Energy-Hole Repair Algorithm for Wireless Sensor Network Based on Cluster

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***Abstract*—Aiming at all existing energy-hole repair algorithms for wireless sensor network must execute repeatedly in every round, energy-hole repair algorithm based on cluster (EHRA) is proposed in this paper. Before any common node is about to die because of exhaustion of energy, it sends failure message to its cluster head, and the cluster head activates suitable redundant node which is in the sensing range of failure node and has the most energy-hole boundary nodes as neighbor nodes. Simulations present that the performance of EHRA is related to sensing radius of nodes and the size of cluster, while EHRA has an advantage over 3MeSH in coverage keeping, energy consumption and time consumption.**

***Index Terms*—wireless sensor network, energy-hole, repair, cluster**

I. INTRODUCTION

Prolonging lifetime of Wireless Sensor Network (WSN) is one of the most important objectives of WSN algorithms [1]. In the process of data collecting in WSN, one node's dead may cause the special region including the dead node can't be monitored effectively, and form an energy-hole. Because of the existence of energy-hole, the data which were transmitted through the energy-hole formerly must be transmitted along the boundary of the energy-hole. Changing transmitting path will raise the energy consumption of network, quicken the dead of boundary nodes of the energy-hole, and enlarge energy-hole quickly, this phenomenon is called funneling effect. Energy-hole and funneling effect together will lead to the quick dead of whole network [2], so how to find out the energy-hole and repair it quickly become more and more important.

Paper [3] presents that energy-hole can be detected by examining whether one node's sensing range can surround its Voronoi polygon. If every node's sensing range can surround its Voronoi polygon, there has no energy-hole, otherwise there has. On the basis, Paper [3] puts forward three methods to repair energy-hole, while all methods' overall train of thought are adjusting all Voronoi polygons' size in network and letting them more and more even by moving nodes. Repairing energy-hole based on Voronoi polygon and moving nodes can secure the coverage of network better in a certain time, but moving nodes will consume much more energy, which can cause the moved node die quickly, and shorten the lifetime of whole network.

Paper [4] puts forward the concept of maximum simplicial complex in order to simplify the connectivity graph of network. On the basis, paper [5] proves that one node can be covered if it can be surrounded by its sub-network (the network composed by its neighbor nodes) in a maximum simplicial complex. So energy-hole can be detected by examining all nodes are covered in maximum simplicial complex or not. Paper [5] repairs energy-hole by deploying new nodes. This detecting and repairing method can repair energy-hole better, but needs to detect energy-hole in every round, and consumes much more energy and time, too.

Paper [6] proposes 3MeSH algorithm in order to detect and repair big energy-hole with at least 4 edges. 3MeSH algorithm judges one node is a boundary node of energy-hole or not by examining the connectivity graph consists of the node and its neighbors can form a 3MeSH ring or not, finds out the energy-hole surrounded by several boundary nodes, and activates prompt redundant node. But 3MeSH algorithm also has two problems, the first one is that it selects several nodes randomly to activate, which can not keep the initial coverage of the network; the second one is that it also needs to detect energy-hole in every round even if there has no energy-hole.

Clustering is an effective way to prolong the lifetime of WSN[7,8], this paper proposes a energy-hole detecting and repairing algorithm based on cluster, which only started when dead node occurs, so as to save time and energy consumption in every round.

II. NET MODEL

(1) In two dimension plane, all nodes except for sink node have the same initial energy. Sink node's energy is not limited.

(2) Every node's sensing range is a circle with the center of itself. All nodes have the same sensing radius named R_s, and R_s is adjustable.

(3) Every node knows its position which can be obtained by several methods [9, 10].

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(4) All nodes' communication radius is R_c, and R_c is adjustable.

III. DEFINITIONS

Definition 1. There are two nodes called A and S, $d(A,S)$ is the distance between A and S, if $d(A,S) < 2R_s$, A and S are neighbors.

Definition 2. As shown in Fig. 1, neighboring nodes A and S have their own sensing cycle named cycle A and cycle S separately. There are two intersection points of cycle A and cycle S named P_L and P_R. Establishing the local coordinate system of node A with the origin of coordinate at the location of node A, the X_A axis paralleling to X axis, and the Y_A axis paralleling to Y axis. The angle between segment $P_L A$ and X_A axis is called intersection left angle ∂_L, the angle between segment $P_R A$ and X_A axis is called intersection right angle ∂_R, this paper defines $\partial_L < \partial_R$, and if P_L is seated in the fourth phase and P_R is seated in the first phase(or the second phase) of the local coordinate system, $\partial_L < 0$.

Definition 3. As shown in Fig. 2, S_1, S_2 and S_3 are the neighbors of node A. The intersection angles of node A and its neighbors are separately $\{\partial_{L1}\ \partial_{R1}\}$, $\{\partial_{L2}\ \partial_{R2}\}$ and $\{\partial_{L3}\ \partial_{R3}\}$. From Fig. 2, we know $\partial_{L1} < \partial_{L2} < \partial_{L3}$, so sort the three pairs of angles in ascending order by intersection left angles as $\{\partial_{L1}\ \partial_{R1}, \partial_{L2}\ \partial_{R2}, \partial_{L3}\ \partial_{R3}\}$, we call $\{\partial_{L1}\ \partial_{R1}\}$ are the front angles of $\{\partial_{L2}\ \partial_{R2}\}$, and $\{\partial_{L2}\ \partial_{R2}\}$ are the next angles of $\{\partial_{L1}\ \partial_{R1}\}$. Cycle S_1 is the front cycle of cycle S_2, and Cycle S_2 is the next cycle of cycle S_1.

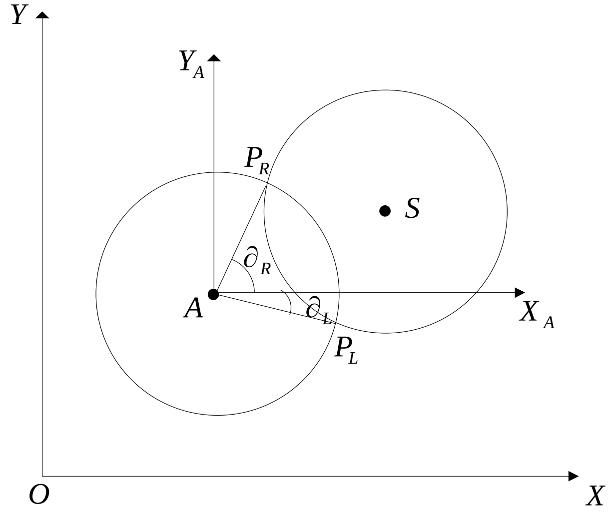

Figure 1. Node position diagram.

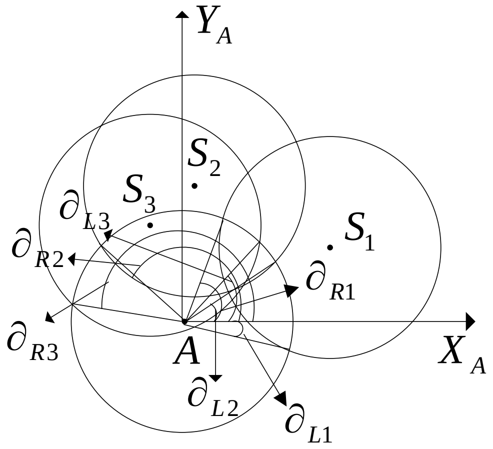

Figure 2. Nodes' intersection angles diagram.

IV. DETERMIN OF REDUNDANT NODES

At the beginning of WSN, the network firstly finds out all redundant nodes, and lets them sleep, then detects energy-holes and repairs them by activating prompt redundant nodes. So the determine of redundant nodes is the base of energy-hole repair.

Theorem 1. Aiming at the cycle sensing model of WSN, node A is a redundant node and can go sleep if it has at least 3 neighbors which satisfy two conditions at the same time: firstly, the distance between them and A are all shorter than R_s; secondly, these neighbors can cover cycle A fully.

Proof: Take three neighbors as example, as shown in Fig. 3.

In Fig. 3, node S_1, S_2 and S_3 are all neighbors of node A, and they are all seated in cycle A. P_3 and P_6 are intersection points of cycle A and cycle S_1, P_2 and P_5 are intersection points of cycle A and cycle S_2, P_1 and P_4 are intersection points of cycle A and cycle S_3, P_7 is the intersection point of cycle S_1 and cycle S_2. If any point H in cycle A is neither in cycle S_1 nor in cycle S_2, it is in the region surrounded by $\overset{\frown}{P_2P_3}$, $\overset{\frown}{P_3P_7}$ and $\overset{\frown}{P_2P_7}$.

Supposing that H is not in cycle S_3.

$$\therefore \qquad S_3 H > R_s \qquad (1)$$

$\because$ Segment $P_1 P_4$ is the perpendicular bisector of segment AS_3

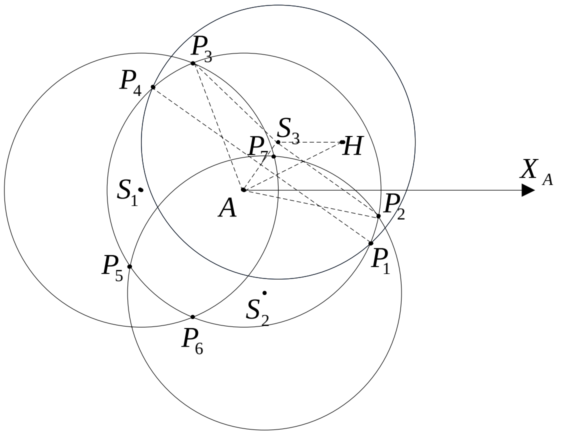

Figure 3. Determine of redundant nodes.

$\therefore$ Any point H in the region surrounded by segment P_1P_4 and $\overset{\frown}{P_1P_4}$

$$S_3H < AH \quad (2)$$

$\because$
$$AH < R_s \quad (3)$$

$\therefore$
$$S_3H < R_s \quad (4)$$

Formula (4) is contradiction with formula (1).

V. Determining of Boundary Nodes

Supposing that redundant nodes have been scheduled, and the dead of any active node will cause energy-hole, this paper supposes that all neighbors of dead nodes are boundary nodes firstly, and then finds out non-boundary nodes of energy-hole in the case of there is a single failure node and there are several failure nodes.

A. Single failure node

Theorem 2. If there is a neighbor node S of node A satisfies two conditions at the same time, the overlap region covered by cycle A and cycle S can be covered by other nodes at the same time, and S is a non-boundary node. The first condition is that the front right angle of node A and node S is bigger than the next left angle of node A and node S. The other condition is that one of the intersection points of the front cycle and the next cycle of S named P is in cycle A, and the distance between P and S is longer than R_s.

Proof: Fig. 2 is redrawn as Fig. 4.

In $\{\partial_{L1}\ \partial_{R1}, \partial_{L2}\ \partial_{R2}, \partial_{L3}\ \partial_{R3}\}$, there is a pair of angles $\{\partial_{L2}\ \partial_{R2}\}$, whose front right angle ∂_{R1} is bigger than their next left angle ∂_{L3}. P_1 and P_2 are two intersection points of the cycle S_2' front cycle S_1 and next cycle S_3, and P_1 is in cycle A. B and D are two intersection points of cycle S_2 and cycle S_3, F is the intersection point of segment BD and cycle A, C and E are two intersection points of cycle S_3 and cycle A.

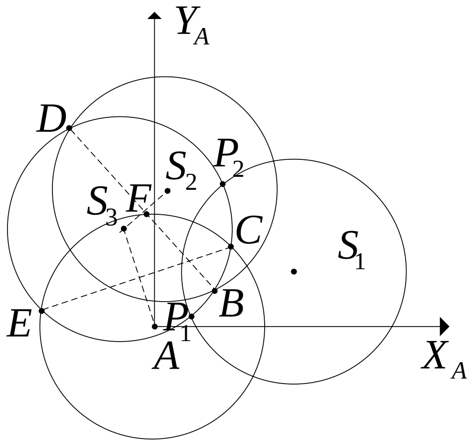

Figure 4. The judgment of non-boundary nodes.

Region 1 is surrounded by $\overset{\frown}{EFC}$ and segment EC, and region 2 is surrounded by $\overset{\frown}{FE}$, $\overset{\frown}{EP_1B}$ and segment BF. Supposing that any point in the overlap region of cycle A and cycle S_2 is not in cycle S_1, it is certainly in the region of union of region 1 and region 2.

Supposing that any point named H_1 in region 1 is not in cycle S_3

$\therefore$
$$S_3H_1 > R_s \quad (5)$$

$\because$ Segment EC is the perpendicular bisector of segment S_3A

$\therefore$
$$S_3H_1 < AH_1 \quad (6)$$

$\because$
$$AH_1 < R_s \quad (7)$$

$\therefore$
$$S_3H_1 < R_s \quad (8)$$

Formula (8) is contradiction with formula (5).

Supposing that any point named H_2 in region 2 is not in cycle S_3

$\therefore$
$$S_3H_2 > R_s \quad (9)$$

$\because$ Segment BD is the perpendicular bisector of segment S_2S_3

$\therefore$
$$S_3H_2 < S_2H_2 \quad (10)$$

$$\because \qquad S_2H_2 < R_s \qquad (11)$$

$$\therefore \qquad S_3H_2 < R_s \qquad (12)$$

Formula (12) is contradiction with formula (9).

So H_1 and H_2 are certainly in cycle S_3.

Points in different location of cycle S_1, S_2 and S_3 can also be proved by the same method.

From Theorem 2 we know that in Fig. 4 if node A dies, node S_2 is a non-boundary node.

If one active node dies, its all neighbor nodes are considered as boundary nodes of the energy-hole caused by the dead node, and then non-boundary nodes are found out based on Theorem 2.

In the case of node density is high, there may several neighbor nodes of node A covering each other, as shown in Fig. 5 and Fig. 6.

In Fig. 5, B is the intersection point of cycle S_1 and cycle S_4 (dotted line), C is the intersection point of cycle S_2 and cycle S_3, and D is the intersection point of cycle S_1 and S_3. The sequence of intersection angles of node A and its neighbors is $\{\partial_{L1}\ \partial_{R1}, \partial_{L2}\ \partial_{R2}, \partial_{L4}\ \partial_{R4}, \partial_{L3}\ \partial_{R3}\}$, there have a pair of angles $\{\partial_{L4}\ \partial_{R4}\}$, whose front right angle ∂_{R2} is bigger than their next left angle ∂_{L3}, as $S_4C < R_s$, S_4 is a boundary node. But there are also a pair of angles $\{\partial_{L2}\ \partial_{R2}\}$, whose front right angle ∂_{R1} is bigger than their next left angle ∂_{L4}, and $S_2B > R_s$, so S_2 is a non-boundary node. If dismiss the pair of angles $\{\partial_{L2}\ \partial_{R2}\}$ from the sequence, the sequence of intersection angles of node A and its neighbors is $\{\partial_{L1}\ \partial_{R1}, \partial_{L4}\ \partial_{R4}, \partial_{L3}\ \partial_{R3}\}$, there have a pair of angles $\{\partial_{L4}\ \partial_{R4}\}$, whose front right angle ∂_{R1} is longer than their next left angle ∂_{L3}, and $S_4D > R_s$, so node

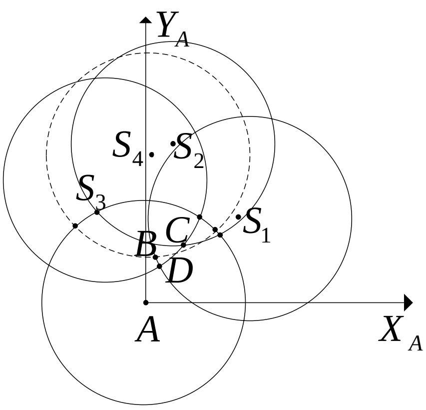

Figure 5. Determining of non-boundary nodes in the case of nodes density is high (case 1).

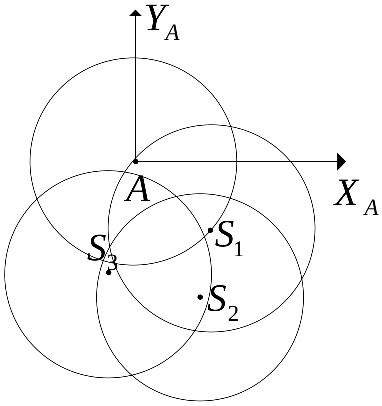

Figure 6. Determining of non-boundary nodes in the case of nodes density is high (case 2).

S_4 is a non-boundary node, so the determine of non-boundary nodes is interrelated.

In Fig. 6, two intersection points of cycle S_1 and cycle A are separately in the third phase and the fourth phase of the local coordination system, the sequence of intersection angles of node A and its all neighbors is $\{\partial_{L1}\ \partial_{R1}, \partial_{L3}\ \partial_{R3}, \partial_{L2}\ \partial_{R2}\}$, so node S_2 is a boundary node according to the analysis above, but in fact, node S_2 is a non-boundary node just from the figure. The sequence of intersection angles must be expanded as $\{\partial_{L1}\ \partial_{R1}, \partial_{L3}\ \partial_{R3}, \partial_{L2}\ \partial_{R2}, 2\pi+\partial_{L1}\ 2\pi+\partial_{R1}\}$, which can secure finding boundary nodes correctly.

So the flow of determining boundary nodes must be adjusted as Fig. 7.

B. Two nodes die at the same time

In the process of operation of WSN, there may be two nodes die at the same time, if the two failure nodes are not neighbors, boundary nodes can be found aiming at every failure node alone, but there may also be two neighboring failure nodes as shown in Fig. 8. Node A_1 and node A_2 are neighboring nodes. Node A_1 has neighbors as S_1, S_2, S_3, S_4, A_2 and S_7. Node A_2 has neighbors as S_7, A_1, S_4, S_5 and S_6. So node S_4 and S_7 are the common neighbors of node A_1 and A_2.

If two neighboring nodes die at the same time, their common neighbors are firstly determined as boundary nodes, other non-common neighbors are determined as single failure node.

In Fig. 8, node S_4 and S_7 are firstly determined as the boundary nodes, other neighbor nodes are determined separately as above, so all neighbor nodes except for node S_5 are boundary nodes.

The process of finding out non-boundary nodes when there are more than two failure nodes can come down to the case of single failure node and two failure nodes.

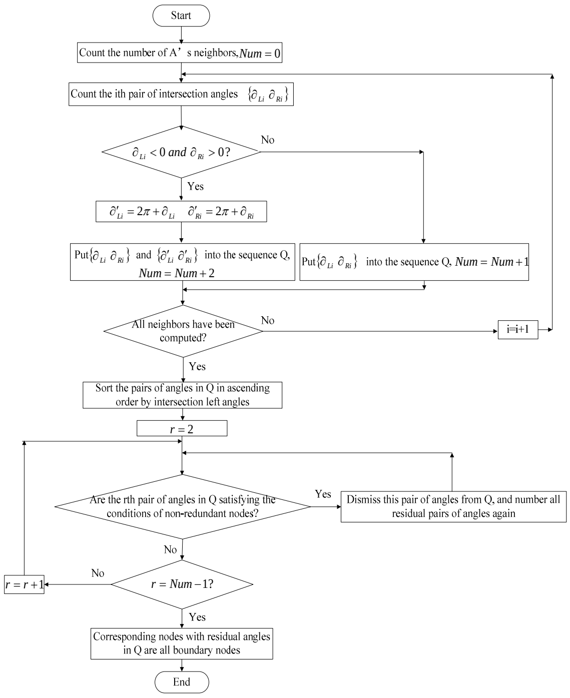

Figure 7. Flow of determining boundary nodes in the case of one failure node.

VI. Selection of Redundant Nodes

The prompt redundant node B to be activated must satisfy two conditions at the same time:

(1) The distance between B and failure node A is shorter than R_s. This because if B is out of the sensing range of node A, the overlap region of B and A is small, the effect of repair the energy-hole is little even if node B is activated.

(2) B has the most neighbor nodes which are boundary nodes of the energy-hole caused by failure node A. This because only the redundant node which has the most neighboring boundary nodes is activated, the energy-hole can be repaired well.

In Fig. 8, node B_1 and B_2 are redundant nodes, when node A_1 failures, because B_2 has neighbors as S_1, S_2, S_3, S_4, A_2 and S_7, while B_1 has only 4 neighbors as

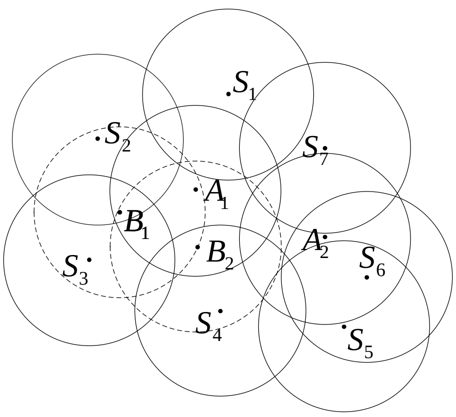

Figure 8. Determining of non-boundary nodes in the case of two failure nodes.

S_1, S_2, S_3 and S_4, B_2 is activated.

VII. Energy-hole Repair Algorithm for WSN Based on Cluster

A. Cluster forming

This paper uses the cluster forming method like LEACH, every node produces a number between 0 and 1 randomly in every round, if the number is smaller than $T(n)$, the node can be the cluster head. The computing method of $T(n)$ is as follows:

$$T(n) = \begin{cases} \dfrac{p}{1 - p \cdot (r \bmod \frac{1}{P})}, n \in G \\ 0, n \notin G \end{cases} \tag{13}$$

G is the set of nodes which have not been cluster heads in the past $\frac{1}{p}$ rounds, p is the percent of cluster heads in the whole net, r is the current round.

After one node is elected as cluster head, it broadcasts its elected message with its biggest broadcast radius, every common node selects the nearest cluster head as its cluster head, and sends its ID number and position message to the cluster head.

B. Cluste head sets up nodes information table

After one cluster head receives all joining message of common nodes, it fuses data from these common nodes, sort nodes according the ID number, and sets up the information table. Information table of nodes in cluster is shown in Table 1.

Node status in Table 1 represents the node is active or not, if the status is 1, the node is active, otherwise sleep. At the beginning of operation, all nodes' status are active.

C. Cluster head judges every node in its cluster is a redundant node or not

Every cluster head judges every node in its cluster is a redundant node or not one by one, if one node is a redundant one, cluster head marks its status as 0. The steps in detail are as follows:

① Sets up the table of distance between nodes in pairs.

Cluster head sets up the table of distance between nodes in pairs in order to avoid computing the distance repeatedly in next steps. The table of distance between nodes in pairs is shown in Table 2.

Where num_i is the number of common nodes in the

TABLE 1.
NODES' INFORMATION TABLE IN CLUSTER

Node ordinal	Node ID	Node coordinate	Current round	status
1	12	(2,6)	1	1
2	15	(3,5)	1	1

ith cluster.

② $j = 1$.

③ Cluster head finds whether there is an active common node in the same position with the jth node. If there is, the jth node is a redundant one, and goes to ⑥, otherwise it is a active one, and goes to ④.

④ Cluster head finds active nodes in the sensing cycle of the jth node.

⑤ Cluster head judges the jth node is a redundant one or not based on the method discussed in part IV. If it is, go to ⑥, otherwise go to ⑦.

⑥ Cluster head marks the status of the jth node as 0, and goes to ⑦.

⑦ $j = j + 1$, if $j < num_i$, goes to ③, otherwise end.

D. Cluster head broadcasts nodes information table in its cluster

After Cluster head judges all nodes' status, it broadcasts the information table in its cluster, every node in the cluster checks its status in the table after it receives the information, if its status is 0, it sleep immediately, otherwise keep active.

Steps above are the basis of repairing energy-hole. The steps of detecting and repairing energy-hole are presented as follows.

E. Failure node sends failure message

Every active node has an energy threshold in order to has enough energy to notify other nodes its failure. If the dying node is a cluster head, the energy it reserves must be enough for sending the failure message to sink node. If the dying node is a common node, the energy it reserves must be enough for sending the failure message to its cluster head.

F. Finds boundary nodes

After receives the node failure message, cluster head finds boundary nodes immediately, the finding method is discussed in part V.

G. Activates redundant nodes

Cluster head finds the prompt redundant nodes using the method discussed in part VI. If sink node receive failure message of a cluster head, it starts a new round for cluster head electing.

TABLE 2.
TABLE OF DISTANCE BETWEEN NODES IN PAIRS

Node ordinal \ Node ordinal	1	2	……	num_i
1	0			
2		0		
……			0	
num_i				0

VIII. ANALYSIS AND SIMULATIONS

A. Time complexity analysis

Because the processes of cluster forming and redundant nodes scheduling are public portion of several algorithm for WSN, so this paper only analyzes the time complexity of repairing energy-hole.

The complexity of every step in the algorithm is as follows:

(1) If the cluster which node A belongs to has N common nodes except for node A, the cluster head must find out all neighbors of node A, compute all intersection angles, and judge node A is a redundant one or not, the time complexity of this step is $O(N)$.

(2) If A failures, supposing that A has D neighbors, while D' neighbors has two intersection points in the first phase and the fourth phase separately in the local coordination system of node A, algorithm needs to judge all D' neighbors are non-boundary nodes or not, the time complexity of this step is $O(D + D' - 2)$.

(3) Cluster head finds redundant nodes satisfying $d(A, B_i) < R_s$, if there are H redundant nodes, the time complexity of this step is $O(H)$.

(4) Cluster head selects prompt redundant node to activate, if the number of redundant nodes satisfying $d(A, B_i) < R_s$ is X, the number of boundary nodes is Y, the time complexity of this step is $O(XY)$.

B. Simulations

In Matlab 7.0, 150 nodes are deployed randomly in 50m×50m square monitor area, while sink node is in the center with the coordination of (25, 25). The value of simulation parameters is shown in Table 3[11].

This paper firstly discusses the effect of R_s on the performance of EHRA, and then compares the performance of EHRA and 3MeSH.

(1) The effect of R_s on the performance of EHRA

R_s has much effect on the performance of EHRA, so take $\{R_s = 8m, 9m, 10m, 11m\}$ to simulate the effect of

TABLE 3.
THE VALUE OF SIMULATION PARAMETERS

parameter	value
E_{elec}	$50nJ$
E_{amp}	$50nJ$
E_{DA} (energy consumption of fusing 1 bit data)	$5nJ$

R_s on the performance of EHRA.

Fig. 9 is the comparison of the life time of network in different value of R_s. From Fig. 9 we know that the life time is becoming longer with the value of R_s increases. For one thing, with the increase of the value of R_s, the number of redundant nodes becomes bigger every round, which can save much more energy. For another thing, in the certain region with certain nodes, the longer the sensing radius is, the more neighbors one node has, the bigger the probability of repairing energy-hole is. While the probability of repairing energy-hole is also influenced by the size of cluster, so the difference of network lifetime in different value of R_s is not much in Fig. 9.

Fig. 10 is the average of energy consumption of detecting and repairing energy-hole caused by failure of common node per round. From Fig. 10 we know that EHRA has no energy consumption in the case of no failure common nodes, once one common node dies, cluster head finds out and activates prompt redundant node immediately, which consumes energy. Energy consumption of detecting and repairing energy-hole in one round in different R_s are general the same, this because EHRA operates based on the node scheduling, cluster head has known all nodes information in its cluster, so in the process of finding boundary nods and redundant nodes needn't exchange information.

Fig. 11 is the average of time consumption of detecting and repairing energy-hole caused by failure of common node per round. From Fig. 11 we know that the time consumption is so small in $R_s = 8m$ that the curve is covered by other curves. The time consumption in $R_s = 10m$ and $R_s = 11m$ are almost the same, and slightly more than in $R_s = 9m$, this because time consumption of detecting and repairing energy-hole is

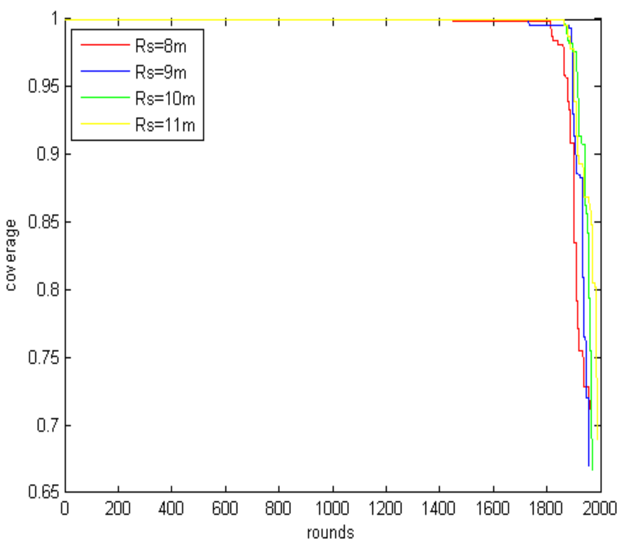

Figure 9. Comparison of network lifetime in different sensing radius of EHRA.

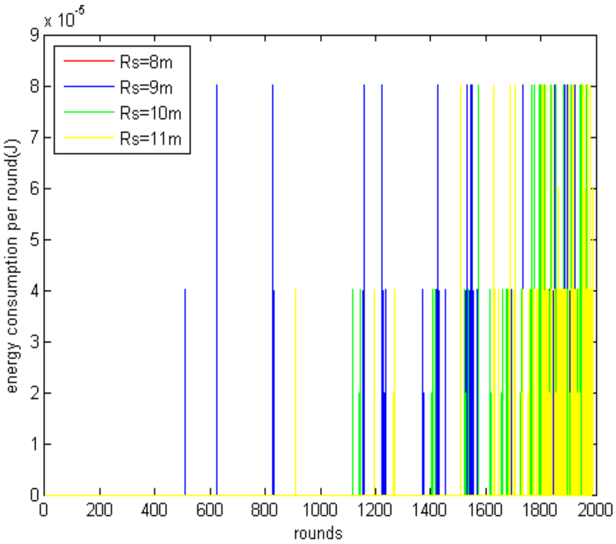

Figure 10. Comparison of average of energy consumption of EHRA per round in different radius.

influenced mainly by the number of neighbors, which is influenced by both number of common nodes in cluster and their sensing radius. When the sensing radius is short, with the increase of radius, the number of neighbors increases, the time consumption of finding boundary nodes also increases, but when the radius is long enough, the time consumption is influenced by the number of common nodes in cluster mainly.

(2) Comparison of EHRA and 3MeSH

In the simulations of 3MeSH, 20 nodes are activated randomly in every round, if other nodes are in the sensing of the active nods, the other nodes go sleep, otherwise go active. EHRA is operated after nodes scheduling, so in the simulations of 3MeSH, the starting is after nodes scheduling, every simulation runs 2000 rounds.

Fig. 12 is the comparison of coverage of 3MeSH in different R_s. As analyzed above, 3MeSH selects several nodes to activate randomly, with the increase of node's sensing radius, the coverage of network increases, but

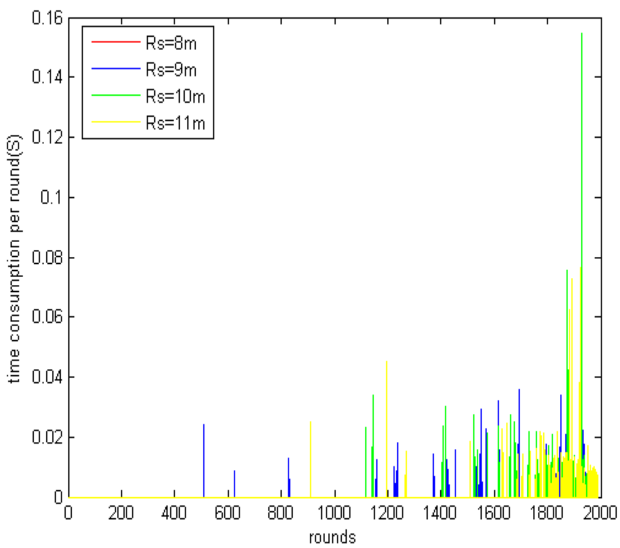

Figure 11. Comparison of average of time consumption of EHRA per round in different radius.

can't reach 100% all the time. This is the most important difference between 3MeSH and EHRA.

Fig. 13 is the energy consumption of 3MeSH per round in different R_s, and comparing between them and EHRA in $R_s = 10m$. From Fig. 13 we know that firstly, energy consumption of 3MeSH in one round is more and more with the increase of node's sensing radius, this because nodes must broadcast with the radius of $2R_s$ in order to keep connectivity of network, which increases the energy consumption. Secondly, energy consumption of EHRA in one round is much less than the energy consumption of 3MeSH in one round, this because 3MeSH needs exchanging message several times in order to find out boundary nodes and energy-hole, while EHRA only detects and repair energy-hole when there has node failure.

Fig. 14 is the time consumption of 3MeSH in one round in different R_s, and compares them with EHRA in $R_s = 10m$. Time consumption is similar with energy consumption.

IX. Conclusion

Aiming at the problem of traditional energy-hole repair algorithms need operate repeatedly in every round, this paper put forward a new energy-hole repair algorithm based on cluster, which goes based on redundant nodes scheduling. Before common nodes failure, they send failure message to their cluster heads immediately, cluster heads find out boundary nodes of energy-hole caused by the failure nodes, and activate prompt redundant nodes. This paper analyzed the time complexity of EHRA, discussed the effect of sensing radius on EHRA, and compared the performance of EHRA and 3MeSH. Simulations illustrated that EHRA can keep the initial coverage of network in a certain time, and its energy consumption and time consumption of repairing energy-hole in every round is much less than 3MeSH's.

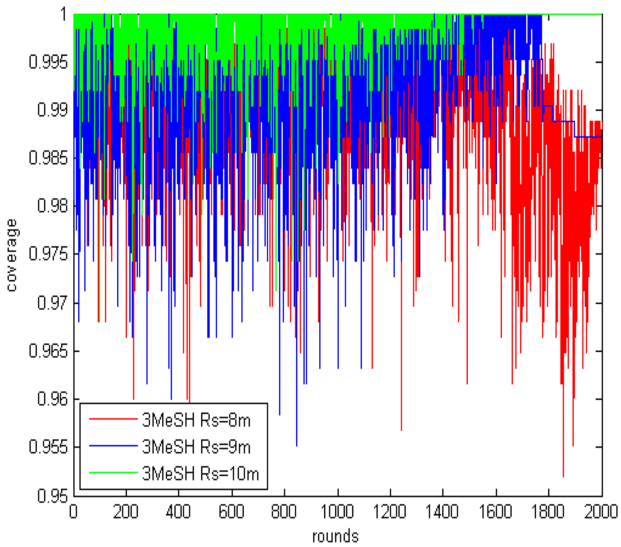

Figure 12. Comparison of coverage of 3MeSH in different sensing radius.

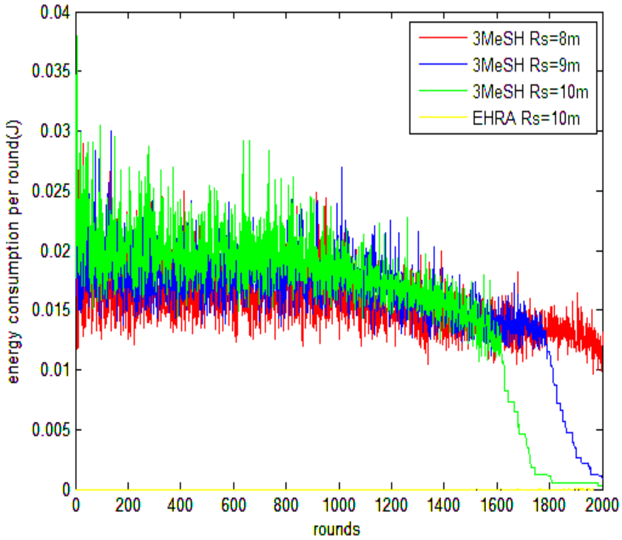

Figure 13. Comparison of energy consumption per round in different sensing radius of EHRA and 3MeSH.

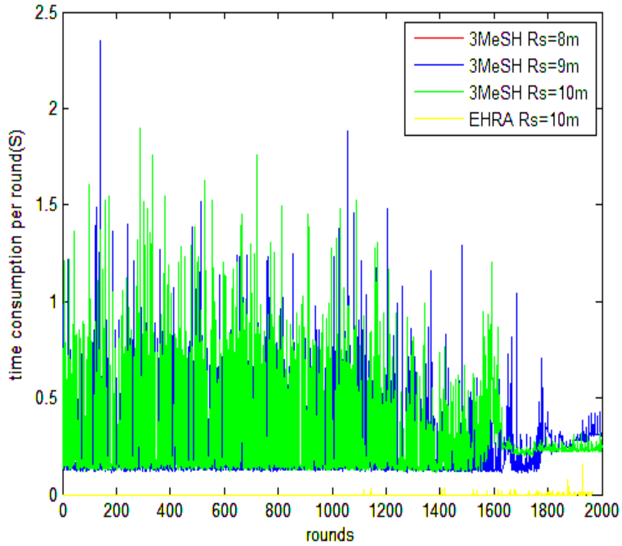

Figure 14. Comparison of time consumption per round in different sensing radius of EHRA and 3MeSH.

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