nodes move in the direction shown by the arrow in Figure 2. In order to calculate in the rectangular coordinate system, the force is decomposed along the X axis and Y axis as shown in Figure 2.

From the perspective of adjusting the distance between nodes, if the distance between each node can be adjusted reasonably, the coverage effect of the monitoring area can also be improved.

The coordinate of node S_a is (x_a, y_a), and the coordinate of node S_b is (x_b, y_b). The distance between node S_a and node S_b is

$$d(S_a, S_b) = \sqrt{(x_a - x_b)^2 + (y_a - y_b)^2}, \tag{1}$$

where $d(S_a, S_b)$ is the distance between the two nodes S_a and node S_b [19].

When $d(S_a, S_b) < 2R_S$,

$$x_a^{\text{new}} = x_a^{\text{old}} + \frac{[2R_S - d(S_a, S_b)]\left(x_a^{\text{old}} - x_b^{\text{old}}\right)\left[d\left(S_b^{\text{old}}\right) + 1\right]}{2\,d(S_a, S_b)\left[d\left(S_a^{\text{old}}\right) + d\left(S_b^{\text{old}}\right) + 2\right]}, \tag{2}$$

$$y_a^{\text{new}} = y_a^{\text{old}} + \frac{[2R_S - d(S_a, S_b)]\left(y_a^{\text{old}} - y_b^{\text{old}}\right)\left[d\left(S_b^{\text{old}}\right) + 1\right]}{2\,d(S_a, S_b)\left[d\left(S_a^{\text{old}}\right) + d\left(S_b^{\text{old}}\right) + 2\right]}, \tag{3}$$

$$x_b^{\text{new}} = x_b^{\text{old}} + \frac{[2R_S - d(S_a, S_b)]\left(x_b^{\text{old}} - x_a^{\text{old}}\right)\left[d\left(S_a^{\text{old}}\right) + 1\right]}{2\,d(S_a, S_b)\left[d\left(S_a^{\text{old}}\right) + d\left(S_b^{\text{old}}\right) + 2\right]}, \tag{4}$$

$$y_b^{\text{new}} = y_b^{\text{old}} + \frac{[2R_S - d(S_a, S_b)]\left(y_b^{\text{old}} - y_a^{\text{old}}\right)\left[d\left(S_a^{\text{old}}\right) + 1\right]}{2\,d(S_a, S_b)\left[d\left(S_a^{\text{old}}\right) + d\left(S_b^{\text{old}}\right) + 2\right]}, \tag{5}$$

$$d\left(S_a^{\text{new}}\right) = d\left(S_a^{\text{old}}\right) + \sqrt{\left(x_a^{\text{new}} - x_a^{\text{old}}\right)^2 + \left(y_a^{\text{new}} - y_a^{\text{old}}\right)^2}, \tag{6}$$

$$d\left(S_b^{\text{new}}\right) = d\left(S_b^{\text{old}}\right) + \sqrt{\left(x_b^{\text{new}} - x_b^{\text{old}}\right)^2 + \left(y_b^{\text{new}} - y_b^{\text{old}}\right)^2}. \tag{7}$$

In formula (2) to formula (7), R_S is the perception radius of the wireless sensor node. $(x_a^{\text{old}}, y_a^{\text{old}})$ is the position coordinate of node S_a before movement. $(x_b^{\text{old}}, y_b^{\text{old}})$ is the position coordinate of node S_b before movement. $(x_a^{\text{new}}, y_a^{\text{new}})$ is the position coordinate of node S_a after movement. $(x_b^{\text{new}}, y_b^{\text{new}})$ is the position coordinate of node S_b after movement. $d(S_a^{\text{old}})$ is the sum of the distance that the node S_a moved before this movement. $d(S_b^{\text{old}})$ is the sum of the distance that the node S_b moved before this movement. $d(S_a^{\text{new}})$ is the sum of the distance that the node S_a moved after this movement. $d(S_b^{\text{new}})$ is the sum of the distance that the node S_b moved after this movement. The main function of formula (3) to formula (8) is to gradually increase the distance between nodes. By calculating the sum of the moving distances completed by the node, if the previous moving distance is too long, the moving distance will be less. If the previous moving distance is short, the moving distance will be longer [20].

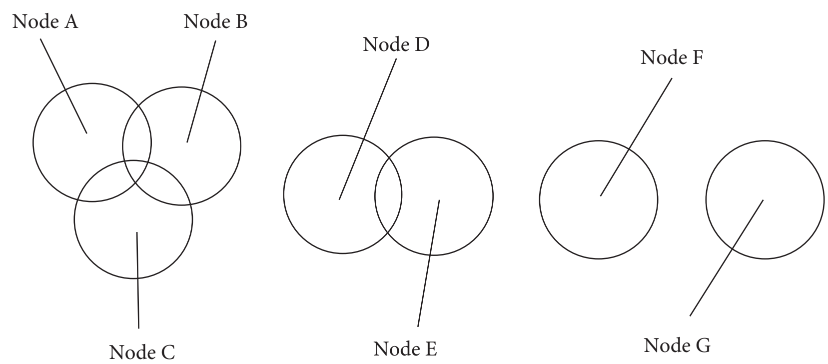

Figure 1: Nodes distribution in wireless sensor networks.

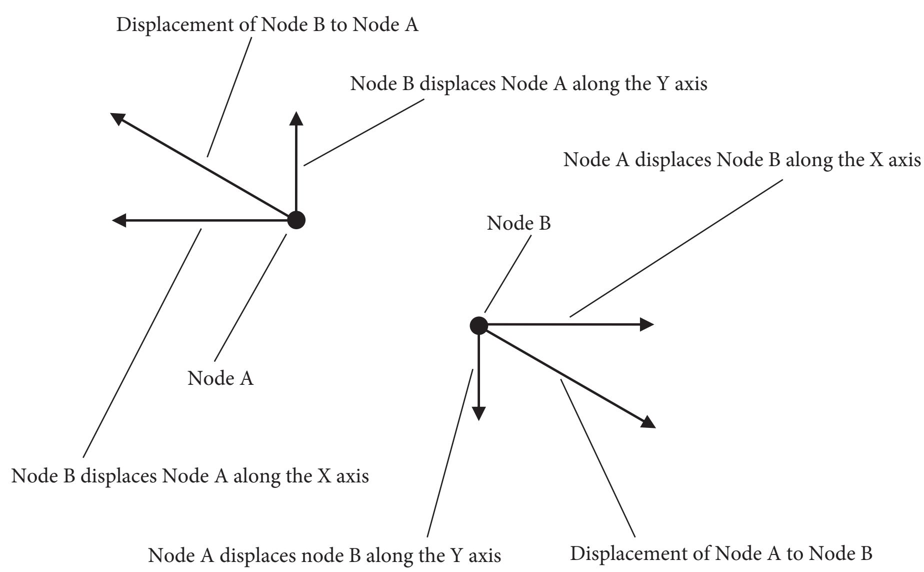

Figure 2: Movement effect caused by the interaction between nodes.

When $d(S_a, S_b) \geq 2R_S$,

$$x_a^{\text{new}} = x_a^{\text{old}}, \tag{8}$$

$$y_a^{\text{new}} = y_a^{\text{old}}, \tag{9}$$

$$x_b^{\text{new}} = x_b^{\text{old}}, \tag{10}$$

$$y_b^{\text{new}} = y_b^{\text{old}}, \tag{11}$$

$$d(S_a^{\text{new}}) = d(S_a^{\text{old}}), \tag{12}$$

$$d(S_b^{\text{new}}) = d(S_b^{\text{old}}). \tag{13}$$

In formula (8) to formula (13), if the distance between nodes is greater than twice the perceived radius of nodes, the distance between the two nodes is far, and there is no problem of repeated coverage between nodes, so neither node needs to move [21] (Algorithm 1).

3.2. Node Movement Process

Step 1. Randomly deploy N nodes into the rectangular monitoring area with length L and width W.

Step 2. In order to ensure that the time of each node is the same, it is necessary to calibrate the time of each node.

Step 3. In each time period T_t, all nodes send data information to the whole network, the main content of which is the location coordinates and a serial number of nodes.

Step 4. If node S_a and node S_b receive the data information sent by the neighbor nodes, update the storage information of node S_a and node S_b.

Step 5. The node S_a and node S_b calculate the distance between node S_a and node S_b according to formula (1).

Input: L, W, N, R_S, (x_i, y_i)
While (maximum iterations are not reached)
    If $d(S_a, S_b) < 2R_S$ then
    Calculate the new position of the nodes according to the formula (2) to formula (5)
    End if
    If $d(S_a, S_b) \geq 2R_S$ then
    The position of the nodes remains unchanged according to formula (8) to formula (11)
    End if
End while
Output: The position of the nodes

Algorithm 1: IVF algorithm.

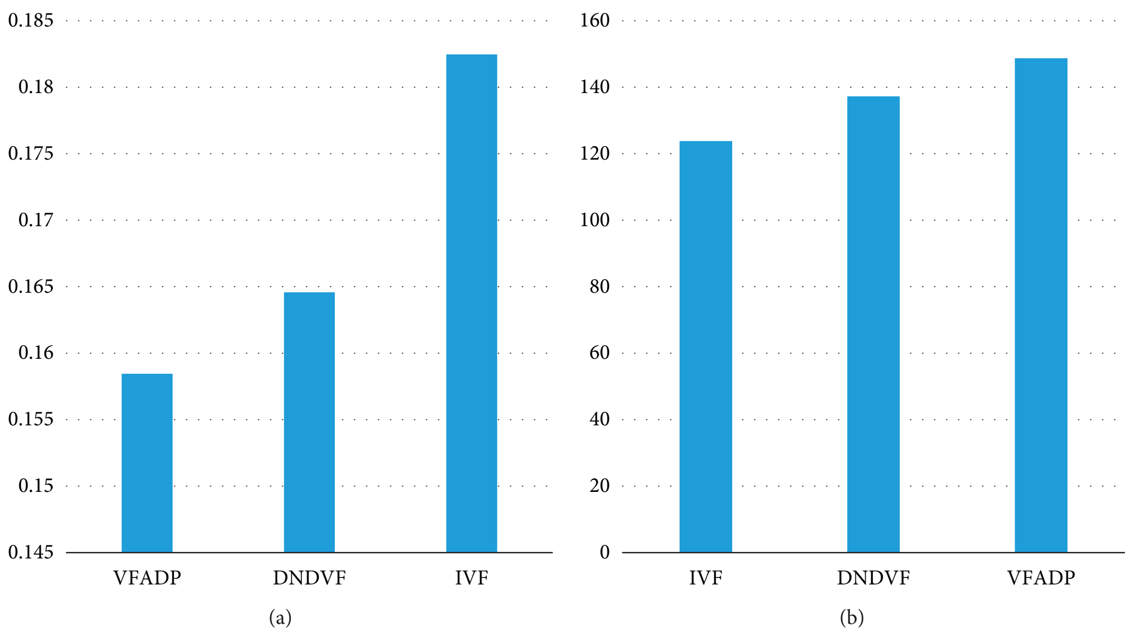

Figure 3: Coverage effect and moving distance in different algorithms when $N = 20$. (a) Coverage effect. (b) Moving distance (m).

Step 6. If $d(S_a, S_b) < 2R_S$, calculate the new coordinates (x_a^{new}, y_a^{new}) of node S_a and the new coordinates (x_b^{new}, y_b^{new}) of node S_b where node S_a and node S_b need to move.

Step 7. If the calculation period T_t is not finished, return to Step 2 and continue the calculation.

Step 8. If all cycles in the calculation process are used up, the algorithm ends and returns the final calculation result.

3.3. Node Movement Pseudocode. 3.4. Time Complexity. The time complexity of step 1 is O(N). The time complexity of step 2 is O(N). The time complexity of step 3 is O(N). The time complexity of step 4 is O(N). The time complexity of step 5 is O(N). The time complexity of step 6 is O(2). The time complexity of step 7 is O(1). The time complexity of step 8 is O(1).

Because the step 7 returns to the step 2 to cycle according to the number of cycles, the time complexity of the entire algorithm is determined by the number of nodes N and the number of cycles T. So, the time complexity for the algorithm to be derived for the proposed works in the paper is O(NT).

4. Simulation

The length of the monitoring area $L = 200$ m, the width of the monitoring area $W = 200$ m, the communication radius of the sensor node $R_C = 20$ m, the sensing radius of the sensor node $R_S = 10$ m, the number of cycles $T = 10$, and the number of nodes $N = 20$, 40, 60, 80, 100. The data set provided by reference [22] is used for simulation. The simulation results are shown in Figures 3–7.

(1) When $N = 20$
(2) When $N = 40$
(3) When $N = 60$
(4) When $N = 80$
(5) When $N = 100$

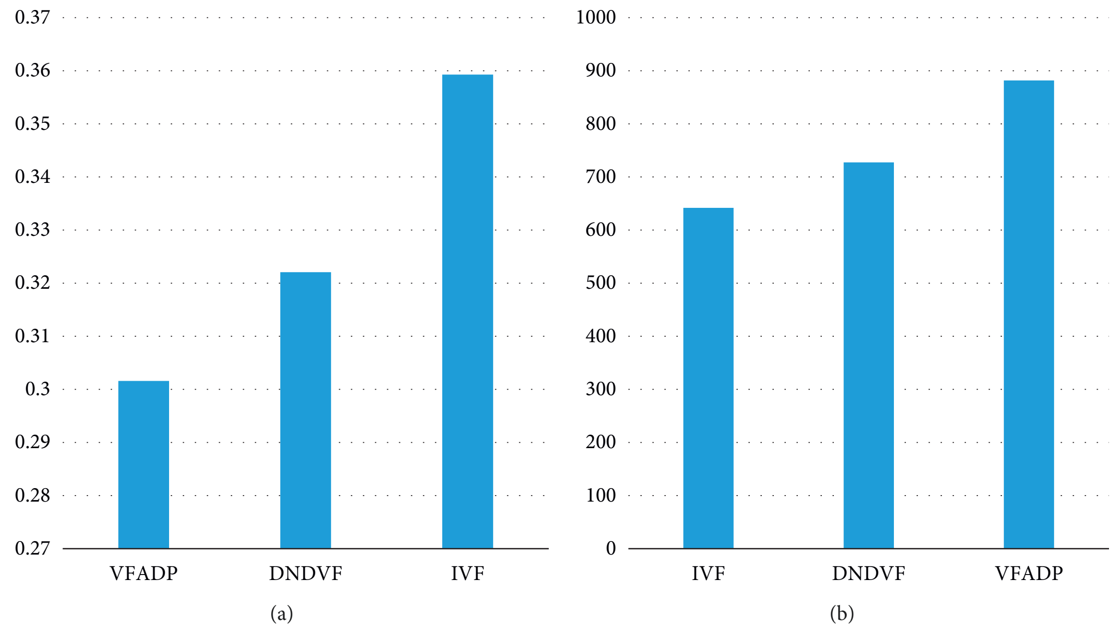

Figure 4: Coverage effect and moving distance in different algorithms when $N = 40$. (a) Coverage effect. (b) Moving distance (m).

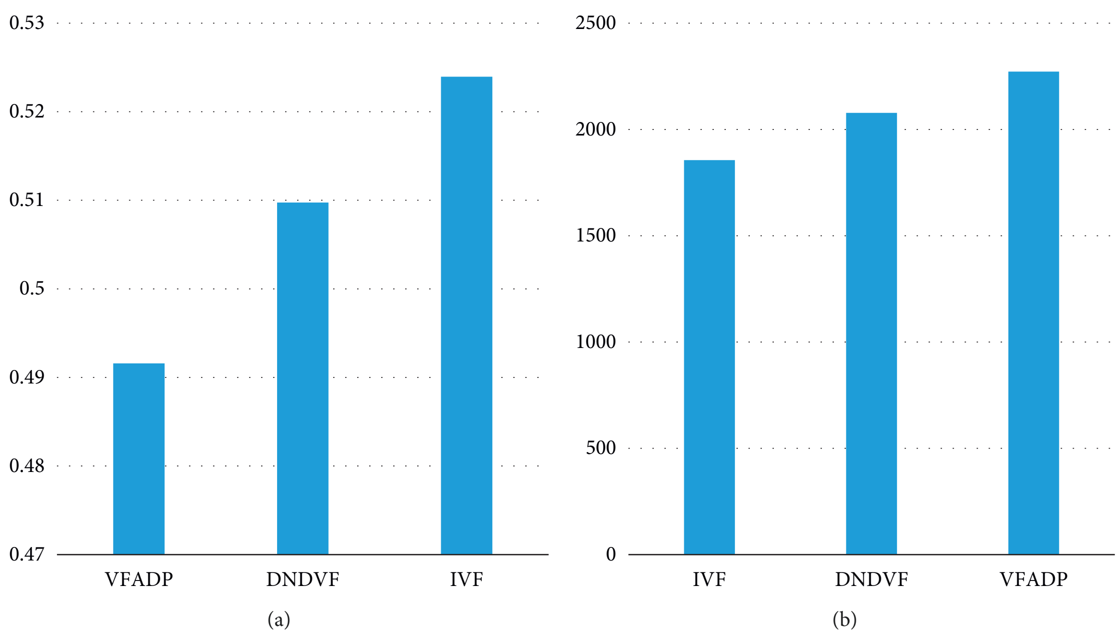

Figure 5: Coverage effect and moving distance in different algorithms when $N = 60$. (a) Coverage effect. (b) Moving distance (m).

As shown in Figures 3–7, the IVF algorithm is suitable for the deployment of sensor nodes in the large-scale network environment. When the size of the monitoring area remains unchanged and the number of deployed nodes increases, the network coverage effect also increases. However, when the monitoring area becomes larger, the sensor nodes can be redeployed according to the needs of the network, which has great deployment flexibility. IVF algorithm not only maximizes the coverage effect of the network but also meets the connectivity between sensor nodes. Compared with the virtual force-based distributed node deployment algorithm (DNDVF) in reference [17] and the virtual force algorithm based on the physical laws of dust plasma system (VFADP) in reference [18], the IVF algorithm has a better coverage effect and reduces the moving distance of nodes. By gradually increasing the distance between wireless sensor nodes, the algorithm slowly disperses the clustered wireless sensor nodes. The algorithm can also achieve the expected effect in the dense area of wireless sensor nodes and make the nodes

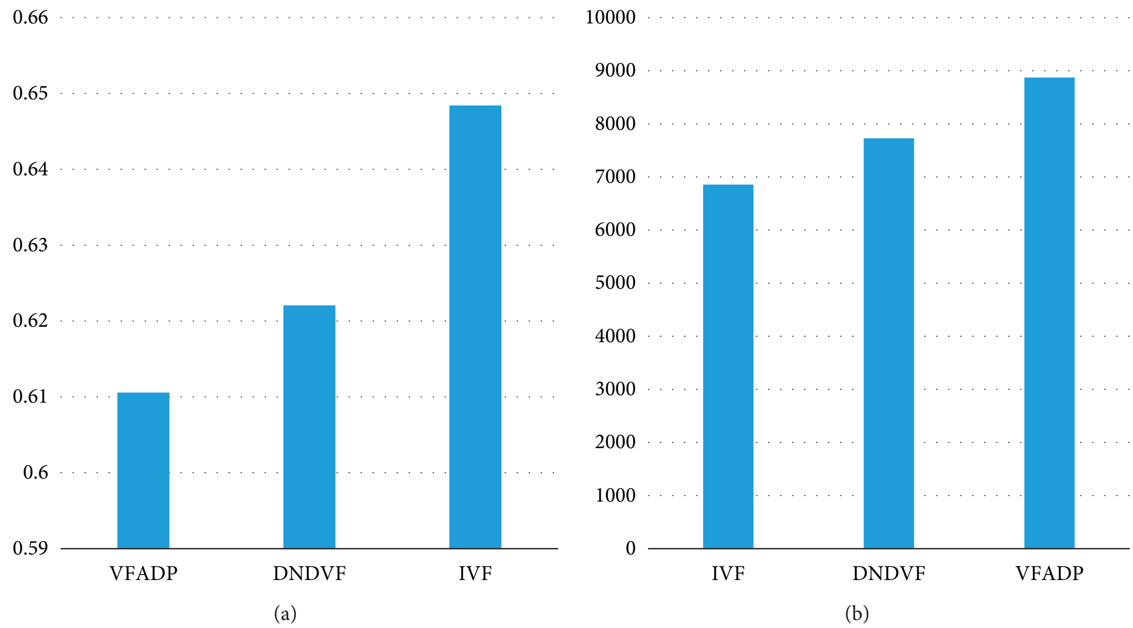

Figure 6: Coverage effect and moving distance in different algorithms when $N = 80$. (a) Coverage effect. (b) Moving distance (m).

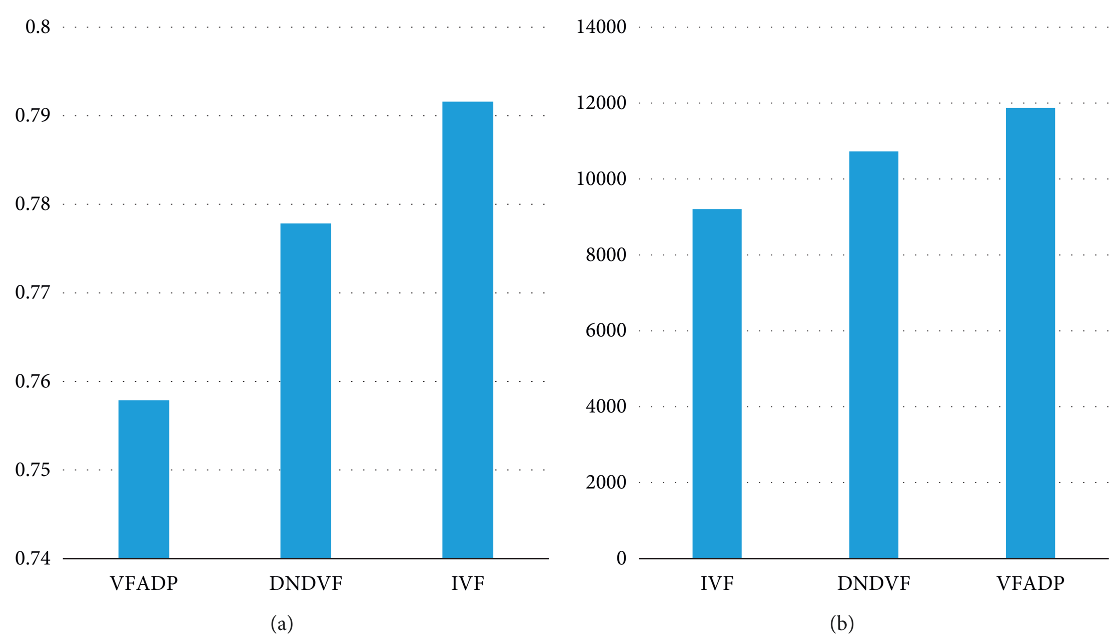

Figure 7: Coverage effect and moving distance in different algorithms when $N = 100$. (a) Coverage effect. (b) Moving distance (m).

gradually move to the best position. The algorithm not only reduces the moving distance of each node but also improves the coverage effect in the monitoring area, making the sum of node moving distances smaller. Compared with the DNDVF algorithm and VFADP algorithm, the coverage rate is increased by about 6% to 16%, and the node moving distance is decreased by about 200 m to 1000 m.

5. Conclusion

Aiming at the poor coverage effect of wireless sensor networks, this paper proposes an optimal coverage algorithm of monitoring area based on a virtual force algorithm. Through simulation comparison, it can be seen that the coverage effect is improved while reducing the moving distance of nodes. If the network needs to be redeployed for some reason, it can be adjusted and redeployed. Compared with the DNDVF algorithm and VFADP algorithm, the coverage rate is increased by about 2% to 6%, and the node moving distance is decreased by about 100 m to 2000 m. The deficiency and limitation of the IFA algorithm are that it does not consider the energy consumption of nodes in the process of motion and data transmission. Therefore, the energy consumption of nodes should be considered in future work.

Data Availability

The data used to support the findings of this research are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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