



Radio Wave Attenuation Character in the Confined Environments of Rectangular Mine Tunnel

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Abstract

The radio waves are more complex in confined environments. In order to obtain the propagation character of radio wave in the mine tunnel, the electric-field intensity and magnetic-field intensity of horizontal polarization wave are deduced according to Maxwell equation and the boundary condition of tunnel. The attenuation coefficients of electric field in horizontal and vertical polarization are deduced through the traveling wave condition of confined space. The attenuation characters of different position transmitter in rectangular mine tunnels are simulated in an experiment tunnel. The results shows the attenuation of electric-field intensity is increase quickly in 50m. When the transmitter is more close to the wall of the mine tunnel, the mode of propagation is more complex and the attenuation is more serious, whereas in the middle of the mine tunnel, the attenuation rate of radio is the least. Factors that influence the attenuation character of radio waves in mine tunnel are analyzed and simulated, which is benefit to evaluate the wireless channel quality in mine tunnel.

Keywords: Radio wave, Mine tunnel, Polarization mode, Attenuation

1. Introduction

The reliable communication in coal mine is the important guarantee of safety production. In a mine accident, the established communication system would be destroyed. In order to ensure the safety of rescue worker, the environment information (such as the gas parameters) of the area which the people are trapped must be acquired timely and reliably, the wireless channel is established easily which can form a emergency wireless link and meet the communication requirement. But mine tunnel is a limited space, and the electromagnetic waves in mine tunnel are more complex, which the direct wave, back wave, refracted wave and diffraction wave are very serious and affected by the tunnel cross section, bend, incline, etc.

Wireless communications in confined environments such as tunnels have been widely studied for years and a lot of experimental results are presented in the literature, mainly to describe mean path loss versus frequency in different types of environment ranging from mine galleries and underground old quarries (M.Lienard,*et al*,2000;M.Ndoh,*et al*,2004; M.Boutin, *et al*,2008), to road and railway tunnels (T.S.Wang, *et al*,2006; D.Didascalou, *et al*,2001). In these last two cases, arc-shaped tunnels are quite usual. They can be approximated by a cylinder whose lower part is flat and supports either the tracks or the road. They are often encountered in mountainous regions and in chalky terrains where tunnel boring machines, or moles, are shaped like a huge cylinder. The prediction and/or interpretation of the field distribution inside such tunnels excited by an electric antenna is thus important for the deployment of a wireless communication system.

The rectangular tunnel model is built with four non ideal electric wall by using the approximate method of simple boundary condition and adopted the way of wave-guide mode to analyze the rules of radio propagation(Emslie,1975),which laid the foundation of the wireless communication in tunnel. The propagation character of radio in trapezium tunnel and the equivalent analysis method are researched (Sun Jiping, *et al*,2003;Sun Jiping, *et al*,2006). The attenuation character of radio was researched in bended tunnel (Shi Qingdong, *et al*,2001); The transmission mode of radio in rectangular tunnel was deal with (Sun Jiping, *et al*,2005); The mix-model of propagation loss in forecast tunnel and the propagation character in long wall work surface are brought out(Zhang Yueping, *et al*,2001; Zhang Yueping, *et al*,2002);Some experiment about the propagation character of the radio frequency signal are tested(Li Wenfeng, *et al*,2008). In order to make sure the reliability of the emergency wireless channel, in this paper, the

propagation character of electromagnetic wave of mine tunnel and the influence factors will be investigated.

2. Radio wave in rectangular mine tunnel

In rectangular mine tunnel, the wireless Mesh network is used and satisfied the emergency rescue of mine accident, then the work frequency is located in Industrial Scientific and Medical (ISM) band usually. The wave length is much less than the tunnel cross-section size, the tunnel can be considered as a medium waveguide, so we can use the theory of waveguide to research it. Emslie built the rectangular tunnel model which neglects the four corner field (Emslie, et al, 1975)s, so it can make the matching condition of tunnel boundary simple; then the attenuation approximate equation were obtained of minimum level propagation mode according to Maxwell equation.

According to the symmetry of rectangular structure, it is very easy to extend the attenuation equation to the higher level mode. We can choose the rectangular coordinate system, the width of tunnel is a , and the height is b , the relative dielectric constant of two walls is ϵ_{r1} , the relative dielectric constant of the top and the floor is ϵ_{r2} , the medium in tunnel is air. That the two major propagation modes are the E_h modulus of horizontal polarization and the E_v modulus of vertical polarization.

For the tunnel waveguide, in terms of the subsequent boundary conditions of tunnel wall tangent electric field and tangent magnetic field, it is met the electromagnetic field component in Maxwell equation for horizontal polarization wave E_h , it is:

$$E_x = E_0 \cos k_1 x \cos k_2 y \exp(-ik_3 z) \quad (1)$$

$$E_y = 0 \quad (2)$$

$$E_z = (ik_1/k_3) E_0 \sin k_1 x \cos k_2 y \exp(-ik_3 z) \quad (3)$$

k_1 and k_2 meet the condition of traveling-wave:

$$k_1 a \approx m\pi, k_2 b \approx n\pi \quad (4)$$

Where m is half wave number of field along the top and floor, n is half wave number of field along the wall. k_1, k_2 and k_3 meet the relationship:

$$k_1^2 + k_2^2 + k_3^2 = 4\pi^2/\lambda \quad (5)$$

Where, λ is the work wavelength.

Because the materials of the mine wall is made of sand and concrete medium, according to the boundary condition of rectangular mine tangent electric field and tangent magnetic field continue, so we know:

$$k_2 = m\pi/b + im\lambda/b^2(\epsilon_{r2} - 1)^{1/2} \quad (6)$$

It can get the following equation from the boundary condition of two wall tangential electric field and tangential magnetic field, because they are zero.

$$k_1 = n\pi/a + in\epsilon_{r1}\lambda/b^2(\epsilon_{r1} - 1)^{1/2} \quad (7)$$

From equation of (6) and (7), we know k_1 and k_2 of propagation mode are similar to the ideal conductor waveguide. There is little difference between the two situations, which is the imaginary part. Because there is total reflection happened in the ideal conductor waveguide. However, refraction phenomenon exists in the tunnel. The imaginary part reflects the refraction phenomenon. According to the relationship of dispersion in the tunnel, k_3 can be obtained:

$$k_3 = k_0 - i\lambda^2/2(m^2\epsilon_{r1}/a^3(\epsilon_{r1} - 1)^{1/2} + n^2/b^3(\epsilon_{r2} - 1)^{1/2}) \quad (8)$$

the imaginary part of k_3 represents the attenuation of z direction, so the attenuation coefficient of E_h is following:

$$L_{E_h} = 4.343\lambda^2 z(m^2\epsilon_{r1}/a^3(\epsilon_{r1} - 1)^{1/2} + n^2/b^3(\epsilon_{r2} - 1)^{1/2}) \quad (9)$$

In the same way, the attenuation coefficient of vertical polarization wave is:

$$L_{E_v} = 4.343\lambda^2 z(m^2/a^3(\epsilon_{r1} - 1)^{1/2} + \epsilon_{r2}n^2/b^3(\epsilon_{r2} - 1)^{1/2}) \quad (10)$$

The equation of (9) and (10) show the approximate attenuation character of horizontal and vertical polarization electromagnetic wave in mine tunnel which is related to the mode and the medium parameter in mine tunnel mainly.

The radio wave transmitted in the tunnel is reduplicated each other by variety mode, so the reduplication of all kinds of transmission mode resulted of the distribution of electric field.

Because of many modes existed, it is impossible and unnecessary to calculate all modes, furthermore ,the attenuation of high level mode is more serious in further field, the effect to the distribution of electronic field is much lesser than the lower level mode. So it is should analyzed according to the sensitivity of particular wireless communication system.

3. Factors that influence the attenuation character in mine tunnel

Because of the mine environment is very complex, the radio waves in the mine tunnel are affected by the working frequency, tunnel size, the roughness and electrical conductivity of wall, turning, branch, tilt, throttle of the mine tunnels, etc.

The following are its general features: the first, radio wave is mainly affected by the cross-section and transmission frequency, the attenuation will decrease when the section of tunnel become larger and the working frequency become higher. Cross-section of tunnel and wavelength are connected with degree of impact of radio wave transmission, When the equivalent radius of cross-section and wavelength has difference of not more than 10 times (Whether the equivalent radius larger than the wavelength, or wavelength greater than the equivalent radius), which has deep influence of radio wave; equivalent radius of cross-section much smaller than the wavelength ,or much larger than the wavelength , it less impact on the radio wave. So cross-section has less impact on MF and others radio wave, has greater impact of HF, VHF and UHF radio waves transmitted. Turning of tunnel, branches and tilt will increase the attenuation of radio wave, and the higher frequency, the attenuation become more.

Secondly, the temporary wind wall of mine has less impact on wave transmission, while permanent wind wall has greater impact on the wave transmission, the higher frequency, the more attenuation. The bypass wind bridge has no effect on the wave transmission, Concrete wind bridge has less impact on wave transmission, canister wind bridge has greater impact on the wave transmission, Wooden throttle and wind shutters has less impact on wave transmission, Steel-wood mixed throttle and wind shutters has greater impact on the wave transmission, Steel throttle and wind shutters can block the spread of radio.

The attenuation characteristics caused by roughness of walls are detailed. Hypothesis the tunnel roughness obey the Gauss Distribution which the mean value is zero and the variance is δ^2 .The angle of incidence is θ_i , when the tunnel surface is rough, the path difference Δd between the two reflected waves is:

$$\Delta d = 2 \times \delta \times \cos \theta_i \quad (11)$$

Then the phase difference is:

$$\Delta \varphi = \Delta d \times k \quad (12)$$

Where $k = 2\pi/\lambda$

If the glancing angle of left and right walls is φ_1 , the glancing angle of roof-floor

wall is φ_2 , then:

$$\sin \varphi_1 = k_x / k = m \lambda / 2a \quad (13)$$

$$\sin \varphi_2 = k_y / k = n \lambda / 2b \quad (14)$$

Radio wave travels along the Z direction, reflection number in left and right walls is:

$$N_1 = z \tan \varphi_1 / a = zm \lambda / a \sqrt{4a^2 - m^2 \lambda^2} \quad (15)$$

Reflection number in roof-floor walls is:

$$N_2 = z \tan \varphi_2 / b = zn \lambda / b \sqrt{4b^2 - n^2 \lambda^2} \quad (16)$$

Rough attenuation factor is defined and obtained:

$$Ra = \exp \left(-4z\pi^2 \delta^2 \lambda^3 \left(m^3 / a^3 \sqrt{4a^2 - m^2 \lambda^2} + n^3 / n^3 \sqrt{4b^2 - n^2 \lambda^2} \right) \right) \quad (17)$$

4. Simulation results of attenuation character in mine tunnel

In the simulation, the width of rectangular mine tunnel is 2.4m, the height is 1.8m, Frequency of sensor is 2.4GHz, the power of transmitter sensor is 100mw, the gain of antenna is one. Because the wall of tunnel is made of sand and concrete, so the related dielectric constant normally is 4.5, and we suppose that the wall of mine tunnel is smooth. The received signals which the transmitter is set in middle of the tunnel show in Figure1.From the Figure1, the attenuation is

quicker when the transmission distance is 30-50m from the transmitter, then it is gently gradually, this is because the distribution of near field is reduplicated with high level modulus. However, when the distance is further, hardly is it affected the basic modulus due to the serious attenuation of high level modulus.

Figure2 shows the attenuation character of the relative dielectric constants of side walls is 10 when the relative dielectric constants of roof-floor change from 2 to 30.The dielectric constant of tunnel walls have great influence on vertical polarization electromagnetic waves than horizontal polarization. Base on the propagation modal of rectangular tunnels, the influences of dielectric constant between side walls and roof-floor of rectangular tunnels on attenuation rate of electromagnetic wave propagation in different polarization modes were studied. In a rectangular tunnel with bigger dimension of the width , when dielectric constant of side walls and roof-floor is equal, attenuation of vertical polarization mode is markedly higher than that of horizontal polarization mode, and with the decreasing of the dielectric constant the attenuation rate of two mode is closing; when dielectric constant of side walls is immobility, the attenuation rate of vertical polarization mode is decreasing with dielectric constant of roof-floor, and finally will less than the attenuation rate of horizontal polarization mode.

Tunnel wall roughness makes waves in the dissemination of the process of scattering in all directions, resulting in energy attenuation. Suppose tunnel wall roughness with a mean of zero and variance of δ^2 Gaussian distribution, $\delta = 0.1\text{m}$, the loss caused by the tunnel wall roughness with frequency as shown in Figure 3.

From Figure 3, the radio waves attenuation which is caused by roughness along with the wavelength increase. But it is usually considered that: the larger the wavelength, δ compared to the λ is smaller, roughness of the tunnel wall has become more level, attenuation caused by roughness should be smaller. Of course, such an analysis is correct, but it needs further analysis: When the wavelength increases, the glancing angle of the tunnel wall become larger, the energy of the medium which reflects into the roadway become larger, the loss becomes larger. Moreover, when the grazing angle become larger, reflections numbers of wave length in the per unit become increase, which also makes the loss larger. Supposed the root mean square of tilted angle of tunnel wall is θ , the attenuation which is caused by tilt of tunnel walls is shown in Figure 4, it shows that the attenuation which is caused by tilt of tunnel walls become increases along with the tilt angle increases.

5. Conclusions

In mine tunnel, with the distance of radio wave propagation become further, the near attenuation of vertical polarization radio will become more slowly than horizontal polarization radio. The attenuation is quicker when the transmission distance is 30-50m from the transmitter, then it will be lowered gradually and gently, this is because the distribution of near field is reduplicated with high level modulus. However, when the distance is further, hardly is it affected the basic modulus due to the serious attenuation of high level modulus. Because of the mine environment is very complex, the radio waves in the mine tunnel are affected by the working frequency, tunnel size, the roughness and electrical conductivity of wall, turning, branch, tilt, throttle of the mine tunnels. The results are benefit to evaluate the channel character of wireless network in mine tunnel.

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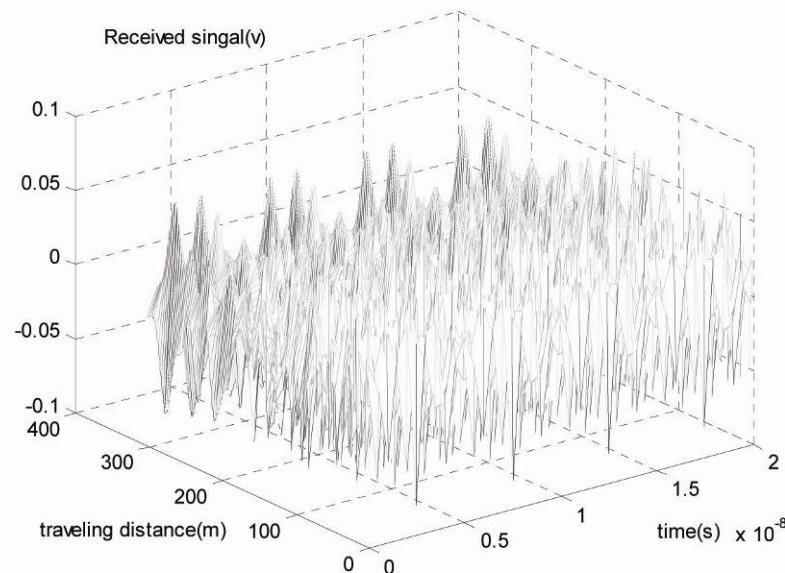


Figure 1. Received signals which the transmitter is set in middle of the tunnel

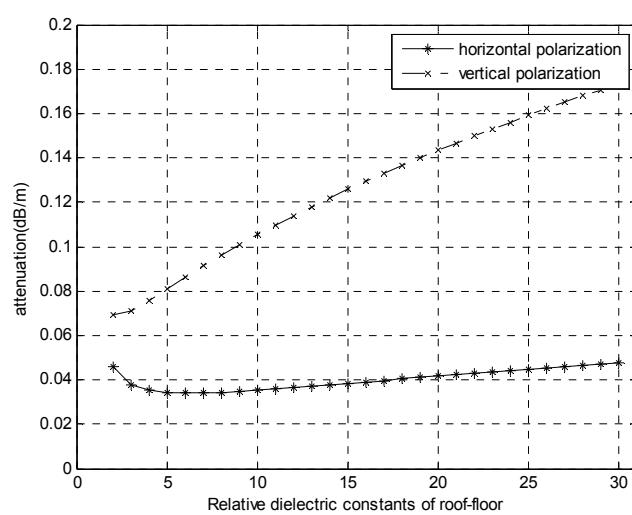


Figure 2. Influence of relative dielectric constants of side walls and roof-floor

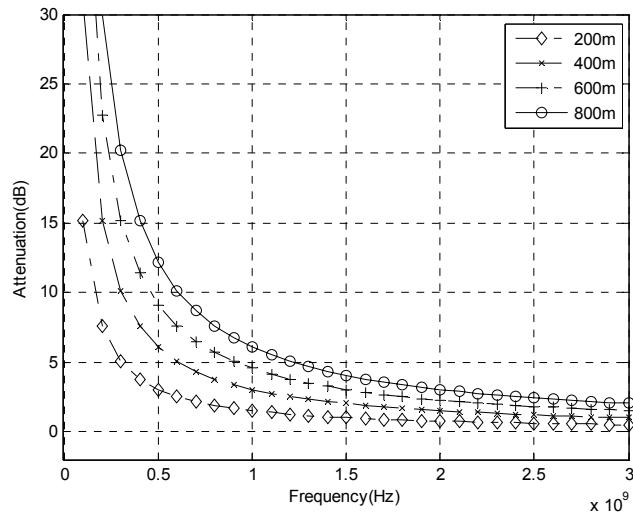


Figure 3. Influence of the roughness in different frequency

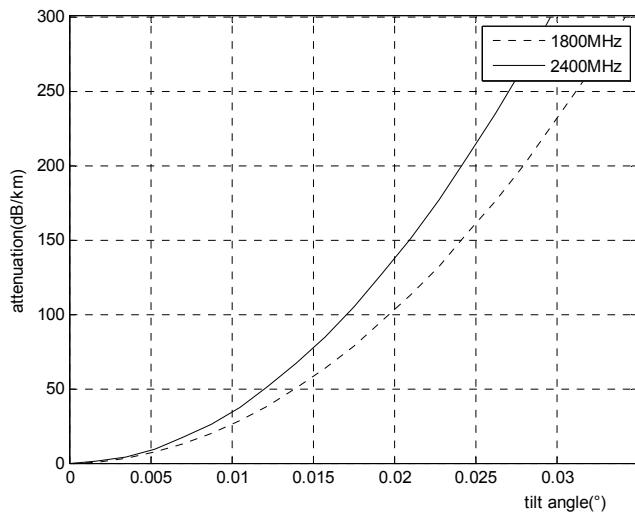


Figure 4. Influence of the tilted angle of tunnel