Strategy of Repairing Coverage Hole for Different Holes Shapes in Heterogeneous Wireless Sensor Networks

Pingzhang Gou, Gang Mao and Shaobin Si

ABSTRACT

For the randomness of the initial deployment of sensor nodes and the exhaustion of node energy during network operation, the problem of covering holes may be generated, the coverage repair strategies for different holes shapes are proposed. Firstly, the holes polygons formed by static nodes of randomly deployed heterogeneous wireless sensor networks are classified. Secondly, according to different polygon types, different repair strategies are adopted to determine the location of virtual repair nodes. Finally, according to the distance between the virtual repair node and the mobile node, the relation function of energy threshold value, and the movement of the mobile node with finite distance, the covering cavity is repaired. Simulation results show that the coverage is improved by adopting different repair strategies according to different holes types.

1. INTRODUCTION

In the heterogeneous wireless sensor networks (HWSNs), sensor nodes are randomly scattered in designated areas, the network cannot be effectively covered and perceived by nodes, resulting in coverage holes in some areas of the network. Coverage holes has become an urgent problem for HWSNs to effectively perceive the
occurrence of network monitoring regional events, repair network coverage holes and improve network Quality of Service (Qos) [1].

Many literatures have studied how to effectively detect and repair WSNs covering holes. Most of the existing coverage holes algorithms are designed based on point coverage and special hole model. Most of the improved algorithms are designed based on neighbor nodes, energy, distance, angle, node redundancy and other factors in order to improve the coverage of nodes to the network. However, there are few literatures on the classification of covering hole types, and different repair strategies are adopted according to different hole types [2-8].

The existing coverage holes algorithm is rarely divided by the coverage holes type, and different repair strategies are adopted according to different holes types. Therefore, this paper firstly identifies the cover holes formed by static nodes initially deployed in the monitoring area and divides them into concave polygons and convex polygons. Then different repair strategies are adopted based on different holes types. Finally, based on the residual energy and distance threshold function of the mobile node, the mobile node moves to the designated location for holes repair under the condition that it does not exceed its maximum moving distance.

2. SYSTEM MODELS AND TERMINOLOGY DEFINITIONS

2.1 Network Model

At the initial moment, N static sensor nodes and M mobile sensor nodes are randomly deployed, all mobile sensor nodes are in a dormant state. When the covering hole is repaired, the mobile nodes are activated and move to the designated position for holes repair according to the distance and energy threshold function. The network model is assumed as follows:

Hypothesis 1: All sensor nodes can send location information to the base station through GPS. The nodes have the same and limited initial energy and unique ID.

Hypothesis 2: The sensing range of static nodes $R_s$ in the network is different, but the communication range of all nodes $R_c$ is twice that of $R_s$, that is $R_c=2R_s$. Both the sensing range and communication range are the sensing disk with the node position as the center and $R_c, R_s$ as the radius.

Hypothesis 3: Because of the randomness of node deployment, a monitoring point in the monitoring area is covered by at least one sensor node, which means that the event at this point can be detected effectively.

2.2 Perceptual Model

The heterogeneous sensor nodes are used for area sensing, and the sensing radius is different. Therefore, a probability perceptual model is used to calculate the node perceptual probability.
\[ p(x) = \begin{cases} 
1 & \text{if } 0 \leq d_{i,j} \leq R_{\text{min}} \\
e^{-\lambda(d_{i,j}-R_{\text{min}})} & \text{if } R_{\text{min}} < d_{i,j} < R_{\text{max}} \\
0 & \text{if } d_{i,j} \geq R_{\text{max}} 
\end{cases} \] (1)

Where, \( \lambda \) and \( \beta \) are the adjustable parameters, \( d_{i,j} \) is the distance between the sensor node \( S_i \) and the target \( T \) in the event occurrence area, \( R_{\text{min}} \) is the minimum sensing radius of the node in the monitoring area, and \( R_{\text{max}} \) is the maximum sensing radius of the node in the area.

### 2.3 Energy Dissipation Model

The energy consumption model proposed in literature [9] is adopted for energy consumption calculation. In order to effectively send data, part of the energy of nodes is used for signal amplification during data transmission according to the transmission distance of nodes. Therefore, the energy consumption of nodes transmitting \( k \) bit data on the link can be expressed as:

\[
E_{tx}(k, d) = \begin{cases} 
kE_{elec} + k\varepsilon_{fs}d^2 & \text{if } d < d_0 \\
kE_{elec} + k\varepsilon_{amp}d^4 & \text{if } d > d_0
\end{cases}
\] (2)

\[
d_0 = \frac{\varepsilon_{fs}}{\sqrt{\varepsilon_{amp}}} \] (3)

Where, \( E_{elec} \) is the energy consumption of node sending 1 bit data, \( \varepsilon_{fs} \) is the signal amplification multiple of free space model, and \( \varepsilon_{amp} \) is the signal amplification multiple of multi-path attenuation model.

The energy consumption of the node receiving \( k \) bit data can be expressed as:

\[
E_{rx}(k) = k * E_{elec} \] (4)

The relationship between the furthest moving distance of a mobile node and energy demand is:

\[
d_{max} = \sqrt{\frac{E_{res}}{k}} \] (5)

\( d_{max} \) is the maximum distance that the mobile node can move, and \( E_{res} \) is the remaining energy of the mobile node.

### 2.4 Hole Model

In this paper, different strategies are used to repair the coverage holes in the bounded region according to the different types of critical intersection points in the network. The randomly generated holes polygons divided into concave polygons and convex polygons, and then repaired them respectively. Fig. 1 shows the holes model formed by 13 randomly distributed static nodes in the monitoring area.
2.5 Terminology Definitions

**Definition 1 (Neighbor Nodes):** In the network, if the Euclidean distance $d_{i,j}$ is less than $2\max(R_{si}, R_{sj})$ between two nodes $(S_i, S_j)$, then the $S_i, S_j$ are neighbor nodes which are one-hop distance away from each other. $\{S_1, S_3, S_4, S_5\}$ are all neighbors of node $S_2$ (Fig. 2).

**Definition 2 (Redundant Nodes):** When the sensor node's sensing area is completely covered by the node $S_j$, or the sensing disk of $S_i$ is completely covered by the single or multiple neighbor nodes $S_{i+1,i=1,2,\ldots,n}$ of neighbor node $S_j$, then node $S_i$ is said to be a redundant node of node $S_j$. The sensing area of nodes $S_1$ is completely covered by nodes $S_2$, and the sensing area of nodes $S_4$ is completely covered by neighbor nodes $\{S_3, S_5\}$ of nodes $S_2$. Nodes $S_1, S_4$ are redundant nodes of node $S_2$ (Fig. 2).

**Definition 3 (Critical Intersection Points, Cip):** In the monitoring area, the intersection of the sensing disc of the node $S_i$ and its neighbor node $S_j$, or the intersection of the node $S_i$ and the boundary of the monitoring area is called a perceptual intersection point. If the intersection point $P_{i,j}$ is no longer covered by the neighbor node $S_k$ of the nodes $S_i$, it is called the Critical intersection point (Cip).
**Definition 4(Convex/ Concave Polygon):** A polygon is said to be convex if none of its interior angle is reflexive angle, otherwise, the polygon is concave. Fig. 3 (a) shows the convex polygon holes model, and Fig. 3(b) is a concave polygon holes model.

### 3. COVERAGE HOLES REPAIR STRATEGIES

#### 3.1 Polygonal Center of Gravity

The geometric center is replaced by solving the center of gravity of the polygon, and the equation of the center of gravity is as follows:

\[
H_{Cx} = \frac{1}{6 \ast H_{Al}} \sum_{i=1}^{n-2} (x_i + x_{i+1}) (x_{i+1}y_i - x_i y_{i+1}) \\
H_{Cy} = \frac{1}{6 \ast H_{Al}} \sum_{i=1}^{n-2} (y_i + y_{i+1}) (x_{i+1}y_i - x_i y_{i+1}) \\
H_{Al} = \frac{1}{2} \sum_{i=1}^{n-2} (x_i y_{i+1} - x_{i+1} y_i)
\]

The center of gravity coordinate of hole polygon is \((H_{Cx}, H_{Cy})\), \(H_{Al}\) is the area of the i-th hole polygon, and the coverage is calculated as follows:

\[
P_{cov} = \frac{A - \sum_{i=1}^{n} H_{Al}}{A}
\]

#### 3.2 Determination of Polygon Convexity

In the model of the anti-clockwise order hole nodes, vector consisting of each side of the polygon can be expressed as \(\overrightarrow{P_nP_{n+2}} \times \overrightarrow{P_nP_{n+1}}\). If the value is positive, the polygon is convex (Fig. 3(a)), the corresponding angle of \(P_8\) is concave angle, and then polygon is concave polygon (Fig. 3(b)). The convex polygon is divided into triangles with small enough area by the center of gravity coordinates and the adjacent two Cip. The concave polygon connects the center of gravity coordinates with each Cip, and a half-fold deployment method is used to locate virtual repair nodes.

\[
A_{tri} = \begin{vmatrix}
  x_1 & y_1 & 1 \\
  x_2 & y_2 & 1 \\
  H_{Cx} & H_{Cy} & 1
\end{vmatrix}
\]

The virtual repair node location calculation steps are as follows:
Step1 Calculate the coordinates of Cip by static nodes $S_i$, neighbor nodes $S_j$ and their respective sensing radii $R_s$, and reorder each node anti-clockwise according to the hole area $H_i$.

Step2 According to Equation (6) and (7), connect Cip to form a closed hole area $H_i$, calculate the center of gravity $(H_{Cx}, H_{Cy})$ of each polygon hole.

Step3 The convexity of polygon is determined by vector cross – multiplication.

Step4 If polygon is convex, the center of gravity of the hole $(H_{Cx}, H_{Cy})$ is respectively connected to the end points of each reordered polygon to obtain multiple triangles, and the center of the triangle inscribed circle is the virtual repair node $V_i$. Traversing the triangle of the whole hole polygon $H_i$, finally, whether a further repair is needed will be determined by the ratio of the inscribed circle area and triangle area, the area of the triangle is calculated by Equation (10). If the polygon is concave, coverage hole of center of gravity $(H_{Cx}, H_{Cy})$ should respectively connect to the Cip of each reorder polygon. Then the virtual repair node $V_i$ is at the midpoint of the center of gravity point and each Cip. If the intersection distance $d_{v,p}$ of $P_i$ and $V_i$ is greater than the radius $V_i$, repair virtual nodes $V_{i+1}$ are placed in its midpoint and successively approximate so as to get each repair virtual node location information in the hole area.

Step5 Get the location information of all nodes to be repaired in the region and store it into the table $R_h$.

3.3 Hole Recovery Phase

At the virtual repair node $V_i$, the most matching mobile node $M_i$ is selected according to the node priority for repair, and $d_{v,m}$ is less than $d_{max}$ that calculated by Equation (5). Node priority is calculated as follows:

$$ f = f_1 \times n_1 - f_2 \times n_2 $$

$$ f_1 = \frac{E_{res} - E_{mavg}}{E_{max} - E_{min}} $$

$$ f_2 = \frac{d_{v,m}}{\sum_{i=1}^{n} d_{m,vi}} $$

Where, $f_1$ is the priority function based on the energy of mobile nodes, and $f_2$ is the priority function based on distance. The value of threshold function determines the priority of node sorting, and the larger the value of $f$, the higher the priority. $E_{mavg}$, $E_{max}$, $E_{min}$ respectively represent the average energy, maximum energy and minimum energy of mobile nodes.
4. RESULTS AND DISCUSSIONS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network area</td>
<td>300m×300m</td>
<td>Mobile node N(_m)</td>
<td>50</td>
</tr>
<tr>
<td>BS location</td>
<td>(150,150)</td>
<td>Static node initial energy E(_s)</td>
<td>1J</td>
</tr>
<tr>
<td>Weighting factor n(_1)</td>
<td>0.3</td>
<td>Weighting factor n(_2)</td>
<td>0.7</td>
</tr>
<tr>
<td>Initial energy of mobile node E(_m)</td>
<td>20J</td>
<td>Radius of perception of mobile node R(_s)</td>
<td>12.5m</td>
</tr>
<tr>
<td>(\varepsilon_{fs})</td>
<td>10pJ/(bit/m(^2))</td>
<td>Communication radius of mobile node R(_c)</td>
<td>25m</td>
</tr>
<tr>
<td>(\varepsilon_{amp})</td>
<td>0.0013pJ/(bit/m(^4))</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In order to verify that the geometric center of the polygon is replaced by the center of gravity, different repair strategies are adopted according to different types of holes. The strategic effectiveness is verified in matlab2016a, and the specific experimental parameters are shown in Table I.

Fig. 4 shows the relation diagram of the number of mobile nodes required when 50 and 70 static nodes are placed in the network monitoring area and the network coverage is greater than 90% when the geometric center of polygon and the center of gravity of polygon are solved by summation respectively. It can be seen from the figure that when the number of static nodes remains unchanged, the network coverage obtained by solving the center of gravity simulation is better than that obtained by using accumulation and solving the polygon geometric center. The coverage of the former has an increase of 3.83% higher over the latter.

![Figure 4. Relationship between the numbers of Polygons mobile nodes and the coverage rate.](image1)

![Figure 5. Relationship between the shapes and coverage rate.](image2)
In Figure. 5, when the number of static nodes in the network is the same, it can be seen that the number of mobile nodes needed to repair concave polygon holes by successive approximation method is more than that of convex polygons to reach the coverage stipulated by the network. In the case where the number of mobile nodes is the same, the coverage of convex polygons is 5.56% higher than that of concave polygons, because the concave polygon is more special than the convex polygon. In the strategy selection, in order to accelerate the convergence speed of the algorithm and avoid excessive redundant coverage, the point where the center of gravity of concave polygons is too close to Cip is treated as the covered area, and there is no need to calculate the position of the virtual repair node corresponding to the change point again.

5. CONCLUSIONS

In conclusion, the coverage hole repairing in HWSN is a key technology. The holes area of polygon formed by the connection of key perceived intersection points is divided into concave polygon and convex polygon, different strategies are adopted to repair the holes. Considering the particularity of concave polygons, pruning strategy is adopted to accelerate the repair strategy to reduce redundancy. After the location of the virtual repair node is determined, the optimal node matching is carried out by using the node energy and distance priority threshold function, and the mobile node moves to the designated position to repair the polygon hole. Simulation experiments show that the feasibility of this strategy, which has certain advantages over the traditional virtual repair node positioning method.

ACKNOWLEDGEMENTS

This work is supported by NSFC (Grant Nos. 61261015, 61561043), Educational and Teaching Research Project of AFCEC (Grant No. 2019-AFCEC-079), and Project of Innovation and Entrepreneurship Plan for College Students in Gansu Province (Grant No. 2019-098).

REFERENCES


