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Node deployment of band-type wireless sensor network for underground coalmine tunnel

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ABSTRACT

Proper node deployment is the first step to build a Wireless Sensor Network (WSN) system. Therefore, a detailed study on mathematical 3D node deployment is carried out in this paper with the purpose of increasing the coverage efficiency of WSN in underground coalmine tunnel. Firstly, a 3D band-type node deployment model is proposed and in which part, several important characteristics of node deployment are discussed in detail, such as radio features, sensing efficiency, redundancy principles and coverage features. Secondly, a targeted node deployment algorithm is brought up and the core method of interval computing is put forward, thus the node interval can be computed accordingly. Thirdly, we use simulated annealing method to optimize the deployment algorithm proposed. The results show that the characteristics of node deployment in coalmine tunnel affect the network coverage dramatically. Moreover, comparing with the current deployment strategies, the optimized deployment provided by us can promote the coverage efficiency markedly.

1. Introduction

Impactful monitoring systems, such as environment monitoring, miner location and machine condition monitoring are used to diagnose equipment faults and provide early disaster warning in coalmine. Wireless Sensor Network (WSN) is adopted to build these robust monitoring systems as it has many characteristics which adapt to the working conditions in underground coalmine, such as mobility of nodes, ease of use, low-cost power consumption, scalability to large scale of deployment. Node deployment is the first step to build a WSN system. According to the manner of node placement, current deployment approaches can be classified into three categories, which are random deployment [1], incremental deployment [2–8] and movement-assisted deployment [9–13]. All this work has brought great progress to node deployment. However, they cannot be used in coalmine directly as the limits of geographical conditions.

Fig. 1 shows a common used monitoring network in coalmine, which consists of both wireless and wired networks. The wireless part is used to gather the data of distributed sensors, and the wired part is used to forward the massive sensor data. As the position of the wired relay nodes are determined by the position of the interface of Coalmine Industrial Ethernet, the most important factor that affects the monitoring system is the deployment of wireless sensor nodes.

2. Related works

So far, researches on node deployment in underground coalmine tunnel are scarce. ZHU et al [14,15] have deployed a 2D band-type wireless sensor network in coalmine. Comparing to the random node deployment strategy, the strategy proposed in this work can prolong the lifetime of the network by two times. WU et al. [16] have proposed a holistic routing approach for underground coalmine by considering different node deployment strategies. Li et al. [17] have deployed a mesh WSN for mining workface. Wang et al. [18] have proposed a node deployment strategy for achieving high-accurate localization and high-reliable communication in coalmine.

These achievements lay a great foundation for deploying a WSN in coalmine, and parts of them are mainly supporting technologies of WSN in coalmine, such as routing protocol and localization algorithm, parts are about approximate deployment in 2D plane. Currently, a much more accurate node deployment model of WSN in coalmine is eagerly needed. Therefore, a detailed research on a mathematical 3D band-type node deployment model which is proposed on the foundation of a more actual situation in coalmine is presented in this paper.

This paper is organized as follows: Section 3 gives a detailed model of 3D deployment in coalmine tunnel including radio features, sensing features and coverage features. A node deployment approach and its optimization are proposed in Sections 4 and 5.

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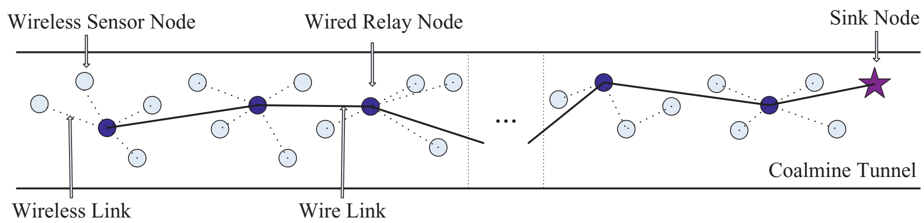

Fig. 1. Monitoring network in coalmine.

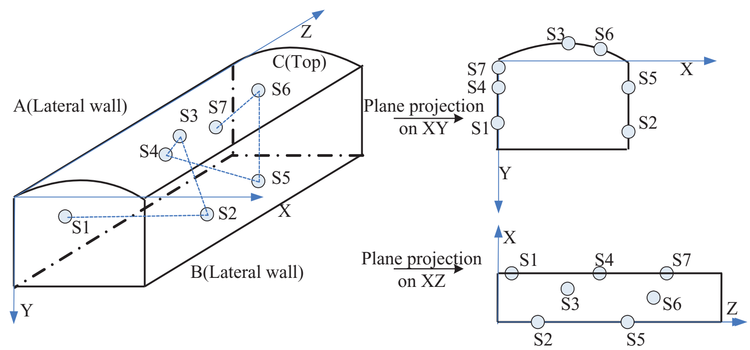

Fig. 2. Sketch of wireless sensor node deployment in underground coalmine tunnel.

Section 6 presents the performances of deployment approach. And Section 7 makes a conclusion for this paper.

3. The 3D band-type node deployment model in coalmine tunnel

3.1. Overview of the node deployment model

For building the model of 3D band-type node deployment in coalmine tunnel, a few reasonable assumptions are given as follows:

Assumption 1. All the sensing nodes are isomorphic.

The nodes have the same physical structure in WSN, that is, all the nodes have the same sensing properties and communication capabilities.

Assumption 2. The sensors carried by wireless nodes are omni-directional.

WSNs in underground coalmine tunnel mainly focus on monitoring environment, positioning and tracking personnel and equipment, and most sensors are omni-directional. Therefore, the sensors carried by nodes are assumed to be omni-directional in this paper.

As shown in Fig. 2, the wireless sensor nodes can only be deployed on the Top and two Lateral walls (the bottom surface is the working area) in coalmine tunnel. From the perspective of the topological graph, nodes are all located in three sides of the XY projection plane and in the internal of the rectangular of the XZ projection plane. Let parameters L, H and D denote the length, height and width of the coalmine tunnel respectively, r_s denotes the sensing radius of a single sensor node, K denotes coverage degree. Our goal is to obtain the optimal coordinates of all nodes based on the parameters (L, H, D, r_s and K).

3.2. Radio features

Both the sensing and communication radii affect the node deployment in WSN. As the communication radius is determined by the radio channel, radio features in coalmine tunnel should be evaluated. In this section, the characterization of the radio channel for ISM 2.4 GHz WSN in coalmine tunnel is presented.

Table 1
3D Ray launching simulation parameters.

Parameters	Value
Transmitted power level	18 dBm
Frequency	2.4 GHz
Receiver sensitivity	−85 dBm
Resolution (cuboids size)	50 cm × 50 cm × 50 cm
Number of reflection	3

For the assessment of the impact generated by the topology and the morphology of these environments on electromagnetic propagation, a 3D ray-launching method [19,20] has been used. A typical coalmine tunnel has been considered for the simulations as depicted in Fig. 3. The length, width and height of the coalmine tunnel are 100 m, 5 m, and 3.5 m. There are 12 miners and 2 mining cars with railway in the tunnel. As shown in Fig. 4, 12 antennas have been distributed in the coalmine tunnel, considering the real antennas properties, where Ai ($i = 1,2,..,6$) denote the transmitters and Bi ($i = 1,2,..,6$) denote the receivers. The parameters defined for the simulations are shown in Table 1.

Fig. 5 shows the obtained received power planes at height 2 m, when the transmitter is placed at the Ai ($i = 1,2,..,6$) shown in Fig. 4. Fig. 6 presents the average received power. It indicates that the position of transmitting antenna produces less influence on received power. As the receiver sensitivity of the most receivers under 2.4 GHz, such as Zigbee Mote, is lower than −85 dBm, the propagation distance of 2.4 GHz radio is larger than 80 m in main tunnel.

Fig. 7 shows the received power at each of receiving antennas Bi ($i = 1,2,..,6$), when the radio is transmitted from A1. It illustrates that the average receiving power is −55.91 dBm when the propagation distance is 70 m, and the position of the receiving antenna produces less influence on the received power in coalmine tunnel.

From the analyses made above, we may come to the conclusion that 70 m is a trusty propagation distance in main coalmine tunnel. Some experimental studies [21,22] have also proved this conclusion. On the other hand, in respect of sensing, the working radii of the sensor carried by nodes are less than 10 m in the most applications of coalmine. As the sensing radius is much less than the

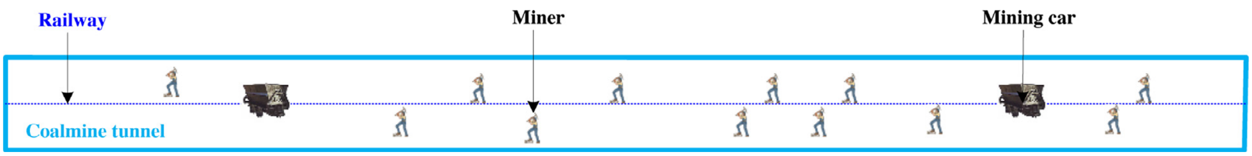

Fig. 3. Simulation scenario.

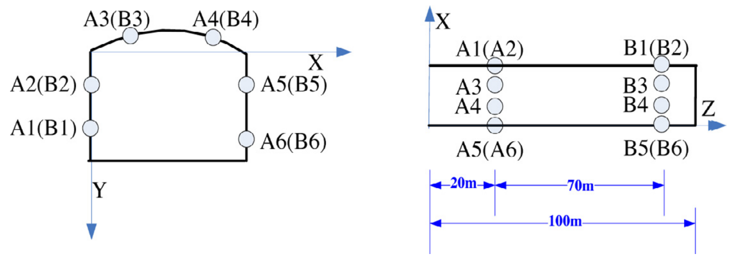

Fig. 4. Positions of antennas.

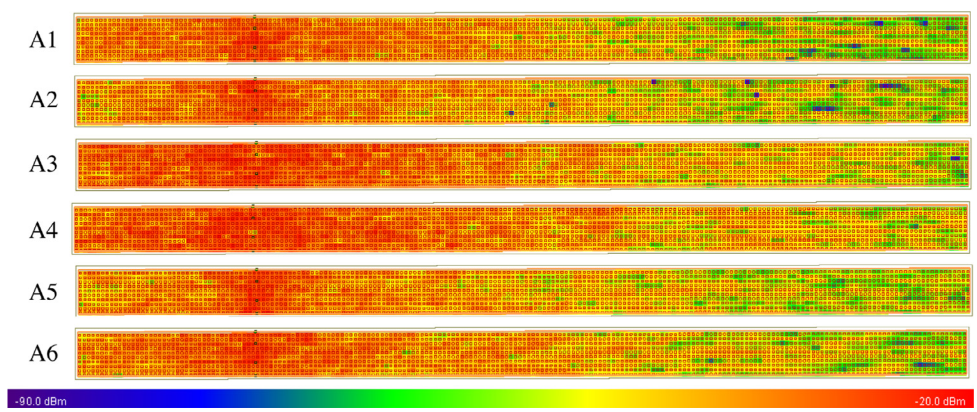

Fig. 5. Received power planes at height 2 m.

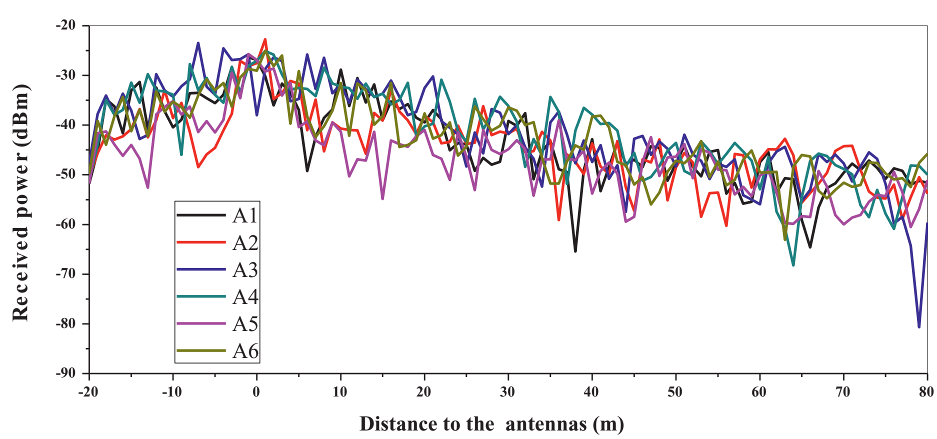

Fig. 6. Average received power at *XY* projection plane.

communication radius, the sensing character of node becomes to the most direct factor of deployment.

3.3. Sensing efficiency

Sensor node coverage is often less than the maximum effective coverage as the limits of the terrain conditions. Here we define the sensing efficiency as the ratio of actual coverage to maximum effective coverage, which is

$$\tau_s = \frac{V_s(r_s)}{V_M(r_s)}$$

Where r_s is the sensing radius, $V_s(r_s)$ is the actual sensing coverage, $V_M(r_s)$ is the maximum sensing coverage.

As the sensor node is omni-directional, $V_M(r_s)$ is the sphere volume with the radius of r_s. Then

$$\tau_s = \frac{V_s(r_s)}{V_M(r_s)} = \frac{V_s(r_s)}{\frac{4}{3}\pi {r_s}^3} = \frac{3V_s(r_s)}{4\pi {r_s}^3} \tag{1}$$

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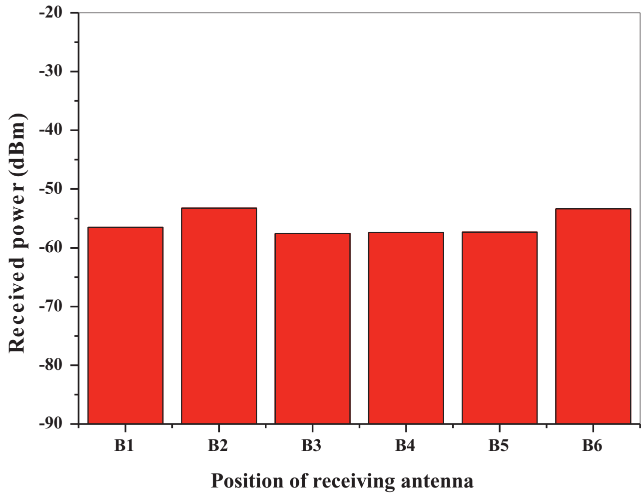

Fig. 7. Received power at each of receiving antennas.

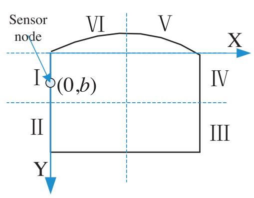

Fig. 8. Node positions on *XY* projection plane in coalmine tunnel.

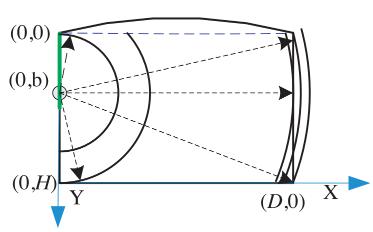

Fig. 9. Coverage volume of wireless sensor nodes.

As shown in Fig. 8, without considering the effect of slightly-arc flat on the top area, it is obviously true that the sensor nodes have the same sensing characteristics in regions I, II, III, IV, V and VI. Therefore, node in region I $(0, b)$ can be used to reflect the sensing characteristics of sensor nodes in coalmine tunnel, where $0 \le b \le H/2$.

Theorem 1. The coordinate of node with maximum sensing efficiency in region I is $(0, H/2)$, and the maximum sensing efficiency is

$$\tau_{sI\,max} = \frac{3\int_0^m \pi\left(r_s{}^2 - x^2\right)dx - 6\int_0^n \left(\left(r_s{}^2 - x^2\right)\arccos\left(H/2\sqrt{r_s{}^2 - x^2}\right) - b\sqrt{r_s{}^2 - (H/2)^2 - x^2}\right)dx}{4\pi r_s{}^3} \quad (2)$$

where

$$m = \begin{cases} r_s & \text{if} \quad r_s \le D \\ D & \text{if} \quad r_s > D \end{cases},$$

$$n = \begin{cases} 0 & \text{if} \quad r_s \le H/2 \\ \sqrt{r_s{}^2 - (H/2)^2} & \text{if} \quad H/2 < r_s \le \sqrt{D^2 + (H/2)^2} \\ D & \text{if} \quad r_s > \sqrt{D^2 + (H/2)^2} \end{cases}.$$

Proof. As shown in Fig. 9, the actual coverage volume is determined by sensing radius, width and height of coalmine tunnel. The coverage volume of node

$$V_{sI}(r_s) = V_{hs} - V_{-hb} - V_{+hb}$$

where V_{hs} is the hemisphere or hemisphere segment volume, V_{-hb} and V_{+hb} are the hemisphere crown volume from *Y*-axis positive and negative direction respectively.

Then, we have $V_{sI}(r_s) = \int_0^m f(x)dx - \int_0^n g(x, b)dx - \int_0^p g(x, (H-b))dx$ where $f(x) = \pi\left(r_s{}^2 - x^2\right)$, $g(x, y) = \left(r_s{}^2 - x^2\right)\arccos\frac{y}{\sqrt{r_s{}^2 - x^2}} - b\sqrt{r_s{}^2 - y^2 - x^2}$, $m = \begin{cases} r_s & \text{if} \quad r_s \le D \\ D & \text{if} \quad r_s > D \end{cases}$,

$$n = \begin{cases} 0 & \text{if} \quad r_s \le b \\ \sqrt{r_s{}^2 - b^2} & \text{if} \quad b < r_s \le \sqrt{D^2 + b^2} \\ D & \text{if} \quad r_s > \sqrt{D^2 + b^2} \end{cases},$$

$$p = \begin{cases} 0 & \text{if} \quad r_s \le H - b \\ \sqrt{r_s{}^2 - (H-b)^2} & \text{if} \quad H - b < r_s \le \sqrt{D^2 + (H-b)^2} \\ D & \text{if} \quad r_s > \sqrt{D^2 + (H-b)^2} \end{cases}$$

It is obviously true that $V_{sI}(r_s)$ is an increasing function in interval $0 \le b \le H/2$ and takes its maximum when $b = H/2$. Then we can easily obtain the results in Theorem 1.

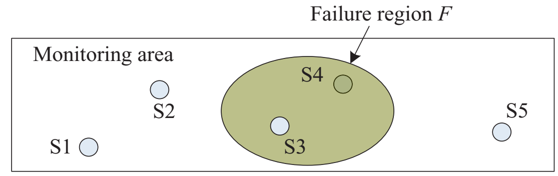

Fig. 10. Sketch of efficient coverage redundancy.

3.4. Redundancy principles

The coverage of a wireless sensor node is often multiple, so there are redundant relationships among neighbor nodes. In practical applications of coalmine tunnel, the failures of nodes are often caused by coal and rock collapse. As shown in Fig. 10, nodes S1, S2, S4 and S5 have part of or complete redundant relationships with S3. S4 will fail to achieve coverage redundancy, if the failure of S3 is caused by collapse of region *F*. Therefore, in order to obtain the most effective coverage, distance among nodes should be as far as possible, and redundant nodes should not be on the same plane. It means that the deployment of wireless sensor nodes in coalmine tunnel should obey the following basic principles.

1. Redundant nodes should be deployed in different planes averagely.

   If the monitoring area is covered by *K* sensing nodes (*K* is the number of the nodes), the *K* nodes should be deployed on three different planes (Lateral wall A, Lateral wall B and Top C) as uniform as possible.

2. The Euclidean distance among redundant nodes should be as maximal as possible.

The adjacent nodes should be deployed on different planes under the premise of maximum sensing efficiency.

3.5. Coverage features

In order to achieve the optimal coverage capabilities of WSN in coalmine tunnel, the coverage features of WSN in coalmine need to be discussed.

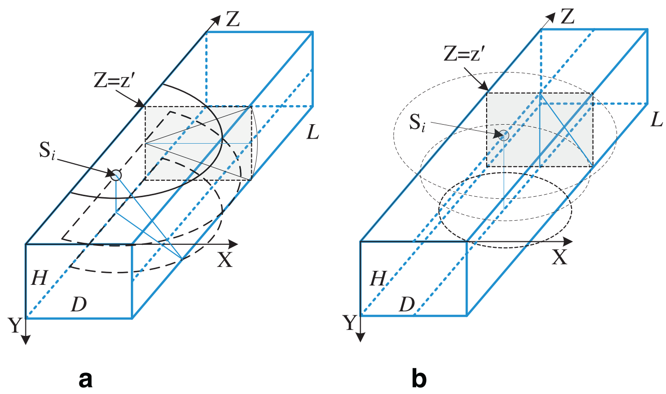

Fig. 11. Mapping from 3D coverage to 2D coverage.

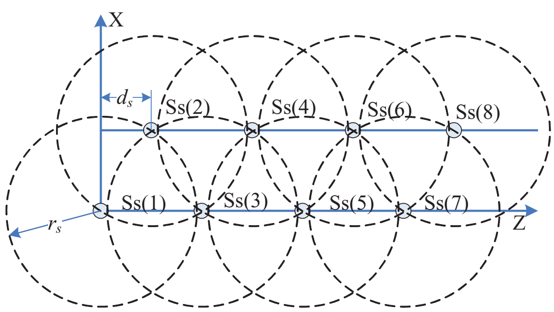

Fig. 12. Average node deployment on two sides.

Theorem 2. The necessary and sufficient condition of 3D *K*-coverage of coalmine tunnel is that the bottom surface of tunnel is covered by *K* sensor nodes.

Proof. As shown in Fig. 11, 3D space can be decomposed into many 2D planes which are perpendicular to *Z*-axis. Similarly, 2D $Y = H$ plane (bottom of the tunnel) can be decomposed into many lines which are perpendicular to *Z*-axis on the same plane. Therefore, the proposition can be further equivalent to that the $Z = z'$ plane is of *K*-coverage when any line on $Y = H$ plane is *K*-covered by sensor nodes and vice versa.

As the wireless sensor nodes can only be deployed on the Top and two Lateral walls in coalmine tunnel, it is obviously true that the intersection line of $Y = H$ and $Z = z'$ plane is farthest from the node *Si*. Therefore, the $Z = z'$ plane is covered by *Si*, when the intersection line of $Y = H$ and $Z = z'$ plane is covered by *Si*.

According to Theorem 2, the problem of 3D coverage in coalmine tunnel turns to be how the nodes on two Lateral walls and Top cover the bottom of tunnel.

4. Node deployments

4.1. K_s-coverage by nodes on two Lateral walls

According to the requirements of the efficient coverage redundancy, adjacent nodes on *XZ* projection plane need to be deployed on two Lateral walls respectively. As shown in Fig. 12, Ss(i) denotes the node which is deployed on two Lateral walls, where $i = 1, 2, \cdots, N_s$, and N_s denotes the total number of nodes on two Lateral walls. Then, we have the maximum node deployment distance on the *Z* direction under K_s-coverage.

$$d_s = \begin{cases} \sqrt{{r_s}^2 - (H/2)^2} + \sqrt{r^2 - D^2} & K_s = 1 \\ \dfrac{\sqrt{{r_s}^2 - (H/2)^2 - D^2}}{K_s - 1} & K_s > 1 \end{cases} \quad (3)$$

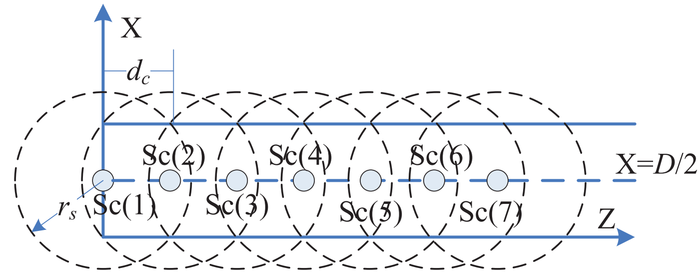

Fig. 13. Average node deployment on the Top.

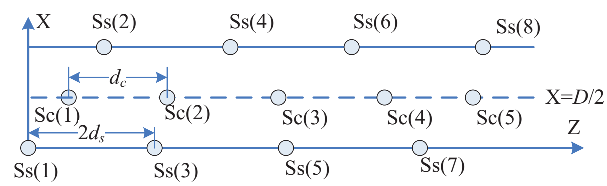

Fig. 14. Node deployment of wireless sensor nodes on *XZ* projection plane.

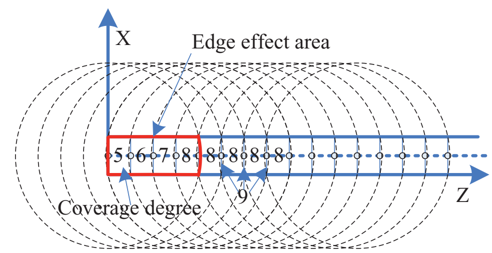

Fig. 15. Average node deployment with 5-coverage on the top.

4.2. K_c-coverage by nodes on the Top

As shown in Fig. 13, Sc(i) denotes the node which is deployed on the Top, where $i = 1, 2, \cdots, N_c$, and N_c denotes the total number of nodes on the Top. Then, we have the maximum node deployment distance on the *Z* direction with K_c-coverage

$$d_c = \begin{cases} 2\sqrt{{r_s}^2 - (H/2)^2 - (D/2)^2} & K_c = 1 \\ \dfrac{\sqrt{{r_s}^2 - (H/2)^2 - (D/2)^2}}{K_c - 1} & K_c > 1 \end{cases} \quad (4)$$

4.3. *K*-coverage by all nodes

As shown in Fig. 14, considering the demand of efficient coverage redundancy on *XY* projection plane, the sensor nodes need to be distributed on two Lateral walls and Top as uniform as possible. We have $K = K_s + K_c$, $K_s = 2 \times K_c$.

5. Optimization of node deployment by using simulated annealing method

5.1. Motivation of optimization

In the practical application of coalmine tunnel, the actual coverage degree is greater than the theoretical value in most of the monitoring regions. In the case of average node deployment with 5-coverage on the Top, as shown in Fig. 15, the coverage degree in most of the region is 8 or 9, and the coverage degree is 5 at one end of monitoring region, namely Edge Effect Area. The length of this area is r_s approximately. Therefore, the node deployment needs to be optimized.

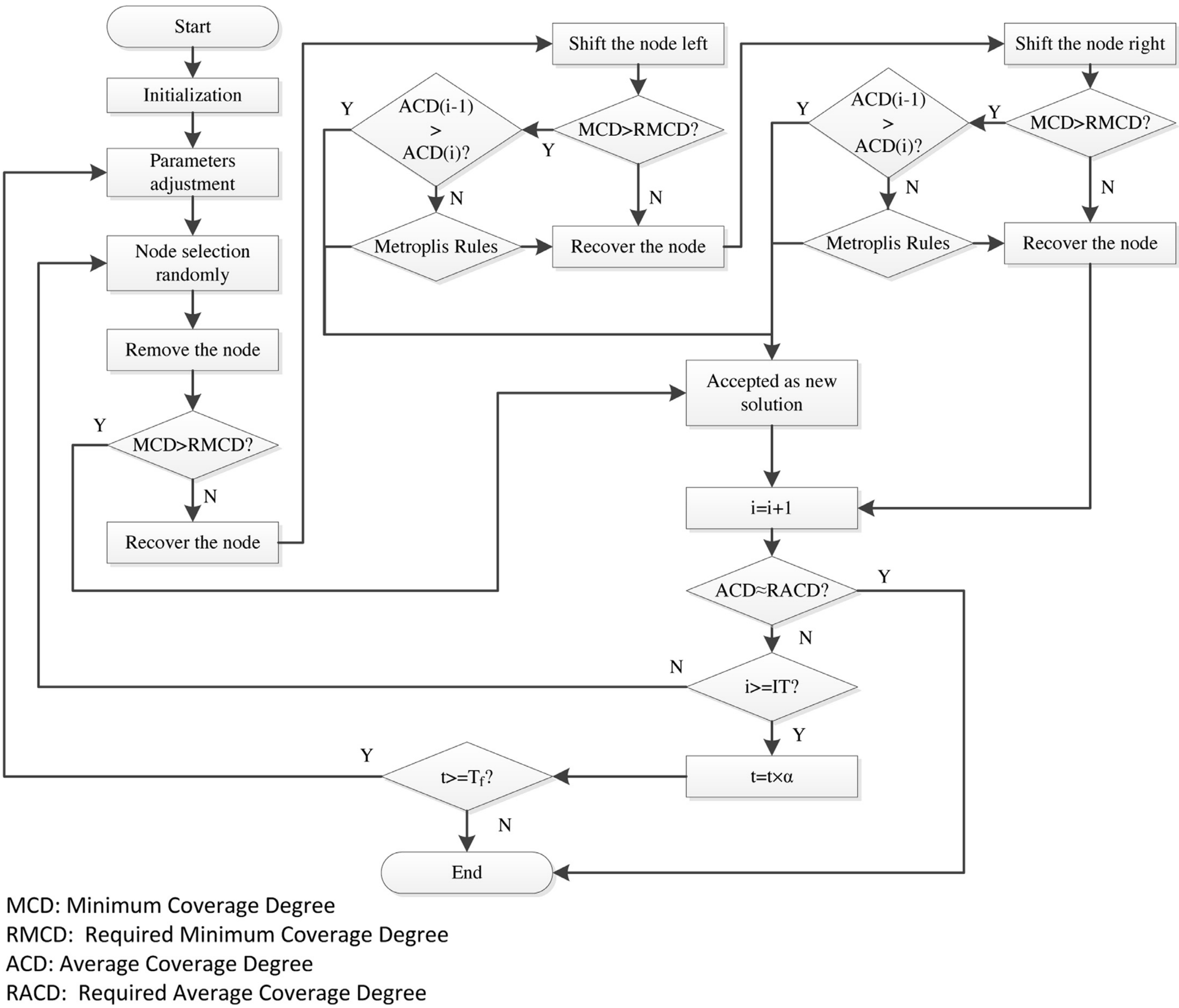

Fig. 16. Flow diagram of optimization using the simulated annealing.

5.2. *Optimization using simulated annealing method*

In order to optimize the deployment, the simulated annealing method has been introduced. Fig. 16 shows the flow diagram of the algorithm.

1. Initialization. This step gives the related parameters in Table 2.
2. Parameter adjustment. This step adjusts the temperature and resets the iteration.
3. Process the new solution. This step selects a node randomly, operates the node (including Deletes, Shifts left and Shifts right), evaluates the new solution using the cost function, then makes the decision.

6. Performances

In this section, we try to evaluate the proposed node deployment method using numerical simulation in Matlab. Rated models and parameters are as follows:

1. Deployment scenarios. The length of the coalmine tunnel $L = 200$ m; the height of the coalmine tunnel $H = 3.5$ m; the width of the coalmine tunnel $D = 5$ m; the sensing radius of a single sensor node $r_s = 7$ m.
2. Control parameters of simulated annealing. Starting temperature $T_0 = 100$; final temperature $T = 10$; cooling rate $\alpha = 0.8$; iterations at each temperature $IT = 200$.

6.1. *Models evaluation*

6.1.1. *Sensing efficiency*

Fig. 17 shows the relationship between the sensing efficiency and the sensing radius, where the node is deployed at $(0, H/2)$on XY projection plane. It shows that the advantage of sensing efficiency is reducing with the increasing of sensing radius. Fig. 18 shows the relationship between the sensing efficiency and the node position, where the sensing radius$r_s = 10$ m. It shows that the sensing efficiency is increasing when the node is approaching to $(0, H/2)$.

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Table 2
Initialization parameters.

Parameters	Definition	Explanatory note
M	Initial solution	Node deployment in Sect.4
$T_0/T_f/\alpha$	Starting temperature/final temperature/cooling rate	Control the temperature decrement
IT	Iterations at each temperature	Times of node selection
CF	Cost function	Hard constraints: MCD > RMCDSoft constraints: ***if*** ACD(i−1) > = ACD(i)accept the new solution; ***elseif*** ACD(i−1) < ACD(i)Accept the new solution with the probability$p = \exp(\frac{\text{ACD}(i)-\text{ACD}(i-1)}{t})$. ***end***

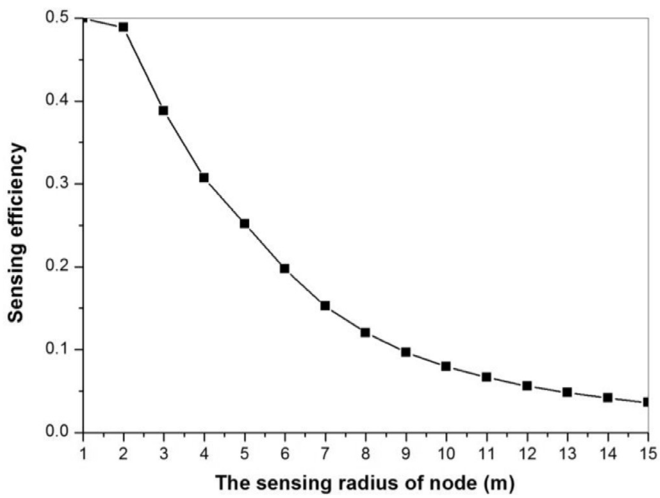

Fig. 17. The relationship between the sensing efficiency and the sensing radius.

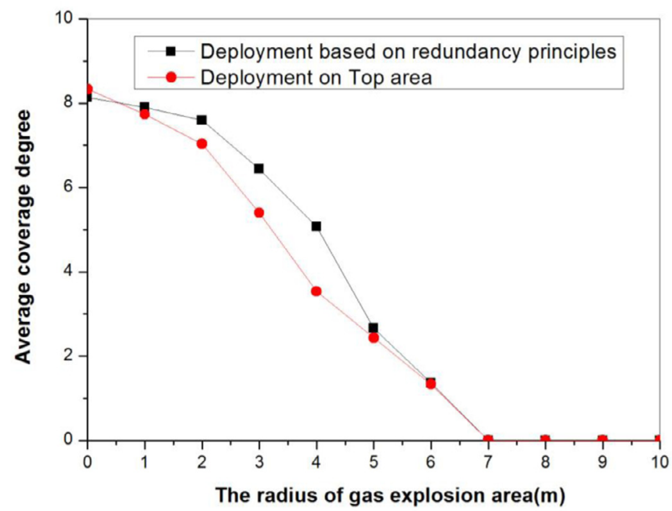

Fig. 19. Average coverage degree in gas explosion area.

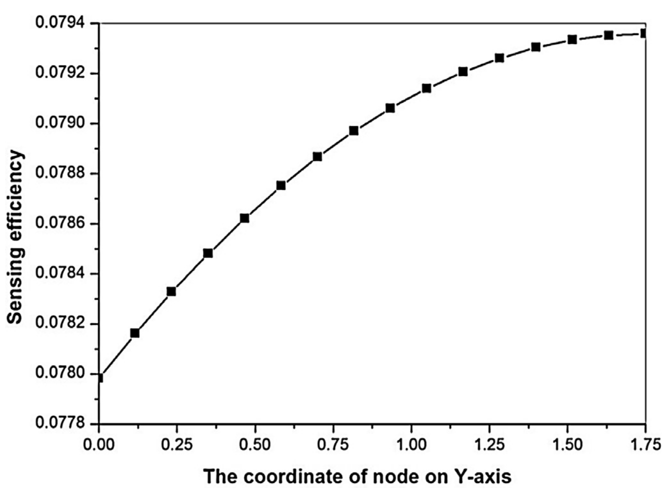

Fig. 18. The relationship between the sensing efficiency and the node position.

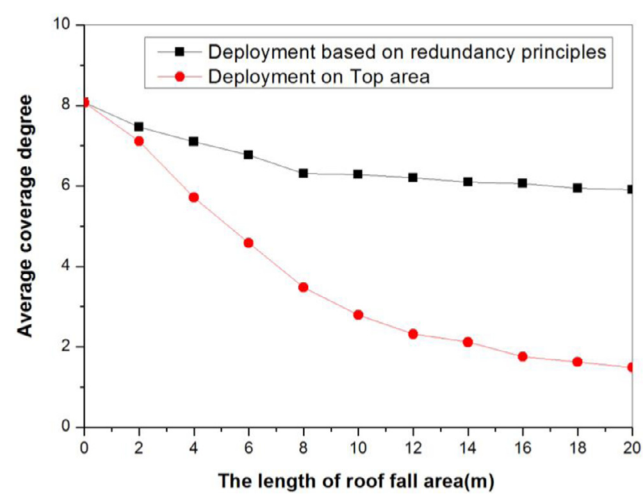

Fig. 20. Average coverage degree in roof fall area.

6.1.2. Redundancy efficiency

Figs. 19 and 20 show the change of network coverage when the coalmine disaster happens. Because the gas explosion accident affects all inner face of the tunnel, the effect of redundancy principle is not so obvious as shown in Fig. 19. However, the effect becomes dramatic when the roof fall accident happens. As shown in Fig. 20, the redundancy principle can ensure the required minimum coverage degree. In this case, the required minimum coverage degree is 6.

6.2. Node deployment evaluation

Fig. 21 shows part of the sketches (100 m–120 m) of 6-coverage node deployment with different strategies. Comparing with the average deployment, as shown in Figs. 22 and 23, the number of nodes of proposed deployment and the deployment strategy in [18] can be saved up 25%, and the coverage efficiency is also increased dramatically. Although the proposed deployment shows no advantages for the deployment strategy in [18], the optimization by simulated annealing can promote the coverage efficiency further.

7. Conclusions

In this paper, we have proposed a mathematical 3D node deployment of band-type wireless sensor network for underground coalmine tunnel. The main contributions and findings are as follows:

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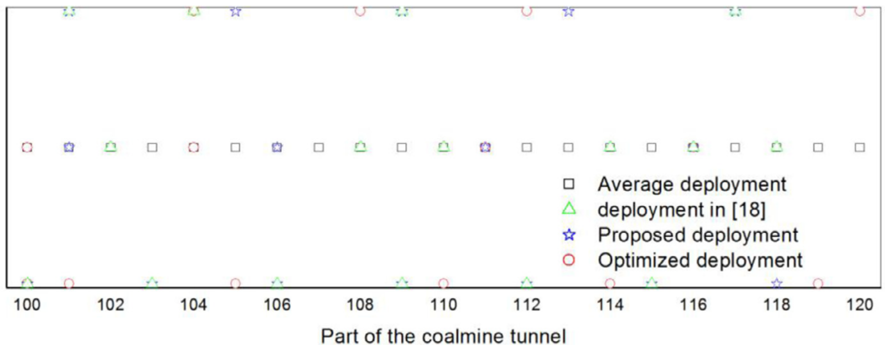

Fig. 21. Sketch of node deployment.

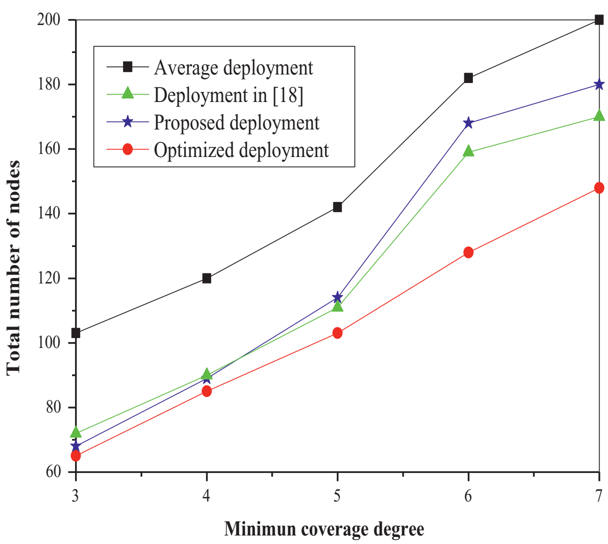

Fig. 22. Total number of nodes under different minimum coverage degrees.

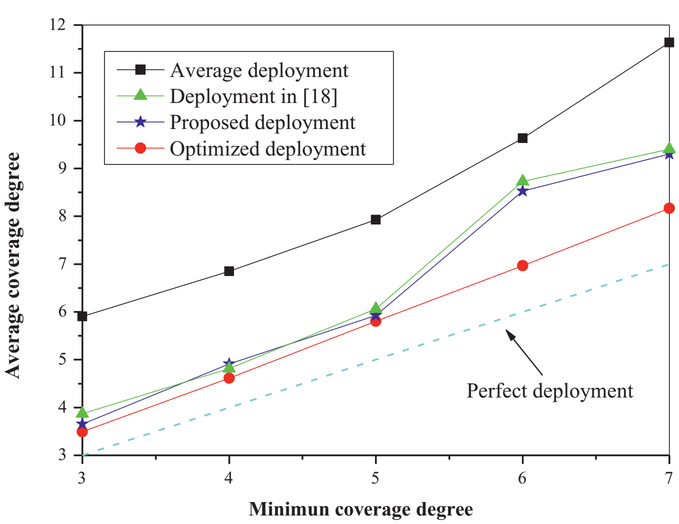

Fig. 23. Average coverage degree under different minimum coverage degrees.

(1) A 3D band-type node deployment model is put forward. Several important characteristics of node deployment are discussed in detail, such as radio features, sensing efficiency, redundancy principles and coverage features. Moreover, several findings are illustrated in this paper as mentioned in the following. Firstly, sensing efficiency is not only determined by the characters of sensors, but also affected by the terrain of monitoring area. Secondly, the redundancy principles affect the coverage efficiency dramatically when the coalmine disaster happens. Thirdly, the mapping of deployment from 3D to 2D is built, which can simplify the deployment algorithm.

(2) A targeted node deployment and its optimization algorithms are brought up. Compared with the average deployment, the optimized node deployment proposed by us can promote the coverage efficiency markedly.

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