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A Novel Coverage Holes Discovery Algorithm Based on Voronoi Diagram in Wireless Sensor Networks

Guoyong Dai[1,2*], Hexin Lv[1], Luyi Chen[1], Binbin Zhou[1] and Ping Xu[1]

[1] *College of Information Science and Technology, Zhejiang Shuren University, 310014, Hangzhou, P.R. China*

[2] *College of Computer Science and Technology, Zhejiang University of Technology, 310023, Hangzhou, P.R. China*

**E-mail: daiguoyong@gmail.com*

Abstract

Coverage is a key and fundamental problem in wireless sensor networks. To provide high quality of service, high coverage ratio of sensor nodes in monitored area should be assured. Coverage holes may lead to routing failure and degrade the quality of service. A novel coverage hole discovery algorithm, VCHDA, is proposed for wireless sensor networks in this paper. The proposed algorithm is based on the well-known Voronoi diagram. It can recognize coverage holes and label the border nodes of coverage holes effectively. Simulations are conducted and the results show that the proposed algorithm is effective and with high accuracy.

***Keywords**: WSN, coverage hole, voronoi diagram*

1. Introduction

WSNs (Wireless Sensor Networks) have attracted considerable attention recently due to their wide application in such as military sensing, traffic surveillance, environment monitoring, intruder detection, *etc.*, [1-3]. Many applications require the employed wireless sensor network to provide a high quality of service. The QoS of network is highly related to efficient routing, high coverage ratio and long lifetime of the network. Coverage is a fundamental problem for high quality of service. In order to achieve tasks of targets monitoring and collecting comprehensive e information, the ROI (region of interest) should be covered by sensor nodes effectively. The sensor nodes are usually deployed randomly (*e.g.*, scattered by an airplane) and battery operated since the ROI may hard to reach for humans. It is impossible to recharge the batteries of sensor nodes so that energy conservation is becoming a key factor for the lifetime of WSNs. Some of the initially deployed sensor nodes are scheduled to be active while others are scheduled to be sleep to keep low energy consumption. Some sub-regions of the ROI may be covered by none of the deployed sensor nodes due to the randomly deployment. Such sub-regions are called coverage holes. Watfa, *et al.*, [4] introduced four reasons which may lead to coverage holes: randomly deployment of sensor nodes, failure of sensor nodes, location change of sensor nodes and obstacles in the ROI. Some problems may be caused by coverage holes, such as incomplete sensing data, routing failure, or even failure of the whole network, which may significantly degrade the performance of network. Therefore, discovery and repairing coverage holes are two key issues for WSNs.

There are already lots of literatures on the topic of coverage control in WSNs and many researchers have concerned discovery and repairing the coverage holes. Nadeem [5] proposed an general definition of coverage holes: Coverage holes exist

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if the required coverage degree is k in specific applications of WSNs, while the number of nodes which covers the region is less than k during the life time of the network. The current works mainly focus on discovery and repairing holes on the basis of 1-coverage. These works can be divided into two categories: one is based on the connectivity between any pair of sensor nodes and the other is based on the location of sensor nodes.

Corke, *et al.*, [6] introduced the concept of path density (PD), which is then employed to their algorithm to detect coverage holes. Feng Yan, *et al.*, [7] divided coverage holes into triangular and non-triangular holes and then proposed a non-triangular holes detection algorithm based on Cech complex and Rips complex. Homology is adopted into coverage detection and the accuracy of homology based method is analyzed in [8]. I.M. Khan, *et al.*, [9] devised a topology based method for hole detection, in which the connectivity between nodes and their x-hop neighbors is utilized without the locations of nodes. A level set based hole detection and healing scheme for hybrid WSNs is designed in [10], which can carry out the number of existing holes and their sizes. A genetic algorithm is then proposed for healing the holes. Hwa-Chun Ma, *et al.*, [11] devised a computational geometry based distributed coverage hole detection protocol. In this protocol, a node with its two neighbors constitute a triangle which is used detect the existence of coverage holes near the triangle.

The current algorithms for coverage detection are inefficient in their high computational complexity and high energy consumption. So we devised a Voronoi diagram based semi-distributed algorithm for coverage holes detection in WSNs. The location information are used to carry out the Voronoi diagram for the ROI, and then some simple geometric calculation are taken to decide if there are holes existed in the ROI. The nodes on the edge of holes are recognized. The computations of building Voronoi diagram are executed on the sink node and the detection algorithm are performed on any nodes in distributed way.

The rest of this paper is organized as follows: the problem description and some preliminaries are given in Section 2. Section 3 introduces the proposed Voronoi based coverage holes discovery algorithm. In Section 4, we conduct some simulations and the results are analyzed. Finally, Section 5 concludes the paper.

2. System Model and Preliminaries

2.1. System Model

In this paper, we made some simple, common and realistic assumptions regarding the network:

1) There are two kinds of sensor node: static and mobile. All the sensor nodes are homogeneous except the mobility. They have the same sending radius and communication range. The mobile nodes have limited mobile range.
2) All the sensor nodes are with the same initial energy, while the sink node has an unlimited amount of energy and more significant computational power.
3) Links are symmetric, i.e. any sensor node can compute the approximate distance to another node based on the received signal strength.
4) The detection probability of a target with distance d to a sensor is given in the following way:

$$P(d) = \begin{cases} 1, & if \quad d \le R_s \\ 0, & otherwise \end{cases}$$

5) The location of each sensor nodes after the initial deployment can be obtained by themselves through GPS devices or other localization approaches.

2.2. Preliminaries

We first introduce some useful definition in this section.

Definition 1 (sensing disk): a disk formed by a sensor node N_i with the coordinates of (x_i, y_i) and sensing radius R_s in a two dimensional plane is called a sensing disk, denoted by S_i.

$$S_i = \{(x, y) \mid \sqrt{(x - x_i)^2 + (y - y_i)^2} < R_s\}$$

Definition 2 (Coverage Hole): a coverage hole CH is a piece of continuous area which cannot be covered by any sensing disk formed by the nodes in the ROI. The information or event in CH cannot be sensed by any sensor node.

Definition 3 (Border Nodes): the nodes adjacent to a coverage hole are called border nodes. In other words, the border nodes are at the border of a coverage hole.

Definition 4 (Coverage Ratio): the coverage ratio is refer to the proportion of the covered area $S(Q)$ to the whole area $S(H)$ of the ROI.

$$\eta = \frac{S(Q)}{S(H)}$$

2.3. Problem and Goal

All the static and mobile sensor nodes are randomly scattered in the ROI initially. We focus on how to discover if there is coverage hole after initial deployment and identify the border nodes that surround coverage holes. The inputs of the algorithm are the location and sensing range of each sensor node. And the outputs are the amount of discovered coverage holes and their corresponding sequences of border nodes. Since the sensor nodes may drift or run out of energy, the algorithm should run periodically. Coverage hole healing is not addressed in this paper.

3. VCHDA: Coverage Hole Discovery Algorithm based on Voronoi Diagram

3.1. Voronoi Diagram

Definition 5 (Voronoi Diagram): Voronoi diagram is a partitioning of a plane into regions based on closeness to points in a specific subset of the plane. Suppose P is a set of points on a plane, $P_1, P_2, ..., P_n \in P$, P can be divided into several regions, in each area there is a point P_i, all points in the corresponding region is closer than to any other any other point in P. Each region $V(P_i) = \{P \mid d(P, P_i) < d(P, P_j), j \neq i, j = 1, 2, ..., n\}$ is also called Voronoi cell, and $V(P) = \{V(P_1), V(P_2), ..., V(P_n)\}$.

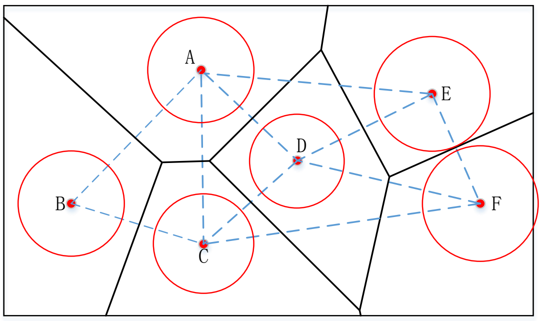

Figure 1. An Example of Voronoi Diagram

Voronoi diagram is the one of the most useful structure in computational geometry. The border between two adjacent Voronoi cells is the perpendicular bisector of the line segment between the two points in these two corresponding Voronoi cells. Recently, Voronoi diagram is applied into coverage control for wireless sensor networks. The ROI can be divided into several Voronoi cells. Figure 1 is an example of Voronoi diagram. Point A, B, C, D, E and F are the sensor nodes in the ROI, the circles are the sensing range of these nodes. Obviously, the coverage ratio is quite low and there exist holes in this case. The relationship between the sensing range of a node and its corresponding Voronoi cell may varies among the following cases: (1) the sensing range covers the Voronoi cell, (2) the Voronoi cell covers the sensing range, and (3) the sensing range and the Voronoi cell overlapped.

3.2. Coverage Hole Discovery Algorithm

Theorem 1. If the distance between the node and the edge of its corresponding Voronoi cell is greater than its sensing range, then there is a hole around the intersection of the edge and the line segment between the two nodes both sides of the edge.

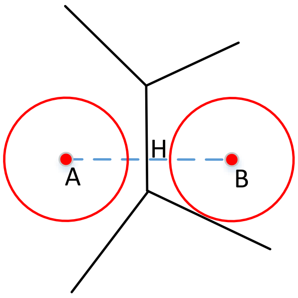

Figure 2. A Case of Coverage Hole

Proof: Without loss of generality, node A and B are two arbitrary nodes in two adjacent Voronoi cells respectively. As Figure 2 shows, the two adjacent Voronoi cells are denoted as $V(A)$ and $V(B)$. According to the property of Voronoi diagram, the distance from any point in the cell $V(A)$ to node A is shorter than that to any other node. The distances from any point on the border of $V(A)$ and $V(B)$ to node A and node B are equal. The line segment AB and the border of $V(A)$ and $V(B)$ intersect at point H, then we have $AH = BH = AB/2$. We prove it by reduction to absurdity. Suppose there is no hole near intersection H, then the point H can be covered by node A. In other words, the point H is in the sensing range of node A which means $AH \le R_s$. It is contradict to the known condition $AH > R_s$. So the theorem holds.□

Theorem 2. If the distance from a sensor node to a vertex of its corresponding Voronoi cell is greater than the sensing range, then there is a hole around the vertex.

Proof. Suppose a Voronoi cell $V(A)$ with node A in it is constitute of 5 vertexes V_1, V_2, V_3, V_4, V_5 and the distance from node A to the vertex V_1 is greater than the sensing range R_s (see figure 3). Obviously V_1 is outside the sensing range of node A. Connect node A and vertex V_1, the line segment AV_1 intersects the sensing circle at point H. X is an arbitrary point on the line segment HV_1. According to the property of Voronoi diagram, the distance from X to node A is shorter than that to any other node. The point X cannot be covered by node A, therefore it cannot be covered by any other node either. In other words, the point X is in a coverage hole. The theorem holds. □

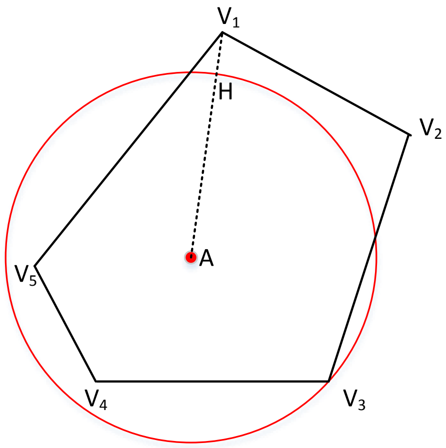

Figure 2. Another Case of Coverage Hole

We design the coverage holes discovery algorithm based on the above 2 theorems. The basic idea behind the algorithm is: build the Voronoi diagram for the deployed sensor network with the collected positions of each sensor nodes, each node carries out the distance from itself to the vertexes and edges of its corresponding Voronoi cell, then the 2 theorems are applied to decide if there are coverage holes. The two stages of the algorithm are construction of Voronoi diagram and holes discovery. The former is performed by the sink node in centralized way. All the sensor nodes send their coordinates to the sink. Then the sink get the overall network topology and carries out the Voronoi diagram. The vertexes information are send back to each sensor node respectively. The later stage is execute in a distributed way. Each sensor node calculate the Euclidean distance from itself to the vertexes and edges of its corresponding Voronoi cell. By comparing these distances with the sensing range, we can infer if there are holes around a specific sensor node. If there is a hole around the node, it is then tagged as a border node. All the border nodes are used to define the hole area.

The pseudo codes of this algorithm are given in Table 1.

Table 1. The Pseudo Codes of the Algorithm

(1): the sensor node get the vertex coordinates of the Voronoi cell $\{V_1, V_2, ...V_n\}$
(2): for(int i=1;i<=n;i++)
(3): {
(4): calculate the distance between the sensor node and V_i as d_V ;
(5): calculate the distance between the sensor node and the edge $V_iV_{(i+1)\%n}$ as d_E ;
(6): if ($d_E > R_S$ or $d_V > R_S$) tag the current sensor node as hole boundary node;
(7): }

4. Simulations

4.1. Experiment Setting and Metrics

The experiments are conducted on Matlab platform. All the sensor nodes are homogeneous with the same communication range and sensing range. The deploy area is a 500m*500m square (see Figure 4). The key parameters used in the simulations are listed in Table 2.

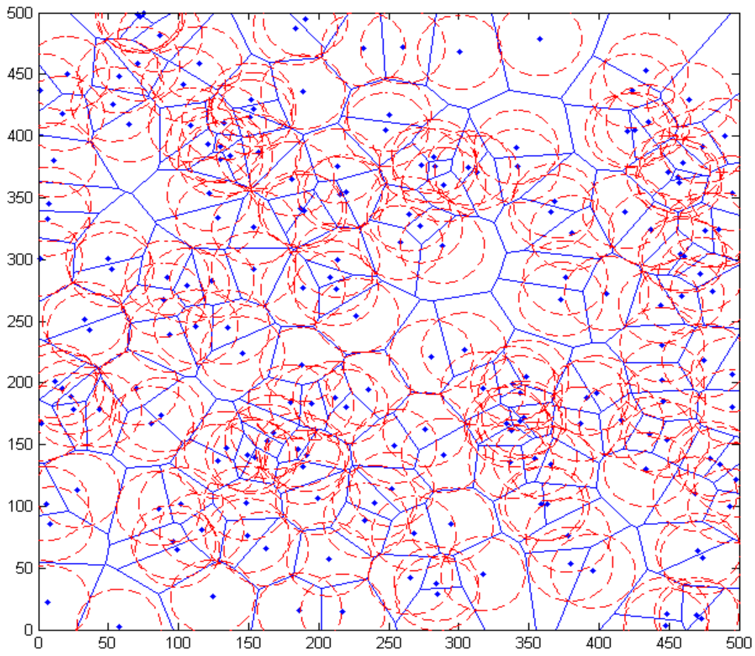

Figure 4. 200 Nodes Deployed in the 500m*500m Area

Table 2. Key Parameters and Their Value

parameter	**value**
Shape of the monitored area	Square
Size of the monitored are	500m*500m
Amount of sensor nodes	200~2000
Communication range	10m
Sensing range	10m~30m
Amount of holes	5~30
Initial energy	100J
Data transfer ratio	250Kbps

Two main metrics are used to evaluate the performance of the proposed algorithm.

1) Average hole discovery time: the average time duration to discover a hole. In other words, it is the total discovery time divided by the amount of holes.
2) Average energy consumption: the average energy consumed to discover a hole. That is the total energy consumption divided by the amount of holes.

4.2. Results and Analysis

First, we evaluate the average hole discovery time by taking different nodes density and sensing range into consideration. We scattered different amount of sensor nodes (varying from 200 to 2000) in the ROI to denote different network density. And the sensing range is set the same as the communication range, double of the communication range or triple of the communication range respectively. The results of the experiments are shown in Figure 5. The average hole discovery time rises almost linearly with the increase of the network density. It is reasonable since the amount of Voronoi cells in the ROI grows when the network density increases. Therefore, both the communication time and computation time will rise. The variation of sensing range also causes the rise of average hole discovery time though the impact is relatively fairly small.

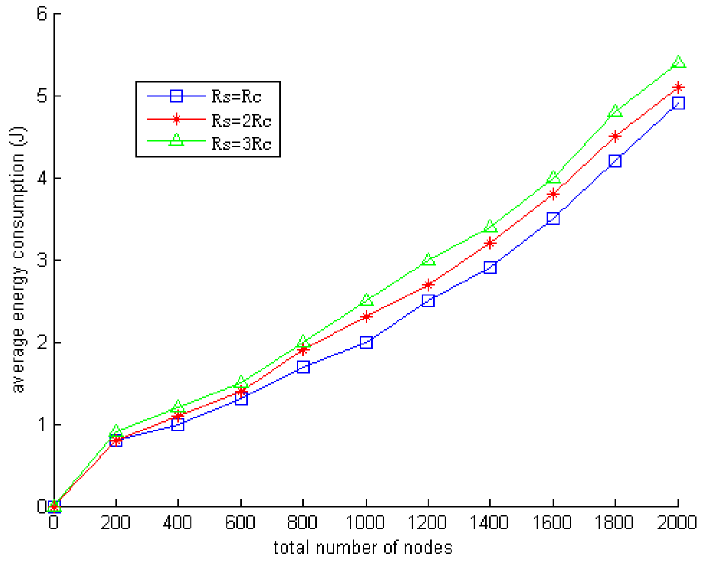

Figure 5. The Average Hole Discovery Time

Next, we evaluate the impact to energy consumption of the network. The same setting with the previous experiments is used. As the results show (Figure 6), the energy consumption is highly related to the network density in the ROI. When the amount of deployed sensor nodes increases, the average energy consumption rises sharply. Since the energy consumption is mainly caused by communication. When more sensor nodes are deployed, the communication cost for neighborhood discovery and control information exchange between common nodes and sink node will rises. So the average energy consumption increases accordingly. Meanwhile, the sensing range has only a little impact to the average energy consumption. The lines for different sensing ranges are very close which means the energy consumption for sensing events is relatively small.

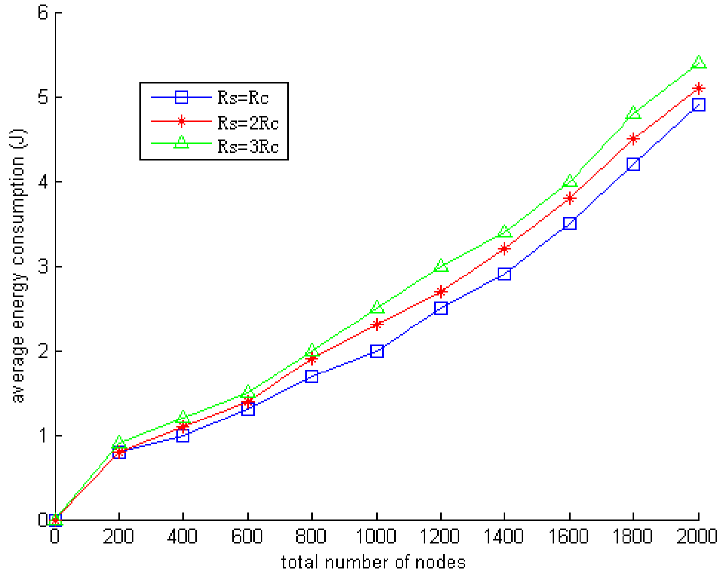

Figure 6. The Evaluation of Energy Consumption

Finally, the performance comparisons between the proposed VCHDA and PD are given. Figure 7 and Figure 8 shows the results of average hole discovery time and average energy consumption of the two algorithms respectively. The proposed algorithm has a better performance both in average discovery time and energy consumption in different network density. Especially, when the network density is not very high, the average hole discovery time of VCHDA is much shorter than that of PD. However, the discrepancy shrinks when the network density grows. For the average energy consumption, the proposed algorithm has a steady superiority to PD algorithm.

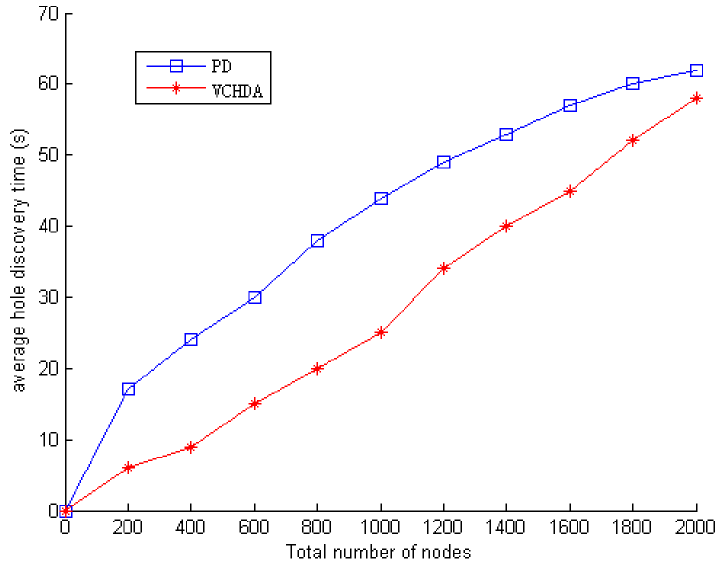

Figure 7. Average Hole Discovery Time Comparison

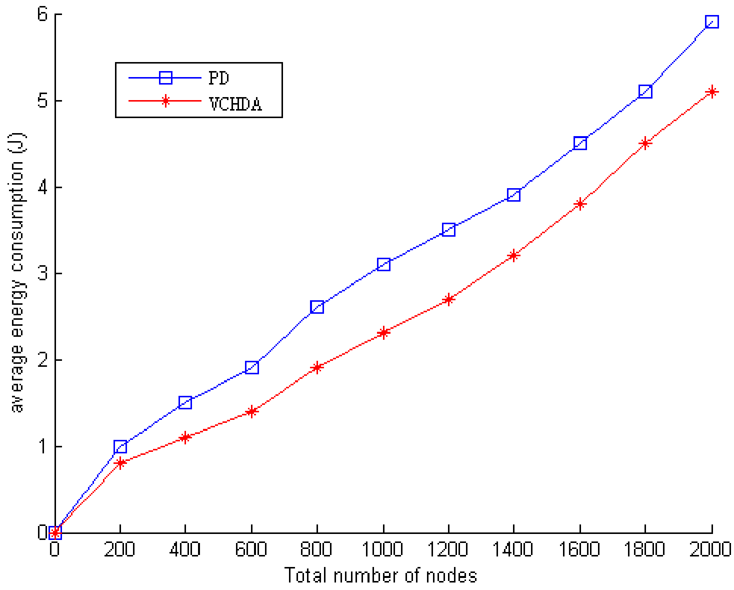

Figure 8. Average Energy Consumption Comparison

5. Conclusion

To address the problem of coverage holes in wireless sensor networks, a novel holes discovery algorithm based Voronoi diagram, VCHDA, is proposed in this paper. The basic idea behind this algorithm is quite simple, so it is easy to implement. The distances from a sensor node to each vertex and edge of its corresponding Voronoi cell are used as criterion for the existence of coverage holes. The VCHDA is a semi-distributed algorithm since the Voronoi diagram is carried out in the sink node while other computations are performed in other common nodes in a distributed way. Some experiments are conducted to evaluate the average holes discovery time and energy consumption of this algorithm. The simulation results shows a good performance of VCHDA compared to the PD algorithm. For the future works, we will research energy efficient hole healing with mobile sensor nodes.

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