The Wireless Channel Characteristic Analysis of Coal Mine Rescue Robot in Unstructured Vertical Working Environment

Xusheng Xue*, Hongwei Ma, Kun Ma and Hongwei Fan
School of Mechanical Engineering, Xi’an University of Science and Technology, No. 58 Yanta Road, 710054 Xi’an, China

ABSTRACT

Coal mine rescue robot wireless communication system is the important premise to the coal mine disaster rescue work. Based on the wireless signal transmission mechanism, we research the rescue robot emergency wireless channel characteristic mode in the vertical roadway of the unstructured environment. In this environment, the signal attenuation law has been revealed. After theoretical analysis, the wireless channel change rule has been grasped in the vertical working environment. It provide the basis to rescue robot in complex environment when build a wireless communication network.

INTRODUCTION

Coal mine rescue robot is the one of the important tools to rescue work [1]. Due to the influence of the unstructured vertical working environment, the effectively real-time communication is limited between robot and Rescue Control Center (RCC) on the ground. Wherefore, the information is detected by the rescue robot can not be reliably transmitted. More seriously, the communication is interrupted between the robot and RCC, the robot could be lost [2].

According to the above problems, we based on the characteristics of radio wave propagation in coal mine roadway, the wireless communication characteristics of coal mine rescue robot in the complicated underground environment are studied in the paper [3]. The coal mine rescue robot wireless communication transmission is affected by many factors. Under the influence of the reflection, refraction, absorption, etc., the electromagnetic wave was attenuated in the underground. We find that the wireless channel transmission direction, transmission bandwidth and speed are changed. Thus the ability of the robot to transmit data is limited in such a complex condition of the wireless channel [4, 5].

VISUAL RANGE LOSS AND MULTIPATH LOSS IN THE IDEAL EMPTY ROADWAY

The wireless electromagnetic wave propagation is studied in the ideal coal mine environment. The ideal environment refers to the roadway is relatively uniform, at the same time, the equipment can run well in the stable environment [6].

In the ideal straight underground space, the electromagnetic wave propagation loss expression as [7-9]:

579
\[
[L_d](dB) = 32.45 + 20\log d (km) + 20\log f (MHz) 
\]  

(1)

In formula, \(d\) is signal transmission distance (km); \(f\) is Working frequency (MHz). We know that the wireless signal transmission loss is directly related to transmission distance and frequency.

In the empty and straight underground environment, the wireless electromagnetic wave reflection transmission loss [10-11]:

\[
[L_d](dB) = 10\log \left( \frac{\lambda}{4\pi} \right) \left[ G_d + \sum G_i R_i e^{\frac{2\pi i (L_i - L_d)}{\lambda}} \right] 
\]

(2)

In formula, \(G_d\) is the receiving antenna gain of line-of-sight path, \(G_i\) is The transmitting antenna gain of line-of-sight path, \(R_i\) is the i-th time reflection path corresponding to the product of reflection coefficient, \(L_d\) is Line-of-sight transmission path distance, \(L_i\) is the i-th time the reflection path transmission distance.

We can know from the upper model, a reflection of radio wave transmission loss associated with reflection coefficient \(R_i\). At the same time, the reflection coefficient \(R_i\) associated with coal mine roadway walls electric parameters, surface roughness and so on.

**CHARACTERISTIC ANALYSIS OF WIRELESS CHANNEL IN THE VERTICAL COAL MINE TUNNEL**

In the ideal environment, we assume the way of wireless channels transmit electromagnetic wave is straight line spread. In coal mine roadway, the tunnel forms including rectangular, arched tunnel and bending roadway. Among them, the vertical bending tunnel is special. The way of channel transmission and its structure as show of Figure 1.

Based on geometrical optics principle of wireless electromagnetic wave propagation, we study the propagation characteristics of wireless electromagnetic waves by ray tracing method. We can get the all possible electromagnetic wave ray path between the sending and receiving antenna in the multipath channel, and the synthetic electromagnetic signal characteristics in the receiving point. Based on ray tracing method, we research the characteristics of electromagnetic waves transmission in the vertical roadway space. Our conclusions are as follows:

1) When electromagnetic wave transmission in the vertical roadway, the straight line transmission path of electromagnetic wave cover \(L_1, L_2, \ldots\).

2) As show Figure 1, when the straight line transmission path of emission source is \(L_2\), it passes in the edge of the surrounding rock in the vertical roadway. Maximum straight path through angle is \(\theta\). Due to it is limited by electrical parameters of coal and rock, we find when the electromagnetic wave penetrate, it largely attenuate. We can neglect the power of the electromagnetic wave penetration in the corner of rib.

3) When the electromagnetic wave source transmission along the vertical roadway, we can effectively receive the electromagnetic wave area is EBC shaded area as shown in Figure 1. In the EBC area, the electromagnetic wave occurs after a reflection or multiple reflections which formed the reflection area of electromagnetic wave (this area...
is ECD as shown in Figure 1). As the same time, the shaded area coverage of EBC and ECD related to the source location. Thus, it related to frequency of electromagnetic wave transmission, diameter of the transmission distance $L_1$ and $L_2$, and the intersection angle $\theta$ with the Y axis.

4) According to the transmission and attenuation characteristic of electromagnetic wave in the ideal coal roadway, the attenuation of the electromagnetic wave energy is very fast during reflection propagation. Thus, the wireless signal is more and more weak in the vertical working, which the long distance communication of the coal mine rescue robot can’t be guaranteed.

![Figure 1. The channel transmission way and structural axis in the vertical bending tunnel.](image)

THE ANALYSIS OF THE WIRELESS CHANNEL ATTENUATION CHARACTERISTICS IN THE VERTICAL COAL MINE TUNNEL

As shown in Figure 2, when the wireless electromagnetic wave source position is not in the vertical tunnel mouth, the wireless signal is obtained by the wireless electromagnetic wave reflection of incidence angle $\theta$ in the vertical tunnel. If other obstacles of reflection are not considered, it can be assumed that the roadway in vertical receives the signal is transmitted by radiation in EBC shadow of electromagnetic wave reflection within the coverage. The wireless electromagnetic wave reflection in the vertical tunnels is as shown in Figure 2.

According to the ray tracing method, we can see that the line-of-sight transmission distance $L_s$ is for the linear transmission of electromagnetic signal source along the straight tunnel. It is that:

$$L_s = L_{ld}$$

(3)

At this point, if a radio signal in the vertical transmission of roadway can encounter the coal wall, the basic electromagnetic wave signal is rebound, only a small amount of signal reflection or scattering ripped into the perpendicular to the roadway. Because of coal wall scattering and reflection principle, the signal can be thought of as negligible. If it was transmitted in vertical tunnels, the radio signal transmitted as line-of-sight along the straight tunnel. The attenuation of transmission loss type is as follows:

$$[L_s](dB) = 32.45 + 20\log d (km) + 20\log f (MHz)$$

(4)
From the type, when the radio waves L/T transmit in roadway straight roadway. The linear transmission distance related to the working frequency.

As shown in Figure 2, wireless electromagnetic signal enter the largest vertical tunnels ray (critical rays) is $L_2$. Ray in angle for the rock is $\theta$. At this point the grazing angle is $\theta$. Study the reflection transmission characteristics of critical rays in the vertical tunnels. We can get a signal in the vertical roadway furthest distance.

**Grazing Transmission Distance $L_2$**

Critical line-of-sight transmission angle is $\theta$ with the rock means the maximum linear transmission path to enter the vertical electromagnetic wave of roadway. Therefore, it is:

$$L_d = L_{c0} + L_2 = a / \sin \theta_1$$  \hspace{1cm} (5)

At this point, the time delay is as follows:

$$\Delta t = L_1 / c$$  \hspace{1cm} (6)

In the formula, $c$ as the speed of light in vacuum.

Critical line-of-sight transmission is from the launch of the wireless signal source electromagnetic signals into vertical roadway maximum critical direct transmission. Critical line-of-sight transmission path loss is as follows:

$$\left[ L_d \right] (dB) = 32.45 + 20 \log L_d (km) + 20 \log f (MHz)$$  \hspace{1cm} (7)

**The Coal Wall Reflection Transmission Loss on Both Sides**

A reflection path on both sides of the coal wall type is as follows:

$$L_2 + L_3 = \sqrt{2a - h_1} + p_1^2$$  \hspace{1cm} (8)

The grazing angle is as follows:

$$\sin \theta_1 = \frac{2a - h_1}{L_2 + L_3}$$  \hspace{1cm} (9)

As a result, an odd number of times of reflection path distance can be we launched and it is as follows:
According to the ray tracing method, we can know the line-of-sight transmission distance is for the linear transmission of electromagnetic signal source along the straight tunnel. It is as follows:

\[
|L_{\text{soa}}|(dB) = 10\log \frac{P_r}{P_a}
\]

\[
= 10\log \left[ \left(\frac{4\pi L_{\text{soa}}}{\lambda}\right)^2 \cdot \frac{1}{R^{(\pm)} G_r G_g} \right]
\]

\[
= 32.45 + 20\log L_{\text{soa}}(\text{km}) + 20\log f(\text{MHz}) - 10\log (G_r G_g) - 10n\log R^{(i)}
\]

On the type, \( P_r \) is wireless electromagnetic waves transmitted power, \( P_a \) is received signal power; \( G_r \), \( G_g \) are receive and transmit antenna gain, \( R^{(\pm)} \) is reflection coefficient of vertical coal mine roadway on both sides of the walls.

By the same token, the second reflection paths on both sides of the coal wall type are as follows:

\[
L_a = L_a + L_2 + L_4 = \sqrt{(a + h)^2 + p^2}
\]

The grazing Angle is as follows.

\[
\sin \theta_1 = \frac{3a - h}{L_2 + L_4 + L_4}
\]

As a result, even time reflection path distance can be launched and it is shown in follows:

\[
L_{\text{even}} = L_2 + L_3 + \ldots + L_{m+1} = \sqrt{(m+1)(a + h)^2 + p^2} \quad (m = 2, 4, 6, \ldots)
\]

As a result, even time reflection path distance can be launched and it is shown in follows:

\[
|L_{\text{even}}|(dB) = 10\log \frac{P_r}{P_a}
\]

\[
= 10\log \left[ \left(\frac{4\pi L_{\text{even}}}{\lambda}\right)^2 \cdot \frac{1}{R^{(\pm)} G_r G_g} \right]
\]

\[
= 32.45 + 20\log L_{\text{even}}(\text{km}) + 20\log f(\text{MHz}) - 10\log (G_r G_g) - 10m\log R^{(i)}
\]

On the type, \( P_r \) is wireless electromagnetic waves transmitted power, \( P_a \) is received signal power; \( G_r \), \( G_g \) are receive and transmit antenna gain, \( R^{(\pm)} \) is reflection coefficient of vertical coal mine roadway on both sides of the walls.

According to the receiving antenna total power formula, there are:

\[
P_R = \left| \frac{\lambda}{4\pi L_{\text{os}}} \cdot G_r G_g \cdot \left[ 1 + \sum_{i=1}^{m} \sum_{k=1}^{i} \sum_{k=1}^{m} R^{(\pm)} e^{i\Delta \phi_{\text{t}}} \right] \cdot P_r \right|
\]

\[
\Delta \phi_{\text{t}} = \frac{2\pi L}{\lambda}
\]
On the type, $\lambda$ represents the wireless electromagnetic wave wavelength; $R^{(i)}$ is the $i$ times the reflection coefficient of coal wall on both sides; $\Delta \varphi_i$ is the phase difference of reflection or grazing path.

As a result, the total loss of wireless electromagnetic waves at the time.

$$
[L_{tot}] (dB) = 10 \log \frac{P_T}{P_R}
$$

$$
= [L_d] (dB) + [L_{wall}] (dB) + [L_{con}] (dB)
$$

$$
= 32.45 + 20 \log p (km) + 20 \log f (MHz) - 10 \log (G_t G_r) - 20 \log \left[ 1 + \sum_{j=1}^{n} \sum_{i=1}^{m} R^{(i)}_{il} e^{j \Delta \varphi_i} \right]
$$

(18)

On the type, $P_T$ is wireless electromagnetic waves transmitted power, $P_R$ is received signal power; $G_t$, $G_r$ are receive and transmit antenna gain, $R^{(i)}_{il}$ is the $i$ times the reflection coefficient of coal wall on both sides, $\Delta \varphi_i$ is the phase difference of reflection or grazing path.

**CONCLUSIONS**

Due to the wireless electromagnetic wave source have some space in the vertical tunnel mouth, which the reflection of the electromagnetic wave is very few on the top and bottom wall. We just have to research about the reflection effect of coal wall on both sides, and ignored the top and bottom reflection signal. We can obtain the receiving point signal from the EBC area and reflection area when the reflection and scattering effects of other obstacles are not considered. Through our study, the transmission loss of the wireless electromagnetic wave in the vertical tunnel has the following three characteristics:

1) It mainly includes the LOS transmission freedom loss of critical line-of-sight transmission area. The loss is related to transmission distance $L_{oc}$, wall angle $\theta$ and antenna transceiver gain.

2) It meets both sides of the coal wall for reflection transmission after the critical direct line-of-sight transmission path loss. The reflected signal is the farthest distance signal transmission path of signal transmission.

3) If the top and bottom transmission path are not considered, so the tunnel mouth signal transmission signal path in the $L/T$ transmission path is relatively simple. Signal strength in multipath fading is smaller.

**ACKNOWLEDGEMENT**

Overall innovation project of Shaanxi province science and technology plan resources leading technology industry (chain) project, Mine Rescue Detect Robot Developed, No. 2013KTCL01-02.

National Natural Science Foundation of China, Research on autonomous navigation and intelligent control of mine rescue robot, No. 50674075
Scientific Research Plan Projects of Shaanxi Education Department of China, Adaptive active balancing technology of grinding wheel motorized spindle based on electromagnetic balancer, No.16JK1494
Xi'an University of Science And Technology Training Fund, Research on intelligent system of coal mine rescue robot distributed wireless communication, No. 201627

REFERENCES