

# The construction of multipath channel models based on low voltage power lines in coal mines<sup>1</sup>

SHAOLIANG WEI<sup>2,3</sup>, FENGYU CHENG<sup>2</sup>, YEMING ZHANG<sup>2</sup>, WENBO QIN<sup>2</sup>

**Abstract.** Due to the fact that coal mines share an information network status in the mine, and based on an analysis of a low voltage power line's network topology in the coal mine, this work points out that the low voltage power line's channel noise, attenuation and the multipath characteristic seriously affect the quality of low voltage power line high-speed data communication. This work puts forward and establishes an attenuation model of the power line's carrier multipath channel. The established multipath channel's attenuation model, which is based on simulation experiments, is in line with the characteristics of actual channel attenuation, and is therefore a good reference in researching low voltage power line communication technology in coal mines.

**Key words.** Coal mine, low voltage power line, multipath effect, channel model, network.

## 1. Introduction

Due to the harsh physical conditions within coal mines, many factors, such as limited communication facilities, layout space, ubiquitous wireless communication barriers, advancing changes in production of working face, information utilization within coal mines has been low over the years, and it was not possible to form a vast underground communication network, which results in an overall lack of effectiveness regarding information transmissions. Power line as the energy carrier interconnects the coal mine equipment, and already formed a network extending in all directions. Therefore the network has the outstanding advantages of extensive coverage, which means there is no need to rewire, and the connection is permanent. Using an existing power line as a channel to transmit data and realize the automation

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<sup>2</sup>Henan Polytechnic University, 454000, China

<sup>3</sup>Email: Ws1\_ify@163.com

and intellectualization of coal mine production has important significance.

The low voltage power distribution network within coal mines has complexity structure, harsh communication conditions, channel noise and attenuation and other problems [1]. When the power line connects different types of loads, it could cause the different impedance of the different power line section and make it difficult for the communication system's impedance characteristics to match [2]–[5]. At the same time, on the low voltage power line, the electrical equipment connects on or cuts off the power line at any time which will create interference for the power line, and when the high-speed data signal transmits on the power line, the reflection signal, the standing wave, resonance or other complex phenomena will be caused. It would lead to the signal's transmission delay when the signal arrives at the receiving terminal, and the signal would be selective fading [6], [7]. Setting up a precise power line's channel model is one of the key technologies necessary to realize a high-speed data signal transmission based on low voltage power lines in coal mines.

## 2. The coal mine low voltage power distribution network's topology analysis

We have performed a great deal of field research into the domestic coal mine topology of low-voltage power lines, and our research results show that the pieces of equipment central to various coal mines are all different. For instance, the recently developed Yanzhou mining bureau is a modernization mine, the coal output is high, and the mines are comprised of fully mechanized equipment. The Feicheng mining bureau consists of small coal mines, with low annual outputs, and the mining equipment is mainly conventional equipment. The Xinwen mining bureau consists of a medium-sized coal mine whose size is medium, with a mixture of fully mechanized equipment and conventional equipment. In order to guarantee the universality and representativeness of this study, we selected a specific coal mine specific to Xinwen mining bureau's low-voltage power line as our research object. The mines are builded early, the underground coal mine environment is relatively complex, and the vertical shaft is deep, carrying with it a number of characteristics common to typical coal mines. The coal mine high and low voltage power distribution network is shown in Fig. 1 [1].

From Fig. 1 we can see the coal mine power supply network is relatively complex, with the following features:

- A. Coexisting high and low voltage. The power supply voltage is usually more than 10kV. When the power transmits to the underground mine, firstly, the high voltage should be turned to the low level voltage by the ground transformer. The coal mine is divided into multiple horizontal mining areas, and these different levels distribute all levels of power with independent central substation. Each level is further divided into a number of transforming units, and then the power is distributed by the transforming units, the low voltage electrical equipment will gain the suitable voltage power.
- B. There are many different kinds of low voltage electrical equipment. First,

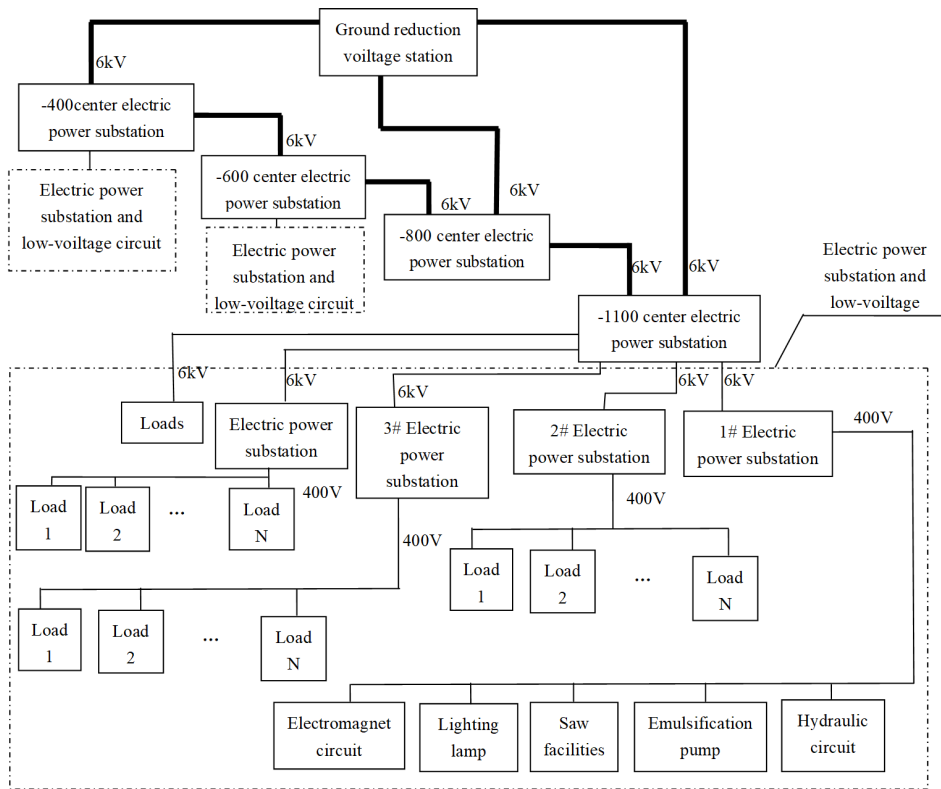


Fig. 1. Structure of power line net in an underground coal mine

there is high-power electrical equipment, such as shearers, scraper conveyors, conveyor belts, and water pumps. However, there are also smaller pieces of electric equipment, such as lighting, sawing machines, and emulsifying stations.

- C. AC/DC power equipment coexists. In order to meet the special requirements for power, speed governing and motor-start, in addition to the AC power equipment, there are a lot of DC equipment in the coal mine. General DC source is derived through rectifying equipment transformation. Therefore, electrical equipment in underground coal mine consists of both AC and DC equipment. There are high-order harmonic components in the power line which produces disturbances for the signal transmission.
- D. Low voltage circuitry has many nodes and an obvious multipath effect. Because the space in a coal mine is long and narrow, electric equipment is scattered; therefore, there are a lot of low voltage power equipments connecting with the power line and there are some nodes in the line, which will show serious reflection, refraction, resulting in an obvious multipath effect.
- E. Power cable is special. The most important characteristic of an underground

power supply is that it is explosion-proof. Therefore, any equipment must be safe; a power supply is generally selected that has negligible cable leakage, with strong, durable packaging. The transmitting characteristics of underground cables are different from the ground general twisted-pair cables and common cables.

- F. The low voltage power distribution network is widespread. The power supply network is distributed to every corner of the coal mine, including the areas which are prone to accidents, such as the mining face, the tunneling head-on, the working face, etc. and including the shaft station, the main roadway, rise roadway and track dip.
- G. Working space with mobility. Before the coal mining the tunneling head-on should be built and supported in the rock or coal seam. Along with the transfer of the mining head the tunneling head-on should be constantly moved forward; consequently, the power supply network must move with it. Secondly, the mining face moves ahead continuously, the mining equipment, transportation equipment and supporting equipment move ahead too. Consequently, the power supply network should be moved ahead. The working face is constantly moving ahead along with the movement of the mining face. Because of the moving characteristics of the working face, the mining face, the tunneling head-on and the working face have the worst monitoring, the worst early warning system, and have caused the greatest number of serious accidents.

Given the coal mine power supply network outlined above, it is important to establish an information network in these coalmines. Because of specific characteristics of the low voltage power supply network, such as widespread coverage and strong cable structures, the low voltage power line network has great advantages of building broadband network. At the same time, the above analysis shows that the underground low-voltage supply network is more complicated and less conducive to signal extraction and transmission factors than the low voltage power supply network on the ground. The key technologies of achieving high speed data communication through the coalmine low voltage power line are channel modeling and communication strategy. Establishing a strong real-time channel model is one of the conditions to realizing communication function. Therefore, this research performed an analysis based on extensive field research and experimental study. The coalmine low voltage power line's channel has the transmission characteristics of a strong multipath effect and a multipath-fading model can correctly reflect the channel.

### **3. The establishment and analysis of the multipath model**

We selected the level low voltage power supply network of  $-400$  as the typical research object; the refinement of its topology structure is shown in Figure.2. A variety of typical equipment of coal mine connects with the network. Mines not only have high-power and extended operation equipment, such as drills, pumps, and hydraulic equipment, but also have generally low power equipment, such as

lighting equipment. The line has many branch lines, and high-speed data signal transmission's attenuation is rapid. The multipath effect is obvious.

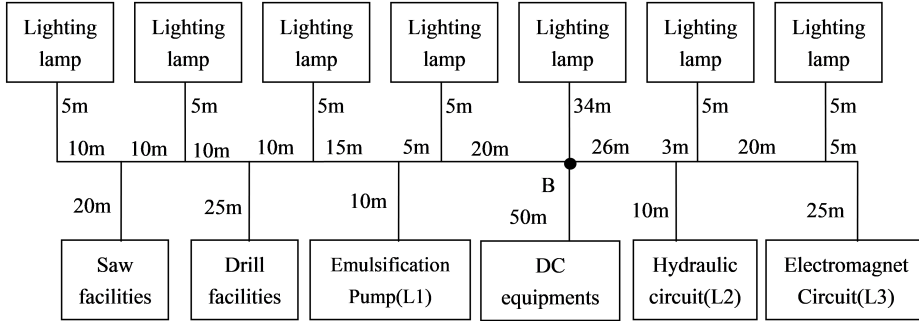


Fig. 2. Realistic underground coal mine power line channel

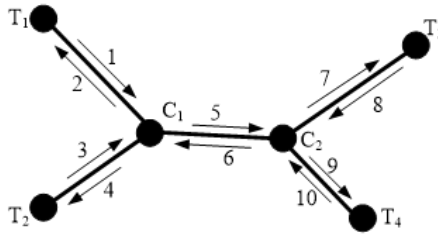


Fig. 3. Example of multipath spread

In order to illustrate the effect of the multipath effect, we selected six nodes in Fig. 2. The constitution is shown in Fig. 3.

Figure 3 shows the path of the signal transmission in all directions, there are 6 nodes in the graph, 7 lines and 10 signal transmitting lines. We could assume that the signal input from the node  $T_1$  and  $T_4$  is the signal's receiver. Then the signal transmission's path has:

$1 \rightarrow 5 \rightarrow 9$ ;  $1 \rightarrow 5 \rightarrow 6 \rightarrow 5 \rightarrow 9$ ;  $1 \rightarrow 2 \rightarrow 1 \rightarrow 5 \rightarrow 9$ ;  $1 \rightarrow 5 \rightarrow 9 \rightarrow 10 \rightarrow 9$ ;  
 $1 \rightarrow 4 \rightarrow 3 \rightarrow 5 \rightarrow 9$ ;  $1 \rightarrow 4 \rightarrow 3 \rightarrow 5 \rightarrow 9$ ;  $1 \rightarrow 4 \rightarrow 3 \rightarrow 5 \rightarrow 7 \rightarrow 8 \rightarrow 9$ ;  
 $1 \rightarrow 4 \rightarrow 3 \rightarrow 5 \rightarrow 7 \rightarrow 8 \rightarrow 9 \dots\dots$

Because the reflection and refraction of the nodes in the path, the signal propagation path in the power line network is complex. The multipath effect of the signals is obvious; the transmission and extraction of signals would cause serious attenuation and delay [8]–[10].

### 3.1. Attenuation caused by multipath time delay

There are a vast number of branches in a power line network. The transmission of signals not only passes the recent path between the sender and the receiver, but

it might also go through another branch channel into the receiver, which would lead to different delay, and the superposition of the received signal and delayed signal could cause the attenuation of signals. The time delay of the signal and the signal propagation's velocity is related to the length of the path

$$\tau_i = \frac{S_i}{v}, \quad (1)$$

$$v = \frac{c_0}{\sqrt{\varepsilon_\gamma}}. \quad (2)$$

In type (1),  $\tau_i$  is the time required for the signals to go through the  $i$  th path. The length of the  $i$  th path is  $S_i$ . The speed of signal transmission is  $v$ . Type (2) is a calculation formula of signal transmission speed, in which  $c_0$  is the speed of light, and  $\varepsilon_\gamma$  is the relative dielectric constant electric insulating materials. The calculation result shows that the signal's speed is the 60% the speed of light commonly found in the power line network transmission [6].

For our purposes, we suppose the launch signal is  $x(t)$ . The number of propagation is  $N$ . The signal strength is  $A$ . Therefore, in the time domain analysis, the time delay signal at the receiving end is as follows

$$r'(t) = \sum_{i=0}^N A \cdot x(t - \tau_i). \quad (3)$$

Figure 4 is a transmission model showing how the signals go through every delay route from the sending end to the receiver.

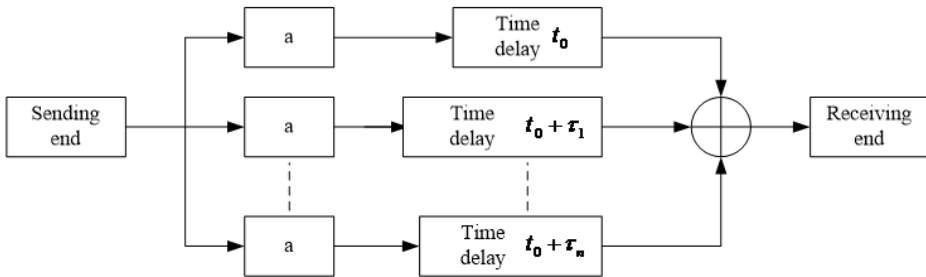


Fig. 4. The transmission model of the delay path

In Fig. 4,  $t_0$  is the inherent time delay of the channel. So the received signal is

$$\begin{aligned} r(t) &= ax(t - t_0) + ax(t - t_0 - \tau_1) + \cdots + ax(t - t_0 - \tau_n) = \\ &= ax(t - t_0) + \sum_{i=1}^n ax(t - t_0 - \tau_i). \end{aligned} \quad (4)$$

On  $r(t)$  Fourier transform, then

$$R(\omega) = aX(\omega)e^{j\omega t_0} + \sum_{i=1}^n aX(\omega)e^{j\omega t_0} e^{j\omega\tau_i} = aX(\omega)e^{j\omega t_0} \left( 1 + \sum_{i=1}^n e^{j\omega\tau_i} \right). \quad (5)$$

In a multipath time delay transfer function  $H(\omega)$  can be expressed as

$$H(\omega) = \frac{R(\omega)}{X(\omega)} = ae^{j\omega t_0} \left( 1 + \sum_{i=1}^n e^{j\omega\tau_i} \right). \quad (6)$$

The factor  $H(\omega)$  changes with changes to the angular frequency  $\omega$ . At a different frequency point, there would be a different attenuation.

### 3.2. The attenuation caused by multipath propagation

The signal's multipath propagation attenuation refers to mediums with differing characteristic impedance, which causes the impedance's discontinuity in the communication channel. There are a great number of breakpoints of the impedance and reflection and refraction occurs when the signal flows through these breakpoints [11]–[14]. Thus we use the T transmission network to analyze the signal attenuation; a multipath transmission network can be composed of many T networks. Figure 5 shows an analysis of a T network. We assume  $A$  is the sender of the signal;  $C$  is the signal's receiver, and node  $B$  is on the communication channel.  $D$  is the other node connected to  $B$ . The length of the three cables connected to node  $B$ , respectively, are  $l_1$ ,  $l_2$ ,  $l_3$ , and we assume that each section of the characteristic impedance, respectively, are  $Z_1$ ,  $Z_2$ ,  $Z_3$ . In the node  $D$ , the load impedance is set to be  $Z_D$ . In order to simplify the calculation steps, we must assume that the input impedance of the sender and the receiver are matched with the characteristic impedance of the cable section 1 and section 3, which means that:  $Z_A = Z_1$ ,  $Z_C = Z_2$ .

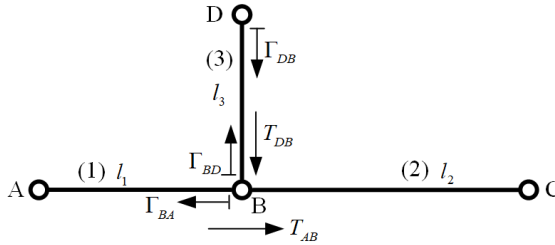


Fig. 5. Multipath propagation in T network

We define the factor of transmission of this process as  $T_{ij}$  when the signal is transmitted from the node  $i$  through node  $j$ . When the signal is transmitted from node  $j$  to node  $i$ , it reflects back to the node. We have used reflection factor  $\Gamma_{ij}$  to represent this process. Under the conditions of our assumption, we can use the

following formula to count transfer factors and the reflection factors in Fig. 5:

$$\Gamma_{BA} = \frac{(Z_2 \parallel Z_3) - Z_1}{(Z_2 \parallel Z_3) + Z_1}, \quad (7)$$

$$\Gamma_{DB} = \frac{Z_D - Z_3}{Z_D + Z_3}, \quad (8)$$

$$\Gamma_{BD} = \frac{(Z_1 \parallel Z_2) - Z_3}{(Z_1 \parallel Z_2) + Z_3}, \quad (9)$$

$$T_{DB} = \frac{2(Z_1 \parallel Z_2)}{2(Z_1 \parallel Z_2) + Z_3}, \quad (10)$$

$$T_{AB} = \quad (11)$$

$N$  paths signal attenuation parameters are shown in Table 1.

Table 1. The parameters of signal propagation paths

Serial number	Signal propagation path	The weighing factor $G_i$	The length of the path
1	$A \rightarrow B \rightarrow C$	$T_{AB}$	$l_1 + l_2$
2	$A \rightarrow B \rightarrow D \rightarrow B \rightarrow C$	$T_{AB} \cdot \Gamma_{DB} \cdot T_{CB}$	$l_1 + 2l_3 + l_2$
3	$A \rightarrow (B \rightarrow D \rightarrow)^2 B \rightarrow C$	$T_{AB} \cdot \Gamma_{DB}^2 \cdot \Gamma_{BD} \cdot T_{CB}$	$l_1 + 4l_3 + l_2$
$\vdots$	$\vdots$	$\vdots$	$\vdots$
$N$	$A \rightarrow (B \rightarrow D \rightarrow)^{N-1} B \rightarrow C$	$T_{AB} \cdot \Gamma_{DB}^{N-1} \cdot \Gamma_{BD}^{N-2} \cdot T_{CB}$	$l_1 + 2(N-1)l_3 + l_2$

$A$  is the weighted factor of the  $N$ th path, which is the function of the transfer factor and the reflection factor. Given the transmission factor and calculation formula of the reflection factor, we know both values are less than 1. Consequently, the value of the weighted factor  $B$  is less than 1, which can be directly expressed in the following formula

$$G_i = \prod_{k=1}^K T_{ik} \prod_{m=1}^M \Gamma_{im} \quad (12)$$

In addition to an increase in the path and reflection, the signal attenuation becomes more serious and the weighted factor decreases [15]–[16]. So the signal transmission abates with an increase to the length of the path [? ].

### 3.3. The attenuation of the line loss

The attenuation of the line loss refers to that the heat loss and the radiation loss when the signal is transmitting through the power line. According to the transmis-



sion line theory, underground power lines can be seen as shown in models consisting of resistance inductance, capacitance, etc. These are shown in Fig. 6.

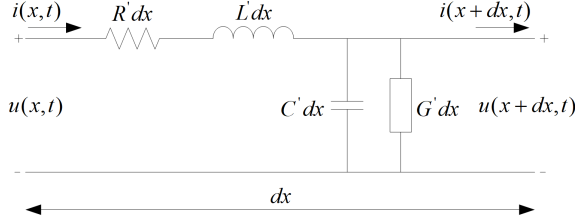


Fig. 6. Power line equivalent model

The factor  $x$  expresses the position in the figure;  $u(x, t)$ ,  $u(x + dx, t)$  respectively expresses the voltages in  $x$  and  $x + dx$ . The values  $R'$ ,  $L'$ ,  $C'$ ,  $G'$  indicate the values of the electric parameters per unit length. These units are, respectively,  $\Omega/m$ ,  $H/m$ ,  $F/m$ ,  $G/m$ . According to Kirchhoff's law, we can obtain the following equation:

$$u(x, t) - u(x + dx, t) = i(x, t) \cdot R'(t) dx + L' \frac{\partial i(x, t)}{\partial t} = 0, \quad (13)$$

$$i(x, t) - i(x + dx, t) = u(x, t) \cdot G'(t) dx + C' \frac{\partial u(x, t)}{\partial t} = 0. \quad (14)$$

Defining two transmission line parameters  $\gamma$ ,  $Z_C$

$$\gamma = \alpha(\omega) + j\beta(\omega) = \sqrt{(R' + j\omega L') \cdot (G' + j\omega C')}, \quad (15)$$

$$Z_C = \sqrt{\frac{(R' + j\omega L')}{(G' + j\omega C')}}. \quad (16)$$

The factor  $\gamma$  expresses the line's transmission coefficient, the factor  $\alpha(\omega)$  is the amplitude attenuation factor, the factor  $\beta(\omega)$  is the mobile phase factor, and the factor  $Z_C$  is the line's characteristic impedance.

For transmitting 1 MHz – 30 MHz high frequency signals, because of  $\omega L' \gg R'$ ,  $\omega L' \gg G'$ , the two parameters of transmission line features  $Z_C$  and  $\gamma$  can be abbreviated as under

$$Z_C \approx \sqrt{\frac{L'}{C'}} \quad (17)$$

$$\gamma \approx \frac{1}{2} \frac{R'}{Z_C} + \frac{1}{2} G' Z_C + j\omega \sqrt{L' C'}, \quad \text{Re}(\gamma) = \alpha, \quad \text{Im}(\gamma) = \beta. \quad (18)$$

According to transmission line theory, the resistance of the unit length of power line is affected by the skin effect. Therefore, we have the following approximate

relationship

$$R' \sim \sqrt{f}, G' \sim f'. \quad (19)$$

Then (15) can be used as a constant to transformation, as follows

$$\gamma \approx k_1 \sqrt{f} + k_2 f + j k_3 f, \operatorname{Re}(\gamma) = \alpha, \operatorname{Im}(\gamma) = \beta. \quad (20)$$

We know the amplitude attenuation factor  $\alpha$  is the function of  $f^k$ , which can be represented as

$$\alpha = a_1 + a_2 f^k, \quad (21)$$

$k$  is the index of the attenuation factor, whose value is commonly between 0 and 1.

When a high-speed data signal goes through the line transmission whose length is  $d$ , its transfer function is

$$H(f) = \frac{U(d)}{U(0)} = e^{-\gamma d} = e^{-\alpha d + (-j\beta d)} = e^{-\alpha d} \cdot e^{-j\beta d}. \quad (22)$$

The real part of the transfer function is the amplitude attenuation. When the high frequency signal transmits in a power line network, the attenuation caused by the line itself is

$$A(f, d) = e^{-(a_0 + a_1 f^k)d}. \quad (23)$$

After integrating the above three kinds of attenuation, then the transmission function of the coal mine power network multipath model can be expressed by type (24)

$$H(f) = |G_0| \cdot a e^{j f \tau_0} \cdot e^{-(a_0 + a_1 f^k)d_0} + |G_1| \cdot (a e^{j f \tau_0} \cdot e^{j f \tau_1}) \cdot e^{-(a_0 + a_1 f^k)d_1} + \dots +$$

$$|G_n| \cdot (a e^{j f \tau_0} \cdot e^{j f \tau_n}) \cdot e^{-(a_0 + a_1 f^k)d_n} = \sum_{i=0}^n |G_i| \cdot A(f, d_i) \cdot (e^{j f \tau_0} \cdot e^{j f \tau_i}). \quad (24)$$

Among the above there is  $e^{j f \tau_0} = 1$ , its corresponding coalmine multipath model can be expressed by Fig. 7.

This model better reflects the multipath attenuation characteristics of the coalmine channel. The signal transmission goes through the path to the receiver. Different paths produce different attenuations. The signal's reception is the superposition of every path's transmission signal [17]–[19].

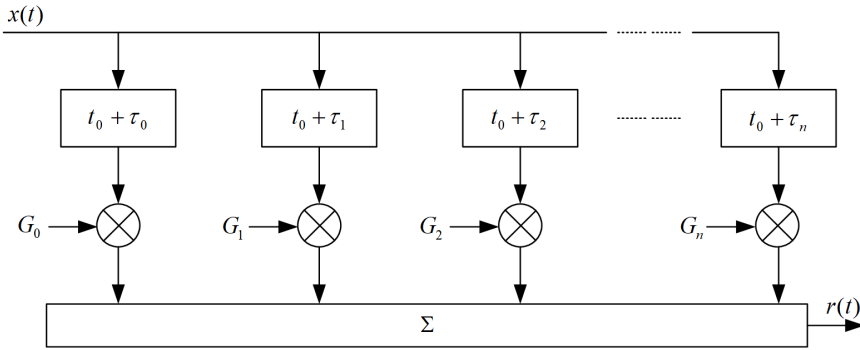


Fig. 7. Multipath model underground coal mine

### 4. Simulation experiment of multipath model

At this point we performed a simulation experiment by taking point *B* in Fig. 2 as an example. According to the signal transmission characteristics of path *B*, we can see there are about four impedance-mismatching points. We then set up a four-path model, whose path length was based on the setting distance of the connection underground path *B*.

According to the formula and transmission line theory, we can obtain the model parameters shown in Table 2.

Table 2. Model parameters

Path	1	2	3	4
The length of the path $d_i$ (m)	20	26	34	50
The weighing factor $ G_i $	0.82	0.47	0.23	0.07
Delay time $\tau$ ( $\mu$ s)	0.13	0.17	0.20	0.26
Attenuation factor index $k$	$a_1 = 0$		$a_2 = 8.0 \times 10^{-10}$	

We created a model simulation for a path of 4, and compared it to the measured characteristic curve in the transmission path *B*. We then obtained the characteristic curve shown in Fig. 8. The implementing line indicates the measured transmission characteristics of path *B* in the figure, and the dotted line refers to the model simulation.

In Fig. 8, we can see that the 4-path model’s simulation satisfies the change trend of the measured curve. The concave points in the measured curve could also be good coincident with the model curve. According to the count, we can find the correlation coefficient of the two curves, which is *A*, and root mean square error, which is *B*. In order to better assess the effect the number of the model’s path has on the simulation characteristics, the given calculated values of the correlation coefficient and the root

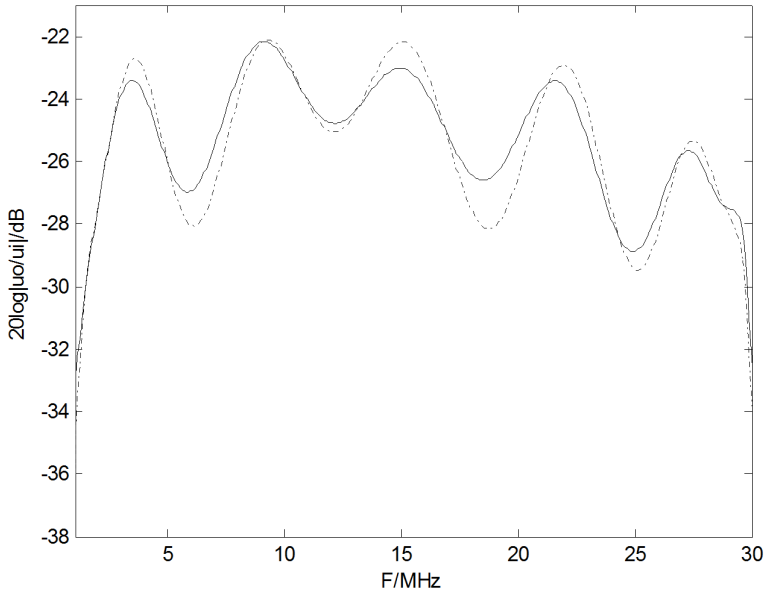


Fig. 8. Four paths model simulation diagram

mean square errors are shown in Fig. 9.

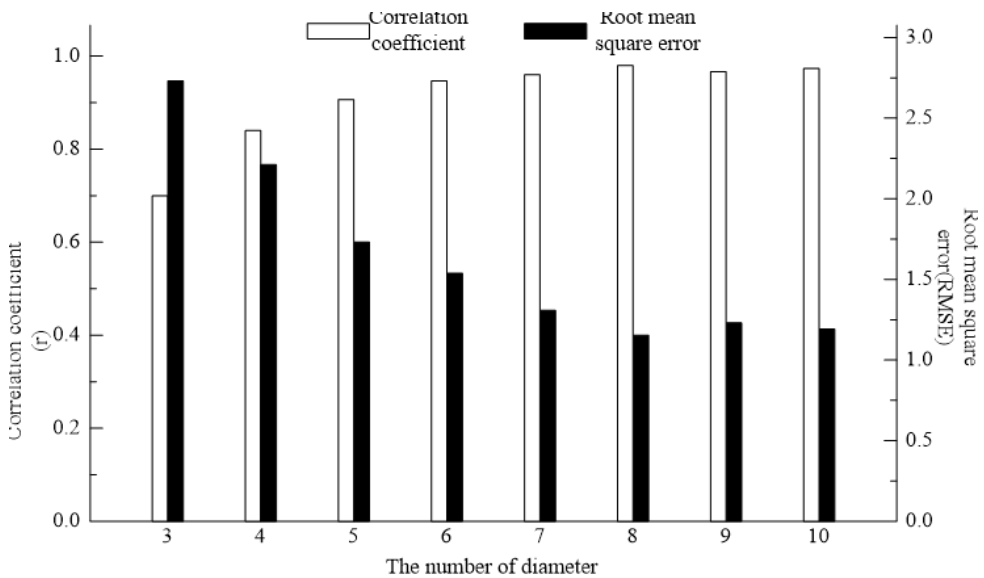


Fig. 9. The  $r$  and  $RMSE$  change trending with paths

From the above graph, we can see when the amount of the model's path is between

3 and 9; the correlation coefficient  $r$  presents a gradually increasing trend and the root mean square error  $RMSE$  presents a gradually reduced trend as the path number increases. But when the path amount is 9 or 10, the correlation coefficient is less than what is found in the 8-path model, and the root mean square error increases. Therefore, establishing a multipath model for power line communication does not guarantee greater accuracy with a greater number of paths.

## 5. Conclusion

Due to the particularity of low-voltage power line carrier communications, this study examined a coalmine low voltage power line's power supply network. This research points out there are more significant differences between the low voltage power line's transmission characteristics and the transmission characteristics of a low voltage power line on the ground, and there are fewer factors that are conducive to high-speed data transmission the underground low-voltage power line in coal mine. Because there are frequency selective attenuation and multipath effect, we selected a certain coalmine actual low voltage power line network and established a low voltage power line multipath attenuation model. We then obtained the transfer function of the multipath model. Our simulation experiments show that the attenuation characteristics of the established multipath attenuation model are consistent with actual measurements. At the same time, these experiments have pointed out that establishing a model for the multipath fading of the channel does not prove a relationship between a more the selective path and higher communication accuracy. This experimental conclusion establishes useful reference significance for related research.

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