Experimentally assessed underground mines propagation model at high UHF frequencies

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Abstract— **This paper shows that a ray-tracing model focused on reflected rays can be used for power prediction in an underground area. The model is calibrated and then validated in scenarios where the received power prediction efficiency is confirmed by experimental measurements recorded along three distinct routes in the same gallery with the transmitting antenna located at three different locations. Different positions of the transmitting antenna and their effects on the model are analysed and the efficiency of the model is shown using three indices such as mean error, standard deviation error or root mean squared error comparison. Some electromagnetic inputs parameters of the model are definitively analysed and their value are proposed to characterize propagation in the gallery area at 2.4 GHz.**

I. INTRODUCTION

Very complex propagation problems [1-4] arise in underground mines (Fig. 1) and operators are short of reliable techniques when planning wireless network operations in these environments. To obtain an acceptable level of automation in the planning process, simulation and optimization tools have to be developed and tested in real operations.

Wireless network were initially used to accommodate survivable emergency communications in confined environment, but with the increasing pressure for automation, complexity of the propagation model needed to be improved by using appropriate tool to predict the power profile in the area. Mine tunnels propagation phenomenon is affected by multipath and diffraction effects due to multiple reflections. Therefore, the established link efficiency has to be analysed with a proposed propagation model which takes into account, reflection from the rough sidewalls, the diffraction, and the scattering of the signal from corners and obstacles. The methods that have been traditionally used to model radio wave propagation in tunnels are modal analysis, geometrical optics [5] and the parabolic equation (PE) approximation [2]. For signal prediction using numerical method, the error difference between measurement and prediction can be improved by decreasing the mesh discretizations which can increase the computing time. The efficiency of these methods is also affected by the electromagnetic parameter of the studied area and the irregular geometry of the considered gallery.

The experimental model proposed here is based on traditional geometrical optics 3 D ray tracing technique. The model prediction [6] accuracy will be analysed and tested in a mining area and its efficiency is assessed using measured signal power data recorded during an experimental campaign. Measurements are performed at three different locations in the gallery shown in fig. 2 and these measurements, taken at 2.4 GHz, are analysed and used to calibrate a ray-tracing model. The performance of our technique is assessed against standard measurements indexes such as mean error, standard deviation error and root mean squared error by simulating a very large number of measurements recorded at many possible locations in the environments. Finally, the corresponding electromagnetic parameters at this frequency and in this typical environment are presented.

Fig. 1 Underground gold mine tunnel.

II. EXPERIMENTAL PROTOCOL

All Measurements are performed by locating the transmitting antenna at three different positions in the gallery, (Fig. 2). Samples are recorded every 1m along the gallery length and 0.5 m along the gallery width [7]. For each position, measurements are recorded along routes numbered route 1, route 2 and route 3 located respectively at the right, in the middle, or left of the gallery. Our measuring equipment records the amplitude of the received power at each position during 60 s. Only the received powers during the 45 latest seconds (Fig. 3) are averaged and plotted for analysis and comparison issues. The minimum and maximum standard variation of the received power recorded at a position is also evaluated. The measurement protocol calls for an transmitting antenna at three different or more positions (Position 1, 2 and 3) in a real mine gallery (Fig. 1). For position 1 and 3, antenna is located at both ends of the gallery whereas for position 2 the transmitting antenna is placed in the middle of the gallery. The measurements were performed at 2.4 GHz in a gallery which both height and width are estimated to about 3 m. For each transmitting antenna position, the number of measured points is 219. A total number of 657 measurement points is then analysed.

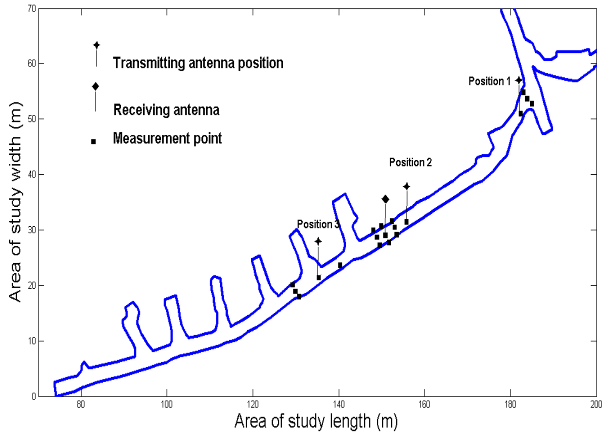

Fig. 2 Measurement points in the gallery used for this study

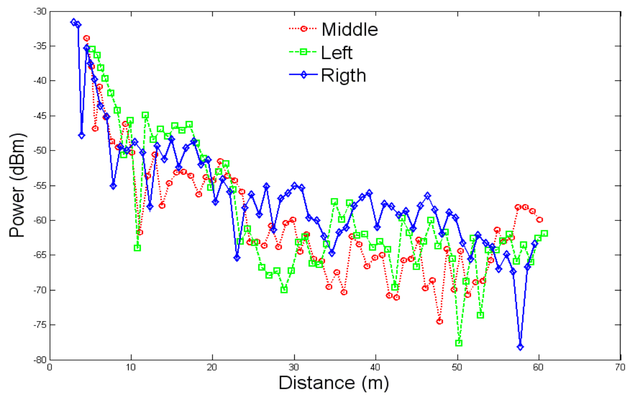

Fig. 3 Measured powers at position 1.

III. RAY-TRACING TECHNIQUE

The ray-tracing technique [5,8-9] is affected by the gallery's dimensions in three dimensions, the angle between immediate galleries, the beamwidth angle of each node radio interface, the number N of rays emitted. Only the contribution of dominant rays is taken into account in our model (1). A ray is considered dominant if it is subjected to an expected minimum number of reflections. The emitter t launches a ray numbered i characterized by its random direction toward the receiver node r, its number of reflection K on one of the sides of the gallery and finally the cumulative distance at each reflection is computed until the ray reaches the receiver node r. The number of reflections is limited to 30 for each launched ray. The mathematical model (1) can be divided into two main parts. A first part which evaluates the contribution of direct and multi reflected rays that reach the receiving antenna and a second part which evaluates contribution of reflected and only one time diffracted rays. In this work, received power profile prediction is addressed in only straight galleries as in Fig. 2 so that corners diffraction effects can be neglected.

$$P_r \approx \left(\frac{\lambda}{4\pi}\right)^2 \times p_t \times \Bigg| \sum_i \Big(\prod_K \Gamma_{i,K}\Big) \times G_{ti} \times G_{ri} \times \frac{\Phi_i}{d_i} + \Big(\sum_l \Big(\prod_K \Gamma_{l,K}\Big) \times \Big(D \times \sqrt{\frac{\rho_{tw}}{\rho_{wr} \times (\rho_{wr} + \rho_{tw})}}\Big) G_{tl} \times \frac{\Phi_l}{d_l}\Big) \times \exp(-j \times k \times \rho_{tw}) \Bigg|^2 \quad (1)$$

with

$$\Phi_i = \exp(-j \times k \times d_i)$$

and

$$k = \frac{2\pi}{\lambda}$$

in (1), G_{xy}, P_t, D, Γ_{xy}, ρ_{xy} are respectively the antenna gain of emitted ray indexed (x, y) in the direction defined by $\theta_{x,y}$ and $\varphi_{x,y}$, transmitted power, traditional 2D diffraction coefficient, reflection coupled with roughness coefficient subjected to ray indexed (x, y) in the direction defined by $\theta_{x,y}$ and $\varphi_{x,y}$ and the distance traveled by the current ray from point x to point y .

The model developed to predict the propagation in the indoor complex environment is based on image theory and ray tracing. As fixed inputs, the model uses the antenna pattern in 3-D, θ and φ are between [60º, 120º]. $\Delta\theta$ and $\Delta\varphi$ are set to one so that 3721 rays are emitted in the gallery. The estimated electrical characteristic of the rough walls (permittivity, conductivity, roughness and reflection coefficient denoted respectively ε_r, σ, Γs and R) is also chosen. The surface roughness is addressed using the Rayleigh criterion which defined a critical height (σ_h) of the surface protuberances for a given angle of incidence. σ_h is the standard deviation of the surface height about the mean surface height. This value is difficult to be evaluated but in this study an appropriated value is proposed. A mine gallery's floor is no longer more flat and the area geometry is irregular.

IV. RESULTS

For different input of the prediction model, the output is appreciated using mean, standard and root mean squared error index. Predictions will be presented according to two scenarios. For the first scenario, prediction is done according to power profile measured along routes when the transmitting antenna is located at a same position. For the second scenario, all routes power profiles' prediction is taken into account during the prediction process but only efficiency according to the transmitting antenna positions are evaluated.

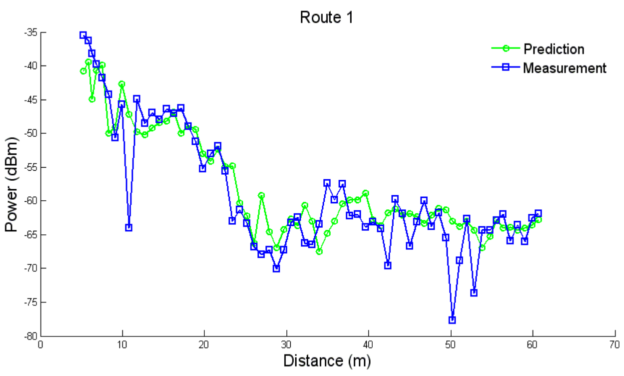

Fig. 4 Power profile along route 1

A. Prediction along routes in a gallery

Our prediction model has been tested at a first location (position 1) in the area against experimental results and its performances are shown in Table I. The efficiency of our prediction technique along route 1 in the studied gallery can easily be observed in Fig.4.

TABLE I
ERROR STATISTICS OF THE COMPARISON BETWEEN MEASURED AND PREDICTED POWER ALONG ROUTES.

	Mean error (dB)	Standard deviation (dB)	RMS error (dB)
Route 1	-0.9	4.4	4.45
Route 2	-2.4	4.4	5
Route 3	1	5.4	5.5

Table I shows the efficiency of our prediction technique as error induced is less than 5 dB in such a complex environment. It also shows the errors involved according to the route followed by the mobile in the environment at the chosen location.

B. Prediction according to transmitting position in a gallery

Our model's efficiency has also been tested at two others locations in the area against experimental results and its performances are shown in Table II. The efficiency of our prediction technique along all routes and various transmitting positions in the studied gallery can easily be observed (Fig.5). Table II shows the efficiency of our prediction technique as error induced is less than 6.5 dB in such a complex environment. It also shows the errors involved according to the transmitting position. The maximum error along the different routes when the transmitting antenna is located to each considered position in this study is shown in Table II.

TABLE II
ERROR STATISTICS OF THE COMPARISON BETWEEN MEASURED AND PREDICTED POWER ACCORDING TO VARIOUS TRANSMITTING ANTENNA POSITION.

	Mean error (dB)	Standard deviation (dB)	RMS error (dB)
Position 1	1.4	5	5.1
Position 2	-0.3	6.5	6.5
Position 3	0.49	5	4.9

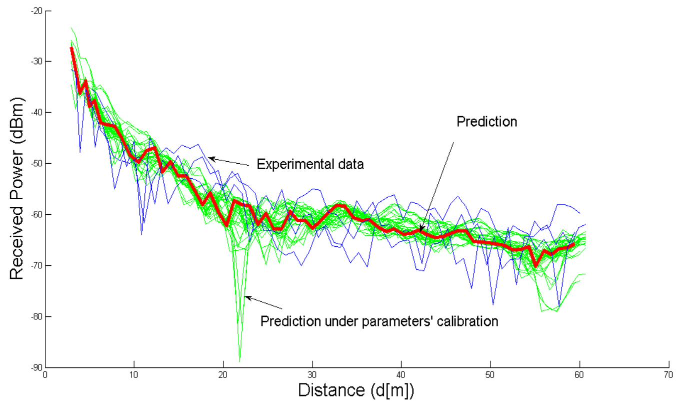

Fig. 5 Received power prediction according to different parameters at position 1.

In Fig. 5, the curve drawn in dark colour represents the best power prediction found in this situation. Parameters set to the model in order to observe this curve is presented in Table III.

The optimal parameters of the model for each transmitting position are also presented in Table III.

TABLE III
OPTIMAL INPUT PARAMETERS OF THE MODEL ACCORDING TO THE DIFFERENT TRANSMITTING ANTENNA POSITIONS.

	X_T (m)	Z_T (m)	X_R (m)	Z_R (m)	ε_r	σ (S/m)	P_t (mW)	σ_h (m)
Position 1	2.7	1.3	1.3	1.5	5.6	0.12	4.3	0.0826
Position 2	2.6	1.6	1.3	2.40	5.3	0.29	1.9	0.0334
Position 3	2.6	1.5	1.7	2.73	5.5	0.17	2.07	0.0877

About the inputs parameters:

X_T and X_R denote respectively the transmitting and receiving antenna abscissa in the 3D reference.

Z_T and Z_R denote respectively the transmitting and receiving antenna height in the 3D reference.

The prediction is rendered difficult for a number of reasons:

1) Transmitting and receiving antennas positions suffer from the mine geometry variation as it can be seen in Table III. The receiving antenna's heights vary according to the transmitting position and need to be well chosen to reach a good level of fitness. In Table III the deviation between Z_R and Z_T is small in position 1 whereas this variation is important in the other positions. This situation can be

explained by the fact that the Mine's geometry is affected by soft diffracting angles and its floor is no longer more flat. During the measurement it is difficult to maintain the antennas in a vertical position. Finally, in our model, antenna positions are evaluated along a smooth surface, whereas during the reflection coefficient evaluation, it is believed that all four sides of the gallery are of the same roughness. Naturally, the floor of the gallery is relatively less rough than the other sides (lateral walls and ceiling) of the gallery.

2) As shown in Tables I and II, the maximum difference between the predictions and the measurements, calculated with both values in a logarithmic scale, is 6.5 dB when combining all comparison indexes considered in this study. The statistics of the comparison are good given that receiver positions far away from the transmitter in deep shadow areas are also included in the calculations. As seen in Fig. 6, the poorest agreement between the measurements and the predictions happens toward the beginning of the route, where the model overpredicts the received power by approximately 15 dB. So, the transmitting power must be well chosen. It is recommended to choose a transmitting power closed to the recorded power at a distant of 1 m (the reference power). It is considered in this study that only positions of receiver (measurement points) separated to more than one meter from the real transmitting antenna's position is predicted.

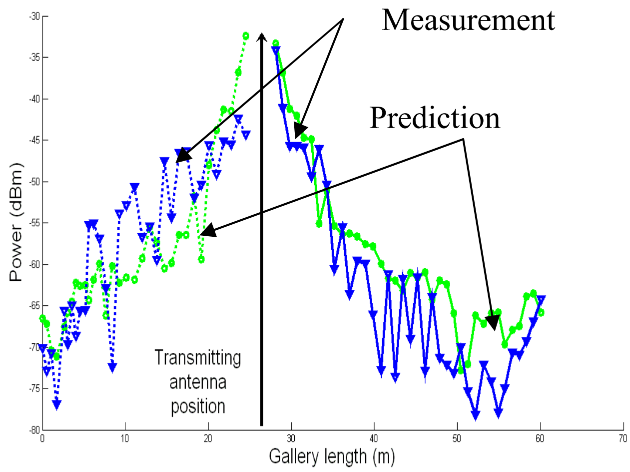

Fig. 6 Received power prediction when the transmitting antenna is at position 2

3) Permittivity and conductivity of the walls in the experimental mine are characterized and their values can be set to about respectively to $\varepsilon_r = 5.3$ and $\sigma = 0.21$ S/m.

4) The area wall side roughness value is about 8.2 cm and it is noticed that this value can be estimated according to the transmitting position. It is observed on Table III that at the middle of the gallery (Position 2), the standard deviation of the wall surface height (σ_h) value is about half of the value found at position 1 and position 2 as it can be seen on fig. 6.

In spite of the complexity of the area, the divergence between predictions and measurements is reasonable, especially since standard deviation up to 7 dB can exist between measurements recorded during experimentation. The model is often very sensitive to the values affected by the electrical characteristics of the wall roughness but in this study appropriated values of those parameter is proposed. For each position of the transmitting antenna in the gallery the input values are presented on Table III. Results obtained showed difficulties related to the use of a ray–tracing algorithm for prediction in a rough and complex media.

V. CONCLUSIONS

A ray-tracing propagation model is calibrated using experimental measurements in an underground mine area. It is presented its effectiveness as the prediction error is less than 6.5 whatever the index comparison evaluated in this study. The global performance of the model is presented and analyzed for various routes and locations of mobile (transmitting antenna) in the mine environment. This study also showed that a ray-tracing technique in a confined area is often not sufficiently reliable for adequate prediction of the signal level due to lack of real knowledge of the electromagnetic parameters and adequate geometry of the medium. Basically, the ray tracing prediction model fails to follow deep fading after about 50 m from the transmitting antenna position along the gallery whatever the scenarios considered..

Automatic calibration of the ray-tracing model can be done by using optimization method such as genetic algorithm. The complete calibration system will be presented in further work.

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