Wireless Sensor Network Node Deployment Based On Regular Tetrahedron

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Abstract. The deployment of nodes in 3D wireless sensor networks has always been the focus of research. In this paper, two algorithms for achieving full coverage are proposed, which are applicable to the even distribution and the uneven distribution of target points. Among them, the characteristics of the spherical and regular tetrahedrons are rationally utilized to achieve the purpose of covering more space with the same nodes. For the three-dimensional space with uneven target distribution, it is proposed to use the DBSCAN clustering method for target point processing, and then perform the same processing in each cluster to avoid wasting more sensor nodes and increasing energy consumption. Finally, considering the problem of energy saving, some nodes are put to sleep and waiting for the next call to reduce energy consumption and extend the working time of the network. Simulation experiments show that the algorithm has improved the number of nodes used and energy consumption.

1. The Introduction

A sensor network is a self-organizing network system that can sense, acquire, and process information about a perceived object in an area and return the information. Sensors can accomplish large sensing tasks by cooperating with each other [1–2]. In the research of sensor network, the deployment of sensor nodes has always been a core research topic [3]. A good node deployment structure will not only determine the coverage of the network, but also affect the use of nodes and network energy consumption. The node deployment research of the three-dimensional sensor network is more in line with the requirements of practical application environment. However, the difficulty of its work is also greatly increased.

At present, reducing the number of nodes and decreasing energy consumption of the network are the hotspots of related research, while guaranteeing the maximum coverage of the network. According to literature [4], Alam S M N et al. found that the coverage effect of truncated octahedron was optimal when the ratio of communication radius to perceived radius reached a certain fixed value through calculating and comparing the volume quotient of several common polyhedra. In literature [5], Zygmunt J proposed a method of dynamically selecting subset of nodes to put redundant nodes into dormancy state, so as to achieve the purpose of energy saving delay. Literature [6] and literature [7] are studies based on traditional equilibrium virtual potential field and unbalanced virtual force potential field respectively. In literature [8], a three-dimensional coverage algorithm with adjustable radius is proposed, which combines the effect of virtual force with radius adjustment mechanism. This algorithm can realize the uniform deployment of the nodes in the wireless sensor network, reduce the overall energy consumption of the network and improve the utilization rate of the nodes. In [9], a deployment strategy based on Voronoi polygonal centroid is proposed, and the coverage problem of the monitoring area is transformed into a...
problem of finding the belonging Tyson polygon for each sensor node. In [10], Abo-Zahhad et al. proposed a centralized node deployment algorithm based on Voronoi diagram. This algorithm makes full use of the characteristics of Voronoi diagram to make the coverage and energy consumption of heterogeneous sensor network reach a good condition, and the deployment speed is fast. Nevertheless, the coverage needs to be further improved. Literature [11] proposes TDADA-Ⅱ, which makes each sensor node move to the center of gravity of Voronoi region. After several iterations, the nodes can move to the optimal location, thus improving the network coverage of the monitored area. But performance needs to improve.

In this paper, a tetrahedron structure is proposed for the coverage and energy consumption of sensor networks. Then, considering that the node distribution may be uneven in actual monitoring area, sensor nodes are deployed from two aspects. And two algorithms are proposed. In order to reduce the energy consumption, some nodes are put into sleep, and the call is activated when the network needs.

2. Relevant Definitions and Analysis

The relevant definitions involved in this paper are as follows:

Definition 1: Binary perception sphere model. In the research of this paper, the sensor node uses the binary perception sphere model, that is, the sensor node is the center of the sphere, and the sensing sphere is formed by the sensing distance Rs as the radius. The communication sphere is formed by the communication distance Rt as the radius, as shown in Fig. 1.

![Figure 1. Binary perception sphere model.](image)

Definition 2: Coverage. Coverage is one of the important factors to evaluate the performance of sensor networks, which can directly reflect the performance of sensor networks. In this study, the probability that target point $S_i$ is covered by sensor node $p$ is shown in formula 1.

$$P_i = \begin{cases} 1, & d(s_i, p) \leq R_s \\ 0, & d(s_i, p) > R_s \end{cases}$$  \hspace{1cm} (1)$$

The overall coverage is shown in formula 2, where $m$ represents the number of target points covered by all sensor nodes and $N$ represents the number of all target points in the target point set.

$$P = \frac{m}{N}$$  \hspace{1cm} (2)$$

Definition 3: the central point of a cluster. Given the coordinates of all points in a cluster $(X_i, Y_i, Z_i)$, the position of the central point $C$ of the cluster can be obtained according to formula 3, where $n$ represents the number of data points in the cluster.

$$X_C = \frac{1}{n} \sum_{i=1}^{n} X_i, \quad Y_C = \frac{1}{n} \sum_{i=1}^{n} Y_i, \quad Z_C = \frac{1}{n} \sum_{i=1}^{n} Z_i$$  \hspace{1cm} (3)$$

In the research process, it is assumed that all sensor nodes in the network are formed by devices of the same specification. Lu J and Zhang H [13-14] et al. have shown that when the sensor communication distance is twice the sensing distance, the network connection between nodes can be ensured under the
condition of complete coverage of the whole sensor network. Therefore, this paper will set the sensing distance and communication distance of sensor nodes according to this, namely \( R_t = 2R_s \).

3. Core Algorithm

3.1. Regular Tetrahedral Structure

Ammari et al. [15] once proposed the optimal deployment theorem in two dimensions. In this paper, an optimal deployment structure in three dimensions is proposed, which is a regular tetrahedron structure. Based on this structure, sensor nodes will be deployed reasonably. Given sensor nodes with a sensing radius of \( R_s \), each node can form a binary perception sphere model with a radius of \( R_s \). Four spheres can form a basic regular tetrahedron structure by being tangent to each other. You can imagine that there are gaps between spheres. In order to avoid this coverage vulnerability in the application of wireless sensor networks, it is necessary to increase the actual sensing distance of sensor nodes. When \( r \) represents the spherical radius of the tetrahedron structure and \( R_s \) represents the sensing distance of the sensor nodes, according to the characteristics of the tetrahedron structure, it can be calculated that \( r \) and \( R_s \) need to meet the conditions in formula 4. Then, we can use this regular tetrahedral.

\[
R_s = \frac{\sqrt{6}}{2} r
\]  

(4)

Given the coordinates of any sensor node \((x, y, z)\), layered deployment is carried out according to the above tetrahedron structure. There are 12 nodes adjacent to this node. Among them, there are 6 nodes in the current layer which are respectively tangent to it, and there are 3 nodes in the upper layer and the lower layer respectively. Their positions can be calculated by the following formula:

6 nodes in the current layer:

\[
\begin{align*}
(x - r, y + \sqrt{3}r, z),
(x + r, y + \sqrt{3}r, z),
(x - 2r, y, z),
(x + 2r, y, z),
(x - r, y\sqrt{3}r, z),
(x + r, y, y - \sqrt{3}r, z)
\end{align*}
\]  

(5)

3 nodes in the lower layer:

\[
\begin{align*}
(x - r, y + \frac{\sqrt{3}}{3}r, z + \frac{2\sqrt{6}}{3}r),
(x + r, y + \frac{\sqrt{3}}{3}r, z + \frac{2\sqrt{6}}{3}r),
(x, y - \frac{2\sqrt{3}}{3}r, z + \frac{2\sqrt{6}}{3}r)
\end{align*}
\]  

(6)

3 nodes in the upper layer:

\[
\begin{align*}
(x + r, y - \frac{\sqrt{3}}{3}r, z - \frac{2\sqrt{6}}{3}r),
(x - r, y + \frac{\sqrt{3}}{3}r, z - \frac{2\sqrt{6}}{3}r),
(x, y + \frac{2\sqrt{3}}{3}r, z - \frac{2\sqrt{6}}{3}r)
\end{align*}
\]  

(7)

3.2. Node Deployment Algorithms

Firstly, for the case where the target points are evenly distributed, the Static Deployment Algorithm based on the regular tetrahedral structure is proposed. The main process is as follows:

Step 1: A 3d monitoring region is given, and \( N \) represents the number of targets to be monitored. Set sensing radius and communication radius of sensor node;

Step 2: Find a vertex position in the three-dimensional space, and use this as the origin to establish a three-dimensional space coordinate system. With the origin as the center, the deterministic node deployment is carried out in the coordinate system according to the node position formula (5), (6), (7) in the regular tetrahedron structure.

Step 3: Find the number \( m \) of coverage points of each sensor node, and put the node into a sleep state if \( m \leq 0 \);
Step 4: The coverage of the whole three-dimensional space is calculated by formula (1) and (2). If the current requirement of full coverage is reached, then step 6 is executed; otherwise, step 5 is executed.

Step 5: Find the target point that is not covered, then select the sensor node that is closest to the point to move and activate the call, and return to step 4 when finished.

Step 6: Output the result and stop the deployment.

However, in reality, there are often many monitoring areas where the target points are unevenly distributed. Then, the DBSCAN Based Algorithm combining DBSCAN clustering method for dynamic node deployment is proposed in an environment with uneven nodes. The main description is as follows:

Step 1: Given a three-dimensional monitoring area with uneven distribution of target points, where the number of targets to be monitored is N, the sensing radius and communication radius of the sensor nodes are set;

Step 2: Collect the location of the target point and build the data set \( S = \{S_1, S_2, S_3 \ldots S_i\} \), \( i \in (1,N) \), Cluster the data set S with DBSCAN, and output M clusters and some outliers;

Step 3: Find the center point \( C_j \) of the cluster \( M_j \) (1≤j≤M) according to the formula 3, and construct a coordinate system with \( C_j \) as the coordinate origin;

Step 4: Calculate the maximum distance \( L_{max} \) from the target point to the center point in the cluster, \( 0 < L_{max} \leq d(C_j, S_i) \), and \( d(C_j, S_i) \) is the Euclidean distance from the center point to the point inside the cluster.

Step 5: In each coordinate system, the deployment of the sensor nodes is started from \( C_j \) according to the above formulas (5), (6), and (7). When the distance from the current node to the center point is greater than \( L_{max} \), the deployment of the node is stopped. After all the clusters have been processed, proceed to the next step;

Step 6: To judge the coverage of all nodes in the cluster, if there are sensor nodes that do not cover any target points, they will be put into sleep, and when there are no such nodes, the next step will be taken.

Step 7: Calculate the coverage of the entire three-dimensional space by using formulas (1) and (2). If the full coverage requirement has been reached, go to step 9. Otherwise, go to step 8.

Step 8: Obtain the location of the target point that is not currently covered. Select the sleeping node closest to the current point to make an activation call and move to the position. Then go to step 7;

Step 9: Output the result and stop the node deployment.

4. Simulation Experiments And Results Analysis

In order to verify the feasibility of the above algorithm, Python 3.5 is used as the simulation platform. The target area is a regular three-dimensional space of 100m×100m×100m. The radius of the binary perception sphere model in the regular tetrahedral model is \( r=10m \), and the actual sensing distance is \( R_s=5\sqrt{6} \) m. In the three-dimensional space with uneven distribution of target points, 300 target nodes will be covered. The result after the initial deployment according to the regular tetrahedron structure is shown in Fig. 2, and the layers are seamlessly connected to each other. In each layer, the perceptual sphere model of nodes also achieves seamless connection. For the uncovered target points on the edge, the deployment result after activating and calling the sleeping nodes is shown in Fig. 3. At this time, the requirement of full coverage has been reached.

For a three-dimensional space with uneven target distribution, full coverage of 300 target points will also be achieved. Firstly, after several parameter adjustments on DBSCAN, it was found that the best effect was achieved when the parameter Eps was taken as \( 5\sqrt{6} \), and the result was shown in Fig. 4. In addition to the target points that are divided into five clusters, there are some abnormal target points (shown as red dots scattered in Fig. 4). The improved result is shown in Fig.5.
Algorithm Analysis

The two algorithms proposed in this paper are all aimed at achieving full coverage of three-dimensional space objects. In literature [11], the algorithm TDADA-II based on Voronoi diagram is proposed to achieve full coverage. The simulation results show that the number of nodes used in Static Deployment Algorithm and DBSCAN Based Algorithm is less than that used in TDADA-II when full coverage is achieved (see Fig. 6). Moreover, the algorithms in this paper consider the problem of reducing the number of redundant nodes and energy consumption. The closed node not only reduces the energy consumption of the network, but also contributes to the target point coverage through activation calls.

Energy consumption is another important factor. Researches show that the larger the moving distance, the higher the energy consumption. Fig. 7 depicts mobile nodes number and the average moving distance of nodes in the simulation experiment. As can be seen from the figure, although the average moving distance of nodes in algorithm TDADA-II is similar to the algorithms in this paper, the number of nodes to be moved far exceeds the results of the algorithms in this paper. Therefore, the algorithms in this paper has better effect in reducing energy consumption and prolonging network usage time.

Conclusion

In this paper, the deployment of sensor nodes in three-dimensional space with even and uneven distribution of target points is studied. The Static Deployment Algorithm and DBSCAN Based Algorithm are proposed respectively to explore how to achieve full coverage of the target point in 3D space and the
influence of the number of nodes on the coverage of the wireless sensor network. The energy consumption is saved and the working time of wireless sensor network is prolonged by activating and calling the redundant nodes in sleep. Finally, the efficiency of the proposed algorithms is proved by simulation experiments. In the following work, the algorithms will continue to be optimized, so that the coverage of the target area can achieve better results.

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