

# A MODEL FOR PREDICTING RADIO WAVE PROPAGATION ATTENUATION IN RECTANGULAR COAL MINE TUNNELS

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**Abstract** - Studying the factors that affect radio wave path loss in coal mine tunnels is of great importance in building a radio communication system in coal mine tunnels. In this paper, we propose using a model of evaluating radio wave propagation path loss in rectangular mine tunnels with factors affecting wave propagation attenuation including signal frequency, tunnel sizes, electric parameters of top-floor and side walls of the tunnel. The model has also been tested via actual measurement in two 100m-long rectangular mine tunnels. The first one has the width  $w$  of 6m and the height  $h$  of 3m. The other has the width  $w$  of 3 m and the height  $h$  of 1.7m at the frequency of 900 MHz and 2.4 GHz. The actual measurement results completely correspond to the model we have proposed.

**Key words** - rectangular coal mine tunnel; radio waves propagation; path loss; wireless communication; electromagnetic waves.

### 1. Introduction

Vietnam is a country owning very large scale mineral mining industry. In each coal mine tunnel, for example in Khe Cham 3, there are hundreds of miners working in thousands of meter long underground tunnels every day. Therefore, researching to build a radio communication system in mine tunnels has attracted the attention of many researchers. Since the environment inside tunnels is very complex, it is necessary to accurately assess factors affecting the propagation loss in coal mine tunnels in order to build a radio communication network efficiently.

Popular mine tunnel shapes are rectangle, circular and arched. There have been a lot of researches on the characteristics of radio wave propagation in various kinds of tunnel with the different sizes. Mr. A.G.Emslie [4] built an attenuation model due to wave polarization, the influence of the surface roughness inside tunnels and the slope of tunnel based on Maxwell's equations. Y.P.Zhang [5] also proposed a model predicting wave propagation attenuation in rectangular tunnel. He split the tunnel into two zones distinguished by a break point. Each attenuation zone is affected by free space and the electrical parameters of walls and top-floor of the tunnel, tunnel size and frequency of signal. Research on wave propagation attenuation in cylindrical mine tunnels [6, 7], in arched one [8] pointed out that various curve of mines, mine size, frequency of signal, material of walls tunnel influence propagation wave loss are different.

In order to design radio wave communication systems in mine tunnels in Vietnam, in this paper we propose using a model of predicting propagation wave path loss including propagation wave path loss in free space and other factors affect for rectangular coal mine tunnel. We also simulate and analyze factors affecting radio wave propagation attenuation. Simultaneously authors tested it by measuring

**Tóm tắt** - Nghiên cứu các yếu tố ảnh hưởng đến suy hao truyền sóng trong hầm mỏ là hết sức quan trọng để xây dựng một hệ thống thông tin vô tuyến trong các hầm mỏ than. Trong bài báo này, chúng tôi đề xuất sử dụng mô hình đánh giá suy hao truyền sóng trong hầm mỏ than hình chữ nhật với các yếu tố ảnh hưởng đến suy hao truyền sóng là tần số thông tin, kích thước hầm mỏ, thông số điện của trần-sàn và bức tường hai bên của đường hầm. Mô hình cũng được kiểm nghiệm bằng đo đạc thực tế trong hầm mỏ có chiều dài 100m; kích thước chiều rộng  $w=6m$ , chiều cao  $h=3m$  và hầm mỏ có kích thước chiều rộng  $w=3m$ , chiều cao  $h=1.7m$  tại tần số 900 MHz và 2.4 GHz. Kết quả đo đạc thực tế hoàn toàn phù hợp với mô hình mà chúng tôi đề xuất.

**Từ khóa** - hầm mỏ than chữ nhật; lan truyền sóng; suy hao; truyền thông không dây; sóng điện từ.

two types of mine tunnel with popular size used in Quang Ninh – Vietnam mine area. The model predicting radio wave propagation loss mentioned throughout this paper serves as a base to build a radio communication system which can runs effectively in mine tunnels in general and Khe Cham – Quang Ninh particularly.

### 2. Mine Tunnel Structure and Model of Radio Wave Propagation Attenuation

#### 2.1. Mine tunnel structure

Mine tunnels studied in this paper are considered equivalent to rectangular dielectric waveguide. Its structure is described in Figure 1.



Figure 1. Structure of rectangular waveguide

$w$  is the width (m),  $h$  is the height (m) of a mine tunnel, two walls and top of the mine tunnel are made of material with conductivity of  $\sigma$ , permeability coefficient of  $\mu$ ,  $\epsilon_1$  and  $\epsilon_2$  respectively are relative dielectric constant of two walls and top – floor of mine tunnel. The atmosphere inside mine tunnels is dry air with dielectric constant of  $\epsilon_0$  and magnetic permeability coefficient of  $\mu_0$ .

#### 2.2. Model of radio wave propagation attenuation

Radio wave propagation loss in mine tunnel environment is due to the effect of free space, its height and width, electric parameter of tunnel walls, its top – floor, horizontally and vertically polarized waves [9,10]. Therefore, we propose

that the function of radio wave propagation attenuation in rectangular mine tunnels composes of attenuation due to free space and above parameters:

$$PL[dB] = 20 \log_{10} \left( \frac{\lambda G_t G_r}{4 \pi d} \right) + \alpha d \text{ (dB)} \quad (1)$$

In there,  $\lambda$  is working wave length,  $G_t$ ,  $G_r$  are gains of transmitting and receiving antennas,  $d$  is distance between transmitting and receivers,  $\alpha$  is attenuation function in decibel.

If we regard rectangular mine tunnels as rectangular dielectric wave guide, the boundary condition which is the tangent of continuous electric field and magnetic field at two sides of wave guide will satisfy horizontally and vertically polarized electromagnetic components in Maxwell equation:

$$E_x = E_0 \cos k_1 x \cos k_2 y \cdot \exp(-ik_3 d) \quad (2)$$

$$E_y = 0 \quad (3)$$

$$E_d = (ik_1 / k_3) E_0 \sin k_1 x \cos k_2 y \cdot \exp(-ik_3 d) \quad (4)$$

$x$  is horizontal,  $y$  is vertical and  $d$  is the length of mine tunnel road.

If  $k_1$  and  $k_2$  satisfy transmitting conditions:

$$k_1 \cong \frac{\pi}{w}, k_2 \cong \frac{\pi}{h} \quad (5)$$

Then  $k_1$ ,  $k_2$ ,  $k_3$  are connected as follows:

$$k_1^2 + k_2^2 + k_3^2 = \frac{4\pi^2}{\lambda^2} \quad (6)$$

$\lambda$  is wave length.

Because the walls of mine tunnels are made of steel concrete and boundary condition at  $y=h/2$ , the tangent of electric field  $E$  and magnetic field  $H$  is continuous [11]. Therefore, coefficient  $k_2$  is written as

$$k_2 = \frac{\pi}{h} + \frac{i\pi}{h^2 \sqrt{\epsilon_2 - 1}} \quad (7)$$

Likewise, with the given boundary condition of  $x=w/2$ , the coefficient  $k_1$  is written as

$$k_1 = \frac{\pi}{w} + \frac{i\pi}{w^2 \sqrt{\epsilon_1 - 1}} \quad (8)$$

Two equations (7) and (8) show that wave transmitting regime in mine tunnels is similar to that in metal waveguide. There is only one difference that is waves spreading in mine tunnels have a virtual component. This is because while wave rays inside metal waveguide are reflected totally, one part of waves spreading in mine tunnels are absorbed, refracted and they are reflected partly only. Substitute (7) and (8) for (6), we have:

$$k_3 = k_0 - \frac{i\lambda^2}{2} \left( \frac{\epsilon_1}{w^3 \sqrt{\epsilon_1 - 1}} + \frac{1}{h^3 \sqrt{\epsilon_2 - 1}} \right) \quad (9)$$

The virtual component of  $k_3$  shows the rate of radio wave propagation attenuation by distance  $d$ . So, the attenuation rate of horizontally polarized wave  $E_h$  is [4]:

$$\alpha_{E_h} = -8.686 \text{Im}(k_3) \quad (10)$$

$$\alpha_{E_h} = 4.343 \lambda^2 d \left( \frac{\epsilon_1}{w^3 (\epsilon_1 - 1)^{1/2}} + \frac{1}{h^3 (\epsilon_2 - 1)^{1/2}} \right)$$

In order to get the attenuation rate of vertical polarized wave, we swap positions between  $w$  and  $h$ ,  $\epsilon_1$  and  $\epsilon_2$ :

$$\alpha_{E_v} = 4.343 \lambda^2 d \left( \frac{1}{w^3 (\epsilon_1 - 1)^{1/2}} + \frac{\epsilon_2}{h^3 (\epsilon_2 - 1)^{1/2}} \right) \quad (11)$$

Attenuation function comprises horizontally and vertically polarized wave attenuation. It depends on the communication frequency parameter, the height ( $h$ ) and width ( $m$ ) of the mine tunnel, relative dielectric constant of its two walls  $\epsilon_1$  and its top-floor  $\epsilon_2$ .

### 3. Measurements and Analyses

#### 3.1. Simulation and analyses

When we study mine tunnels in Khe Cham – Quang Ninh, we notice two kinds of mine tunnel size. The main tunnel road has the height  $h$  of 3m and the width  $w$  of 6m. Tunnel road branches are 1,7m high and 3m long. Each tunnel road branch has the average length of 80 – 100m. Since its two walls and top are made of steel concrete, the relative dielectric constant of the two walls is  $\epsilon_1 = 5$  and that of the top-floor is  $\epsilon_2 = 7$ . During the process of simulating, we suppose that the gains of transmitting antenna  $G_t$  and receiving antenna  $G_r$  are 1dB.

Figure 2 demonstrate the simulating result of wave propagation loss by horizontal and vertical polarization when the distance between transmitter and receiver is 50m, the main mine tunnel is 3m-high, 5m-wide and the branch one is 1,7m-high, 3m-wide. The simulation result shows that at the frequency smaller than 1.5 GHz, the wave propagation attenuation of vertical polarization is much greater than that of horizontal polarization in various tunnel sizes. And if the height size is far different from the width one, the rate of attenuation percentage has quite a huge variation. At the frequency of 900 MHz, the mine tunnel with the width  $w$  of 3m, height  $h$  of 1.7m has the wave propagation loss of -55dB. When the width is 6m, the height is 3m, the attenuation is -65dB. This proves that if the radio communication network in rectangular mine tunnel using the frequency smaller than 1.5 GHz, the rate of attenuation due to tunnel size is very high.

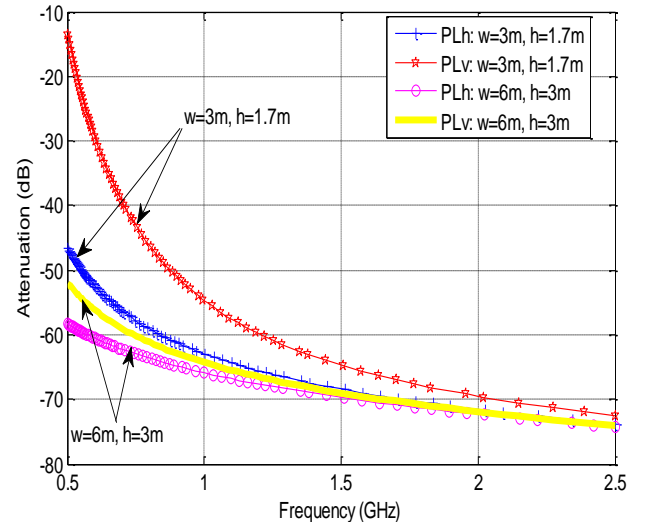
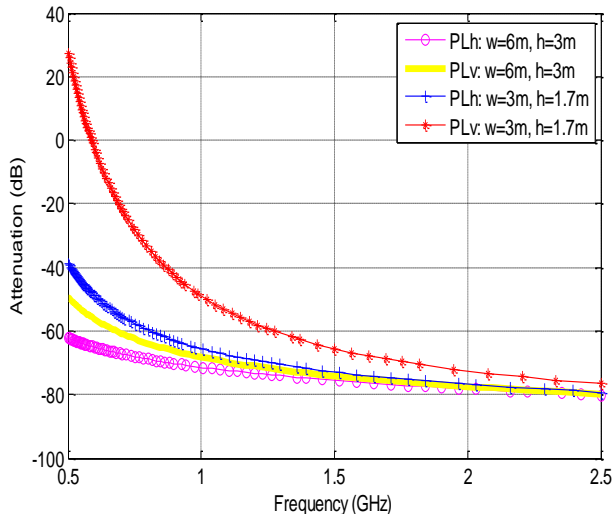


Figure 2. Wave propagation path loss by frequency at the distance between transmitter and receiver of 50m

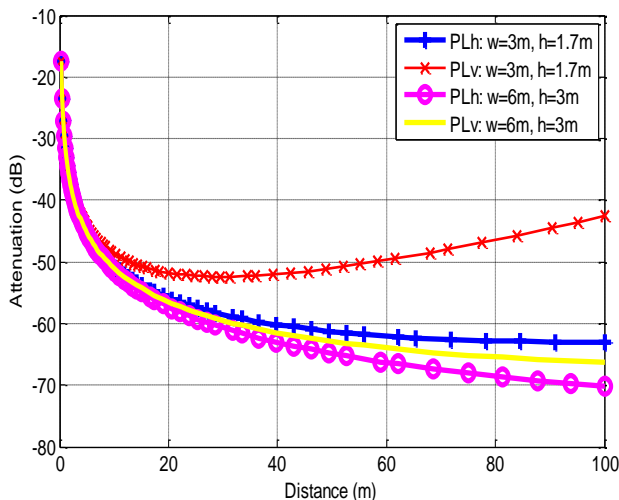
However, at the frequency band of 1.5 GHz - 2.5 GHz, wave propagation attenuation of horizontal and vertical polarization in different tunnel sizes are equivalent. At the frequency of 2.4 GHz, the propagation is -73dB.

Keeping the parameter values of Figure 2, we change the distance between the transmitter and the receiver into 100m to get the simulation result as shown in Figure 3.

Figure 3 says that wave propagation loss at the distance between transmitter and receivers of 100m and frequency of 2.4 GHz of two different size mine tunnels are both about -78dB. So we can come to a conclusion that if radio communication network in rectangular mine tunnels uses the frequency of 2.4 GHz, the rate of attenuation affected by the tunnel size is insignificant.



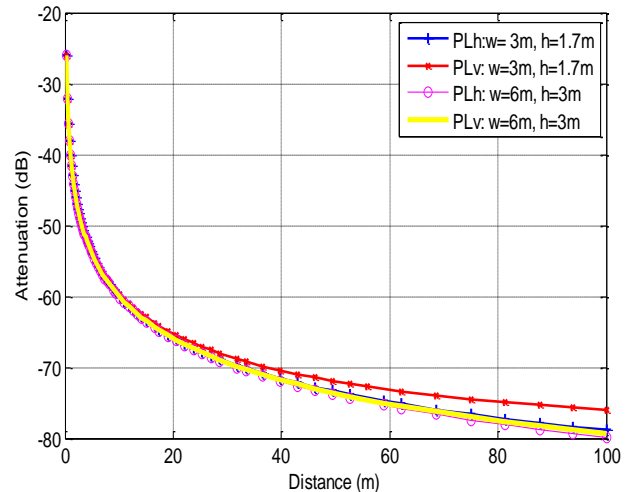
**Figure 3.** Radio wave propagation attenuation by frequency at the distance between transmitter and receiver of 100m



**Figure 4.** Wave propagation loss by distance (0-100)m at 900 MHz

At the frequency of 900 MHz (Figure 4) and the distance between the transmitter and the receiver smaller than 20m, the rate of wave propagation loss in two different size mine tunnels are equivalent. The horizontally and vertically polarized wave loss are the same too. However, if the distance is bigger than 20m, the wave propagation loss of horizontal and vertical polarization shows a great variation. When it is bigger than 50m, the effect of tunnel size on wave propagation attenuation starts increasing.

From the above analyses, we choose the frequency of 2.4 GHz to simulate wave propagation loss prediction in different size tunnels as shown in figure 5. It is clear that at the frequency of 2.4 GHz, the wave attenuation in two mine tunnels with different sizes and the attenuation rate of horizontal and vertical polarization are equivalent.



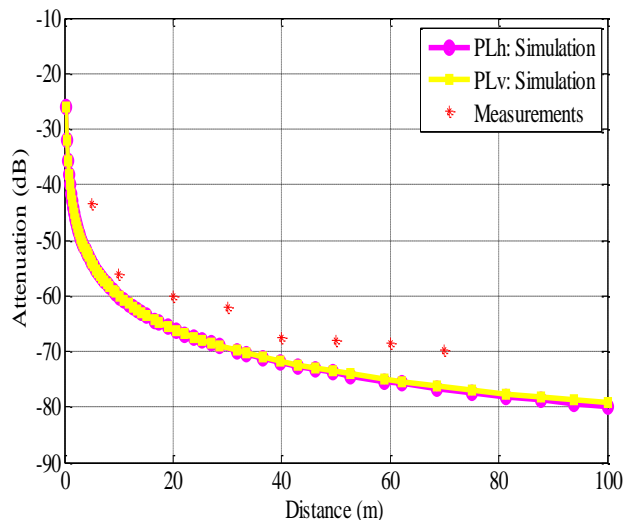
**Figure 5.** Wave propagation attenuation by distance (0-100)m at the frequency of 2.4 GHz

### 3.2. Analyses of actual measurement and comparison with theoretical model

To test the accuracy of the model of predicting radio wave propagation loss in proposed rectangular mine tunnels, we carried out measuring the rate of wave propagation attenuation in the main mine tunnel with the width  $w$  of 6m, height  $h$  of 3m and the tunnel branch with the width  $w$  of 3m and the height  $h$  of 1.7m. They are the parameters of Khe Cham mine tunnel located in Quang Ninh province. The frequency there is put at 900 MHz and 2.4 GHz. The equipment for testing is the HP 44233B signal generator which is used as a transmitter operating in the frequency band 900 MHz – 2.5 GHz and transmitting capacity of -70dB. The equipment measuring signal intensity R/S ESV is used as a signal receiver. We placed the transmitter at the beginning of the tunnel road. The receiver is moved from the start to the end of the road.

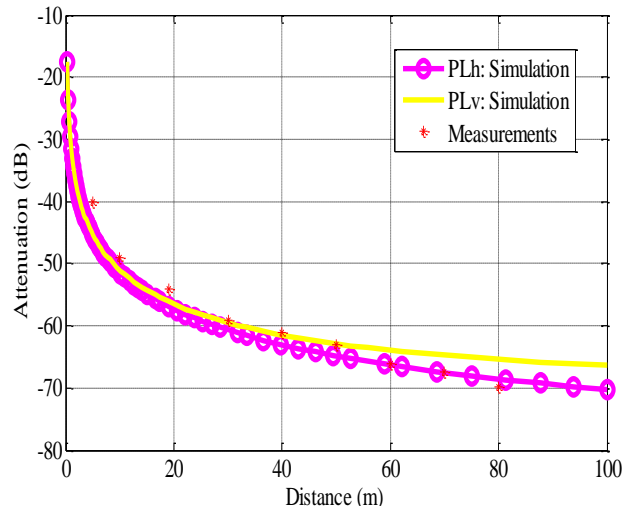
We have tested a main tunnel which is 6m-wide and 3m-high and a branch tunnel which is 3m-wide and 1.7m-high at the frequency of 2.4 GHz. The test results are recorded and shown in figure 6 and 7.

Figures 6 and 7 indicate that measurement results match perfectly with the proposed model. When the receiver is located 20m far from the transmitter in the main tunnel road ( $w=6m, h=3m$ ) and in the tunnel road branch ( $w=3m, h=1.7m$ ), the attenuation rate respectively is -60dB and -59 dB. If the distance is 40m, the rate is -67.5 dB and -64,3dB in turn. If the distance is 60m, the rate is -68.6 dB and -67.3 dB accordingly. Nevertheless, when the receiver is moved to the distance of 70-100m from the transmitter, we can not receive any signal from the transmitter which is put at the beginning of the tunnel road in two types of the tunnel road. This is because the transmitting capacity of transmitter for testing is -70dB. This also helps prove that proposed model is suitable.

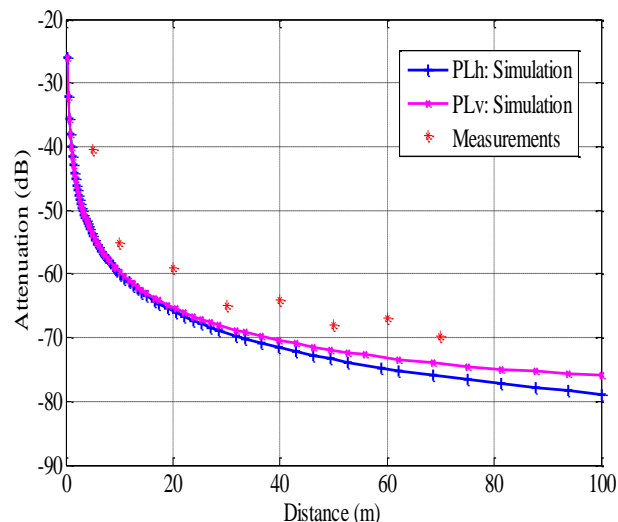


**Figure 6.** Comparison between measurement results and simulation of radio wave propagation attenuation prediction by distance (0-100)m at the frequency 2.4 GHz in Khe Cham – Quang Ninh mine tunnel with the width of 6m and the height of 3m

- 2.5 GHz in various size tunnels, the attenuation rate is the same. If we use the frequency of 900 MHz, the propagation varies enormously. This leads to trouble for calculating and designing the radio communication system effectively.



**Figure 8.** Comparison between measurement result and simulation of radio wave propagation attenuation prediction by distance (0-100)m at the frequency of 900 MHz in Khe Cham – Quang Ninh mine tunnel which has the width of 6m and the height of 3m

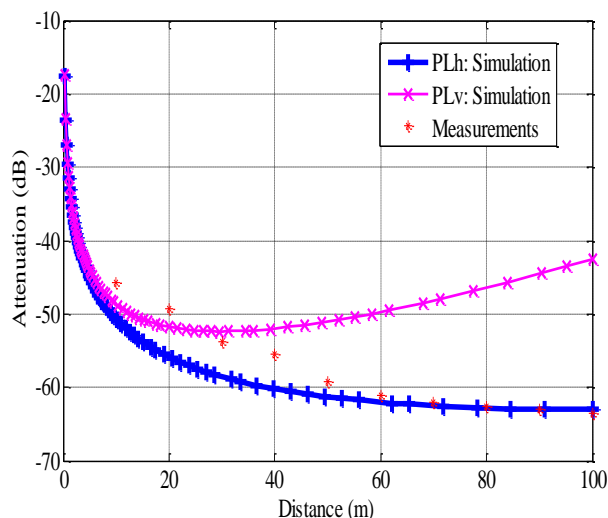


**Figure 7.** Comparison between measurement results and simulation of radio wave propagation attenuation prediction by distance (0-100)m at the frequency of 2.4 GHz in Khe Cham – Quang Ninh mine tunnel with the width of 3m and the height of 1.7m

We took the same test for a tunnel road which has the width of 6m and the height of 3m and another tunnel road which is 3m-wide and 1.7m-high at the frequency of 900 MHz. Its result is described in Figures 8 and 9.

The results in Figures 8 and 9 show that the proposed model fits the reality. However, at the mine tunnel with the width of 6m and the height of 3m, when the receiver is located 80-100m far from the transmitter, there is no signal anymore. In case of the tunnel road branch with the width of 3m and the height of 1.7m, the attenuation rate recorded at the place which is 100m far from the transmitter is -63.5 dB. This proves that proposed theoretical model matches the reality.

The actual measurement results in both the main tunnel and the tunnel road branch at 900 MHz and 2.4 GHz show that the proposed model is absolutely suitable. But this model also says that while designing radio communication system in mine tunnels, if we use the frequency band 2 GHz



**Figure 9.** Comparison between measurement results and simulation of radio wave propagation attenuation prediction by distance (0-100)m at the frequency of 900 MHz in Khe Cham – Quang Ninh mine tunnel with the width of 3m and the height of 1.7m

#### 4. Conclusions

The model of radio wave propagation attenuation prediction proposed in this paper is a general one which calculates radio wave propagation attenuation along the length of the tunnel. It comprises attenuation due to free space, the influence of tunnel size, the electric parameter of tunnel wall material and wavelength of signal. The model shows that at the frequency smaller than 1.5 GHz, the wave propagation loss depends much on tunnel size. Simultaneously, propagation by horizontal and vertical polarization varies much. At the frequency band 1.5 GHz - 2.5 GHz, radio wave propagation attenuation due to tunnel size and propagation loss due to horizontal and vertical

polarization is insignificant. This model is perfectly suitable to the characteristics of mine tunnels. And it is a basis for building radio communication systems which operate in mine tunnels in Vietnam.

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