Narrowband Propagation Characteristics at 2.45 and 18 GHz in Underground Mining Environments*

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Abstract— **In this paper, we present the propagation characteristics at 2.45 and 18 GHz resulting from the statistical analysis of a narrowband measurement campaign in an underground mining environment. Parameters such as the amplitude distribution of the envelope, level crossing rate, average fade duration and coherence time of the channel have been examined. An analysis by linear regression has been also used to study the variations of the received power according to the transmitter-receiver distance.**

I. INTRODUCTION

Truly ubiquitous wireless communications are often described as the next telecom frontier. As such, in-building environments have received much attention for this purpose but other peculiar environments present significant opportunities for the wireless industry. And while the characterization of propagation, within tunnel roads and subways, has been the purpose of many investigations in the last thirty years [1] [2] [3] [4] [5] [6], the study of propagation in an underground environment such as a mine was somewhat neglected. In fact, the corresponding open literature has been quite sparse. Some of the accomplished work was limited, with regard to narrowband measurements, to the evaluation of the attenuation of the received field according to the distance in an underground gallery [7] [8]; typically, these measurements were taken at frequencies in the vicinity of 150, 450 and 900 MHz. Other measurements taken around 2 GHz in a wide tunnel (13 meters in width), which is not representative of the typical underground mine (generally much narrower with rough surfaces), were the subject of a statistical study, which was limited in its narrowband analysis to examine the amplitude distribution of the envelope of the received signal [9].

The narrowband propagation results at 2.45 GHz presented herein were obtained within the framework of a development project concerning a WLAN system adapted to underground mines with narrow veins (which is representative of many underground mines). Measurements at 18 GHz were also performed to take into consideration the importance of higher frequency bands for future WLAN and broader-band wireless systems. In the following sections, we will describe briefly the measurement environment as well as the experimental protocol. The results of the measurements are then analysed and discussed.

II. DESCRIPTION OF THE ENVIRONMENT AND THE EXPERIMENTAL PROTOCOL

The measurements were carried out in an underground gallery of a former gold mine, the laboratory mine "CANMET" in Val-d'Or, 700 kilometers north of Montréal, Canada. Located at a 40 m underground level, the gallery stretches over a length of 75 meters with a width and height both of approximately 5 meters. The figure below illustrates the plan of the gallery with all its under adjacent galleries as well as the positions of the transmitter and the receiver. It is obvious to note that the gallery has a curvature implying a non line of sight case when the receiver is located just after the point R_1. The transmitter was located for the entire measurement campaign at point E. The points R_2, R_3 and R_4 are then non line of sight reception points and are selected in order to cover the entire gallery.

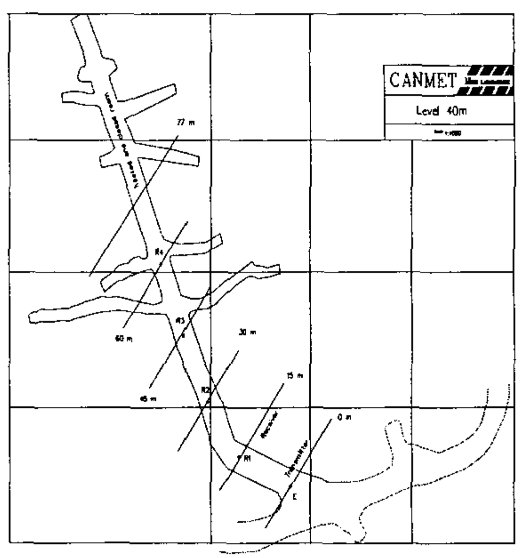

Fig.1. Map of the underground gallery.

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In order to characterize the variations of the received signal on a small scale, one has to carry out a spatial sampling of the channel by using a square grid centered at a certain point R_i of the gallery. An actuator moves the reception antenna at a constant speed over a distance of one meter. One measurement per spatial separation of 5 centimeters was taken.

III. STATISTICAL ANALYSIS

A. Attenuation of the field

The following figures present the received field according to the transmitter – receiver distance, at the two considered frequency bands.

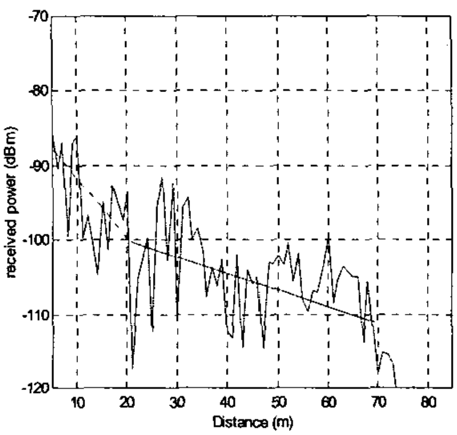

Fig.2. Variation of the received power versus the transmitter-receiver distance at 2.45 GHz.

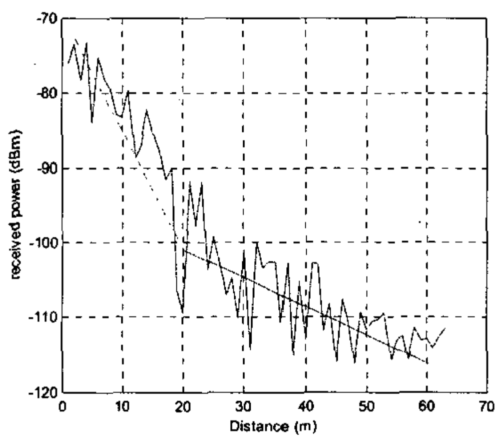

Fig.3. Variation of the received power versus the transmitter-receiver distance at 18 GHz.

An analysis by linear regression is employed to study the variations of the received power according to the transmitter-receiver distance. One can distinguish two distinct areas of propagation separated by a critical point localized at 20 meters of the transmitter. This critical point coincides with the point of curvature of the underground gallery. In the area located at the left of the critical point, the received power at 2.45 GHz passes from -90 dBm (at 3 meters) to -100 dBm (at 20 meters). Hence, the propagation loss for the distance of 17 meters is given by 10 dB. Whereas in the area located on the right of the critical point, the level of the received signal decreases slowly. The signal's attenuation is 20.2 dB/100m. Beyond 70 meters from the transmitter, the received power is close to the sensitivity of the receiver. In our analysis, this area has not been taken into account since the received signal is under the noise floor. As can be noted in Fig. 3, the distinction of the two areas of propagation is apparent at 18 GHz. In this frequency band, the loss of propagation is evaluated to be 25.3 dB at a distance of 17 meters for the area located at the left of the critical point and 37.5 dB/100m for the area located at the right of the critical point. A later study of the attenuation of the received signal at 18 GHz will be considered in future work for a radiolocation application in an underground mining medium. Table 1 summarizes the various attenuations of the received signal in the two considered frequency bands.

Frequency band (GHz)	Area located at the left of the critical point	Area located at the right of the critical point
2.45	60.27	20.2
18	148.7	37.5

Table 1. Attenuations of the received signal (dB/100m)

It can be seen from Figs. 2 and 3 that the attenuation of the signal is as expected much more important at 18 GHz.

B. Cumulative Distributions

The aforementioned results assume that the underground gallery channel can be characterized by a hybrid propagation model [8]. However, it can also be determined that the appearance of these two areas of propagation can be induced by the absence or the presence of a line of sight between the transmitter and the receiver. This study will be the subject of the present section. Fig. 4 gives the amplitude of the envelope of the received field on a square meter grid. The transmitter and the receiver, for line of sight conditions, are located at points E and R_1, respectively. Measurements were taken in an empty environment.

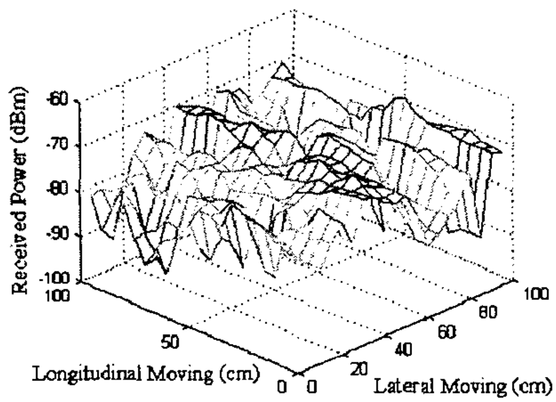

Fig.4. Received Power at one square meter grid

The observed fast fluctuations of the signal are due primarily to the displacement of the mobile. These fluctuations follow a known statistical law which has to be determined. From an inspection of the theoretical distributions' graph whose vertical scale is a logarithm, as illustrated in Figs. 5 and 6, it is easy to conclude that the lower tail of the distribution best matches the Rice distribution.

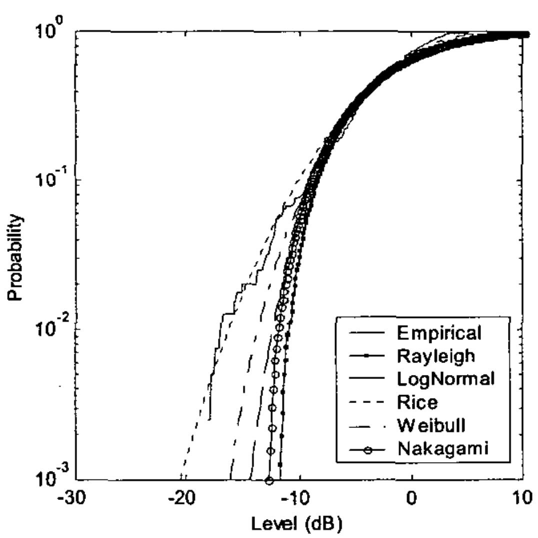

Fig.5. Cumulative probability distribution at point R_1

The dominant component of the received signal results mainly from the direct path of the wave. However, one can note that, even in absence of the line of sight between the transmitter and the receiver, the amplitude variations of the envelope of the received signal follow a Rice distribution. This can be explained by the presence, at the receiver's level of a signal contributing more significantly than the others. The latter results from the signal's reflection on the walls of the gallery. It has been noted that this contribution becomes less significant as the mobile moves away from the transmitter, which is not in direct line of sight with the receiver. In particular, the amplitude variations of the envelope of the received signal at point R_4 follow, as one can see in Fig. 6, a Rayleigh distribution.

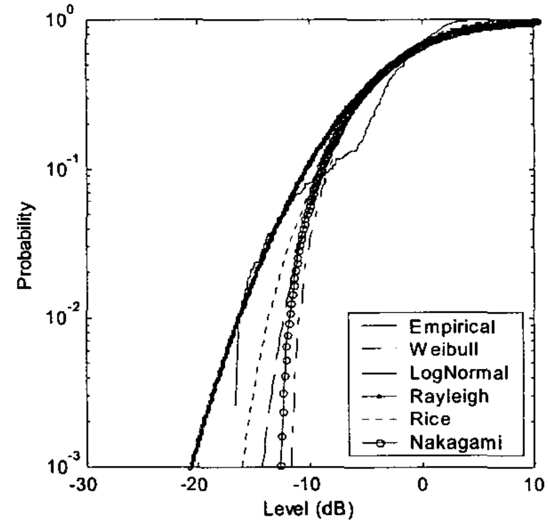

Fig.6. Cumulative probability distribution at point R_4

For the frequency band centered around 18 GHz, one can note that the Nakagami distribution is best matched to the empirical distribution.

In the following, the analysis will be concentrated to the frequency band centered around 2.45 GHz.

C. *Level crossing rate and average fade duration*

The level crossing rate N has been evaluated for thresholds standardized with spatial local averages, for all points R_i of the gallery. Fig. 7 illustrates the level crossing rate according to different thresholds, evaluated at point R_4. It is interesting to note the proportionality between N and the empirical probability density function of the envelope (*pdf*). The maximum rates observed for all points R_i of the gallery range between 73 and 97 Hz. These fast fluctuations are due primarily to the movement of the mobile. Moreover, the study showed that the position of these maxima as well as the width of the curves giving the level crossing rates agree rather well with the local average powers and the standardized standard deviations of the envelope's amplitude, respectively. This is a consequence of the proportionality relation which exists between N and the *pdf*. The analysis also showed that the influence of the human activity on the level crossing rate, for the considered frequency band, is negligible. Similar conclusions were given in a more general context [10].

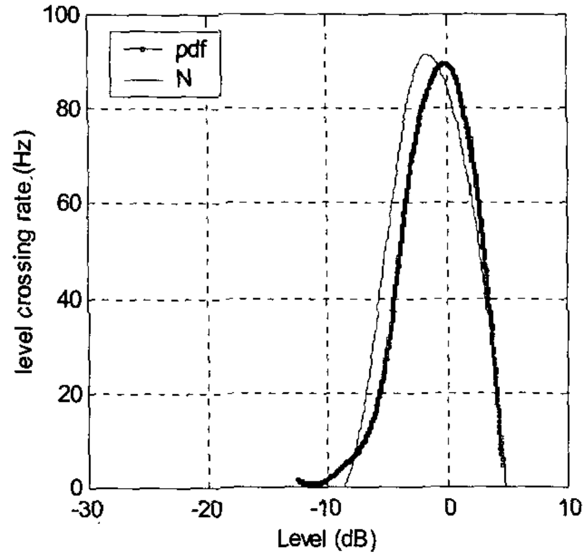

Fig.7. Level crossing rate versus the Level.

Fig. 8 presents the average fade duration as a function of thresholds standardized to the local spatial average, evaluated at point R_1. One can note that the curve, which is also true for all other points R_i of the gallery, exhibit a linear behavior for low threshold values. Similar behavior was noted in the context of [11] [12]. One can also note that a minimal value of 2 milliseconds for the average fade duration, is common with all measurements and that it corresponds to the sampling period of the system.

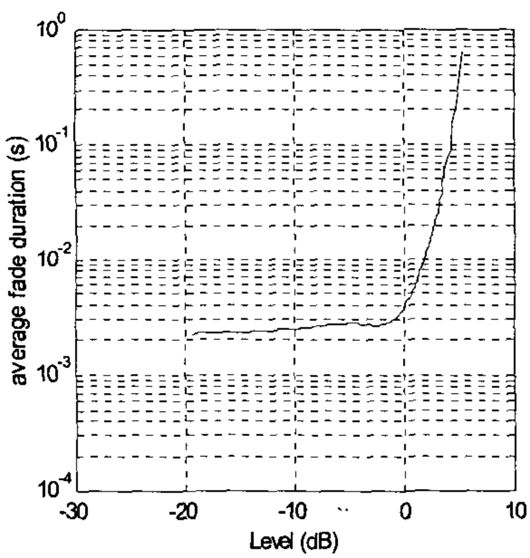

Fig.8. Average fade duration versus the Level

The analysis has also revealed that the influence of the human activity on the behavior of the average fade duration is negligible. This conclusion becomes stronger for low values of the threshold.

D. Coherence time

The coherence time, for a stationary process *a(t)*, is evaluated by considering a temporal correlation coefficient given [13] by

$$\zeta_a(\Delta t) = \frac{E\left[\left(a(t) - E[a(t)]\right)\left(a(t+\Delta t) - E[a(t+\Delta t)]\right)\right]}{\sqrt{E\left[\left(a(t) - E[a(t)]\right)^2\right]}\sqrt{E\left[\left(a(t+\Delta t) - E[a(t+\Delta t)]\right)^2\right]}}$$

In spite of the stationarity of the process *a(t)* representing the envelope of the received signal, during the acquisition period, the temporal correlation coefficient is estimated by taking the average over the temporal segmentation of the envelope. Taking ΔT_0 as the duration of each interval during which *a(t)* is considered locally a stationary process, a value of 1.024 seconds yields the desired behavior for the correlation coefficient. Fig. 9 gives the Coherence Time as a function of the duration ΔT and evaluated at point R_1.

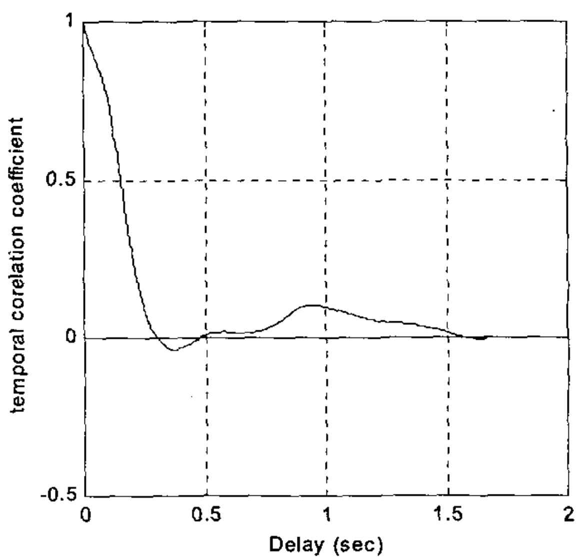

Fig.9. Coherence time of the propagation channel.

For all points R_i of the gallery, one can observe that for a coefficient of 50%, the maximum delay does not exceed 150 milliseconds. The analysis showed also that the influence of the human activity is also negligible.

IV. Conclusion

This paper has presented a statistical analysis of the narrowband propagation measurements performed within an underground gallery of a mine. Two frequency bands, 2.45 GHz and 18 GHz, were used for the characterization, and to extract the important parameters from the envelope of the received signal. An analysis based on linear regression was used in order to study the variations of the received power according to the transmitter-receiver distance. Two distinct areas of propagation separated by a critical point located at the point of curvature of the underground gallery, were highlighted, in particular in the frequency band centered at 18 GHz. An attenuation ranging from 20.2 to 148.7 dB/100m, depending on the frequency band used and on the presence or the absence of a line of sight between the transmitter and the receiver, has been observed. The statistical analysis of the results showed that the spatial fluctuations of the received signal's envelope follow a Rice distribution, even in the absence of a line of sight between the transmitter and the receiver. However, beginning from a certain distance separating the transmitter from the receiver, the statistical analysis of the results showed that the spatial fluctuations of the received signal's envelope follow a Rayleigh distribution. For the frequency band centered at 18 GHz, the Nakagami distribution is the best descriptor of the empirical obtained results. Further work is planned with respect to radiolocation techniques in this frequency band. As such, wide-band measurements will also be performed to support this study. Finally, this study made also possible the extraction of other parameters of the envelope such as the level crossing rate, the average fade duration and the coherence time of the channel. For a correlation coefficient of 50%, a delay not exceeding 150 milliseconds has been observed.

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