A novel coverage hole repair algorithm based on vertical bisection

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ABSTRACT

The paper aims at the problem of coverage hole affecting network service quality in WSN, a Coverage Hole Repair Algorithm based on Vertical Bisection (CHRAVB) is proposed. Three principles for selecting optimal driving node are constructed and the location of optimal target repair is determined based on vertical bisection method. Simulation experiment results indicate that the CHRAVB algorithm achieves the low redundancy and the complete repair of coverage holes with a few mobile nodes.

Keywords: Coverage hole, vertical bisection, driving nodes, complete repair, mobile nodes

1. INTRODUCTION

In sensor node' deployment area, there exists some areas that are not covered by any sensor node's sensing range, these areas are called coverage hole[1]. In large-scale application scenarios of wireless sensor network, all sensor nodes are usually randomly deployed, it is prone to coverage hole problems. Although accurate deployment can ensure the complete coverage for monitoring area, uneven node energy consumption, unreasonable sleep scheduling mechanism and hardware and software failures can also lead to coverage hole. Coverage hole causes a series of problems such as congestion of network data transmission, decrease of data collection rate and network disconnection. More and more literatures have studied the techniques of hole repair in wireless sensor network, these techniques include the methods of secondary replenishment of nodes, increase of node power and change of node position. The secondary node supplement realizes the repair of coverage hole by adding new nodes, it has the advantages of simple process and easy implementation, but has serious redundancy problems[2]. The technique of enhancing node power generally does not need to add additional nodes, but this kind of method may not completely repair the all holes, and may increase the area of coverage hole. In recent years, a number of mobile sensor nodes are introduced into static sensor networks to form hybrid sensor network, the idea of repairing coverage hole by repositioning the position of nodes has attracted wider attention[3]. A coverage hole repair algorithm based on mobile node relocation technology is proposed to effectively reduce the average energy consumption of network nodes. However, this algorithm is a centralized algorithm, it is not suitable for the large-scale network application scenarios, and cannot guarantee that the coverage holes can be completely repaired[4]. The hole boundary nodes are determined by whether the triangle region formed by the detected node and its neighbour nodes is completely covered[5]. A distributed hole repair algorithm based on virtual force is proposed, in which the nodes around the coverage hole meeting constraint conditions are selected to repair coverage hole[6]. A coverage hole repair algorithm without node location information is proposed. However, the distance error reduces the rate of hole repair, and the algorithm is only suitable for closed coverage hole repair[7]. The algorithm for repairing coverage hole based on the dichotomy is proposed, it improves the rate of hole repair, but cannot guarantee the complete repair of all holes[8]. Based on the estimation of the areas of coverage holes, an algorithm called the Center[9] determines the mobile nodes by optimizing the redundancy, the node' energy and the moving distance, it reduces the redundancy of hole repair. A Chord-based Hole Covering algorithm (CBHC) is proposed[10]. It can realize the complete repair of coverage holes, but cannot avoid the appearance of hole fragment.

To sum up, some of the existing researches on hole repair technologies aim at improving the rate of hole repair by mobile nodes, and some aim at realizing the complete repair of coverage holes. None of them can achieve the low redundancy and the complete repair for coverage holes. Therefore, a distributed Coverage Hole Repair Algorithm based on Vertical Bisecting (CHRAVB) is proposed in the paper. It can realize the low redundancy and the complete repair of coverage holes with a few mobile nodes.

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2. OVERALL DESIGN OF THE CHRAVB

2.1 Optimization principles for driving node

Iinitiating node selects driving node to repair hole. The driving node is used to determine the hole repair position and drive the mobile node to repair the hole at the proper hole repair position. The selection of driving nodes should follow the following principles to maximize the area of hole repair.

Principle 1: It should be ensured that the introduced mobile node can completely cover the hole-boundary arc of the driving node at the hole repair position.

Coverage holes are composed of hole-boundary arcs of the boundary nodes. Principle 1 ensures that each introduced mobile node can eliminate at least one hole-boundary node. According to the following theorem 1, the introduced mobile node can always find the appropriate position for repairing the hole inferior arc. Therefore, the hole-boundary arc of the driving node selected according to the principle 1 should be inferior arc. According to the following theorem 2, although the covering disk of the mobile node cannot completely cover the hole optimal arc. However, according to the following theorem 3, if the coverage hole is not completely repaired, the hole-boundary node with inferior arc can always be found in the set of hole-boundary nodes, so that the driving node selection method based on principle 1 can continue to repair the coverage holes.

Principle 2: On the basis of principle 1, the introduced mobile node should avoid segmenting the hole at the hole repair position.

Principle 2 means that each repair should not generate new holes to reduce the number of mobile nodes required for repairing holes, it is because the segmentation of coverage hole may lead to an increase in the number of coverage holes, so a large number of mobile nodes are needed to repair these fragments to meet the application requirements. The number of mobile nodes increases, redundant coverage exists in some areas, which wastes node resources and increases network costs.

Principle 3: When the boundary arcs of boundary nodes are all inferior arcs and the introduced mobile nodes do not segment holes, the hole boundary nodes that cover the most incomplete intersection points should be selected as the driving node.

This principle ensures that the mobile node introduced by the selected driving node can restore the maximum area of the hole-region at the repair position. The coverage hole is composed of boundary arcs of multiple boundary nodes, each boundary node has at most two incomplete covering intersections in the hole-region. If a mobile node can only eliminate a hole-boundary node, the mobile node is transformed into a hole boundary node if the coverage hole is not completely repaired. In this case, the speed of hole repair is slow. If a mobile node can eliminate more incomplete intersections, it means that more hole-boundary nodes are eliminated, which will accelerate the speed of hole repair and reduce the number of mobile nodes. If certain mobile node removes all intersections, it indicates that all holes has been repaired completely.

Theorem 1: The mobile node introduced by the driving node can always find the repair position, so as to completely cover the inferior arc of the hole-boundary of the driving node.

Proof: As shown in Figure 1, it is assumed that node N_i is the hole-boundary node, arc P_1AP_2 is an inferior arc on the covering disk of node N_i, the line segment connecting the endpoints P_1 and P_2 of the arc is denoted as P_1P_2, The two points of intersection between the perpendicular of segment P_1P_2 through N_i and the covering disk are denoted as A and K respectively, and the intersection with the line segment P_1P_2 is denoted as C, B is the point on segment N_iA that satisfies the relation $|BC| = |N_iC|$.

For the sake of convenience, the length of any line segment XY is denoted as $|XY|$.

Let D be a point on N_iB, the relationship (1) and (2) exist in right triangle N_iP_1C and DP_1C.

$$|N_iP_1|^2 = |N_iC|^2 + |P_1C|^2 \tag{1}$$

$$|DP_1|^2 = |DC|^2 + |P_1C|^2 \tag{2}$$

Because of the relationship $|N_iC| > |DC|$, the following relationship can be concluded:

$$|DP_1| < |N_i P_1| = R_s \tag{3}$$

And because of the relations $|DA| < |N_i A| = R_s$, combining the symmetries of the two position points P_1 and P_2, it can be concluded that the covering disk of mobile node with *D* as the centre and R_s as the radius can always cover the endpoint P_1 and P_2 as well as the position point *A*. Therefore, the mobile node must be able to cover the inferior arc at position *D*.

Theorem 2: In the process of repairing coverage hole, the mobile node cannot completely cover the hole optimal arc at any position.

Proof: As shown in Figure 2, by using the method of disproof, it is assumed that arc P_1KP_2 is an arbitrary optimal arc on the disk of node N_i. According to the definition of optimal arc, arc P_1KP_2 must contain two points *E* and *F*. Taking any point *G* in the plane, it is assumed that the sensing disk with *G* as the canter and R_s as the radius can cover both *E* and *F*. The following relationship exists:

$$|GE| \le R_s \text{ and } |GF| \le R_s \tag{4}$$

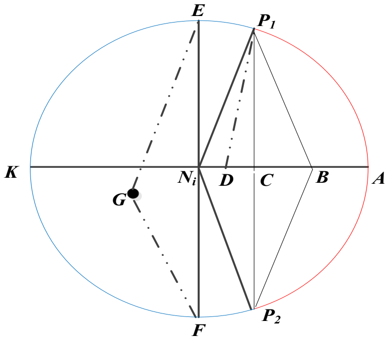

Figure 1. Repair of hole-boundary arc.

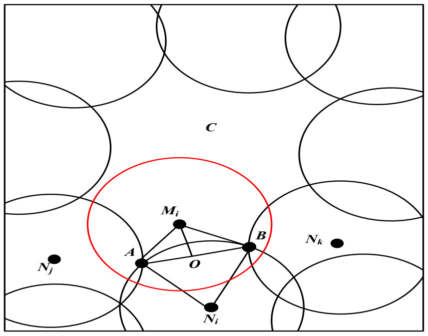

Figure 2. Analysis of optimal repair location.

The following relationships can be obtained:

$$|GE| + |GF| \le 2R_s \tag{5}$$

The sum of any two sides of a triangle is greater than the third side, so the following relation can be concluded:

$$|GE| + |GF| > |EF| = 2R_s \tag{6}$$

The above two formulas (5) and (6) are contradictory, that is, if any point *G* is taken as the centre of the circle, and the circle with radius R_s cannot cover both *E* and *F*, which contradicts the hypothesis.

Theorem 3: In the process of repairing coverage hole, these nodes with inferior arcs of hole boundary can always be found in the set of hole-boundary nodes, so that the algorithm can continue to repair the holes according to principle 1.

Proof: By using the method of disproof, it is assumed that the hole is composed of *N* nodes, and the inferior arc of the hole-boundary cannot be found in the repair process of the coverage hole. The N-sided shape is formed by connecting the incomplete intersections of adjacent hole-boundary nodes. The boundary arcs of each hole-boundary node are optimal arcs, so any interior angle of the N-sided shape is greater than 180 degrees, it makes the sum of interior angles of the whole N-sided shape will exceed 180×N degrees. This contradicts the sum of the inner angles of the N-sided shape obtained by the following formula.

$$\alpha = 180 * (N - 2) \tag{7}$$

2.2 Optimal repair location based on vertical bisection

The mobile node introduced by the driving node N_i is denoted as M_i, and the corresponding optimal repair position is denoted as T_i. As shown in Figure 2, according to the above principle 1, the mobile node M_i has covered the hole-boundary arc *AB* of N_i, and the vertical line of the segment *AB* is drawn from the point M_i, and the corresponding vertical foot is marked as *O*.

According to the formula (8), the area *S* of $\Delta M_i AB$ is calculated, and it can be concluded that if *S* reaches the maximum value, the hole-area repaired by the mobile node M_i reaches the maximum value.

$$S = \frac{1}{2}|AB||OM_i| \tag{8}$$

In the above formula, the value of $|AB|$ is fixed, *S* reaches its maximum if $|OM_i|$ is at its maximum.

In $\Delta OM_i A$, there is the following relationship:

$$|OM_i|^2 = |M_i A|^2 - |OA|^2 \tag{9}$$

Since the coverage range of the node M_i includes intersection point *A*, so there is the following relationship:

$$|M_i A| \leq R_s \tag{10}$$

Considering that the problem proved is symmetric, in $\Delta M_i AB$, the relationship $|M_i A| \geq |M_i B|$ is assumed to be true, and there is the relation $|OA| \geq |OB|$ according to the nature of the triangle, further combining with the relation $|OA| + |OB| = |AB|$, it is easy to get the following relation:

$$|OA| \geq \frac{1}{2}|AB| \tag{11}$$

In order to ensure that $|OM_i|$ can obtain the maximum value, $|M_i A|$ in formula (10) should take the maximum value R_s, and $|OA|$ in formula (11) should take the minimum value. In this case, *O* happens to be the equipartition point of the line segment *AB*, so there is the relationship $|M_i A| = |M_i B| = R_s$. It is concluded that the optimal repair position T_i of the mobile node M_i should be located on the middle perpendicular line of the endpoints *A* and *B* on both sides of the arc of the hole boundary, and the distance between the repair position point and *A* and *B* is equal to the node sensing radius R_s.

3. EXPERIMENT SIMULATIONS AND ANALYSIS

In the simulation process, all sensor nodes are uniformly deployed in the 100*100m area. All static nodes cannot move again once deployed. The node' sensing radius and communication radius are isomorphic, R_s =10m, R_t =20m. The paper compares the algorithm CHRAVB with the existing algorithms Center[9] and CBHC[10] in terms of the number of mobile nodes for repairing coverage holes, the hole repair rate and the average moving distance of mobile nodes.

The number of all mobile nodes is limited to 200. Figure 3 reflects the actual number of mobile nodes required for repairing coverage holes under different coverage hole areas for the three algorithms. It can be seen clearly that that the number of mobile nodes increases with the increase of coverage hole area in the three algorithms. Compared with the algorithm Center, the average number of the mobile nodes required for repairing hole in algorithm CHRAVB decreased by 28%. This is because that: firstly, the CHRAVB adopts the optimization mechanism for driving node; secondly, on the basis of the complete repair of coverage holes, the repair position of mobile node is determined based on the vertical bisection method to ensure that the repaired hole area each time can reach the maximum; thirdly, the non-parallel repair strategy further reduces the redundancy of hole repair.

It can be seen clearly that that the number of mobile nodes in algorithm CHRAVB is lower than that in CBHC, it is because although some optimization measures are taken to reduce the number of mobile nodes in CBHC, there may be some hole fragments, which increases the number of mobile nodes for repairing coverage holes.

The repair rate of coverage hole is generally defined as the ratio of the hole area actually repaired by the introducing mobile nodes to the total hole area. The comparison of hole repair rate is shown in Figure 4. It is noticed that the hole repair rates increase with the increase of the number of mobile nodes in three algorithms. If the number of mobile nodes is relatively small, the hole repair rate is low in three algorithms, it is because the number of mobile nodes is insufficient for completely repairing coverage hole, while the CHRAVB requires the least number of mobile nodes, so the repair rate of coverage hole in CHRAVB is the highest. If mobile nodes account for more than 29% of all nodes, the repair rate of coverage hole can reach 100% in CHRAVB. The repair rate of coverage hole in Center is lower than that of the CHRAVB, and more mobile nodes are required to reach the same hole repair rate. Although the Center can achieve complete hole repair, the proportion of mobile sensor nodes is more than 50%. The hole repair rate of the Center is lower than that of the CHRAVB, it is because that the Center only considers the mobile nodes within one hop of the hole boundary node, which leads to the insufficient mobile sensor nodes. In the process of hole repair, the CBHC may produce hole fragments, which increases the number of mobile sensor nodes required for completely repairing coverage hole and reduces the hole repair rate.

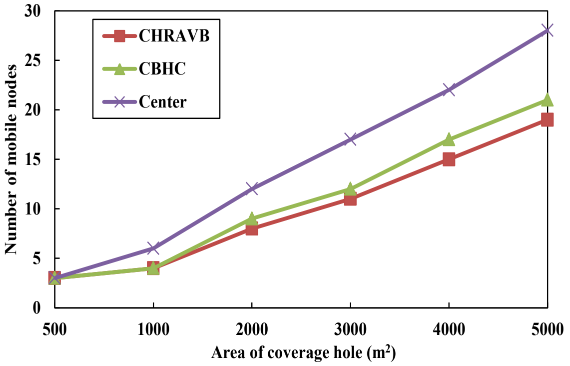

Figure 3. Area of coverage hole and number of repaired mobile nodes.

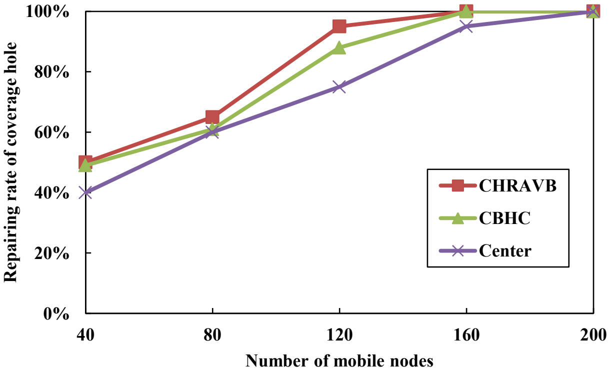

Figure 4. Number of mobile nodes and hole repair rate.

The coverage hole area is limited to 2000m^2. Figure 5 shows the average moving distance of all mobile sensor nodes. The distance decreases with the increase of the number of mobile sensor nodes, it is because that the increase is more conducive to choose the node closer to the target position as hole repair node. Compared with the Center and the CBHC, the average moving distance of moving nodes in CHRAVB is reduced by 25.4% and 35.6%, respectively, it is because the CHRAVB uses the non-parallel vertical partition method to determine the location of hole repair of mobile nodes. In CBHC and Center, the selection of repair position of mobile node is combined with various factors such as the energy consumption, which makes the moving distance of the mobile nodes longer.

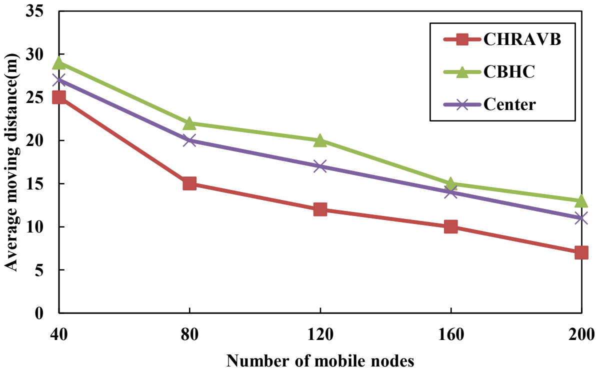

Figure 5. Number of mobile nodes and average moving distance.

4. CONCLUSION

Aiming at the quality-of-service requirement in WSN for complete coverage of monitoring area, a repair algorithm for coverage holes called CHRAVB is proposed. The algorithm realizes the low redundancy and the complete repair of coverage holes by optimizing driving nodes. Simulation experiment results indicate that the algorithm is effective for completely repairing of coverage holes.

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