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EXPERIMENTAL CHARACTERIZATION OF A WIRELESS MIMO CHANNEL AT 2.4 GHz IN UNDERGROUND MINE GALLERY

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Abstract—This paper deals with several aspects relative to the Multiple-Input Multiple-Output (MIMO) propagation channel. Measurement campaigns, made in a real gold mine at 2.4 GHz under line-of-sight (LOS) and non-line-of-sight (NLOS) scenarios, have been analyzed to obtain the relevant statistical parameters of the channel. It was shown that the MIMO exploit the multipath propagation in rich scattering environment to increase the capacity. Hence, the channel is characterized in terms of K-factor, path loss, shadowing, and capacity. Results show a propagation behavior that is specific for these underground environments with rough surfaces.

1. INTRODUCTION

There is now a growing interest on implementing MIMO systems in underground and confined areas like mines and tunnels aiming the improvement of the communication performance in these environments, since it is well known that high data rate and/or a decrease of the error rate can be achieved using MIMO systems [1]. A key feature of MIMO systems is the ability to turn multipath propagation, traditionally a pitfall of wireless transmission, into a benefit for the communication system. In fact, MIMO takes advantage of random fading [1–3] and when available, multipath delay spread [4, 5], for multiplying transfer rates. While the characterization of propagation for MIMO systems, within tunnel

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roads and subways, has been the purpose of many investigations in the last 30 years, for instance, the works of Jose et al. [6–8] and Martine and Degauque [9, 10], the study of propagation in an underground environment, such as a mine, was somewhat neglected. 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.. To the best of our knowledge, no measurements of radio propagation for MIMO systems in underground mines have been reported in literature. The results presented in this paper are based on radio channel measurements made in a former underground gold mine, now operated by the Canadian Center for Minerals and Energy Technology (CANMET) as a mine laboratory in northern Canada. A central frequency of 2.4 GHz has been used throughout the measurements, in order to ensure compatibility with wireless local area network (WLAN) systems, which may be used for various data, voice, and video communication applications.

The main goal of this paper is to characterize experimentally the underground propagation channel under LOS and NLOS scenarios using a set of MIMO antenna. The obtained channel parameters can be used then for communication applications at 2.4 GHz, leading to operational enhancements and safety for the mining industry.

2. EXPERIMENTAL SETUP

2.1. Description of the Underground Mining Environment

Measurements were conducted in an underground gallery of a former gold mine located at a 40-m deep underground level. The gallery stretches over a length of 75 m with a width and height both of approximately 5 m. The environment mainly consists of very rough walls and the floor is not flat and it contains some puddles of water. A photography of the underground mine is shown in Fig. 1.

2.2. 2×2 MIMO Antenna Design

The MIMO antenna system consists of a patch antenna set as shown in Fig. 2, developed in our laboratory and have been used for transmission and reception of the RF signal, at 2.4 GHz.

The scattering parameters of the antenna array have been simulated using CST antenna design software based on the Finite Integration Technique. The simulation are compared to the measurements and shown in Fig. 3. There is an isolation of about 17 dB and the return loss is below the target −10 dB at both port at 2.4 GHz.

Figure 1. Photography of the mine gallery.

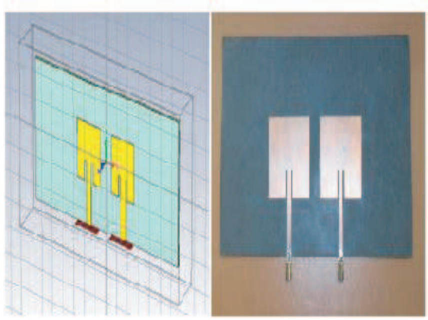

Figure 2. The 2×2 MIMO Patch antennas: Design model versus Fabricated one.

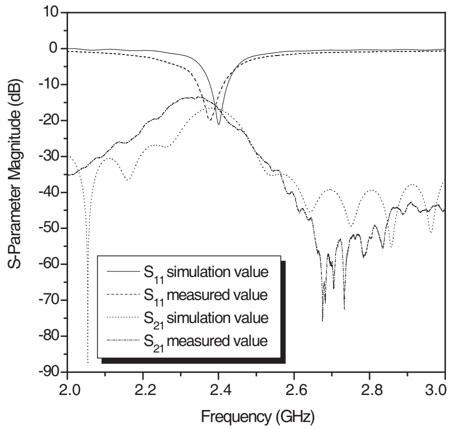

Figure 3. Measured and simulated S-parameter for the patch.

In an antenna array, the isolation between antenna elements is a critical parameter in many practical applications such as MIMO communication systems [11]. In fact, the spacing between elements is generally set to $\lambda/2$. In this case, the impact of mutual coupling on antenna performance is no longer negligible. Since mutual coupling affects the current distribution, which results in deformations of the radiation pattern of each antenna element and, consequently, the MIMO systems' performance will be affected due to channel correlation. Typically, in MIMO systems, independent and uncorrelated signaling between channels is required to improve channel capacity.

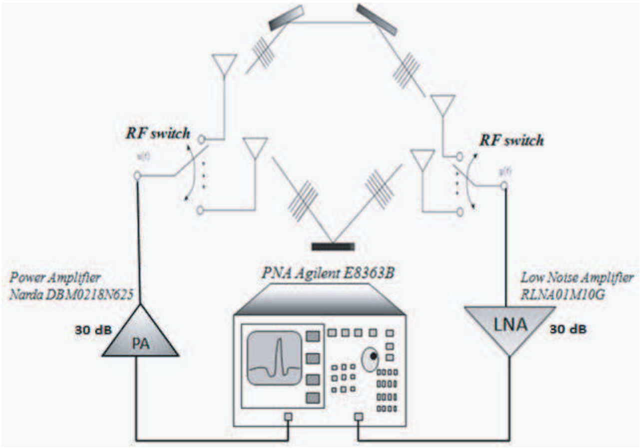

Figure 4. Measurement setup.

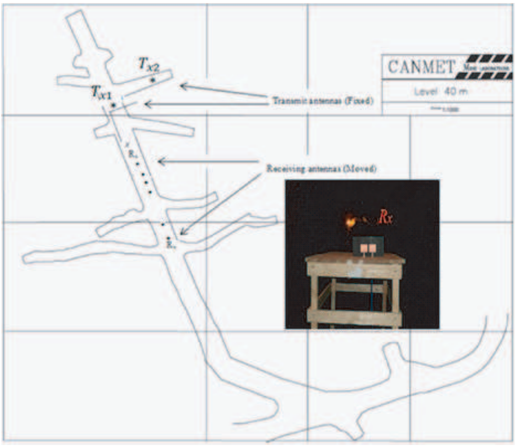

Figure 5. The underground gallery plan.

2.3. Measurement Campaigns

The measurements were performed in frequency domain using the frequency channel sounding technique based on measuring S_{21} parameter using a network analyzer (Agilent E8363B). In fact, the system measurement setup, as shown in Fig. 4, consists of a network analyzer (PNA), two sets of 2×2 MIMO patch antenna system, two switches, one power amplifier for the transmitting signal and one low noise amplifier for the receiving signal.

During all measurements, the wireless channel is assumed to be static with no significant variations and the height of the transmitting and receiving antennas were maintained at 1 m in above the ground level. The transmit power was set to 10 dBm.

For LOS scenario, the transmitter remained fixed at T_{x1}, where the receiver changed its position along the gallery, from 1 meter up to 25 meters far from the transmitter. While for NLOS the transmitter remained fixed at T_{x2} and the T_x-R_x separation varies from 6 m up to 25 m. Fig. 5 illustrates a photography of the receiver location and a map of the underground gallery.

3. EXPERIMENTAL RESULTS

3.1. Ricean *K*-factor

The Ricean K-factor was measured for several locations of the receiver, maintaining the transmitter fixed. This parameter characterises the relative strength of the direct path signal power to that of the reflected (scattered) signals. The method used to calculate the Ricean factor in this paper was presented in [12] where this factor is evaluated from several observations of the channel response H. For a matrix H containing these observations, the K-factor can be calculated as follows:

$$K\ (\mathrm{dB}) = \left(\frac{\varepsilon[|H|]^2}{2\mathrm{var}(|H|)}\right) \tag{1}$$

where ε denotes the expectation (mean) value and var corresponds to the variance of the observations matrix H.

Using the method mentioned above, the K-factor was calculated for each distance between the transmitter and the receiver. Fig. 9 presents the cumulative distribution function (CDF) of this parameter in both LOS and NLOS scenarios.

Concerning the LOS case, the direct path is greater than the multipath components. Consequently, the K-factor has positive values in the undertaken gallery with an average equal to 1.59 dB. Moreover, our results are compared to those in other confined environments such as corridors. A mean value of 3.78 dB is obtained [13]. This higher value can be explained by the difference in the scattering environment. However, it is demonstrated for the NLOS case that multipath dominate direct path resulting to a negative K-factor. In fact, the transmitted energy is no longer concentrated on the direct path but it is rather diffused among multipath components. Therefore, the ricean factor takes negative values. Similar results are obtained for the NLOS in [14]. Table 1 lists some statistical values obtained for different scenario.

Table 1. Ricean K-factor Statistics.

	Minimum/Maximum	**Mean/Standard deviation**
LOS scenario	$-1.23/3.9$	$1.59/1.58$
NLOS scenario	$-9/-2.32$	$-5.99/1.97$

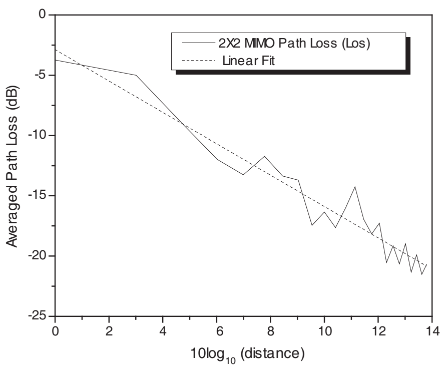

Figure 6. Average path loss versus distance in LOS scenario.

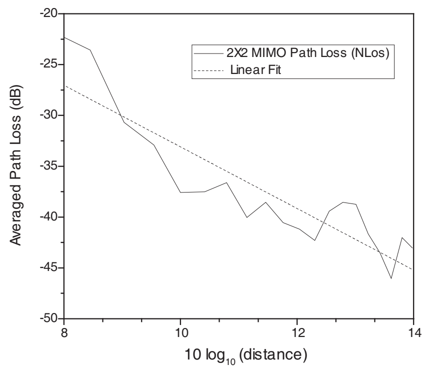

Figure 7. Average path loss versus distance in NLOS scenario.

3.2. Path Loss

The Path loss in the channel is normally distributed in decibel (dB) with a linearly increasing mean and is modeled as:

$$PL_{dB}(d) = \overline{PL_{dB}}(d_0) + 10\alpha \log\left(\frac{d}{d_0}\right) + X \tag{2}$$

where $\overline{PL_{dB}}(d_0)$ is the mean path loss at the reference distance d_0, $10\alpha\log(d/d_0)$ is the mean path loss referenced to d_0, and X is a zero mean Gaussian random variable expressed in dB. Path Loss as a function of distance are shown in Fig. 6 and Fig. 7 for both LOS and NLOS scenarios respectively. The mean path loss at the reference distance d_0 and the path loss exponent α were determined through least square regression analysis [15]. The difference between this fit and the measured data is given by the Gaussian random variable X. Table 2 lists the values obtained for α and σ_x (standard deviation of X).

From the results shown in Table 1, the path loss exponent has been determined to be less than the free space exponent $\alpha = 2$ for

Table 2. Path loss exponent α and standard deviation of X (σ_X).

	MIMO LOS	MIMO NLOS
$\boldsymbol{\alpha}$	1.73	3.03
$\boldsymbol{\sigma_X}$	1.29	2.75

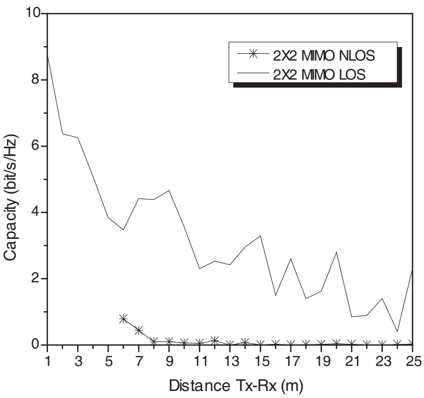

Figure 8. Channel capacity for LOS and NLOS scenarios.

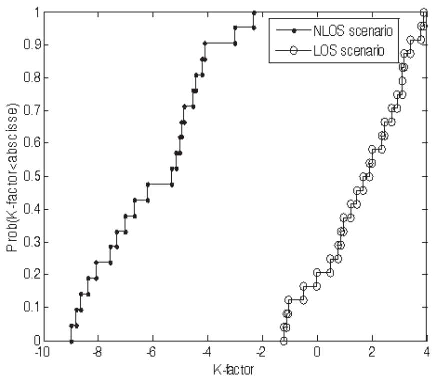

Figure 9. CDF of the Ricean K-factor in LOS and NLOS scenarios.

the LOS scenario, and this is due to the underground gallery structure which guides the wave. In fact, all multipath components contribute constructively in enhancing the received power. Thus, propagation in mine tunnels can exhibit low attenuation, and it is behaving as an oversized waveguide. Much literature analyzes propagation in a tunnel by representing the tunnel as a hollow conductor that acts as a waveguide [16] by launching rays in the tunnel [17] and by modeling statically experimental data extracted from measurement campaigns [18]. In addition, our results are compared to those obtained in the same mine, but in another gallery using a conventional SISO link [19]. The obtained path loss exponent is 2.01. In fact, this value is greater than obtained in this work, and this may due to the difference in gallery dimensions and antennas characteristics. Another study in a subway platform at 2.5 GHz showed a path loss exponent of 1.34 [20]. However, the path loss exponent is equal to 3.03 for the NLOS scenario. Indeed, the obstruction caused by the underground mine walls are very significant and affects strongly the transmitter-receiver link. Almost similar results are found for the NLOS case in [19].

3.3. Capacity

Foschini and Gans [21] demonstrated that for a wireless MIMO system composed of m transmitting antennas and n receiving antennas, the capacity of a memoryless narrow band channel, when there is no knowledge of the channel response at the transmitter and in the presence of additional white Gaussian noise (AWGN), is given by:

$$C = \log_2 \det(I_\Omega + \sigma * Q)$$
$$Q = \left\{ \begin{array}{ll} HH^H & \text{if } m > n \\ H^H H & \text{otherwise} \end{array} \right\} \tag{3}$$

where σ is the average signal to noise ratio per receiving antenna; I_Ω denotes the identity matrix of size $\Omega = \min(m, n)$ and Q is the Wishart matrix defined as above, the upper script H represents the hermitian conjugate of the matrix, and $\det(X)$ means the determinant of a matrix X.

To clearly point out the MIMO performance for the LOS and NLOS cases, the ergodic capacity is calculated for a fixed transmitted power and the SNR at the receiver is determined by the path loss. In this case, the capacity includes both effects related to received power and spatial richness. However, it is interesting to compare the MIMO capacity in LOS to the capacity that would be obtained in NLOS.

The relationship between the channel capacity C and the distance d_{Tx-Rx} based on Equation (3) is shown in Fig. 8. Obviously, one can see that the NLOS suffers from its higher path-loss exponent, this is due to the directional radiation pattern of the MIMO patch antenna, which could not reach NLOS positions resulting in lower capacity compared to the LOS case by about 3 bit/s/Hz.

4. CONCLUSION

In this paper, a 2×2 MIMO channel was studied. The results presented herein are based on radio channel measurements, made in a real underground gold mine under line-of-sight (LOS) and non-line-of-sight (NLOS) scenarios. The measurement campaign was performed at 2.4 GHz using a vector network analyzer. Frequency responses were obtained for one transmitter location and different receiver locations in the undertaken galleries. Results show propagation behavior that is specific for these underground environments, and multipath characteristics vary considerably depending upon the transmit/receive antenna separation. The path-loss exponent is found to be less than 2 in LOS scenario. Whereas, for NLOS, the path loss exponent is around 3. It is also demonstrated that the Ricean K-factor varies randomly with distance with a mean value of 1.59 dB and standard deviation around 1.58 dB in LOS scenario and a mean value of −5.99 dB and standard deviation of 1.97 dB in NLOS scenario. In addition, it is proven that directional MIMO antennas are not beneficial for NLOS positions since it has a very low channel capacity. However, the integration of MIMO technology in a LOS scenario at 2.4 GHz can be considered as a promising solution to achieve high data rates and good reliability for medium-range communications in underground mine tunnels enabling to improve miners security and productivity.

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