An approach to propagation prediction in a complex mine environment

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Abstract

Propagation loss measurements taken in a real gold mine in Val-d'Or, Northen Québec, Canada at 900 MHz and 2.45 GHz are reported and compared with the ray tracing technique and the cascade impedance method. Significant statistical parameters for wireless communication such as mean, standard deviation, fast fading are presented. The probability laws and pdf density in the case of propagation in a mine tunnel are discussed and compared with the Rayleigh, Rice and statistical analaysis of measurements in the case of fast fading, direct and multipath component ratio.

Keywords: channel modeling, propagation, tunnel mine, wireless communications.

1. INTRODUCTION

The prediction of electromagnetic waves propagation in underground mines is a major issue when implementation of modern technology such as wireless LAN are considered for these difficult environments. This new technology, with radio-localization, appears to be of the utmost importance. The shape of many mines are diverging considerably from a straight tunnel approach. Some have canonical , i.e. semi-circular, cylindrical or rectangular shapes. Some have non canonical or bending forms with sidewalls exhibiting very severe roughness factor.

The consequences of these arbitrary shapes are several attenuation patterns, fast and slow fading, multipath and diffraction phenomenons. However, the prediction of radio waves propagation conditions is of the utmost importance for systems design. Many strategy and approaches such as ray-tracing techniques or geometrical theory of diffraction have been use in the case of classical (regular shape)mine tunnels. However, many of them failed in a rigourous attempt to model the propagation characteristics when the mine tunnels have non canonical or bending forms with rough sidewalls.

Some papers have proposed methods for the prediction of electromagnetic propagation in complex confined and diffracting media [1],[2],[3],including a recent one on Cascade Impedances Method (CIM) [4]. This last paper presents a comparison of electromagnetic waves propagation in conventional and non conventional waveguides. This paper addresses the propagation problems of millimetric waves in conventional and non-standard type of environments such as canonical and non canonical segment or bending rough mine tunnel, using 2D and 3-D propagation models. Comparisons is done using available analytical, statistical and experimental results for waves propagation in highly diffractive media .

2. MEASUREMENT ENVIRONMENTS

Figure 1 shows the layout of the gallery of the Federal laboratory gold mine Canmet. This mine is located at 70 m undergroung level, in the city of Val-d'Or, about 700 km north of Québec City , Canada. The length of the gallery is more than 800 m, width and height are aproximatevly 4 m and 4 m. The temperature in the mine is 5~6 degree. The dielectric sidewalls are very rough. Severals radio channel measurements have been taken in different parts of this mine gallery.

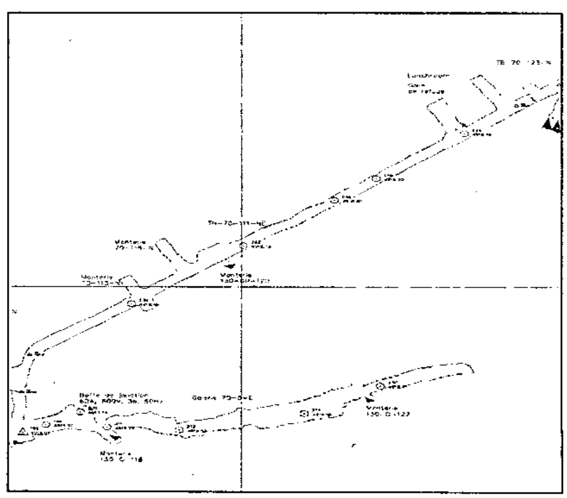

Fig.1. Canmet mine gallery, Val-d'Or ,Québec, Canada.

3. MEASUREMENT SETUP

The radio channel measurement system is illustrated in Fig.2 and the values of some of the key parameters are also indicated. The thickness d_v of the rough walls is around 25 cm. The transmitting antenna T_X is a directional antenna at height h_x=2.8m ,positioned at a fixed location. The receiver can be moved and has two omni directional monopole antennas at different heights.

The spatial variation of the signal (fading) is obtained by moving the receiver with constant speed in the mine corridor.

During the measurement process, all the spatial variations of the signal is measured using the network analyzer and computer system at 900 MHz and 2.45 GHz (Fig. 3).

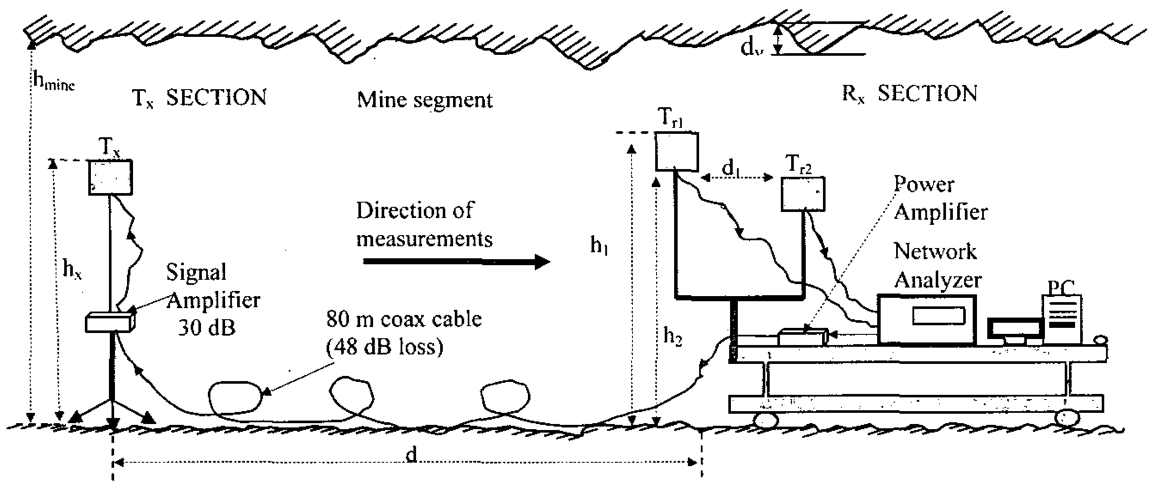

Fig.2. Measurement setup at 900 MHz.

4. RAYS TRACING TECHNIQUE

The reflection and diffraction mechanisms encounter by radio waves in mine tunnels can be described using ray tracing technique. To be efficient, the method should use a maximum of rays.

The receive signal between the transmitter and mobile antenna can be obtained using the following model:

$$[f_r]=[f(a_i,b_i)]\cdot f_o\cdot\left|\sum_{m=1}^{M}\frac{e^{jkr_m}}{r_m}+\sum_{n=1}^{N}\left(\sum_{p=1}^{P=4}\left[\left|R_n^{(p)}(h,v)\right|\right]\right)\frac{1}{r_n}\cdot\left[e^{j\Delta\Phi_n}\right]\right|^2 \quad (1)$$

were the matrix of phase differences between the direct and reflected paths is given by:

$$[\Delta\Phi_m]=\frac{2\pi[\Delta l_m]}{\lambda} \quad (2)$$

In eq. 1, $[f(a_i,b_i)]$ is the matrix of variables heights and widths of the mining tunnel segment, $[R_m^{(p)}(h,v)]$ is the matrix of reflected roughness coefficients and r_n and r_m are respectively the lengths of direct and reflected paths of rays. f_o depends of the transmitter power, the gains of the transmitter and receiver antennas and the constant of proportionality.

$$f_o=P_t\left(\frac{\lambda}{4\pi}\right)^2\cdot G_rG_t \quad (3)$$

5. THE CASCADE IMPEDANCES METHOD (CIM)

The basic original idea comes from the fact that, in spite of the multiple reflections, diffraction and attenuation due to roughness and the complexity of the channel in mining tunnel, it's still remains a transmission channel and consequently it can ultimately be considered as transmission line.

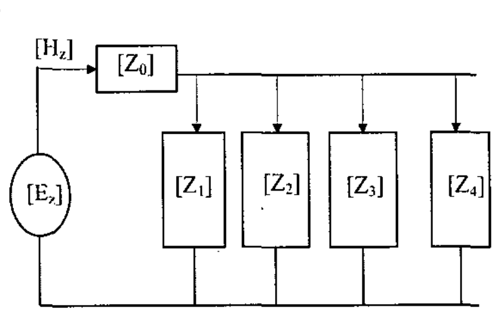

Fig. 3. Impedance model

With this assumption, it is possible to statistically predict the roughness of the surface of the mining tunnel by assuming its behavior to be analogous to that of a cascade dielectric impedances with looses. Using the Cascade Impedances

Method (CIM), the general solution of the field in a cascade impedance waveguide is given by:

$$[E_z]=[H_z]\cdot[Z_o]\left(1+\left|[T_{eq}]\right|\right) \quad (4)$$

where $[T_{eq}]$ is the equivalent transmission coefficient of the impedance walls.

5. COMPARISON WITH MEASUREMENTS IN THE NARROW BAND CASE

Fig.4 presents a comparison between the results obtained with the rays method, the cascade impedance method and experimental measurements.

The measurements,due other authors [5] were made in an empty straight section of a coal mine haulageway tunnel at 900 MHz. The simulation results are presented for both the cases of rays technique (horizontal polarization) and impedance method. The considered width is equal to 4.2m, the height 2.9m, ε_r=2.5 and the conductibility is σ=0.001 S/m.

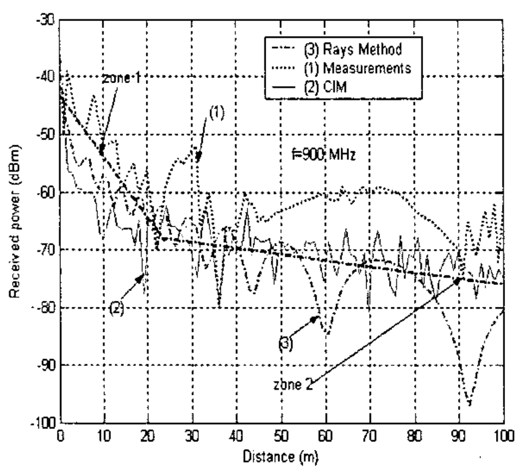

Fig. 4. Measured and simulated received power at 900 MHz.

First, the narrow-band comparison in Figure 4 demonstrates that the received signal, in the case of the empty mining tunnel with either smooth and rough sidewalls, has two propagation zones. In the first zone, the attenuation is acceptable while, in second zone, the receive signal is very close to the threshold of sensitivity. This fact is very important for the radiolocation and wireless systems since it emphasizes the point that a probe antenna will be necessary each 20 or 25 m in underground mine tunnel. To receive adequate signal for radio localization.

Secondly, the comparison shows that the Cascade Impedance Method (CIM) presents more efficiency than the Ray Tracing Method. Both theoretical methods present several fluctuations but the average error with the measurement is 5 dB with the Cascade Impedance Method, and around 10 dB with the ray method.

7. THEORETICAL MODELS AND MEASUREMENTS FOR STATISTICAL MODELING

The statistical models of the received signal envelope imply the probability laws. It is known that for multipath in a built-up area, the variations of the received reflected or refracted signals without any direct or main component follow a Rayleigh probability density [6]

$$f(r)=\frac{r}{\sigma^2}\exp\left(-\frac{r^2}{2\sigma^2}\right) \quad (5)$$

were σ is the variance. If the transmitter and receiver antennas are very close or if the radio link is dominated with major constant of direct wave LOS then, in this case, the radio channel fits the Rician model with the probability density function.

$$f(r)=\frac{r}{\sigma^2}\exp\left(-\frac{r^2+s^2}{2\sigma^2}\right)I_o\left(\frac{rs}{\sigma^2}\right) \quad (6)$$

where s^2 represents the constant (or specular) component of the power and $I_o(.)$ is the zero-order of modified Bessel function of the first kind. For s=0 , the Rician distribution becomes the Rayleigh distribution. The cumulative distribution is given by:

$$F(x)=\int_{-\infty}^{x}f(r)dr \quad (7)$$

and the complementary cumulative distribution function is given by

$$CF(x)=1-F(x) \quad (8)$$

Figure 5 presents the comparison of the received signal envelope in the case of Cascade Impedance Method (CIM) and Rays Tracing Technique Model. The frequency of the signal is 2.4 GHz and the longitudinal step is $\Delta z=\lambda/12$. The dielectric of walls is ε_r=2.5 and the conductibility is σ=0.001 S/m. The length of the tunnel mine equal to z=6 m and the maximum transversal and vertical dimensions are considered equal to a=3.6 m, b=2.2 m. The maximun tickness of the walls is 25 cm.

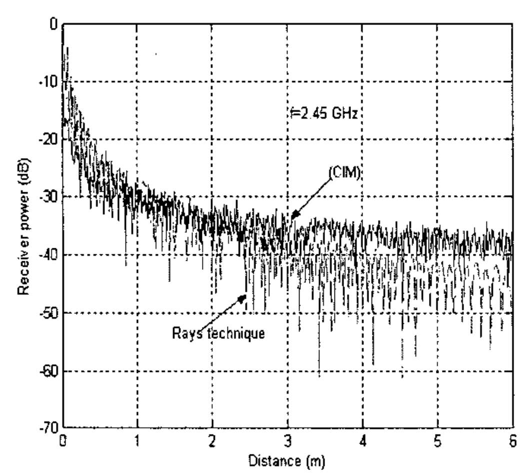

Fig. 5. Predicted received signal level at 2.45 GHz.

Using the figure 5, the probability density function in the case of the ray model is given by:

$$f_{Ray}(r) = \exp\left(-\frac{r^2}{\sqrt{k\sigma}}\right) \quad (9)$$

were k is a parameter equal to k=0.9. The probability density function in the case of the Cascade Impedance Method (CIM) is given by::

$$f_{CIM}(r) = \exp\left(-\frac{r^3}{\sqrt{\sigma}}\right) \quad (10)$$

The standard deviations are 7.5 dB for the cascade impedance variation and 9.3 dB for ray method. Using equations (7,8,11,12) , the cumulative distribution functions of the two models are given by:

$$F_{Ray}(x) = \int_{-\infty}^{x} f_{Ray}(r)dr \quad (11)$$

$$F_{CIM}(x) = \int_{-\infty}^{x} f_{CIM}(r)dr \quad (12)$$

and the complementary cumulative distribution functions are given by:

$$CF_{Ray}(x) = 1 - F_{Ray}(x) \quad (13)$$

$$CF_{CIM}(x) = 1 - F_{CIM}(x) \quad (14)$$

Figure 6 depicts the comparison of the complementary cumulative distribution function of the normalized receive signal envelope. The predicted received signal levels of figure 5 have been normalised to the Rms value. Using the model of equations (13,14), the normalized signal in the case of a Cascade Impedance Method (CIM), the ray tracing technique model, the Rayleigh and Rice distributions are compared with the measurements.

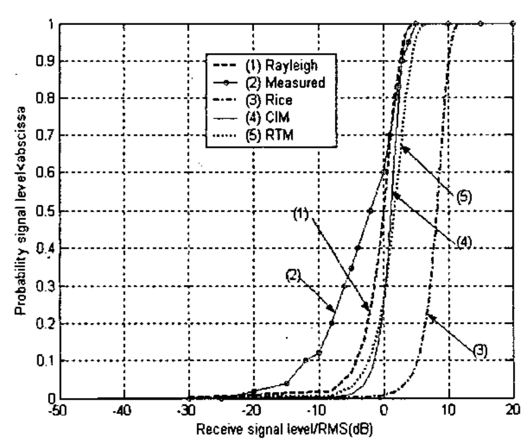

Fig. 6. Predicted and measured distribution functions

Figure 6 shows that, when the probability is equal to 0.5, a Rician channel will yield 8 dB more energy than others channels. The average error between both theoretical methods and the measurements is about 5 dB. As an example, when the probability is equal to 0.1, Figure 6 indicates that the Cascade Impedance Method (CIM) and ray tracing method presents the smallest efficiencies. In the particular case of ray technique, when the parameter k is equal to k=0.15 in equation (9), the representattion of the complementary cumulative distribution function (equation 13) of the ray tracing model will be similar with the complementary cumulative distribution function of Rayleigh.

8. CONCLUSION

Two differents models have been compared for the characterization of the propagation of millimeter waves signal in a mine with rough sidewalls. Efficiency and accuracy of the models has been tested and compared with several measurements taken in a real gold mine. Two important propagation zones have been identified and reported.

The probabiblity density functions, the cumulative and the complementary cumulative distribution functions of the receive signal envelope have been determined and specified using statistical analysis in the case of the cascade impedances model (CIM) and the rays tracing techniques. Narrowband results show satisfactory agreement between simulation and measurements.

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