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Coalface WSN Sub-area Model and Network Deployment Strategy

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Abstract. According to the distribution of hydraulic supports in coalface, two communication spaces were defined. Then the ray tracing method was used to analyze the electromagnetic wave propagation in hydraulic supports space. Three different transmitting areas were described, they were: near area, transition area and far area. The numerical value of each sub-area space was calculated. The law to describe the wireless signal coupling between two communication spaces was given. Strategies of WSN nodes deployments in coalface were proposed according to the coupling law.

Keywords: two communication spaces; coalface; sub-area; node deployment; hydraulic supports

1. Introduction

Wireless sensor network characteristics, such as self-organization, wireless communication, autonomous distribution and easy-maintenance, made WSN system outstanding in the application of coal mine safety monitoring systems[1]. Especially when applied to coalface, the characteristics of wireless self-organization can not only meet the requirement of the complex environment of coalface, but also make the monitoring network follow the advance of working face effectively. However currently the researches on coal mine WSNs are mainly focus on network protocols in different layers and specific algorithms[1][2], materials related to constructing coalface WSN architecture are rare. In addition, the vast majority of these researches on coal mine WSN are based on common tunnel condition[3][4], there is no WSN deployment designed especially for the specific application environment of coalface. Coalface is a significantly complex limited rectangle communication space with coal walls and metal equipments. Wireless communication features are easily affected by the size of coalface, equipment arrangement, electromagnetic frequencies and many other factors. This paper analyzes the characteristic and influencing factors in coalface communication space. Two communication spaces are divided according to the arrangement of hydraulic supports. The ray tracing method is applied to analyze the electromagnetic wave propagation in hydraulic supports space. According to the analysis three different signal transmitting areas are described, they are: near area, transition area and far area. Wireless coupling law between two communication spaces in coalface is presented. Some strategies of WSN nodes deployments in coalface are proposed according to the coupling law.

2. COALFACE COMMUNICATION SPACE FEATURES AND MODEL

Many large-scale mining equipments, staffs and other materials are distributed in coalface, which have great influences to wireless transmission. Usually, the height and width of coalface are within 2~5 meters, the length is around hundred meters. Generally all personnel and equipment activities are in the shield space under hydraulic supports, so we only need to consider the region between hydraulic supports, which is also the coalface WSN communication space. The hydraulic supports have two lines of metal cylindrical pillars, are called front row and back row; coalface was divided into two parallel unique tunnel spaces by the two

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pillar rows as in figure 1. The two communication spaces are called the first communication space and the second communication space described as follows:

The first communication space: this region's top and bottom are support's top girder and foundation; there is scraper conveyor and some other equipment in this area; the other two sides are metal wall (front row of support pillars) and coal wall. The shearer is moving back and forth in the region along the direction of front row pillars.

The second communication space: staff walking and working area, the region's top and bottom are support's top girder and foundation; the other two sides are two rows of support pillars (the front row pillars and the back row pillars).

Fig. 1: Two communication spaces of coalface

Figure 2 is the simplification of figure 1, the horizontal section of the coalface communication space, two communication spaces are divided by metal supports.

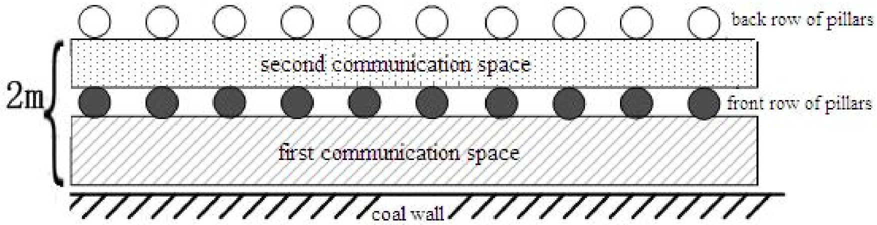

Fig. 2: Horizontal section of the coalface communication space

3. EFFECTS OF COALFACE HYDRAULIC SUPPORTS ON WIRELESS TRANSMISSION

For coalface the fix deployment of WSN nodes is preferred by hanging nodes on the supports, making the monitoring network keeping pace of the advance of coalface to ensure the coalface always under monitoring and control. This section will discuss the influence caused by row of support pillars to wireless transmission under the condition of known position of nodes and metal support.

3.1 Effects of Support on Signal Transmission Property

Because of the complex reflection and scattering, it is impossible to use the free-space transmission theory to calculate the electromagnetic wave energy of coalface. So, ray tracing method will be used to analyze the wireless propagation in coalface environment[5][6][7].

Firstly the analyzing of electromagnetic wave transmission among cylinders for single node is shown in figure 3. S is the wireless source. Most energy is reflected when ray from S transmits to metal support, and reflection area is formed. The reflection area was divided in to two parts by the line from S source to the center of the metal support pillar, the forward reflection area (on the left of the line) and backward reflection area (on the right of the line), shown in figure 3. The variables illustrated in figure 3 are: the support cylinders are numbered 1, 2…n; the radium of cylinder is r; the distance between adjacent cylinder is d; the distance between S source and the link line of all centre of cylinders is D; the angle of line linked the centre of the first cylinder to source S is α1, the rest angles for other cylinders may be deduced by analogy as α2, α3…αn; the angle of the boundary of forward reflection area of first support is β1, the rest angles for other cylinders' forward reflection boundary may be deduced by analogy as β2, β3…βn; intermediate variables are θ1, θ2…θn, they are the angle of forward reflection of each cylinder; b is the distance between the projection of S source on the link line of all centre of cylinders and the centre of cylinder 1.

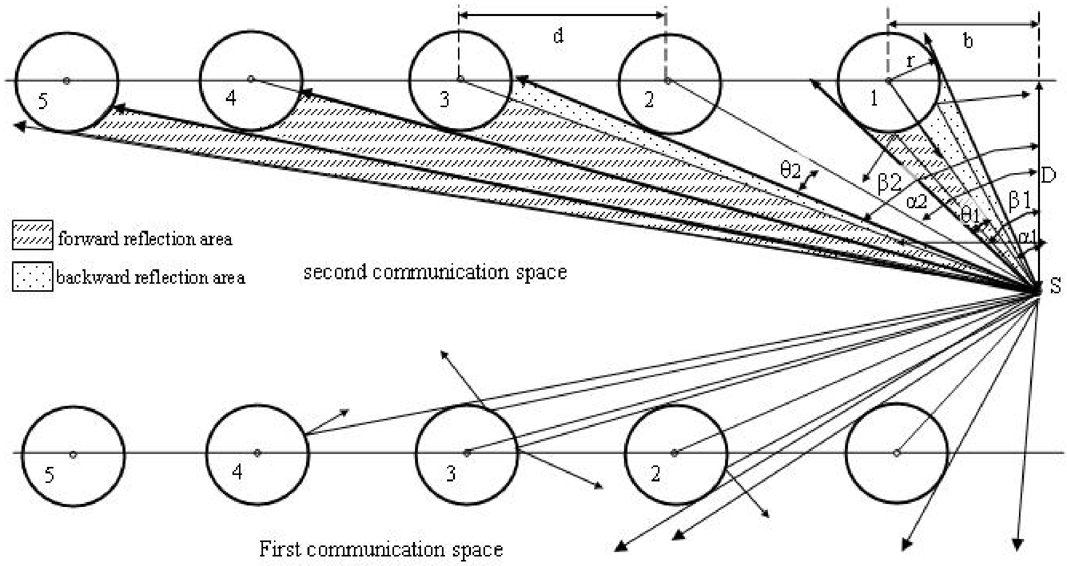

Fig. 3: Rays of single node between two communication spaces

In Figure 3, the following phenomena are concluded:

- Both forward and backward reflection area exists. And direct transmission areas exist if the metal cylinder is near to the S source. For example, S source can radiate directly to the opposite of pillars through the spacing of cylinder 1 and 2, or S source can be reflected to the opposite side by reflecting in backward area.
- Backward reflection area of farther cylinder mostly covered by forward reflection area of nearer cylinder, so forward reflection area are more, the backward reflection is reduced. Such as the reflection wave from S source in cylinder 3: the backward reflection area of support 3 is partly covered by the forward reflection area of cylider 2. There is no direct radiation area from source S to pillars' opposite area in the situation.
- With the distance between cylinder and S get longer, there are only forward reflection areas, but no backward reflection area. For example the backward reflection area of cylinder 4 is totally covered by forward reflection area of support 3, therefore no signals from S source can get through the gap between cylinder 3 and 4.
- When the cylinders get farther from S, forward reflection area begins to be covered by the forward reflection area of nearer cylinder. For example, cylinder 5's forward reflection area is reduced.
- It can be deduced that when cylinders are far away from S source, the forward reflection area will be reduced to nearly a point. It can be deduced that in far area, metal cylinders can be regarded as a metal wall that electromagnetic rays of source S can only be reflected like the reflection on metal waveguide wall.

From the phenomena above the coalface communication space with metal supports can be divided into three areas: near area, transition area and far areas.

3.2 The Definition of Sub-areas

Near area: from source S to support cylinder that the backward reflection area is just covered, in this area a cylinder can have both forward and backward reflection rays of source S. The reflections are something like indoor.

Transition area: only obvious forward reflection areas exit, there is no backward reflection wave caused by cylinder in this area. There are only forward reflecting rays back to the communication space, but the reflection direction is rather arbitrary.

Far area: the distance farther from source S that metal cylinders can be approximately regarded as a metal wall, and electromagnetic wave of source S can only be reflected like the reflection on metal waveguide wall, it means the reflection direction is constant.

3.3 The iterative Equations of Sub-areas

From figure 3 the iterative equations to calculate the distance of sub-areas are as follows:

$$\mathbf{b} = \mathbf{D} * \mathbf{tg}(\alpha_1) \quad (1)$$

$$\alpha n = \sin^{-1}\left[\frac{b+(n-1)d}{\left\{[b+(n-1)d]^2 + D^2\right\}^{1/2}}\right] \approx \frac{b+(n-1)d}{\left\{[b+(n-1)d]^2 + D^2\right\}^{1/2}} \quad (2)$$

$$\theta n = \sin^{-1}\left[\frac{r}{\left\{[b+(n-1)d]^2 + D^2\right\}^{1/2}}\right] \approx \frac{r}{\left\{[b+(n-1)d]^2 + D^2\right\}^{1/2}} \quad (3)$$

$$\beta_n = \alpha_n + \theta_n \qquad n \geq 1 \quad (4)$$

$$dr_n \approx \left\{[b+(n-1)d]^2 + D^2\right\}^{1/2} * \sin(\beta_{n+1} - \beta_n) \approx \left\{[b+(n-1)d]^2 + D^2\right\}^{1/2} * (\beta_{n+1} - \beta_n) \quad (5)$$

So we can get, with the increasing of n, dr_n is decreasing, that is, the farther the cylinder to sources S is, the smoother the pillar row looks. As discussed above, we can simplify the three parts as (suppose: when $dr_n \leq \lambda/10$, cylinders can be regarded as metal wall for source S)：

Near area：the region is from source S to $\beta_{n+1} - \beta_n \leq \theta_n$, both forward and backward reflection areas are exist.

Transition area：the region is from $\beta_{n+1} - \beta_n \approx \theta_n$ to $dr_n \approx \lambda/10$, there is only forward reflection area.

Far area：the region satisfies $dr_n \leq \lambda/10$, the forward reflection area looks like a point.

According to an actual coal mine data, the variables are: D=500 mm, d=1200mm, r=150mm, b=600mm, α1=π/4, take the most commonly used frequency in coal mine wireless transmission system 900MHz as an example, $\lambda/10$ =300/9 mm=33.33mm.

According to the calculation results: the nearest four cylinders to source S form the near area, about 4 meters; from the 5th to 12th cylinder is transition area, that is from 4 meter to about 14 meter; farther than 12th cylinder becomes far area, that is farther than 14 meter. The distance of the transition area not only depends on the size of coalface, the position of S and support cylinders, but also on the frequency of the signal. WSN nodes mainly working at 2.4GHz, λ/10=12.5mm. The near area is the same about 4 meters; transition area becomes 23 meters, far area is farther than 23 meter. The magnetic wave transmission features of the three areas are different: in near area, the reflection effect of cylinders on S source is like indoor diffuse reflection; in transition area, the rays are reflected totally back to the communication space that the source S located, but the reflection direction is rather arbitrary; in far area, the reflection looks like on a waveguide wall, reflection direction is constant.

3.4 Wireless coupling law between Two Communication Spaces in Coalface (TCSC coupling law)

From above sub-area principle it can be known that only in near area there exists direct radiation and reflected rays between two communication spaces for source S. So the wireless coupling law between two communication spaces in coalface (TCSC coupling law) is presented as follows:

TCSC coupling law: in coalface with hydraulic supports, the two row cylinders divide the coalface into two communication spaces, for a wireless source S in any one communication space there are signal coupling between two spaces only in the near area of S. The distance of near area is determined only by the parameters of hydraulic supports and the position of source S, there is nothing to do with the wireless signal frequency.

Above analysis illustrates the correction of TCSC coupling law. From the definition of sub-areas and the iterative equations of sub-areas, we can find the distance of near area is nothing to do with signal frequency (wavelength). Figure 3 shows the coupling rays of two communication spaces for a single node.

4. Conclusion

Some deployment strategies of WSN in coalface can be inferred by using TCSC coupling law. a) Deploying WSN nodes only in one communication space, it is not easy to get reliable and 100% coverage for coalface; b) Deploying WSN nodes in two communication spaces, when the distance of two adjacent nodes in two different communication spaces is larger than two near area, the two WSN are independent each other. In this situation routing is simple and data rate is high; c) Deploying WSN nodes in two communication spaces, but the distance of two adjacent nodes in two different communication spaces is less than near area, then the two WSN become one network. There are redundant channels in the situation, but routing is more complex.

5. Acknowledgements

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6. References

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