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2.4 GHz Radio Wave Propagation Characteristics in Coal Mine Workface Tunnels

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Abstract

We proposed a novel ray-tracing based radio waves propagation (RTRWP) Law suitable for under-tunnel complex coal mine workface. The energy consumption model evaluation in complex coal mine workface is derived. Theoretical analysis about calculating the multiple reflections of the radio waves in coal mine workface is also provided. Computer simulations and field tests in workface tunnels show that this proposed RTRWP law can work effectively to describe the actual radio wave propagation environments in complex coal mine workface.

Keywords: *coal mine workface, Ray-tracing based radio waves propagation (RTRWP) law, multi-path model, energy loss*

1. Introduction

In recent years, with the development of wireless communication technology, more and more wireless devices are applied for automatic monitoring in coal mine. However, the propagation characteristics of the radio waves in coal mine tunnels, especially in coal mine workface tunnels, are different from them in free space. Because the coal mine workface is a limited confined space of heterogeneity, when transmitting in such environment, the radio waves have serious attenuation and complex propagation. Therefore, researching the characteristics of radio waves is helpful to provide a better use of wireless communications equipments in coal mine workface.

Y.P.Zhang [1] and Guorui Han [2] provided theoretical model and experiment results of radio wave propagation in coal mine tunnels respectively. Kermani, M.H. also gives the UHF signals' propagation characteristics in coal mine tunnels [3]. However, these studies are based on 900MHz frequency band and the conclusions don't become a unified theory, there is still no research on higher frequency radio waves (for example, common used 2.4GHz radio waves) propagation in coal mine workface tunnels. So, we proposed RTRWP (Ray-Tracing based Radio Waves Propagation) Law based on ray tracing method to give a theoretical explanation of the wireless channels in coal mine workface tunnels. In addition, this paper gives the detail computing method of energy loss according to RTRWP Law. Simulation results show that the energy loss calculated by this method is similar to the experiment results and RTRWP Law is well applied for researching the radio wave propagation characteristics in coal mine workface.

2. Ray-tracing Based Radio Waves Propagation (RTRWP) Law

There are lots of hydraulic supports in the coal mine workface, which consist of four walls, threes are metal baffle plates and the residual one is the coal wall. The propagation of wireless radio waves in such special circumstances is different from the general free space. As is shown in Figure 1, the left side is coal wall, the top and bottom sides are steel baffle plates and in the middle is hydraulic supports. As the existence of the hydraulic supports, the radio rays have energy which have energy loss in the scattering process could not transmit for a long distance.

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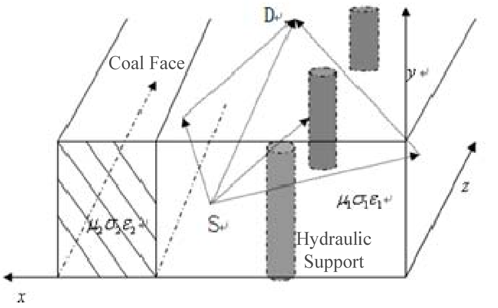

Figure 1. Schematic Diagram of the Coal Mine Workface

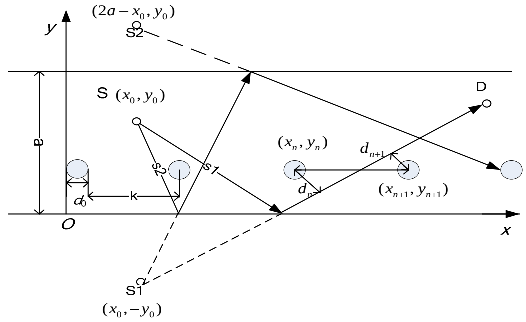

Figure 2. Vertical Incident Plane Propagating in Coal Mine Workface

CFRWP Law reveals the radio waves propagation in coal mine workface, and also gives the judgment method that whether the radio ray can transmit cross all hydraulic supports to the destination point.

Figure 2 is the platform of the roof in coal mine workface, *a* is the width of the coal mine workface, *k* is the distance between the two supports, *S* is the sending point, *D* is the receiving point, S_1 is the mirror point in the first reflection and S_2 is the mirror point in the second reflection. The judgment method is shown as follow:

a) According to the characteristic of arithmetic progression (the distance between of hydraulic supports is equal), get the abscissa of the *n* hydraulic support's circle center:

$$\begin{cases} x_n = (n-\frac{1}{2})d_0 + (n-1)k \\ y_n = y_0 \end{cases} \quad (1)$$

b) Gives the equation of S_1D is $y-K(x+x_s)+y_s=0$, *K* is the slope of S_1D ($|K|$ is relevant to the number of times of reflection).

c) Find out the cross-point of S_1D and line $y=y_0$, whose coordinate is (x'_n, y'_n) located between *n* and *n+1* hydraulic support; $n = ceil(x'_n/(d+k))$, ***ceil*** is a function means to take the smallest integer which is not less than the independent variable.

d) Calculate the distance d_n and d_{n+1} which are the distance between *n* and *n+1* hydraulic supports' circle center and ray S_1D .

$$d_n = \frac{|y_n - K(x_n + x_0) + y_0|}{\sqrt{1+K^2}} \quad (2)$$

If $d_n>d_0$ and $d_{n+1}>d_0$, ray S_1D can go through hydraulic support *n* between *n+1*, otherwise, the vertical incidence plane will be hindered by the hydraulic supports.

3. Multi-path Loss Model Based on CFRWP Law in Coal Mine Work-face

The CFRWP Law is helpful to find all the paths that the radio rays propagate cross all hydraulic supports from the transmitter to the receiver. That means CFRWP Law is useful to research the multi-path loss of the radio waves in coal mine workface. So, we propose detail computing method of multi-path energy loss according to RTRWP Law.

Since, we know that the power of receiving point in the direct line of sight is:

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \quad (3)$$

P_t, G_t, G_r , λ are the transmit power, transmit gain, receive gain and wavelength; *d* and *L* are the path length and system losses (usually the value is 1). If the radio waves reflect *k* times in the transmission path, the receive power can be calculated by the Equation (4).

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d_k{}^2 L} \rho_k{}^2 \tag{4}$$

ρ_k is decay factor after reflected *k* times which is related with reflectivity and the number of reflections.

In coal mine workface, the roof and the bottom is metal, while one side is coal wall and the other three sides are metal baffles and they of different reflectivity. So, how can we calculate the power of receiving point after the radio wave reflected *k* times in this complicated transmission environment? We give the method as follow.

First, calculate decay factor ρ_k .

The following analysis is about the condition that there is *m*+0 reflective rays or *m*+*n* reflective helical curves in the transmission according to the RTRWP Law.

If the first reflection on the metal baffle, the number of reflections on metal baffle is *m*/2 (*m* is even number) or (*m*+1)/2 (*m* is odd number), while the number of reflections on coal wall is *m*/2 (*m* is even number) or (*m*-1)/2 (*m* is odd number). Then calculation method of ρ_k is:

$$\rho_k = \begin{cases} \Gamma^{\frac{m}{2}} R_1^{\frac{m}{2}} R_2{}^n \\ \Gamma^{\frac{m+1}{2}} R_1^{\frac{m-1}{2}} R_2{}^n \end{cases} \tag{5}$$

Γ is the reflectivity of coal mine workface, R_1 is the reflectivity of the metal baffle on the side wall, R_2 is the reflectivity of the metal baffle on the roof and bottom, *m* is the number of reflections in side walls, *n* is the number of reflections between roof and bottom.

If the first reflection on coal wall, the number of reflections on coal wall is *m*/2 (*m* is even number) or (*m*+1)/2 (*m* is odd number), while the number of reflections on coal wall is *m*/2 (*m* is even number) or (*m*-1)/2 (*m* is odd number). Then calculation method of ρ_k is:

$$\rho_k = \begin{cases} \Gamma^{\frac{m}{2}} R_1^{\frac{m}{2}} R_2{}^n \\ \Gamma^{\frac{m-1}{2}} R_1^{\frac{m+1}{2}} R_2{}^n \end{cases} \tag{6}$$

Γ is the reflectivity of coal mine workface, R_1 is the reflectivity of the metal baffle on the side wall, R_2 is the reflectivity of the metal baffle on the roof and bottom, *m* is the number of reflections in side walls, *n* is the number of reflections between roof and bottom.

If the electric field E_i in the incident plane, we call it horizontal incident or vertical polarization; if the electric field E_i perpendicular to the incidence plane, we call it the vertical incident or horizontal polarization. So, we can get the reflection coefficient of the vertical incident wave (3) and horizontal incident wave (4) from the air to the medium [1, 2].

$$\Gamma_v = \frac{E_r}{E_i} = \frac{-\varepsilon_r \cos\theta_i + \sqrt{\varepsilon_r - \sin^2\theta_i}}{\varepsilon_r \cos\theta_i + \sqrt{\varepsilon_r - \sin^2\theta_i}} \tag{3}$$

$$\Gamma_p = \frac{E_r}{E_i} = \frac{\cos\theta_i - \sqrt{\varepsilon_r - \sin^2\theta_i}}{\cos\theta_i + \sqrt{\varepsilon_r - \sin^2\theta_i}} \tag{4}$$

ε_r is the relative dielectric constant, θ_i is incidence angle. For the rough reflector, the reflection coefficient need to be corrected by multiplying the scattering coefficient ρ_s [9]:

$$\rho_s = exp[-8(\frac{\pi\sigma_h \cos\theta_i}{\lambda})^2] I_0 [8(\frac{\pi\sigma_h \cos\theta_i}{\lambda})^2] \quad (5)$$

Second, calculate the transmission distance *L*.

According to Fermat's principle, the 3-dimensional transmission path of the radio waves can be mapped in two 2-dimension plane (vertically incident plane and horizontal incident plane), as is shown in Figure 3. Then the transmission distance *L* can be calculated respectively by the classical image method in the two incident planes.

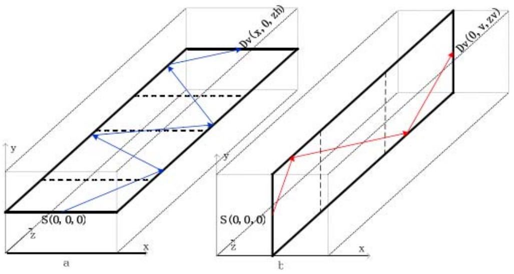

Figure 3. Propagation Paths in Incident Plane

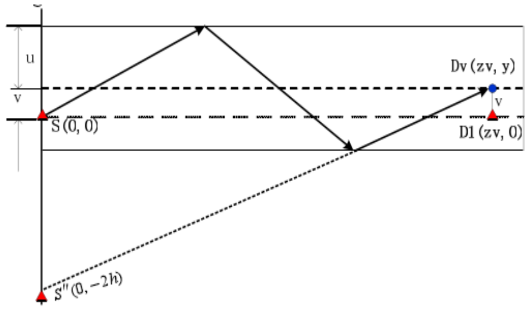

Figure 4. Calculation of Propagation Distance

Third, we the received power can be calculated by formula (4) when get *L* and ρ_k.

4. Simulations and Experiment

In order to simulate the multi-path loss of 2.4GHz radio waves, we measured the corresponding parameters in coal mine workface (Jiahe Coal Mine, Xuzhou, China), which are shown as follow:

$$a = 5.13m, d_0 = 0.5m, u = v = 1, \varepsilon_{r1} = 3.2$$
$$\varepsilon_{r2} = 2.4, f = 2.4GHz, e = 0.15$$
$$\sigma_1 = 1.62578*10^{-2}, \sigma_2 = 7.7*10^6$$

In order to confirm the theoretical model, we also have carried on the scene test in Jiahe coal mine workface, using 2.4GHz WIFI Access Point whose emissive power is 0dbm and receive threshold is -90dbm.

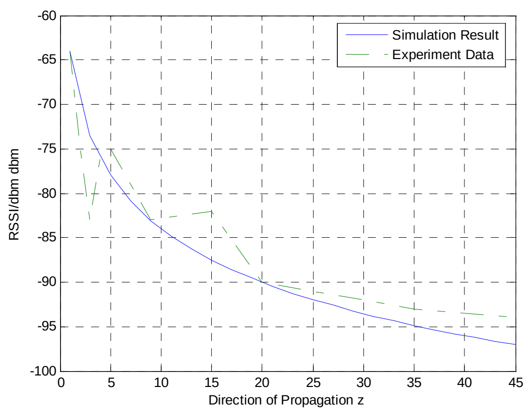

Figure 5. Experiment Results and Simulation Results

Table 1. Received Power and Received Packets Rate in Coal Mine Workface

Distance/m	1	2	3	5	9	15	20	25	30	35	45
RSSI /dbm	-64	-75	-83	-75	-83	-82	-90	-91	-92	-93	-94
Packets received rates %	100	100	99.4	99.8	97.2	95.4	79	16.8	45.2	44.8	10.8

According to experiment result, the effective transmitting range in coal face is about 20 meters; Received signal intensity and packets received rates are shown in Table 1. Figure 5 shows the relationship between the theoretical calculation result and the actual survey result.

5. Conclusion

Based on the analysis of proposed CFRWP Law, 2.4GHz radio waves transmission multi-path attenuation characteristic in coal mine workface is studied. By the comparison of the simulation result and the actual experiment data, it can be concluded that the theoretical model is basically consistent with the actual measurement results. So, this thesis offers a method for wireless transmission research in workface, and the results are helpful for wireless communication in workface.

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