A Coverage and Repair Optimization Algorithm for Hybrid Sensor Networks

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Abstract

Node deployment is a basic requirement of active monitoring in hybrid sensor networks, especially for unmanned monitoring and dangerous scenes. This paper proposes an optimal coverage, exploration and deployment (OCED) algorithm. A basic behavior set for coverage detection of mobile nodes was designed, the node deployment in non-obstacle areas can completed via a combination of these basic behaviors. When there is an obstacle in the deployment process, the mobile node calculates the position coordinates automatically, and determines whether a static node is deployed according to the distance from the obstacle, thus, the mobile node deploys near-minimal number of sensor nodes and achieves full sensing coverage even services to some unpredicted relatively regular obstacles scene. Moreover, due to the coverage hole caused by the failed nodes, an improved Dijkstra-based deployment strategy is presented to realize network repair. The controllability of the mobile nodes is effectively improved because the deployment behaviors are fulfilled definition and combination. Simulation results show that the proposed OCED algorithm offers deployment efficiency gain with high coverage percentage.

Keywords: Hybrid sensor networks, Mobile node, Coverage, Deployment

1 Introduction

Hybrid sensor networks (HSN) add mobile nodes into wireless sensor networks (WSN) and rely on the controllability and mobility of these mobile nodes. They can implement enhancements of node deployment, coverage detection, and coverage hole repair [1-7]. Node deployment is one of the essential issues in the research field of HSN. According to deployment methods and application requirements, the field can be divided into two subunits: deterministic deployment, also known as fixed deployment; and random deployment, such as the detrimental or dangerous situations of war zones, lack of staff, or other unfavorable situations. The deployed sensor nodes (including static nodes or mobile nodes) self-organize a mesh network, sharing information among all sensor nodes, with the number of deployed sensor nodes being very important for overall costs.

Furthermore, with regards to a deployed WSN monitor area, failure of static nodes (e.g. due to low battery) can cause coverage holes; the coverage repair can then be implemented via mobile nodes. A self-deployment and healing algorithm for installing sensor nodes on the robot base, and verified the navigation performances in environments with and without obstacles is proposed in [8]. In [9], a route planning for network maintenance is proposed, and the charging efficiency of the sensor node is evaluated. Therefore, in order to ensure the coverage of the network, Tian et al. proposed a semi-non-synchronous power-saving mechanism to meet the coverage requirements of regional node deployment [10]. A computational geometry problem of monitoring services based on wireless sensor networks is student in [11], A network deployment and coverage algorithm based on energy priority is proposed in [12]. On the basis of obtaining the residual energy of each node, a node redeployment algorithm is presented to optimize the overall network life in a target monitoring area [13], Wang et al. have proposed a coverage configuration protocol (CPP) algorithm to meet the demands of various regional coverage levels, as well as to dynamically adjust the rate of coverage according to application requirements [14]. Zou et al. introduced a node coverage scheduling algorithm based on virtual forces to realize target location through cluster head nodes on the basis of probability [15]. In summary, all of the above studies discuss the decision problems of network connectivity, coverage, and redundancy in situations where some redundant nodes are placed in sensor networks.

Concerning the WSN with low costs and limited number of nodes, the network coverage repair can predominantly be achieved via external influences,

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such as the recharging of failure nodes, movement of mobile nodes for the deployment of new nodes, or mobile nodes directly acting as new sensor nodes. The results of this study include: Batalin et al. proposed a LRV (least recently visited) coverage detection algorithm, in which node deployment was realized by robots and the deployed nodes can conduct navigation controls for these robots [16]. Chang et al. introduced an OFRD (Obstacle-free robot deployment) algorithm [17-18]. Published literature [19] has introduced a CED (Coverage, exploration and deployment) algorithm, in which robots have realized the coverage deployment and the navigation controls have been done for the robots in the network. Chellappan et al. suggested that the lowest energy consumption algorithm should be studied in the Flip-based sensor network, thus optimizing the displacement distance of robots [19]. Under the condition of constrained energy, node deployment algorithms suited for large cavity areas are proposed in [20-22]. These research methods can achieve full coverage in most cases; however, in case of special monitoring scenarios, coverage will be subjected to vulnerabilities, or to achieve full coverage, more computational overhead will have to be spent.

This paper proposes an optimal coverage, exploration, and deployment (OCED) algorithm. The basic behaviour set of the coverage detection of mobile nodes has been designed. The mobile nodes finish node deployment within monitor areas through a strategy of Z-shaped environmental detection; full-area coverage is satisfied via priority-based deployment strategy and the deployed nodes conform to honeycomb distribution to realize optimal coverage. Moreover, with respect to failure in network connectivity and possible coverage holes in monitor areas, an improved Dijkstra network repair algorithm has been proposed to realize network repair. Finally, the validity of the mentioned algorithm has been verified via simulation analysis.

2 Coverage Model Definition

As shown in Figure 1, a rectangular deployment area was assumed, the coverage strategy of node deployment was based on the Boolean sensing model (BSM) [23], and all of the senor nodes have an identical sensing performance. Events within the monitor area can be detected reliably, while events outside the monitor area cannot be sensed. The strength of the sensor output signal when the senor node at the location of P observes the event at the location of q is:

$$S(p,q)=\begin{cases}\alpha, \|p-q\|_2 \le r_s \\ 1, \ otherwise\end{cases} \quad \textbf{(1)}$$

where $\|.\|_2$ is the Euclidean distance between two nodes, and α is the square of constant measurement value.

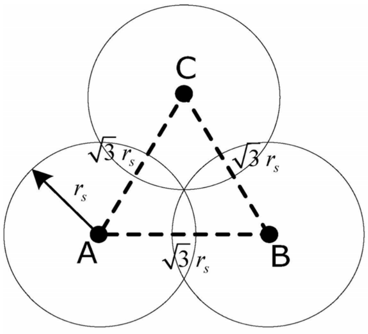

Figure 1. Coverage model of node deployment

Considering both aspects of connection features and coverage features of senor nodes and supposing that the senor nodes can perceive the event within the distance r_s, and the communication radius of nodes r_c ($r_c \ge \sqrt{3}r_s$). The optimal deployment coverage includes a circular sensing area of the three sensor nodes of *A*, *B*, and *C* converging at one point due to the three sensor nodes being adjacent. In this case, the distance between any nodes of A, B, and C is $\sqrt{3}\,r_s$. Therefore, the overlapping monitor area of sensor nodes is strictly controlled, thus the minimum number of sensor nodes has been used to achieve complete coverage.

3 OCED Algorithm

3.1 Basic Behavior of Node Deployment

Assuming the existence of obstacles in the rectangular covering detection area, mobile nodes equipped with distance detection sensors can effectively detect obstacle distance, and the distance as well as the direction of the movement of mobile nodes can be obtained in real time.

According to task requirements of mobile nodes safely moving to target points without collision, the coverage detection rule of U_i for mobile nodes in the horizontal direction (as shown in Figure 2) and the coverage detection rule of V_i for mobile nodes in the vertical direction (as shown in Figure 3) have been designed. The definitions for U_i and V_i are shown in Equation (2) and Equation (3). U_i and V_i define the basic behavior rules set of the mobile nodes, and the deployments in an obstacle free environment is implemented based on the basic behavior rules.

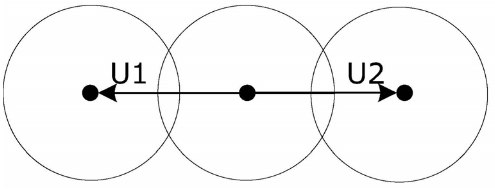

Figure 2. Horizontal rule of coverage direction

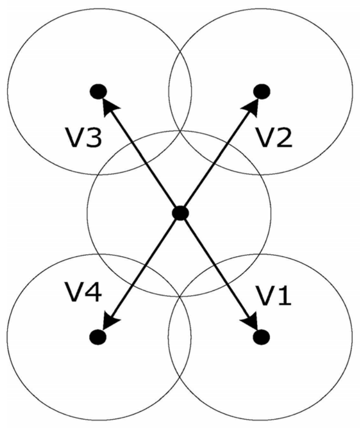

Figure 3. Vertical rule of coverage direction

The coverage detection rule for mobile nodes in the horizontal direction can be defined as follows:

$$\mathrm{U_i} = (r_s, \rho_i) \quad \textbf{(2)}$$

where $\rho_i \in \{0, \pi\}$.

The coverage detection rule for mobile nodes in the vertical direction can be defined as follows:

$$\mathrm{V_i} = (r_s, \theta_i) \quad \textbf{(3)}$$

where $\theta_i \in \{\frac{\pi}{3}, \frac{2\pi}{3}, \frac{4\pi}{3}, \frac{5\pi}{3}\}$.

3.2 Accumulated Cost Evaluation of Coverage Detection

Assuming that no obstacles exist and that the rectangular coverage detection area, both in the horizontal and vertical direction, is composed of the basic behavior set, *K* is defined as the maximum number of nodes deployed with the basic behaviors.

In the process of deployment and detection of mobile nodes, the cumulative costs of the whole detection path can be obtained via summation of the costs of the basic behavior set path and the deployment around the obstacles. For example, according to the above definition of cost functions, the costs of path *l* are:

$$\cos t(l) = \sum_{i \in \mathbb{I}} i\, r_s + \sum_{q \in \mathbb{Q}} q\, l_q \quad \textbf{(4)}$$

where, $\mathbb{I}$ is the location collection selected by mobile nodes according to the basic behaviors of coverage detection, $\mathbb{Q}$ is the total number of obstacles encountered by mobile nodes, l_q is the total path if the mobile node encountered obstacle and moved along it to the prescribed deployment point.

The above equation reveals that the cumulative costs of the deployment path of mobile nodes includes the basic behavior set and the perimeter of obstacles, and avoids the deployment points in the basic behavior set that are close to obstacles from multiple directions and the detection path among obstacles, which improves the total detection path in the whole coverage area.

Mobile nodes at each deployment point cover only one single static node. The boolean variable of $x_{i,k}$ was introduced to denote the alternative relation between the mobile node coverage detection point of *i* and the static node of *K*:

$$x_{i,k} = \begin{cases} 1, \textit{node k is deployed in point i} \\ 0, \textit{otherwise} \end{cases} \quad \textbf{(5)}$$

The variable σ was defined to denote the deployment and detection direction of mobile nodes.

$$\sigma = \begin{cases} 1, & \textit{deploy t}\text{oward the left and down direction} \\ -1, & \textit{deploy t}\text{oward the right and upward direction} \end{cases} \quad \textbf{(6)}$$

Regarding the coverage detection area, the location of mobile nodes for deployment and detection, according to the basic behavior set was defined as follows:

$$\begin{cases} \mathrm{x_i^j} = \sigma(\sqrt{3}(\mathrm{i}-1)\ \mathrm{r_s} + (\mathrm{j}\text{-}1)\frac{3\sqrt{3}}{2}\mathrm{r_s}) \\ \mathrm{y_i^j} = \sigma(\frac{1}{2}(\mathrm{i}-1)\ \mathrm{r_s} + (j-1)\frac{3}{2}\mathrm{r_s}) \end{cases} \quad \textbf{(7)}$$

where $j \geq 1$ and are odd numbers.

$$\begin{cases} \mathrm{x_i^{j+1}} = \mathrm{x_i^j} + \sigma\frac{\sqrt{3}}{2}\mathrm{r_s} \\ \mathrm{y_i^{j+1}} = \mathrm{y_i^j} + \sigma\frac{3}{2}\mathrm{r_s} \end{cases} \quad \textbf{(8)}$$

where $j \geq 1$ and are even numbers.

When conducting deployment around obstacles, three continuous standard deployment points (The black spots shown in Figure 4) in the direction of the *X* axis, and the distance between the mobile nodes and the obstacles, are used to evaluate whether the static nodes are deployed near the obstacles.

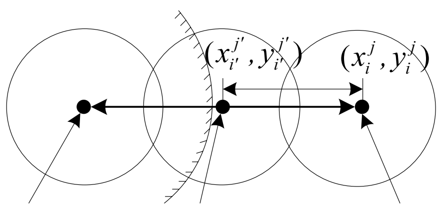

Figure 4. Deployment principle near obstacles

If the condition of Equation 9 is met, the deployment of a static node is carried out; if not, deployment is given up.

$$\begin{cases} \left|\mathrm{x_{i'}^{j'}} \text{-} \mathrm{x_i^j}\right| > \frac{\sqrt{3}}{2} r \\ \left|\mathrm{y_{i'}^{j'}} \text{-} \mathrm{y_i^j}\right| = 0 \end{cases} \quad \textbf{(9)}$$

Deployment Algorithm: OCED for autonomous deployment

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Status: $(x, y, \theta)$ and base vector:
$u = (a, 0), v = (1/2a, \sqrt{3}/2a)$.
Result: Hexagonal grids based courage.
The mobile node implements node deployment coverage strategy, and $\lambda_{ac} \leftarrow 0$;
If exist unconvered hole then
    $(\frac{(i-1)}{2}\sqrt{3}\cdot r, \frac{(3j-2)}{2}\cdot r) \rightarrow \{V_c\}$,
    $i, j \in N, i = \mathrm{INT}(m, \sqrt{3}\cdot r)$ and $j = \mathrm{INT}(n, \frac{3}{2}\cdot r) + 1$;
    If $\mathrm{mod}(m, \sqrt{3}\cdot r) > \frac{\sqrt{3}r}{2}$ then
        $(m, \frac{(3j-2)\cdot r}{2}) \rightarrow \{V_c\}$;
Else
    Save $(\hat{x}_i, \hat{y}_i)$, and Mobile node keeps avoid-obstacle moving;
    For each $B_i$ do
        If $\sum_{l=1}^{k} \bar{B}_l > \tilde{\lambda}$ then Save $(x_{B_l}, y_{B_l})$
        Else
            $\lambda_{ac} \leftarrow \lambda_{ac} + \lambda_{current}$;
            If $\mathrm{mod}(\sum_{l=1}^{k}(\bar{B}_l \cdot \cos(\lambda_{ac})) - \hat{x}_i, \sqrt{3}a) \cdot \mathrm{mod}(\sum_{l=1}^{k}(\bar{B}_l \cdot \sin(\lambda_{ac})) - \hat{y}_j, \frac{3}{2}a) = 0$
            then $B_k \rightarrow \{V_c\}$;
        End
End
```

The aim for the detection selection of mobile nodes was to minimize deployment path under the premise of meeting the coverage requirements in all areas, while minimizing the number of deployment nodes. Therefore, this problem can be described as the following optimization problem that meets specific restrictions.

$$\max \quad l \tag{10}$$

$$s.t. \quad |x_n - x_{n-1}| > \frac{\sqrt{3}}{2}r \tag{11}$$

$$\sum x_{i,k} \leq \mathbb{K}, \forall i \in \mathbb{I} \tag{12}$$

$$\sum_{i \in \mathbb{I}} x_{i,k} = 1, \forall k \in \mathbb{K} \tag{13}$$

Equation 11 shows that the detection selection strategy of mobile nodes cannot cover excessively; thus, repeated detection was not allowed under the condition of complete coverage. Equation 12 indicates that the deployment and detection scheme of mobile nodes must satisfy the limitation of not exceeding the total number of nodes. Equation 13 expresses that each deployment point can only deploy one static node.

3.3 Deployment Algorithm Procedure

Assuming a rectangular coverage area of $m \times n$ results in a deployment and coverage process of mobile nodes. Mobile nodes start the operation of node deployment from the location $(0, r/2)$. $\{V_c\}$ is the set of distribution points, $\{B_k\}$ is the set of obstacle detection points, and N is the set of natural numbers. The *INT* function is rounded down to the nearest integer.

4 Simulation Results and Analysis

This paper assumes that the mobile nodes are equipped with obstacle detection sensors, such as infrared, ultrasound, etc., and the motion behavior of mobile nodes can be accurately controlled. To verify the validity of the proposed OCED algorithm, a rectangular region with concave obstacles is presented in Figure 5. The above mobile nodes have been used to deploy movement behaviors. The above mobile node deployment behavior was used. The communication and sensing range of each node are set at both 40m, maximum number of deployed nodes is 100, and the total number of obstacles encountered by mobile nodes is 50. The red dotted circle denotes node-sensing areas; the red straight line denotes the movement track of mobile nodes; and each black dot denotes locations of node deployment. When the mobile node starts carrying out the deployment tasks from the top left corner and in the process of moving to target locations, a hole appears at the front-left of the obstacle at the north of the mobile node, which is detected at the location of Point 35. The mobile node conducts detection along the obstacle towards the left, moves to the location of Point 36, then crosses an obstacle again and successfully arrives at the location of Point 37. Consequently, it successfully reached the inner side of the "trap" environment and avoids the coverage hole mentioned in previous publications [19-20]. Similarly, the mobile node adopts the same node deployment strategy to accomplish complete coverage in the right area.

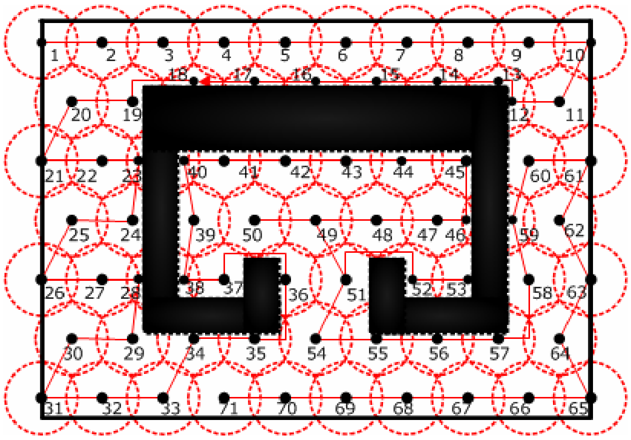


Figure 5. Node deployment strategy in a concave region

A comparison of coverage rates in the OCED algorithm, OFRD algorithm, CED algorithm, and LRV algorithm under the environment of obstacles with different shapes, is shown in Figure 6. The OCED algorithm uses the connected path coverage and the deterministic area / point covering method; therefore, the coverage efficiency is high. The node deployment and coverage conforms to a honeycomb distribution, and the complete network coverage was obtained via a priority-based deployment strategy. This approach revealed that the OCED algorithm could realize complete coverage under the environment of different obstacles.

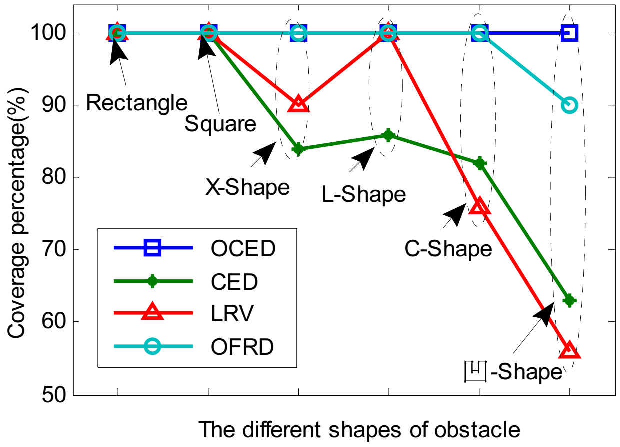


Figure 6. Coverage rate evaluation with different sharp obstacles

Network coverage should guarantee continuous network connectivity and the complete coverage of target areas, including that there should be no coverage holes. Moreover, it should minimize the number of deployed sensor nodes and must have higher deployment and coverage efficiency. The analysis of deployment efficiency of the OCED algorithm is shown in Figure 7. This analysis reveals that the deployment time for complete coverage in the OFRD algorithm is noticeably less compared to both the CED and LRV algorithms. Furthermore, the deployment efficiency of the OCED algorithm is higher than that of the OFRD algorithm, because the way of a straight-line movement was used in the OCED algorithm. Therefore, the deployment and coverage efficiency has been improved in the OCED algorithm.

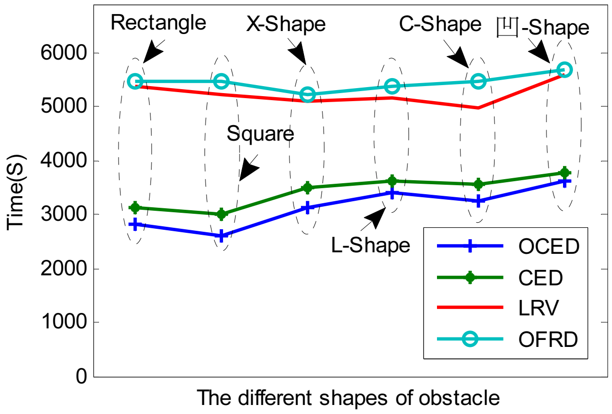


Figure 7. Deployment efficiency evaluation with different shape obstacles

For mobile nodes, the sensing range has different effects on deployment efficiency. In the obstacle condition shown in Figure 5, the comparison of deployment time under different sensing ranges is shown. Figure 8 shows that the proposed OCED algorithm performs best in terms of deployment efficiency. Moreover, when the sensing range is small, the mobile node will detect the characteristics of the obstacle, and the deployment time will increase. Simultaneously, when the sensing range increases to a certain situation, the node deployment time will gradually become stable.

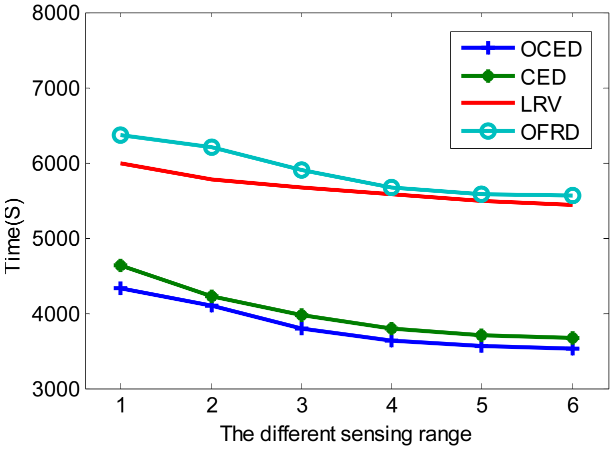


Figure 8. Comparison of deployment time under different sensing range

5 Dijkstra-based Optimal Repairing Algorithm

Path planning of sensor network repair means that the mobile node searches for an optimal or approximately optimal collision-free path from the start state to target state according to an optimal walking path. For the stage of node deployment to detect the monitoring environment, the mobile node has obtained information about the location, shape, and size of some obstacles. In the process of network repair, the mobile node should avoid colliding with encountered obstacles.

The implementation process of the Dijkstra algorithm produced a tree with s as the root node. With the step execution of the Dijkstra algorithm, the tree stretches out in every direction until it reaches the node of t . As the energy of nodes in sensor networks is limited, it is necessary to optimize the algorithm to reduce redundant branches and delete some of these during algorithm processing. Therefore, reducing the time required to calculate the shortest path, and improving algorithm execution efficiency.The following summarizes the optimization progress of the Dijkstra algorithm: Assuming a regional map is firstly established, when updating the shortest path and selecting the node with minimum path value, only the neighbor mother node set of nodes and the difference set of the neighbor mother node set of all nodes in the marked set and that in the already marked set will be involved. Furthermore, when looking for a path from a starting point to an end point on the map, the path that is close to the line connecting both points will be considered first. Irrelevant branches should be removed at the starting point of each path, thus reducing the calculated amount in the algorithm and ultimately improving the efficiency of network repair.

Input. the regional map is established and fuzzy processing is performed for irregular obstacles; a specific number of representative nodes is taken from the network node set to establish both node sets of s and t ; therefore, arriving at the Cartesian product $C=S\times T=\{(s,t)\,|\,s\in S,t\in T\}$. Each element in C is the source of the unknown shortest path and the pair of target nodes. The serial number of network nodes is 1, 2, …, n and the position coordinate of nodes is (x_i,y_i) ($i=\overline{1,n}$). The edges (e_{i1} , e_{i2} , …, e_{ij}) of the neighbor mother nodes, which are related to the node of i are arranged in a counterclockwise direction from small angles to large angles.

Output. The shortest path between s and t .

① Initialize S = {s}, $T=M-S$, $W_i=d_{si}\ (i\in NB_s)$, where NB_s is the mother node set of the neighbor node of s; otherwise, $W_i=\infty(i\notin NB_s)$.

② Connect s and t to form a straight-line segment of $\overline{st}$; if there is one edge between s and t , the edge is the desired path; if there is one edge chain on $\overline{st}$, the edge chain is the desired path; otherwise, go to ③.

③ If $\lambda_{s,r}=\min\lambda_{s,j}(j\in NB_s\text{且}r\le n)$, when $t\not\subset S$, $S=S\cup\{r\}$ and $Count_{s,r}=\sum W_r$; when $t\subset S$, $Count_{s,t}=\sum W_r$ and the algorithm terminates. Continue to execute ③ until $S=S\cup\{r,r+1,\cdots,r+k\}$.

④ Replace s with $r,r+1,\cdots,r+k$, respectively to repeat the processes of ② and ③, and calculate the weight of each connected component in the sub-tree with the roots of $r,r+1,\cdots,r+k$, respectively according to the following equation:

$$Count_{s,x}=d_{s,y}+\sum W_{s,y} \qquad \textbf{(14)}$$

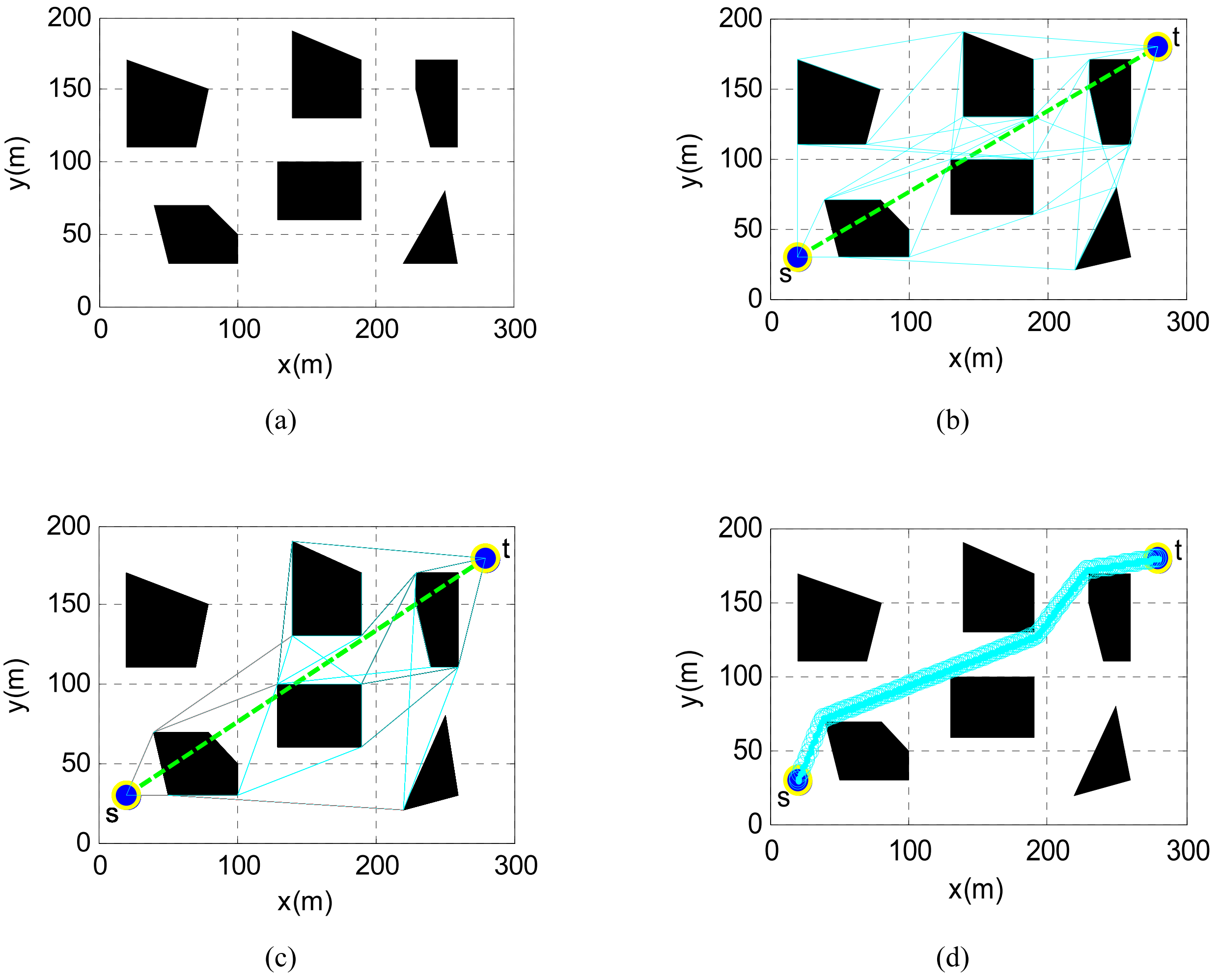
where, $\sum W_{s,y}$ is the total weight of the branch in the prior sub-tree and $d_{s,y}$ is the weight of new edges.

⑤ If $|S|=n$, all nodes are identified and the algorithm terminates; the smallest node of W_j in the $S\ (i\in S)$ is selected and should be grouped into $S\ (i\in S)$ ($Count_{sum}=\min Count_{s,x}$); otherwise, go to ②.

This Dijkstra-based optimal repairing algorithm is used for detection in a typical obstacle environment, as shown in Figure 9. Figure 9(a) reveals that the shortest path from s to t is the polyline, which consists of segments and its starting point. End points are s and t , respectively. The number of neighbor mother nodes in Figure 9(b) is set to 3. The number of neighbor mother nodes in Figure 9(c) is set to 2. The shortest repair path of the mobile node is shown in Figure 9d, revealing that when updating the value of the shortest path and selecting the smallest node with the shortest path value, only the neighbor mother node set of nodes and the difference set of the neighbor mother node set of all nodes in the marked set and that in the already marked set are involved in the optimized Dijkstra algorithm; the running time depends on the number of elements in the neighbor mother node set of connection points. Furthermore, the path that is closest to the line connecting starting point and end point is preferably selected; therefore, the nodes involved in the calculation are reduced, thus reducing energy consumption of the node.

6 Conclusions

Node deployment is a basic problem in HSN-based applications, reflecting the status of being monitored and tracked in a certain WSN monitoring area. This study introduces an OCED algorithm, where the mobile node finishes node deployment via a strategy of Z-shaped environmental detection. The deployed nodes conform to a honeycomb distribution to realize optimal coverage. Moreover, an improved Dijkstra network repair algorithm has also been proposed: when updating the value of the shortest path and selecting the smallest node with the shortest path value, only the neighbor mother node set of nodes and the difference set of the neighbor mother node set of all nodes in the marked set and that in the already marked set are



(a) (b) (c) (d)

Figure 9. Deployment repair simulation process

involved in the improved algorithm. The running time depends on the number of elements in the neighbor mother-node set of connection points. The path that is closest to the line connecting the starting point and the end point is preferably considered; therefore, the nodes involved in the calculation are reduced, thus reducing energy consumption of the nodes and consequently improving the efficiency of network repair.

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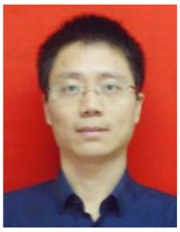
Biographies



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