Application of Computational Geometry in Coal Mine Roadway 3D Localization

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Abstract: *The Voronoi diagram principle in the computational geometry was researched and the relationship between the anchor nodes and Voronoi diagram was analyzed in this paper. A new arrangement method of coal mine roadway nodes was proposed to construct the Voronoi diagram of the roadway on the basis of new node arrangement method and increase numerous virtual anchor nodes for the roadway space under the condition of no increase of network cost and increase the number of anchor nodes communicating with the sensor nodes. Through the combination with the range-free DV-Hop algorithm, the scheme of coal mine roadway localization was proposed to finally achieve the localization of underground roadway. The simulation results show that, compared to the traditional range-free algorithm, the algorithm in this paper can more accurately estimate the location of the nodes under the same network condition. The increase of the positioning accuracy of the algorithm can suit the node localization of underground wireless sensor network in coal mine.*

Keywords: *Wireless sensor network, roadway; voronoi diagra, virtual anchor node.*

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1. Introduction

The Wireless Sensor Network (WSN) technology has played a more and more important role in the people's lives and industrial productions due its characteristics of low cost and low power consumption. The application of the WSN to the safety monitoring and control of coal mines can effectively improve the work safety level of coal mines and reduce the accidents of coal mines. It is necessary to know the specific positions of corresponding data and information during the safety monitoring of coal mines before the data feedback information can be processed in time.

A new arrangement method of coal mine roadway nodes is presented in this paper. The node network in the roadway obtained via this method is a hybrid network consisting of chained network and mesh network. The Voronoi diagram of roadway space [17] was constructed to increase numerous virtual anchor nodes for the roadway space under the condition of no increase of network cost and increase the number of anchor nodes communicating with the sensor nodes. Through the combination with the range-free DV-Hop algorithm, the scheme of coal mine roadway localization was proposed to finally achieve the localization of underground roadway.

2. Roadway Model of Coal Mine

The underground roadway of the coal mine is basically long and narrow, with slight arc structure at the top and a little bump at the sides. In the traditional algorithm, the roadway was approximately considered into the rectangular structure and it was subject to a sectional division by a certain length, and the anchor nodes were arranged on the edges of the cuboid in pairs, namely, the coordinate of Axis X and Axis Y for each pair of anchor nodes is the same and only the coordinate of Axis Z is different [8, 9, 10, 18], as shown in Figure 1.

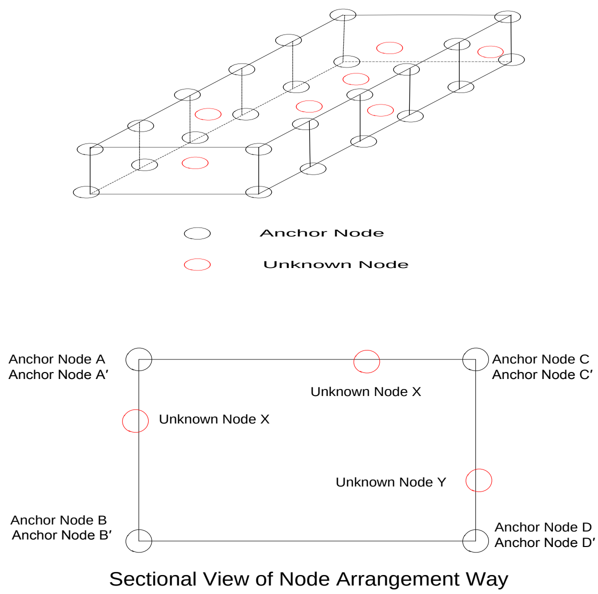

Figure 1. Arrangement rules and sectional view of anchor nodes in roadway.

The monitoring of coal mine roadway is mainly reflected in gas concentration, temperature, humidity, etc., and the top of the roadway is the focal position for gas monitoring, so, a significant number of nodes shall be arranged at the arc top of the roadway.

However, the roadway was approximately considered as a cuboid in the traditional arrangement of nodes, which would lead to a bigger estimation error for the node positions at the arc top. In addition, the arranged nodes on the roadway walls were relatively redundant in the traditional node arrangements, which will be easy to cause the waste of resources.

A slight arc existed at the top of coal mine roadway in the actual situation and the arrangement region of anchor nodes in the roadway was not quite regular and the spacing of the regions was usually 12-15m. With regard to such a case, a new node anchor of roadway was presented in this paper. The sensor nodes were arranged on the roadway walls of each small region in a diagonal form and a node was arranged at the center position of the arc top of each region space. The arrangement way of nodes is shown in Figure 2.

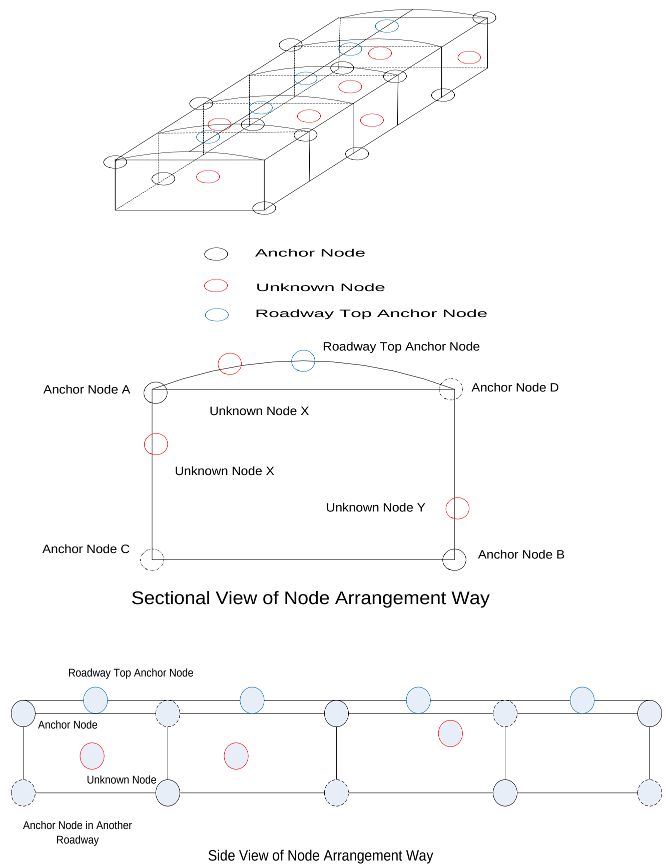

Figure 2. Arrangement rule, sectional view and side view of new anchor nodes.

3. The Establishment of Positioning Model

3.1. Aufbau Principle of Voronoi Diagram

Take P_1,P_2as two points in the plane and *L* as the perpendicular bisector of the line segment. *L* divided the plane into two parts L_l (left half plane) and P_1 (right half plane). Point P_1 in L_1 meets: $d(p_l, p_1) < d(p_l, p_2)$, where $d(p_l, p_i)$ represents the Euclid distance between P_1 and P_2 *i*=1,2. This means that the points in L_l are the track closer to p_1 than other points in the plane, and it is recorded as *V* (p_1); Similarly, the points in L_r are the track closer to P_2 than other points in the plane, as shown in Figure 3.

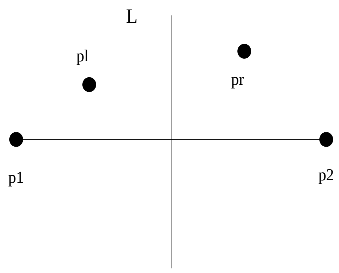

Figure 3. Diagrams of $V(p_1)$ and $V(p_2)$.

$V(p_1)$ represents the half plane L_l and $V(p_2)$ represents the half plane L_r. Given n points in the plane,take point set as S, then $S=\{p_1,p_2,.....,p_n\}$.$V(p_i)$ represents that the track closer to p_1 than other points in the plane is a intersection of half plane *n*-1 and it is a convex polygon domain not more than N-1 edges, called the Voronoi polygon associated with p_i [7, 8, 17]. In Figure 4, $n = 5$, where each point in the S can form a Voronoi polygon, and thus the diagram composed of many Voronoi polygons is called Voronoi diagram, recorded as *Vor*(*S*). Each polygon domain $V(p_i)$ only contains a point in S and the edge of *Vor*(*S*) is a line segment of perpendicular bisector of certain dot pair in S and so it is shared by the two polygon domains where this dot pair is located.

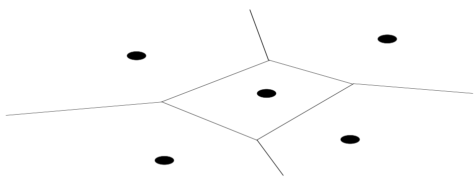

Figure 4. Diagram $V(p_1)$ for *n*=5.

3.2. Virtual Anchor Node Model in Coal Mine Roadway

The sensor nodes were placed in the roadway and the anchor nodes were set up in the corresponding positions according to the roadway model and node arrangement method presented in this paper, and each anchor node was responsible for monitoring the adjacent areas. Afterwards, the virtual node information of the roadway was created in light of the principle of Voronoi diagram. Considering the special environment of the roadway and the 3-D situation and that the Voronoi diagram was established in the plane, so it was necessary to separately consider the plane composed of the roadway wall anchor nodes and the plane composed of the roadway wall anchor nodes and the roadway top anchor node while establishing the Voronoi diagram of the roadway.

- *Step 1*. Establish the virtual anchor node in the plane composed of roadway wall anchor nodes.

According to the node arrangement method presented in this paper, there were only two anchor nodes in the single roadway wall region, which could not meet the requirements of Voronoi diagram, so at least two roadway wall regions were needed while establishing the Voronoi diagram of the roadway walls. Meanwhile, in order to ensure the positioning accuracy of virtual nodes, the communication of anchor nodes selected in this paper must be within one hop while establishing the Voronoi diagram. For this reason, two neighboring regions were selected in this paper to build the virtual anchor nodes. Furthermore, the arrangement method of roadway nodes presented in this paper was regular, and the virtual anchor nodes determined in two neighboring regions could exhibit the situation in the whole roadway. The virtual anchor nodes obtained from the plane composed of roadway wall anchor nodes in the two neighboring regions are detailed in Figure 5.

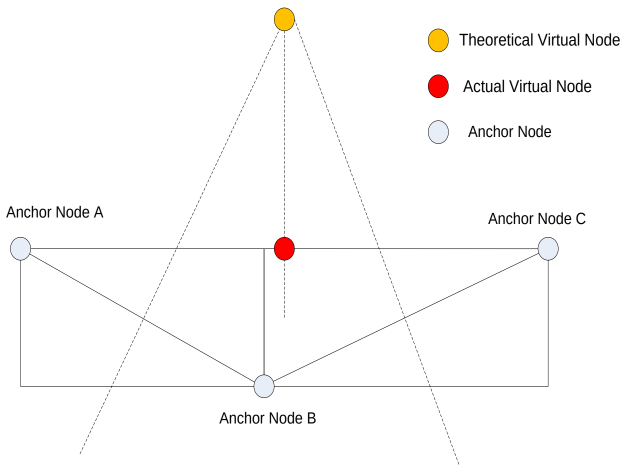

Figure 5. Establishment of virtual anchor nodes in the plane composed of roadway wall anchor nodes.

It could be learned from the figure that the roadway wall model is rectangular and the virtual node position obtained by establishing the Voronoi diagram of roadway wall was one point in the space, which was shared by three anchor nodes, so it could not meet the actual condition of the roadway. However, its position information was determined, so it was projected onto the top of the roadway in this paper to ensure the shortest distance between them so as to reduce the distance error. The coordinate information of this virtual node was recorded.

- *Step 2*. Determine the virtual anchor nodes in the plane composed of wall anchor nodes and top anchor nodes.

The effect diagram obtained by taking any partition area and roadway top anchor nodes to establish the Voronoi diagram of the space is shown in Figure 6.

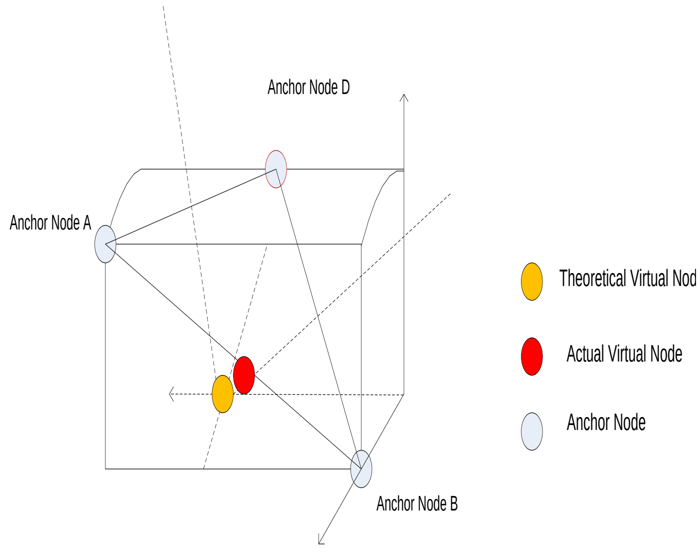

Figure 6. Establishment of virtual anchor nodes in the plane composed of any wall anchor node and top anchor nodes.

It could be learned from the figure that the plane composed of three anchor nodes in 3-D space is a spatial plane and therefore the position of virtual nodes established by it was in the space, which could not meet the actual requirements of the roadway. It was projected into the roadway walls in this paper to ensure the shortest distance between them so as to reduce the distance error. The coordinate information of this virtual node was recorded.

Similarly, the effect diagram obtained by taking another neighboring partition area and the plane composed of two roadway wall anchor nodes and top anchor nodes in this area to establish the Voronoi diagram is shown in Figure 7.

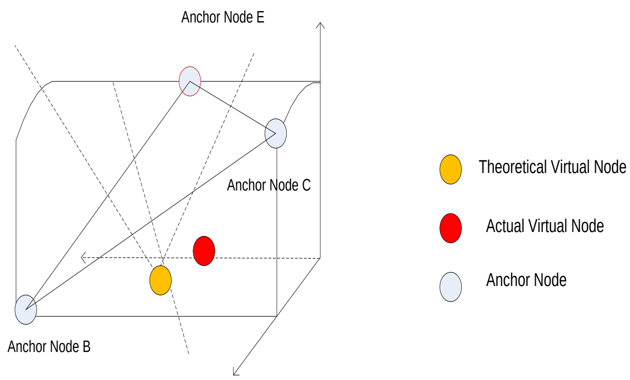

Figure 7. Establishment of virtual anchor nodes in the plane composed of neighboring area wall anchor nodes and top anchor nodes.

The treatment method of the virtual anchor nodes in this area was similar to the said area.

Through the said two processes, the number of virtual anchor nodes in the two partition areas was gradually increased, which could increase the information quantity of anchor nodes communicated with the sensor nodes in the space under the condition of no increase of network cost and power consumption. The coordinates of the virtual anchor nodes established are recorded by the anchor nodes. It shall be noted that the anchor nodes of this kind do not have an ability to execute, and they cannot transfer the information like the normal anchor nodes. Therefore, the virtual anchor nodes shall store their own position information into the anchor nodes to indirectly participate in the localization. The advantage of this method is that no any hardware equipment is used and only the mathematical method is used to increase the information of virtual anchor nodes into the network so as to increase the information of anchor nodes into the positioning space. For this reason, with the increase of the number of anchor nodes communicated with the sensor nodes, the information determined by the sensor nodes themselves will increase to achieve the purpose of taking into account the network cost and positioning accuracy.

4. Description of DV-Hop Algorithm

DV-Hop algorithm [3, 4, 5, 6, 11, 12, 16] is one of the traditional range-free algorithms. This algorithm can estimate the average node distance for each hop in light of a small number of anchor nodes, and there will be a better positioning accuracy under the condition that the anchor node is distributed at the network edges [15]. By researching and comparing the disadvantages and advantages of different range-free algorithms through the positioning model presented in this paper, we find that the DV-Hop algorithm is suitable for the positioning model presented in this paper.

The positioning process of DV-Hop algorithm is similar in both 3-D space and the 2-D space and it is divided into three stages:

- *Stage 1*. Compute the minimum hop count of unknown nodes and each anchor node. The typical distance vector exchange protocol shall be firstly used to ensure all network nodes to obtain the hops of the anchor nodes. The anchor node will broadcast the information packets of its own positions to the neighboring nodes, including the hop count, with the initialized value as 0. Receive the minimum hop counts of each anchor node and ignore the larger hop count from the same anchor node, and then add 1 to the hop count and transfer it to the neighboring nodes. Through this method, each node in the network can obtain the minimum hop of each anchor node.
- *Stage 2*. Compute the actual hop distance of unknown node and the anchor node. For each anchor node, Equation (1) is used to estimate the average distance of each hop according to the position information of other anchor nodes and distance hops recorded in the first stage.

$$Hopsize_i = \frac{\sum_{i \neq j} \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}}{\sum_{i \neq j} h_j} \quad (1)$$

Where, (x_i, y_i, z_i) and (x_j, y_j, z_j) is the coordinates of the anchor nodes i and j and $h_j$is the hop count between anchor nodes i and $j (i \neq j)$.

Then, the anchor nodes broadcasts the computed average distance of each hop (or hop distance) into the network through the packets with lifetime fields, and the unknown node only records the first received average distance of each hop and transfers it to the neighboring nodes. This strategy has guaranteed that vast majority of nodes only receive the average distance of each hop from the nearest anchor node. After the unknown node has received the average distance of each hop, the distance of anchor node D_i is estimated according to the recorded hop count, as shown in Equation (2).

$$D_i = Hops \times Hopsize_{ave} \quad (2)$$

Where, represents the minimum hop from unknown node to anchor node.

- *Stage 3*. use the trilateration or maximum likelihood method to compute its own positions. After the distance from unknown node to the anchor node has been estimated, the trilateration or maximum likelihood method can be used to calculate its own coordinate of the unknown node.

5. Description of Proposed Algorithm

In view of existing problems in range-free positioning algorithm [12, 13, 14], a WSN positioning algorithm based on Voronoi diagram and DV-Hop algorithm is presented in this paper with the help of Voronoi diagram and DV-Hop positioning algorithm, and meanwhile, it is combined with the roadway node arrangement method mentioned in this paper. Compared with the traditional DV-Hop algorithm, this algorithm has increased a number of virtual anchor node information to the positioning space without the increase of network cost. When positioning the unknown nodes, it has made full use of all anchor nodes and virtual anchor nodes in the space, which guaranteed the information amount of anchor nodes in the DV-Hop algorithm. This makes the position of unknown node obtained to be more accurate and greatly improves the positioning accuracy of DV-Hop algorithm.

6. Simulation Results and Analysis

To verify the positioning accuracy advantages of positioning methods and positioning algorithms presented in this paper, matlab will be used for a simulation in this paper. Because the width and height of coal mine underground roadway are different in different regions, the simulation model is designed as a number of irregular rectangular 3-D spaces with length of 12-15m, width of 5m, top edge height of 5m and center height of 6m. The anchor nodes for reference are arranged according to the arrangement method designed herein. Take10 unknown nodes at random from the space and label them, and then obtain the estimated coordinates of unknown nodes via the DV-Hop algorithm. The error between the actual coordinate and the estimated coordinate is exactly the positioning error of this algorithm.

The virtual nodes are not considered in the positioning model of this paper and only the previously set anchor nodes in two partition areas are used. In such a case, the unknown node was positioned using the DV-Hop algorithm, and the positioning effect was as follows in Figure 8:

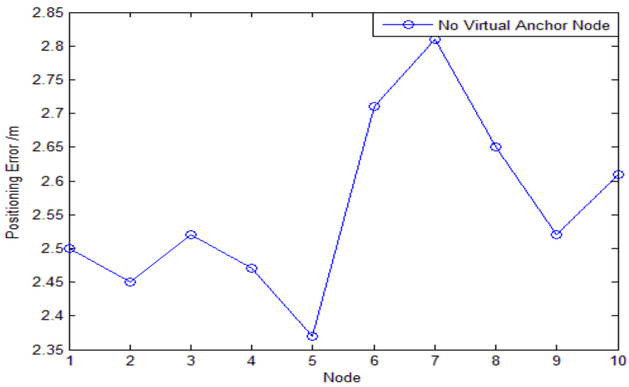

Figure 8. Positioning effect as the anchor nodes are only considered.

Then, the anchor nodes of roadway wall of two partition spaces were taken into account. In such a case, the area composed of two partition spaces contained eight anchor nodes and two virtual nodes. The positioning effect obtained was as follows in Figure 9:

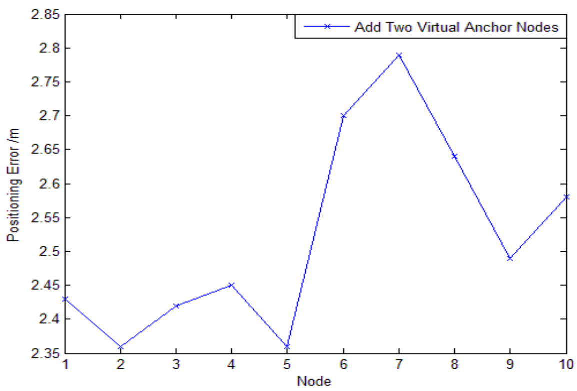

Figure 9. Positioning effect as virtual anchor nodes in the plane of roadway wall were considered.

At last, all virtual anchor nodes determined by the two partition areas were integrated. In this case, the area composed of two partition spaces contained eight anchor nodes and two virtual nodes while positioning the nodes via the DV-Hop algorithm. The information amount of anchor nodes that could be provided in this area significantly enhanced and the positioning effect obtained was as follows in Figure 10:

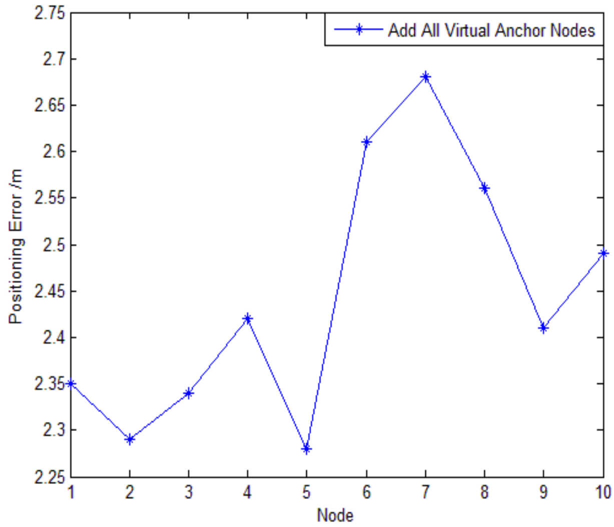

Figure 10. Positioning effect as all virtual anchor nodes were considered.

The comparison chart of the aforesaid positioning effects is shown in Figure 11.

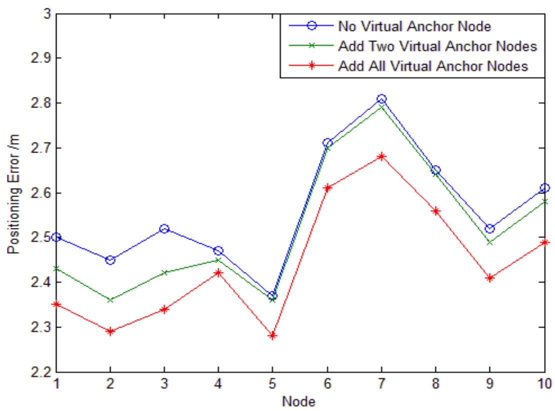

Figure 11. Comparison chart of positioning effects.

Table 1. Error analysis of sensor nodes.

Node No.	Error for No Virtual Anchor Node/m	Error for Two Virtual Anchor Nodes/m	Error for All Virtual Anchor Nodes/m
1	2.50	2.43	2.35
2	2.45	2.36	2.29
3	2.52	2.42	2.34
4	2.47	2.45	2.42
5	2.37	2.36	2.28
6	2.71	2.70	2.61
7	2.81	2.79	2.68
8	2.65	2.64	2.56
9	2.52	2.49	2.41
10	2.61	2.58	2.49

It could be learned from the integration of Figure 11 and Table 1 that, with the addition of virtual anchor nodes and the increase of node quantity during the positioning process, the positioning accuracy of sensor nodes in the space gradually increased via the algorithms in this paper, and the positioning accuracy achieved a faster magnitude growth. Thus, it could be learned that the virtual anchor nodes and anchor node information exerted a very big impact on the algorithms.

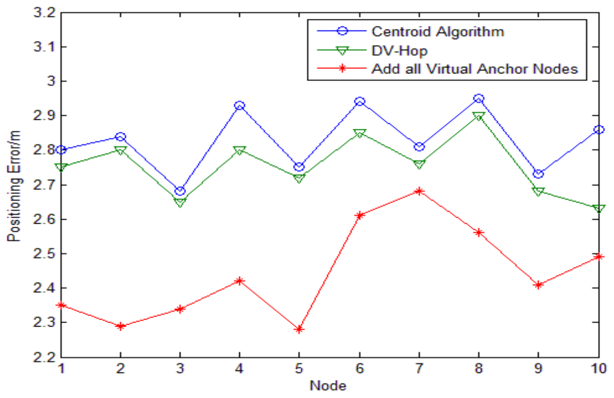

Figure 12. Comparison Chart of Positioning Effects with other algorithm.

Can be seen from the Figure 12, adding the virtual anchor nodes, the positioning error is less than the other two algorithms.Meanwhile, the positioning effect is significantly better with the increase of the number of virtual anchor nodes.

7. Conclusions

In order to satisfy the needs of network cost and positioning accuracy in the coal mine roadway, a new arrangement method of roadway sensor nodes is presented in this paper. Compared with the traditional node arrangement methods, this method can ensure the reduction of number of anchor nodes under the condition of meeting the positioning requirements. A roadway 3-D positioning algorithm based on the computational geometry is then presented in this paper. By creating the Voronoi diagram, this algorithm has increased a number of virtual anchor nodes in the positioning space and increased the information amount of anchor nodes in this space. The 3-D localization of coal mine roadway is finally achieved by combining it with the DV-Hop algorithm. The simulation results show that, as for the DV-Hop algorithm, the introduction of roadway model and virtual anchor nodes in this paper has improved the positioning accuracy, and meanwhile, the positioning effect issignificantly better with the increase of the number of virtual anchor nodes. Thus, the method proposed in this paper is suitable for the positioning requirements of coal mine underground roadways.

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