A Novel Algorithm for Solving the Coverage Hole and the Complete Coverage Range in Wireless Sensor Networks

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Abstract—**Based on the area problem of coverage hole and the complete coverage range in wireless sensing networks, in this paper, First, the expression of node coordinates is given; Second, the node deployment based on the united expression of the node coordinates is described. Third, an algorithm is programmed to calculate the area of coverage hole and the total coverage range. At last, the numerical example shows that given a kind of node deployment, a group of area values and ratios corresponding to the different numbers of failed nodes and simulation times can be successfully obtained.**

Index Terms—**coverage range, node coordinates, node deployment, wireless sensor networks**

I. Introduction

In recent years, the rapid developments of wireless communication technology and microelectronics enable wide application of the low-cost, low-power, multi-function and tiny wireless sensor nodes which basically consist of sensing units, processing units, transceiver units and power units. Hundreds and thousands of wireless sensor nodes distributed throughout a particular area constitute a wireless sensor network (WSN). Connected by wireless communication protocols, the sensor nodes perceive the intended information by their internal sensing units from the target region monitored by the WSN and transfer the information having been processed by processing units to the terminal users or base station through the interconnected wireless communication network of the sensor nodes. WSNs have widespread application value and prospect in both military and civil fields, such as environmental monitoring, inventory management, disaster recovery, object tracking and intrusion detection and so on [1].

Since most of the low-power sensor nodes have limited battery life and replacing batteries on tens of thousands of these devices is infeasible, it is well accepted that a sensor network should be deployed with high density in order to prolong the network lifetime [2]. However, it is unnecessary to keep all the nodes in the active mode for such sensor networks to perform their normal functions. On one hand, a mass of information collected by the nodes is likely to be highly uncorrelated and redundant. On the other hand, excessive packet collision may occur when the nodes attempt to send packets simultaneously in the presence of certain triggering events [2]. As a result of the above reasons, a large amount of energy will be wasted. So to gain the density control of the nodes is essential.

Aiming at the issue of how to maintain sensing coverage and connectivity of WSN while keeping a minimum number of sensor nodes in the active mode, Zhang and Hou [2] investigated the relationship between coverage and connectivity, and proved that if the radio range is at least twice the sensing range, complete coverage of a convex area implies connectivity among the working set of nodes. And further, under the ideal case in which node density is sufficiently high, Zhang and Hou [2] devised a set of optimality conditions under which a subset of working sensor nodes can be chosen for complete coverage. Based on the optimality conditions, a decentralized density control algorithm, Optimal Geographical Density Control (OGDC) is devised for density control in large scale sensor networks. Still, to maintain both sensing coverage and network connectivity and further realize configuration of the network to any feasible degrees of coverage and connectivity in order to support different applications and environments with diverse requirements, Wang et al [3] design and analyze novel protocols. The uniqueness of their work lies in the fact that they present a Coverage Configuration Protocol (CCP) that can provide different degrees of coverage requested by applications.

In the actual working process of WSNs, individual sensor node usually fails due to the simple structure, asymmetric load distribution, limited energy or other factors. The system structure optimization [4-6] should be viewed as a combinatorial optimization problem. As a result, there maybe exist some parts which are not covered by at least k nodes, (k is the required degree of coverage for a particular application) in the target region; that is to say, the coverage holes appear. The existence of coverage holes will lead to the loss of much information, which will result in the insufficiency to meet the application requirements. So the study on the coverage holes is highly significant. Duncan et al [7] introduced a formal mathematical definition of an approximate hole coverage area for wireless sensor networks and then present a simple proof for a decentralized solution to the approximate hole coverage

doi:10.4304/jsw.9.6.1567-1573

problem. Hsieh and Sheu [8] developed distributed protocols to identify the boundary nodes surrounding the holes of the sensing filed in WSNs without using any location information. Their experimental results demonstrate that the algorithm can precisely and correctly identify the boundary nodes even in sparsely sensors deployed regions. Kosar et al [9] proposed a redeployment method to mitigate the coverage hole problem. Image processing algorithms are used for identifying the coverage holes [10-13]. A portion of the sensors are kept as spare and after identifying the holes, they are redeployed over the holes [14, 15]. The results indicate that the method leads to a considerable increase on the sustainable sensing quality of the network.

Based on the optimal sensing coverage to a convex region, this paper proposes an algorithm coded by MATLAB completes the calculation of the area problem. The rest of the paper is organized as follows. In Section II, the expression of node coordinates is given. Section III describes the node deployment based on the united expression of the node coordinates. An algorithm is programmed to calculate the area of coverage hole and the total coverage range by computer in Section IV. Section V gives the simulations of node failure in optimal sensing coverage and a group of area values along with their ratios are obtained. Some conclusions are got in Section VI.

II. Expression of Node Coordinates

Assumption:

(A1)The sensor density is high enough that a sensor ban be found at any desirable point [2].

(A2) The sensing radiuses of all the nodes are equal.

Under the assumption (A1) and (A2), the node deployment for the optimal coverage of a convex region R is shown in Fig. 1 below. For designing the algorithm, above all, establish coordinate system on the plane of the nodes. The coordinate origin is set in the position of some node, which is the one located nearly in the middle of the region preferably. And then take the line connected by the coordinate origin and any of its adjacent nodes as x axis.

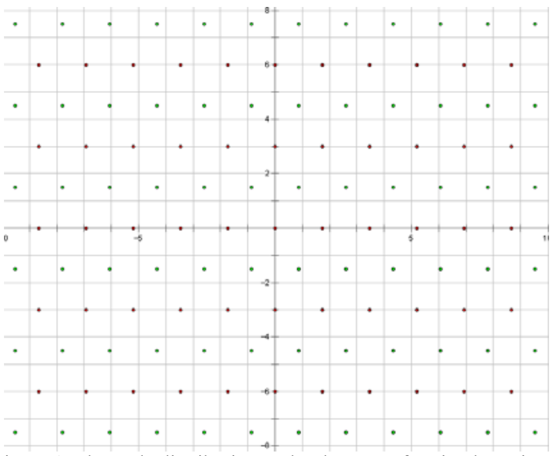

Figure 1. The node distribution under the case of optimal sensing coverage

As shown in Fig. 1, the node distribution has obvious regularity. Still, considering that node coordinates play an important part in the two calculating formulas of areas of coverage hole and target region R, the analysis of the general expression of node coordinates is made as follows.

As shown in Fig. 1, the distance between adjacent nodes is $\sqrt{3}r_s$ which is $\sqrt{3}$ times of sensing range. Arbitrary three nodes, any two of which are adjacent, form an equilateral triangle with sides of $\sqrt{3}r_s$.

As shown in Fig. 1, the nodes on x axis except the one at $(0,0)$ can be seen the results of translation with the distances of integer multiple of $\sqrt{3}r_s$ based on the node at $(0,0)$. So the coordinates of the red nodes on x axis can be expressed as $\left(0+p\cdot\sqrt{3}r_s,0\right)$. In the positive or negative direction of x axis we can see that the nodes distribute in layers paralleling with x axis and the height difference of any two adjacent layers is $\frac{3}{2}r_s$. It can be seen that at arbitrary two layers with two such height differences, there are pairs of nodes with the same abscissa and the ordinates differ by $2\times\frac{3}{2}r_s$. So in Fig. 1 the coordinates of the red nodes can be expressed by $\left(p\cdot\sqrt{3}r_s, q\cdot 3r_s\right)$. With the coordinate origin included, $p,q=0,\pm1,\ldots\ldots$, namely $p,q\in Z$.

In the same way, for nodes on the first layer above x axis, start with the node with coordinate $\left(\frac{\sqrt{3}r_s}{2},\frac{3r_s}{2}\right)$, the other nodes can be seen the results of translation with the distance of integer multiple of $\sqrt{3}r_s$ based on it. So the coordinates of nodes of this layer can be expressed as $\left(\frac{\sqrt{3}r_s}{2}+m\cdot\sqrt{3}r_s,\frac{3r_s}{2}\right)$. And further, the coordinates of all the green nodes can be expressed as $\left(\left(\frac{1}{2}+m\right)\cdot\sqrt{3}r_s,\left(\frac{1}{2}+n\right)\cdot 3r_s\right)$, $m,n=0,\pm1,\ldots\ldots$.

So the coordinates of all the nodes can be expressed as either $\left(p\cdot\sqrt{3}r_s,q\cdot 3r_s\right)$ or $\left(\left(\frac{1}{2}+m\right)\cdot\sqrt{3}r_s,\left(\frac{1}{2}+n\right)\cdot 3r_s\right)$, which can be unified into one expression $\left(x\cdot\sqrt{3}r_s,y\cdot 3r_s\right)$, where $x=\frac{s}{2}$, $y=\frac{t}{2}$, $s,t\in Z$ and s,t must be either even or odd numbers simultaneously. Till then, not the detailed coordinates but a pair of numbers x,y can determine the location of a sensing node. As a result, the calculation of m_i^f and n_1 is simplified greatly.

III. Node Deployment Based on the United Expression of the Node Coordinates

For the research of the coverage hole problem, it is necessary to give a target region R firstly, so as to the deployment of nodes can be determined, which is even more important to us. The area calculation has ignored the detailed shape of the target region R due to the arbitrariness of its boundary under the assumption that the region is large enough in comparison with the sensing range of each sensor node.

In Section II, it has been obtained that the location of a node is uniquely determined by a pair of numbers x, y . So the description of the node deployment is to give (x, y) of all the working nodes.

Proposition 1: $y = t/2 (t \in Z)$ continuously takes values following the rule $\ldots, -2.0, -1.5, -1.0, -0.5, 0, 0.5, 1.0, 1.5, 2.0, \ldots$. And for the nodes distributed in the same layer marked with y , if y is an even number, $x = s/2 (s \in Z)$ continuously takes values following the rule $\ldots, -3.0, -2.0, -1.0, 0, 1.0, 2.0, 3.0, \ldots$ while if y is an odd one, $x = s/2 (s \in Z)$ continuously takes values following the rule $\ldots, -2.5, -1.5, -0.5, 0, 0.5, 1.5, 2.5, \ldots$.

Proof. As the result of the analysis in Section 2, the united expression of node coordinates is $\left(x \cdot \sqrt{3} r_s, y \cdot 3 r_s\right)$, where $x = \dfrac{s}{2}$, $y = \dfrac{t}{2}$ $(s, t \in Z)$ and s, t must be either even or odd numbers simultaneously.

In Fig. 1, in the positive or negative direction of x axis we can see that height difference of the nodes in the two adjacent layers paralleling with x axis is $\pm \dfrac{3}{2} r_s$, that is to say y accordingly differs by ± 0.5 ; in the same way, in the positive or negative direction of y axis we can see that horizontal distance of the nodes in the two adjacent layers paralleling with y axis is $\pm \dfrac{\sqrt{3}}{2} r_s$, that is to say x accordingly differs by ± 0.5 .

If after the target region R is given and the node deployment is finished, two adjacent layers paralleling with x axis in which y values of nodes differ by one can be found inside R , that is to say, the shortest distance between the nodes in the two layers is $3r_s$, which is longer than $2r_s$. As a result, coverage hole between the two layers must exist. Otherwise, the R is not a convex region. The coverage hole is certainly inevitable in the case that there exist two adjacent layers in which y values of nodes differ by more than one. In the same way, if two adjacent layers paralleling with y axis in which y values of nodes differ by one can be found inside R , that is to say, the shortest distance between the nodes in the two layers is $2\sqrt{3} r_s$, which is longer than $2r_s$, there must exist coverage hole between the two layers. Otherwise, the R is not a convex region. The coverage hole is certainly inevitable in the case that there exist two adjacent layers in which y values of nodes differ by more than one.

So the optimal full coverage of the target region R is completed, y continuously takes values following the rule $\ldots, -2.0, -1.5, -1.0, -0.5, 0, 0.5, 1.0, 1.5, 2.0, \ldots$. And for the nodes distributed in the same layer marked with y , if y is an even number, x continuously takes values following the rule $\ldots, -3.0, -2.0, -1.0, 0, 1.0, 2.0, 3.0, \ldots$ while if y is an odd one, $x = s/2 (s \in Z)$ continuously takes values following the rule $\ldots, -2.5, -1.5, -0.5, 0, 0.5, 1.5, 2.5, \ldots$.

□

Proposition 2: upper and lower limits of x of nodes in two adjacent layers mutually constrain: upper limit of x of nodes in the lower layer can not be less than the difference of lower limit of x of nodes in the upper layer subtracting 0.5 and lower limit of x of nodes in the lower layer can not be more than the sum of upper limit of x of nodes in upper layer and 0.5.

Proof. Between two adjacent layers, if the upper limit of x of nodes in lower layer is less than the difference of lower limit of x of nodes in upper layer subtracting 0.5, all the sensing disks corresponding to the two layers are detached. That is to say, the coverage range of all the nodes breaks off among the two layers and there must exist coverage hole. Otherwise R is not a convex region. The same is with the latter case.

□

By the analysis above, the description of node deployment is to give the value range of y and the value range of x for each y for all the nodes according to Propositions 1 and 2 presented above.

IV. Algorithm Description

Step 0: collect the information of x, y that upper and lower limits of y and those of x for each y value for all the nodes, which is entered by keyboard. Judge the entered values whether conform to the requirements obtained in section 2 and section 3 or not. If not, enter the corresponding information again. Turn to step1.

Step 1: Save the information that (x, y) of all the nodes collected in Step0 into an array of $2 \times n$ dimensions.

Substep 1: the number of the layers paralleling with x axis, m can be obtained according to the upper and lower limits of y , which is equal to $(\text{upper limit of } y - \text{lower limit of } y) \times 2 + 1$. Save all the values of y into the first column of array A of $m \times 3$ dimensions and the two values of x corresponding to each y value in the second and third column in the same row with the y .Turn to Substep2.

Substep 2: The number of nodes in each layer marked by y , is obtained by corresponding upper and lower limits of x and saved in the array B of $m \times 1$. Turn to Substep3.

Substep 3: Starting with the nodes in the first layer paralleling with x axis and following the order of right-to-left and top-to-bottom, we successively save the values of x in the array C of $1 \times n$ dimensions and save the corresponding y values in array D of $1 \times n$ dimensions. At last, integrate the arrays C and D into the array E of $2 \times n$ dimension to saving $\left(x, y\right)$ of all the nodes.

Turn to step2.

The two steps above are common for calculating m_i^f in formula (1) and n_1 in formula (2).

The subsequent steps for calculating m_i^f are shown as follows:

Step 2: Save the entered number of failed nodes, n_f and judge the entered number whether conform to the corresponding requirements for a specific example or not. If not, enter again. Turn to step3.

Step 3: Randomly select n_f nodes as the failed nodes from array E . The corresponding index values of failed nodes in array E are saved in an array of $1 \times n_f$ dimensions.

Step 4: Use two nested for loops to calculate the value of m_i^f according to the formula $m_i^f = \sum_{i=1}^{n_f - 1} \sum_{i<j\le n_f} I_{ij}$.

Save the value of m_i^f in the variable mf , which is initialized with 0.

$k = 1 : n_f - 1$

$p = k + 1 : n_f$

Read $\left(x, y\right)$ of the p th failed node from the array E according to the index values obtained in step3.

If

$$\left(\left|y_k - y_p\right| = 0, \left|x_k - x_p\right| = 1\right) or \left(\left|y_k - y_p\right| = \left|x_k - x_p\right| = \frac{1}{2}\right)$$

then

$$mf = mf + 1$$

End if

End

End

$m_i^f = mf$.

At the end of the two nested loops, the value of mf is that of m_i^f we want.

The subsequent steps for calculating n_1 are shown as follows.

The value of n_1 is the total number of the nodes whose adjacent nodes with the distance of $\sqrt{3}$ is smaller than 6.

For an arbitrary node, its adjacent nodes with distance $\sqrt{3}$ from it must locate in the layer, in which the node locates, as well as the upper, lower one. Further, both x and y of the node differ from those of its adjacent nodes in the upper and lower layers by 0.5 and those of its adjacent nodes in its layer by ± 1 , 0. So n_1 can be solved as the steps below.

Create a n dimensional vector F with all the elements being 0.

Cycle from top to bottom:

The nodes in the top and bottom layers must be the outer nodes because their adjacent nodes with $\sqrt{3}$ from them are less than 6. And the corresponding elements of F are assigned to 1.

For judging whether a node locating not in the top and bottom layers is outer or not, check the nodes in the layer the node locates in as well as the upper, lower ones and count the number of its adjacent nodes by calculating the differences of x, y . If the number is smaller than 6, the node is outer and the corresponding element of F is assigned to 1.

Finally, accumulate all the elements of F and the sum is n_1 .

V. Numerical Example

In the failure simulation, first of all, the node deployment need to be determined by inputting the data that the upper and lower limits of y for all the nodes and those of x corresponding to each y in a coordinate system. And it must be noted that the constraints given in property 2 should be paid attention to. Then with the prompt of the program, the number of failed nodes needs to be input. Till then, the input of necessary data is completed and the program will give the calculation results we want, including the total number of nodes n , the number of intersecting parts formed by the n_f failed nodes m_i^f , the number of outer nodes n_1 and the areas of coverage hole and complete coverage range obtained based on n , m_i^f and n_1 . So the approximate ratio of the area of coverage hole to that of target region can be calculated finally.

But before the actual simulation some analyses needs to be made:

The two formulas of approximately calculating areas of the coverage hole and target region R are $S_h = n_f \cdot S_{\text{c-hex}} + m_i^f \cdot S_i$ and $S_c^{all} = nS_c - \left(3n - n_1 - 3\right) S_i$. So we can see that S_c^{all} is determined by the total numbers of working nodes and outer nodes in the initial-time deployment. Therein the number of outer nodes is determined by total number n as well as the node deployment. So S_c^{all} is determinant with the total number and the deployment of the nodes fixed. And the coverage hole area seems to be determined by n_f and m_i^f . Further, m_i^f , the number of intersecting parts formed by the n_f failed nodes, is jointly determined by the total number and deployment of all the nodes as well as the number of failed nodes n_f . However, because of the randomness of the selection of failed nodes, although the node total number and deployment as well as the number of failed nodes are all fixed, m_i^f is unfixed and stochastic. So in failure simulation with the node total number and deployment in initial time fixed, five simulations are carried out for each value of the failed node number.

So the simulation begins with deploying the nodes and data input for the deployment is as follows:

The upper and lower limits of y are 6 and -6 separately. The upper and lower limits of x are 3 and -3 separately when y takes integral values and 2.5 and 2.5 when y takes non-integer ones.

Based on the deployment given above, we assign eight values to n_f and carry out five simulations for each one. Forty simulations have been carried out altogether and the calculation results are as follows: n =163, n_1 =60. So we get that $S_c^{all} = \left(21\pi + 213\sqrt{3}\right) r_s^2$.

TABLE I

THE CALCULATION RESULTS FOR DIFFERENT n_f AND SIMULATION TIMES

The number of failed nodes n_f	simulation times	m_i^f	S_h	The ratio of area of coverage hole to that of R
6	1	0	0	0
	2	0	0	0
	3	0	0	0
	4	0	0	0
	5	0	0	0
8	1	0	0	0
	2	2	$\left(23\sqrt{3} - 7\frac{1}{3}\pi\right) r_s^2$	3.86%
	3	2	$\left(23\sqrt{3} - 7\frac{1}{3}\pi\right) r_s^2$	3.86%
	4	0	0	0
	5	1	$\left(23.5\sqrt{3} - 7\frac{2}{3}\pi\right) r_s^2$	3.82%
12	1	3	$\left(34.5\sqrt{3} - 11\pi\right) r_s^2$	5.79%
	2	1	$\left(35.5\sqrt{3} - 11\frac{2}{3}\pi\right) r_s^2$	5.71%
	3	5	$\left(33.5\sqrt{3} - 10\frac{1}{3}\pi\right) r_s^2$	5.88%
	4	1	$\left(35.5\sqrt{3} - 11\frac{2}{3}\pi\right) r_s^2$	5.71%
	5	2	$\left(35\sqrt{3} - 11\frac{1}{3}\pi\right) r_s^2$	5.75%
16	1	2	$\left(47\sqrt{3} - 15\frac{1}{3}\pi\right) r_s^2$	7.64%
	2	5	$\left(45.5\sqrt{3} - 14\frac{1}{3}\pi\right) r_s^2$	7.77%
	3	6	$\left(45\sqrt{3} - 14\pi\right) r_s^2$	7.77%
	4	6	$\left(45\sqrt{3} - 14\pi\right) r_s^2$	7.81%

	5	4	$\left(46\sqrt{3}-14\frac{2}{3}\pi\right)r_s^2$	7.73%
20	1	3	$\left(58.5\sqrt{3}-19\pi\right)r_s^2$	9.57%
	2	9	$\left(55.5\sqrt{3}-17\pi\right)r_s^2$	9.82%
	3	8	$\left(56\sqrt{3}-17\frac{1}{3}\pi\right)r_s^2$	9.78%
	4	4	$\left(58\sqrt{3}-18\frac{2}{3}\pi\right)r_s^2$	9..62%
	5	11	$\left(54.5\sqrt{3}-16\frac{1}{3}\pi\right)r_s^2$	9.91%
24	1	7	$\left(68.5\sqrt{3}-21\frac{2}{3}\pi\right)r_s^2$	11.63%
	2	8	$\left(68\sqrt{3}-21\frac{1}{3}\pi\right)r_s^2$	11.67%
	3	8	$\left(68\sqrt{3}-21\frac{1}{3}\pi\right)r_s^2$	11.67%
	4	14	$\left(65\sqrt{3}-19\frac{1}{3}\pi\right)r_s^2$	11.92%
	5	8	$\left(68\sqrt{3}-21\frac{1}{3}\pi\right)r_s^2$	11.67%
28	1	16	$\left(76\sqrt{3}-22\frac{2}{3}\pi\right)r_s^2$	13.89%
	2	9	$\left(79.5\sqrt{3}-25\pi\right)r_s^2$	13.60%
	3	13	$\left(77.5\sqrt{3}-23\frac{2}{3}\pi\right)r_s^2$	13.77%
	4	16	$\left(76\sqrt{3}-22\frac{2}{3}\pi\right)r_s^2$	13.89%
	5	12	$\left(78\sqrt{3}-24\pi\right)r_s^2$	13.73%
32	1	16	$\left(88\sqrt{3}-26\frac{2}{3}\pi\right)r_s^2$	15.78%
	2	13	$\left(89.5\sqrt{3}-27\frac{2}{3}\pi\right)r_s^2$	15.66%
	3	17	$\left(87.5\sqrt{3}-26\frac{1}{3}\pi\right)r_s^2$	15.83%
	4	20	$\left(86\sqrt{3}-25\frac{1}{3}\pi\right)r_s^2$	15.59%
	5	16	$\left(88\sqrt{3}-26\frac{2}{3}\pi\right)r_s^2$	15.78%

From Table I, it can be seen that with the same n_f, the larger m_i^f, the larger the coverage hole area so the larger their ratio. n_f is given during simulations and m_i^f is a random variable constrained by the node total number n and deployment as well as the number of failed nodes n_f. With the node total number and deployment fixed, the more the failed nodes the larger m_i^f probably but not necessarily. In terms of simulation results, coverage hole area and the ratio increase with the increasing of the number of failed nodes.

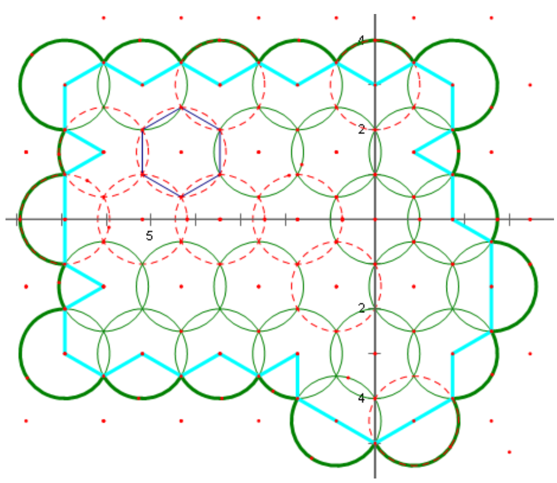

Figure 2. All the nodes in completely covering region

In figure 2, all the nodes completely cover region. The thick green contour line of the complete coverage changes and the polygon with blue sides, connected by the outer nodes and intersection points of their disks on the boundary of the complete coverage range.

The simulation results are practically approximate. Of course, the larger the region is compared to the sensing range of the nodes, the closer the values of S_h and S_c^{all} as well as their ratio are to the real values.

VI. CONCLUSIONS

This paper has discussed the algorithm for solving the coverage hole and the complete coverage range in wireless sensor networks. Its main conclusions can be summarized as follows.

(1)The expression of node coordinates is given. The coordinate origin is set in the position of some node, which is the one located nearly in the middle of the region preferably.

(2)The node deployment based on the united expression of the node coordinates is described. It has been obtained that the location of a node is uniquely determined by a pair of numbers.

(3)The numerical example shows that given a kind of node deployment, a group of area values and ratios corresponding to the different numbers of failed nodes and simulation times can be successfully obtained. The areas of coverage hole and target region as well as their ratio in the optimal coverage are all successfully got for different number of failed nodes at different simulation times.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the Henan province science and technology research plan project (Grant No. 102102310372).

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