Characterization and Modeling of a Wireless Channel at 2.4 and 5.8 GHz in Underground Tunnels

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Abstract— **Underground tunnels, such as caverns and mine galleries, are indoor environments far more hostile, in terms of wireless communication, than conventional ones like road tunnels, offices or factories. Wireless propagation behavior in these areas is found to be fairly peculiar, mainly due to the extreme roughness of wall surfaces. This paper presents comprehensive broadband measurement and modeling results of electromagnetic wave propagation in real underground mine tunnels at 2.4 and 5.8 GHz. Broadband radio propagation in these environments is observed to exhibit behavior that is quite different from conventional indoor environments with smooth surfaces. Notably, signal variation can be highly locally specific and site-specific, rms delay spread varies randomly with transmitter-receiver distance and no path arrival clustering effect is observed. These path time arrivals tend to follow a Modified Poisson distribution and amplitude tends to follow Rice and Rayleigh distributions for line-of-sight and non-line-of-sight cases, respectively. Extensive simulations have shown the models to be very close to reality.**

Keywords-underground mine; tunnels; statistical modeling; characterization; modified poisson; rayleigh; rice; propagation; path time arrivals; path amplitude; clustering effect.

I. INTRODUCTION

The LRCS (*Laboratoire de Recherche en Communications Souterraines*) has access to a former gold mine (CANMET) in Val d'Or (Quebec, Canada) in order to perform *in-situ* experiments in a realistic environment. Such confined areas differ significantly from conventional indoor environments (e.g. offices) as a result of narrow labyrinths with rough surfaces, curvatures, side galleries, etc.

Wireless propagation in typical underground environments (e.g. mines and caverns with rough surfaces, curved galleries and side shafts) is a challenge to model theoretically with high precision and low complexity. As such, this field still presents many open research avenues and available results at the state of the art provide "rules of thumb" and guidelines to understand the impact of various environmental characteristics (e.g. surface roughness) and generate parameters for statistical simulations.

This paper describes the mine environment under consideration, the propagation characteristics for the frequency bands of 2.4 and 5.8 GHz, as well as the results of wideband statistical modeling. Finally, simulations are performed following the modeling process before concluding on the most suitable models for representing radio wave propagation in this peculiar environment.

II. EXPRIMENTAL PROTOCOL

The experiments have been done in an underground mine gallery at a 70 m depth in CANMET. The environment description, material setting and experimental protocol are described in the following.

A. Environment Description

The gallery has very rough wall surfaces, adjacent galleries, LOS (line-of-sight) and NLOS (non-LOS) areas, and is very confined and humid. The floor, albeit flatter than the ceiling and walls, has some water puddles [1][2]. The gallery stretches over a length of 70 meters with 2.5 to 3 meters in width and about 3 meters in height [2]. There are three areas of interest : one LOS area (from 1 to 22 meters) and two NLOS areas (NLOS1 from 23 to 46 meters, and NLOS2 from 47 to 70 meters).

B. Material Setting

Omnidirectional antennas with a vector network analyzer have been used for transmission and reception of the RF signal, at both frequencies of 2.4 and 5.8 GHz (bandwidth of 200 MHz), as shown in Figure 1. For all experiments, the transmitter remained fixed, while the receiver changed position along the gallery, from 1 meter up to 70 meters distant from the transmitter, thus passing through the three areas as shown in Figure 2. During all measurements, the wireless channel is assumed to be static with no significant variations. The transmit power was set to 10 dBm.

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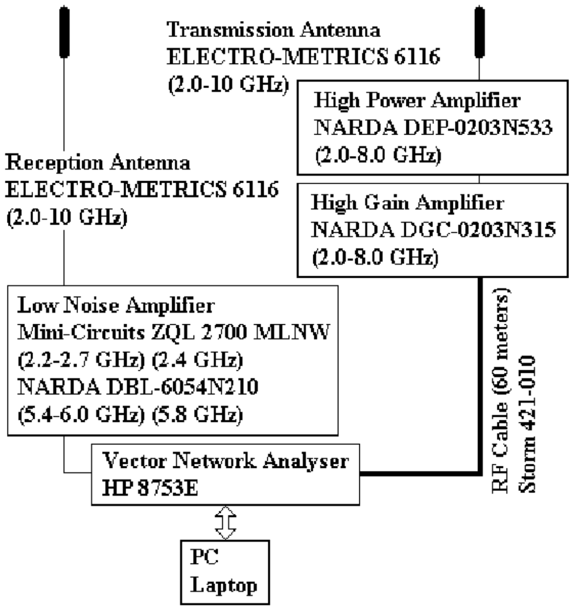

Figure 1. Schematic diagram of the measurement system.

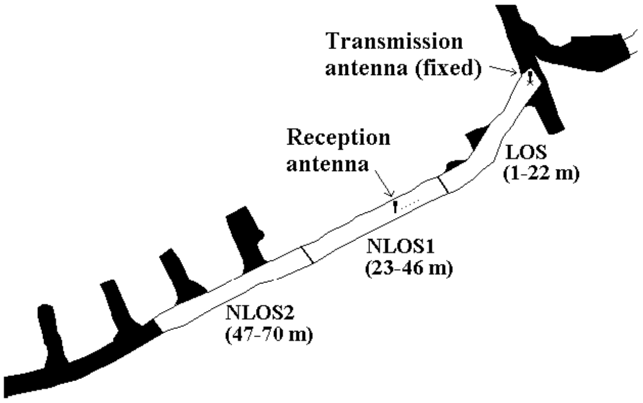

Figure 2. Measurement areas in the mine gallery (only areas in white colour are considered).

C. *Experimental protocol*

In order to investigate the statistical behavior of the channel, 420 transfer functions were measured, for each frequency, for the different locations of the receiver along the gallery. Each measure is actually a temporal average of ten transfer functions taken at exactly the same location, for different observation times. These transfer functions have been converted to impulse responses, by inverse Fourier transform, for the sake of a temporal behavior study. A predefined threshold for the multipath noise floor has been used; it was set to four times the standard deviation plus the mean of the noise measured over the tail of the considered impulse response. The time axis of each experimental impulse response is discretized into 8-ns time bins (as per the experimental protocol) by considering the inflexions and peaks to find the multiple paths of each impulse response [3].

III. MEASUREMENT RESULTS

From the magnitude of the computed time domain response for a specific transmitter-receiver separation, the time dispersion parameters and relative multipath total power have been extracted and are presented in the following.

A. *Time Dispersion Parameters*

The rms delay spread of each impulse response, for all the 420 measurements along the gallery and for both frequencies, tends to be flat, as can be seen in Figure 3. However, we have not observed exactly the same phenomenon at the 40 m depth of the mine [4], where the gallery is wider (5 meters). Both galleries (40 m depth and 70 m depth), have a different rms delay spread behavior as a function of distance and even differ significantly from what is commonly found in indoor building environments with smooth surfaces [4][5]. In these conventional indoor environments, the rms delay spread initially monotically increases and then monotically decreases with distance. Results thus show that underground multipath characteristics are quite specific and vary considerably depending upon the gallery dimensions and the transmitter-receiver distance.

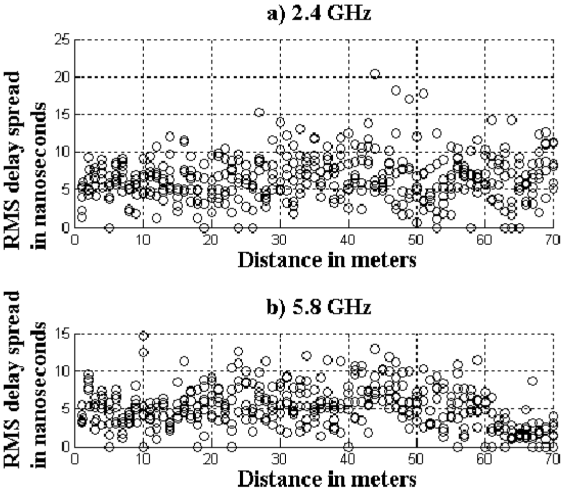

Figure 3. RMS delay spread as a function of distance at (a): 2.4 GHz and (b): 5.8 GHz.

The mean excess delay and maximum excess delay were computed from all measurements. The former is higher at 2.4 GHz, while the latter is higher at 5.8 GHz. The maximum number of multipath components for the 2.4 GHz band is 9, while it is 10 for the 5.8 GHz band ; the mean value is 4 and 3.9, respectively. As can be seen here, the frequency of operation does not really affect this parameter.

B. *Relative Multipath Total Power*

It can be seen on Figure 4 that the curvature of the gallery (about 17 meters from the transmitter) does not have a significant effect on the attenuation of the signal for both frequencies. The attenuation remains close to the free space value on both sides of the curvature. Following the hybrid propagation model defined in [7] for rectilinear mine tunnels, this area would thus be within the first Fresnel zone clearance.

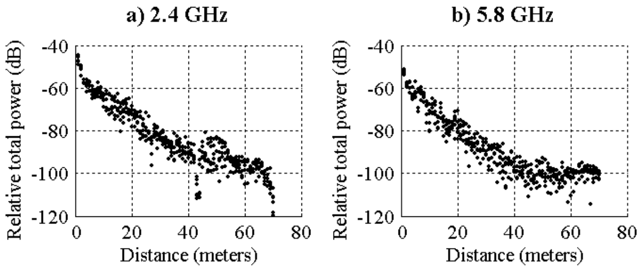

Figure 4. Relative multipath total power as a function of distance at (a): 2.4 GHz and (b): 5.8 GHz.

However, an abrupt fall in the signal power in the 2.4 GHz band was noticed for the two specific transmitter-receiver distances of 43 and 44 meters. The same phenomenon was noticed around 70 meters at 5.8 GHz. This can be explained by multipath destructive combinations as a result of local gallery topology. It should be noted that these local signal variations are likely highly site-specific.

IV. WIDEBAND STATISTICAL MODELING

Propagation characteristics specific to such a confined environment have been observed, leading to the necessity to extract models representing the radio wave propagation behavior of this underground environment. In [8], a deterministic wideband modeling approach was developed as an initial step. Being very complex and limited in capturing the very specific nature of propagation in confined gallery with rough surfaces, a statistical modeling approach based on real measurements was developed. Also, statistical modeling does not require a large number of environmental parameters and thus is not too highly site-specific. Statistical modeling is attractive in that it can quickly and reliably generate simulated impulse responses for a particular frequency and topography based on accurate models derived from experimental measurements. This avoids gathering a huge amount of experimental measurements and simulated impulse responses can be readily available to test the performance of new applications for mines such as wireless geolocation [9]. To the best of our knowledge, this work is the first to study statistical modeling of the impulse response structure in confined environments with rough surfaces, such as underground mines.

For the remaining results, the large-scale fading effect is superfluous in this specific small-scale fading part of the modeling process and was removed prior to testing the candidate amplitude distribution with the experimental impulse responses. An example is presented in Figure 5.

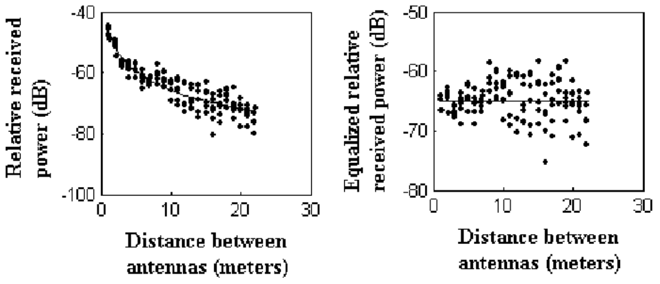

Figure 5. Example of path loss effect removal (at 2.4 GHz, LOS).

However, this fading effect is reinserted during the simulation process in order to reflect the real propagation environment [10]. The three areas (LOS, NLOS1 and NLOS2) for both frequency bands are modeled separately, leading to 6 models based on about 140 sample measurements each.

A. Mathematical Model

A radio propagation channel can be completely characterized by its random impulse response *h(t)* as per:

$$h(t)=\sum_{k=0}^{N-1} a_k \delta(t-t_k) e^{j\theta_k}, \qquad (1)$$

where N is the number of multipath components, α_k, t_k and θ_k are the random amplitude, arrival-time and phase of the k^{th} path, respectively, and δ is the delta function. The path arrivals t_k and amplides α_k are modeled in the following sections by comparing them to some already known distributions frequently used in the literature. The phases θ_k are assumed to be, a priori, statically independent uniform random variables over $[0, 2\pi)$.

B. Path Time Arrival Modeling

The most commonly used distributions for path time arrivals in the literature [11] are Poisson, Modified Poisson and Weibull, and are used for modeling to find the more appropriate model. The parameters of each of these distributions are estimated from experimental measurements, based on the minimum mean square error as the example depicted in Figure 5.

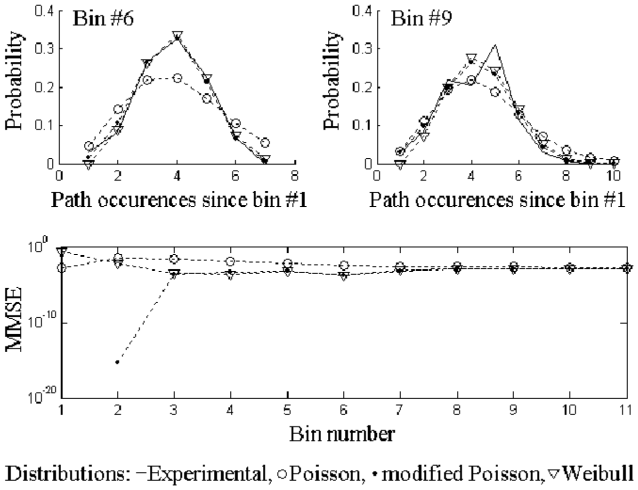

Figure 6. Example of parameter estimation for the path arrival ditributions (at 2.4 GHz, LOS).

Results suggest that the Modified Poisson distribution is closer to reality, in all cases [12]. Moreover, no clustering effect of path time arrivals has been observed, as is the case for more conventional indoor environments [13]. This is likely as a result of the highly random reflection and diffraction effects caused by the rough wall surfaces of these peculiar mine gallery environments. Consequently, clustering has not been included in our modeling process. The Modified Poisson distribution is the more suitable probably as a result of its high flexibility to model specific multipath randomness.

C. Path Amplitude Modeling

The most popular distributions for path amplitude, especially for indoor environments [11], are Rayleigh, Rice, Nakagami, Weibull and Lognormal. They are used for modeling to find the more appropriate model. In order to estimate the parameters of each candidate distribution at each time bin, the method of moments is used with the experimental results. A curve-fitting technique is used to obtain decreasing exponential curves [14] of the form:

$$y = Ae^{-(x-1)/B} + C, \qquad (2)$$

for both amplitude average and standard deviation as a function of time bins. An example of such a technique is presented in Figure 6.

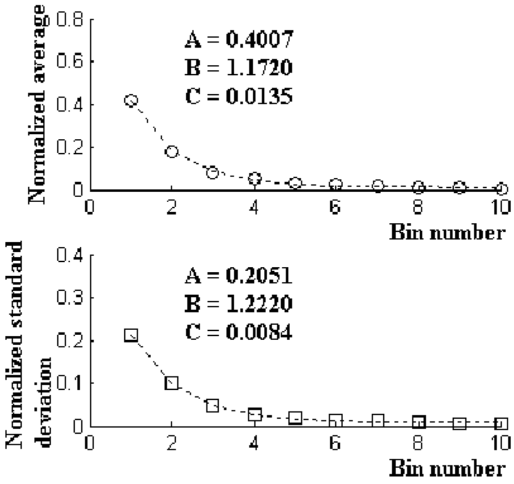

Figure 7. Example of decreasing exponential curves used by the method of moments (at 5.8 GHz, LOS).

Then, the first and second fitted moment make it possible to approximate the parameters of the five amplitude distributions for each time bin. The simulation process is however required in order to determine which of these distributions is the most suitable to model the propagation channel.

D. Simulation Process

The three necessary steps to simulate impulse responses are :

a) Generating path time arrivals (for time bins of 8-ns) following the Modified Poisson distribution.

b) Generating five sets of path amplitudes following the five different distributions mentioned previously, having their parameters computed from the decreasing exponential curves obtained during modeling.

c) Combining the set of path arrivals with each set of path amplitudes, resulting in a set of impulse responses.

d) Reinserting the large-scale fading effect which has been removed prior to model path amplitude.

The rms delay spread, the main comparison criterion, is extracted from both simulated and experimental impulse responses. The Kolmogorov-Smirnov test is then used to identify the most suitable amplitude distribution to represent real experiments as shown in Figure 7.

The whole procedure is repeated for each area, for each frequency band. Finally, results show evidence of the Rice distribution to best represent amplitude variation for the LOS case, while it is Rayleigh for the NLOS case, regardless the frequency of operation.

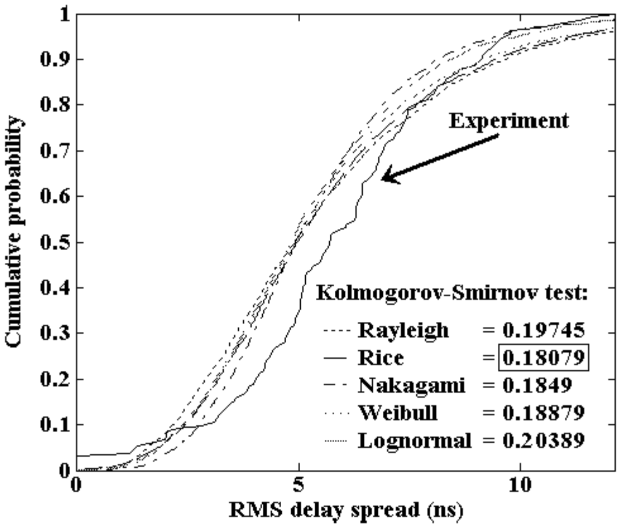

Figure 8. Example of the use of the Kolmogorov-Smirnov test on the RMS delay spread (at 2.4 GHz, LOS).

After comparing a set of 100 simulations to the experimental results (each simulation including 3000 impulse responses), the best amplitude distribution for each area of the mine gallery and for each frequency is shown in Table I, where the performance score of each distribution is reported.

TABLE I. MATCH RESULTS IN % BASED ON THE RMS DELAY SPREAD.

	LOS	NLOS1	NLOS2
2.4 GHz			
Rayleigh	0	88	92
Rice	91	0	0
Nakagami	2	4	2
Weibull	7	6	5
Lognormal	0	2	1
5.8 GHz :			
Rayleigh	1	90	94
Rice	89	2	1
Nakagami	2	4	3
Weibull	8	2	1
Lognormal	0	2	1

V. CONCLUSION

Radio propagation characteristics obtained in this confined underground environment have proved to be fairly different from what has been found in conventional indoor environments. Time dispersion parameters, as well as the total power as function of distance, show the need to develop wideband statistical models specific to such relatively new wireless environments. Such models yield the possibility to simulate a large number of impulse responses, as opposed to collecting time-consuming measurements.

Path time arrivals tend to follow a Modified Poisson distribution in all cases observed, while path amplitudes tend to follow Rice and Rayleigh distributions, for the LOS and NLOS case, respectively. The operating frequency yields different distribution parameters to use for simulation, without however demanding different distributions. The path phase is considered, a priori, to be uniformly distributed.

It is clear that wireless propagation in underground mine tunnels can be a challenge to model accurately in view of the hostile nature of the environment. The next step might be to generate models using ultra-wideband measurements, focusing on the objective of future wireless networking in mine tunnels or caverns.

REFERENCES

[1] M. Djadel, C. Despins and S. Affes, “Narrowband Propagation Characteristics at 2.45 and 18 GHz in Underground Mining Environments”, Proc. of IEEE GLOBECOM 2002, Taipei, Taiwan, November 2002.

[2] A. Benzakour, S. Affes, Charles Despins and P-M. Tardif, “Wideband Measurements of Channel Characteristics at 2.4 and 5.8 GHz in Underground Mining Environments”, Proc. of IEEE VTC’04-Fall, Los Angeles, California, USA, Vol. 5, pp. 3595-3599, September 26-29, 2004.

[3] Turin G. L., Clapp F. D., Johnston T. L., Fine S. B. et Lavry D. “A statistical model of urban multipath propagation”. *IEEE Transactions on Vehicular Technology*, vol. 21, no. 1 (1-9 February). 1972.

[4] C. Nerguizian, M. Djadel, C. Despins, and S. Affes, “Narrowband and Wideband Radio Channel Characteristics in Underground Mining Environments at 2.4 GHz”, Proc. of IEEE PIMRC’03, Beijing, China, vol. 1, pp. 680-684, September 7-10, 2003.

[5] A. F. AbouRaddy, S. M. Elnoubi and A. El-Shafei, “Wideband Measurements and Modeling of the Indoor Radio Channel at 10 GHz, Parts I and II”, 15th National Radio Science Conference, February 1998.

[6] R. J. C. Bultitude at al., “The Dependence of Indoor Radio Channel Multipath Characteristics on Transmit/Receive Ranges”, IEEE JSAC, Vol. 11, No. 7, September 1993.

[7] Y. P. Zhang, G. X. Zheng and J. H. Sheng, “Radio propagation at 900 MHz in underground coal mines”, *IEEE Transactions on Antennas and Propagation*, Vol. 49, No. 5, May 2001.

[8] M. Ndoh, and G. Y. Delisle, “Underground Mines Wireless Propagation modelling”, Proc. of IEEE VTC’04-Fall, Los Angeles, California, USA, September 26-29, 2004.

[9] C. Nerguizian, C. Despins and S. Affes, “Geolocation in Mines with an Impulse Response Fingerprinting Technique and Neural Networks”, to appear in *IEEE Transactions on Wireless Communications.*

[10] M. Boutin, S. Affes, C. Despins, and T. Denidni, “Statistical Modelling of a Radio Propagation Channel in an Underground Mine at 2.4 and 5.8 GHz”, Proc. of IEEE VTC’05-Spring, Stockholm, Sweeden, May 30-June 1, 2005.

[11] H. Hashemi, “The Indoor Radio Propagation Channel”, Proceedings of the IEEE, vol. 81, no. 7 (July), pp. 943-968. 1993.

[12] M. Boutin, “Modélisation statistique de la propagation radio dans une mine souterraine à 2.4 et 5.8 GHz”, Master thesis, Institut national de la recherche scientifique : énergie, matériaux et télécommunications (INRS-EMT), Montreal, 2005 (french).

[13] Saleh A., Valenzuela R. "A statistical model for indoor multipath propagation". , *IEEE Journal on Selected Areas in Communications*, vol. 5, no. 2, pp. 128-137. February 1987.

[14] Ganesh R. et Pahlavan K. “Statistical modelling and computer simulation of indoor radio channel”. Communications, Speech and Vision, IEE Proceedings I, vol. 138, no. 3 (June), pp. 153-161. 1991.