Modeling and Understanding MIMO propagation in Tunnels

Jose-Maria Molina-Garcia-Pardo
Technical University of Cartagena, Dep. TIC, Cartagena, Spain
Email : josemaria.molina@upct.es

Martine Lienard, Paul Stefanut and Pierre Degauque
University of Lille, IEMN/TELICE, Lille, France
Email: {pierre.degauque, martine.lienard}@univ-lille1.fr

Abstract—**This paper first presents an application of the modal theory for interpreting experimental results of the electromagnetic field variation along a tunnel. The transmitting frequency is assumed to be high enough so that the tunnel behaves as an oversized waveguide. Then, for a Multiple-Input Multiple-Output channel, theoretical results of the channel capacity are given. To explain the decrease of the capacity at large distance from the transmitter, even by assuming a constant signal to noise ratio, an approach based on the calculation of the eigenvalues of the transfer matrix in a reference scenario is described.**

Index Terms — **MIMO, propagation, information theory, modal theory, measurements.**

I. INTRODUCTION

Wireless communications in confined environments such as tunnels have been widely studied for years and a lot of experimental results are presented in the literature, mainly to describe mean path loss versus frequency in different types of environment ranging from mine galleries and underground old quarries [1-3], to road and railway tunnels [4-5]. In these last two cases, arc-shaped tunnels are quite usual. They can be approximated by a cylinder whose lower part is flat and supports either the tracks or the road. They are often encountered in mountainous regions and in chalky terrains where tunnel boring machines, or moles, are shaped like a huge cylinder. The prediction and/or interpretation of the field distribution inside such tunnels excited by an electric antenna is thus important for the deployment of a wireless communication system.

Unfortunately, the internal surface of an arched tunnel cannot be easily described by a canonical coordinate system and, consequently, no analytical formulation is available. A numerical ray-optical wave propagation modeling based on ray-density normalization is described in [6] to tackle problems of arbitrary shaped tunnels, while an approach based on the resolution of a vectorial parabolic equation can be applied to curved tunnels [7]. However these approaches are not easy to implement. In order to get an idea of the field behavior, another possibility is to make a drastic simplification of the tunnel shape, assuming its cross section to be either rectangular or circular. A modal analysis of the radio wave propagation in circular waveguides has been described by Holloway et al. [8], and by Dudley and Mahmoud [9], extensive references to other works being given in these two papers. For the rectangular tunnel, let us mention the works of Emslie et al. [10] and Mahmoud and Wait [11] among many others. Another potential approach could be made on a statistical modeling which has been used for many years in conventional wireless systems [12]. However, complex stochastic models such as the COST-273 MIMO model [13] have not successfully been used in tunnels. Recently, an empirical UWB MIMO model has been proposed in [14].

On the other hand, there is now a growing interest on implementing Multiple-Input Multiple-Output (MIMO) systems in tunnels with the aim of trying to improve the communication performance, since it is well known that high data rate and/or a decrease of the error rate can be achieved [15-16]. However, the number of random scatterers in a tunnel is rather small and the application of the MIMO concept to a waveguide must be based on the propagation of orthogonal modes, each mode being associated with a diversity order [17]. An example of application for railway tunnels is given in [18].

If we first consider a lossless waveguide, the number of modes is limited by the cut-off frequency of the guide and there is no longitudinal attenuation. For this configuration, the upper limit of the channel capacity is obtained if, at the transmitting site (Tx), all modes are identically excited and if, at the receiving site (Rx), the amplitude of the modes can be recovered [19]. This can be obtained by putting planar dense arrays in the transverse Tx and Rx planes, the elements of the Tx array being fed with equal currents. An extension of this approach to tunnels whose walls have a finite conductivity is presented in this paper.

Section II gives an application of the modal theory of the electromagnetic propagation in rectangular or circular tunnels, in order to satisfactorily interpret experimental results. Few results of the variation of co-polarized fields (in the low frequency range and along the tunnel axis) are given. A simplified shape for the tunnel allowing a simple calculation of the propagation characteristics is then chosen. The influence of the position of the transmitting and receiving antennas on the transverse plane of the tunnel is studied.

Manuscript received December 1, 2008; revised March 17, 2009; accepted March 23, 2009

An application of the modal theory to a MIMO configuration is presented in Section III. The variation of the capacity versus the distance between the transmitting and receiving arrays is first studied. To interpret the results, a reference configuration corresponding to the excitation by a uniformly excited dense array is considered in Section IV. Finally, the concept of multipath richness, already introduced by B. Andersen in [20], is then applied as a measure of MIMO performance.

II. Modal Analysis

A. The measurement campaign and a few experimental results

Extensive measurement campaigns have been performed in a straight 2-way tunnel, 3 km long, whose cross section is represented in Fig. 1. The origin of the system of coordinates (x,y,z) is placed at the center axis of the cylinder, having a radius of 4.3 m, the abscissa z = 0 corresponding to the transverse plane containing the transmitting antenna. Three frequencies, 450 MHz, 510 MHz and 900 MHz, and various transverse positions of the transmitter have been considered. The transmitted power is 5 W in all cases. Half-wave dipoles were used at 450 MHz and 510 MHz, and patch antennas at 900 MHz. The half power beamwidths of the patch antennas are 65º and 75º in the H plane and E plane respectively. Since at large distances, typically beyond a few hundred meters, only rays impinging the walls with a grazing angle of incidence play a leading part in the propagation, the aperture of the antenna radiation pattern is not critical.

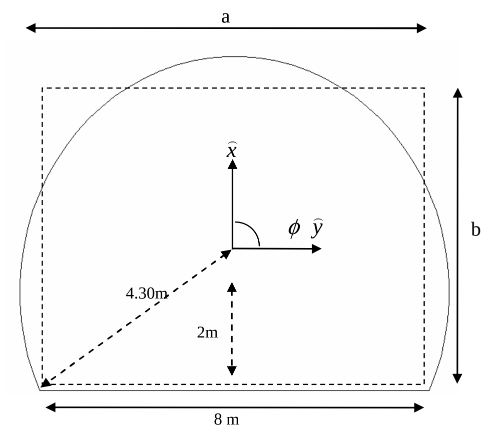
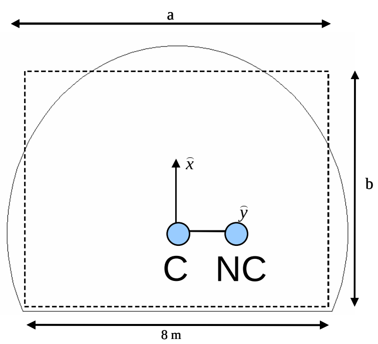


Figure 1: Transverse plane of the tunnel.

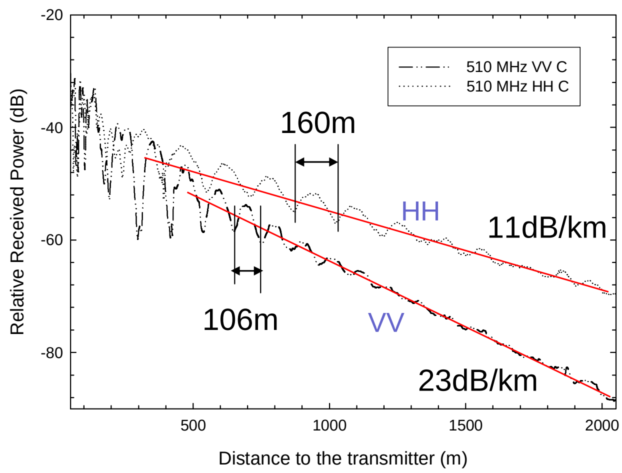
Two orientations of the linearly-polarized antennas have been studied: vertical (*x*-axis aligned) and horizontal (*y*-axis aligned). In the following, V stands for vertical polarization and H for horizontal polarization. In order to specify the respective polarization of the transmitting (Tx) and receiving (Rx) antennas, the two letters HV will be used. The first one refers to the polarization of the transmitting antenna, the second one, V in this example, referring to the receiving antenna.

The transmitting (Tx) and receiving (Rx) antennas are placed either at the center of the cylindrical part ($x= y=0$), corresponding to point C (for "centered") in Fig. 2a, or at 1/4 of the tunnel width (x = 0, y = 2m, point NC). In both configurations, the height of the antennas above the ground is 2 m.

In Fig. 2b, we display results for the field strength, expressed in dB referred to an arbitrary value, versus axial distance, both for VV and HH polarization, the antennas being centered. In this case, the transmitting frequency is 510 MHz. If we first compare results for vertical and horizontal polarization, we observe that the field decay is exponential, or linear in dB, with a slope of 23 dB/km for VV and 11 dB/km for HH. For interpreting the field amplitude variation in the co-polar case considering the arched tunnel as a circular one is thus not possible. This is due to the fact that the properties of rotation-symmetry are not experimentally found. Besides, we note a pseudo periodicity of the fading is different depending on the polarization: 160 m for VV and 106 m for HH. Therefore, a circular tunnel does not seem appropriate to simulate the propagation in this kind of structure.



a)



b)

Figure 2: a) Position of the antennas and b) Received Power (dB) in the arched tunnel for two polarizations at 510 MHz.

The curve VV NC (NC for "Not Centered") in Fig. 3 refers to the case of both antennas (transmitter and receiver) situated at the same height as previously, but in a non centered position (in the middle of one of the lanes, 1/4 of the tunnel width) and for a frequency of 450 MHz.

If we compare now the two curves in Fig. 3, VV C and VV NC, we observe that, by moving the transmitting and receiving antennas from position C to NC, an 8 dB offset is observed at large distance between the average received powers. It is thus interesting to know if a modal theory applied to a rectangular tunnel is able to predict the results above, obtained for a co-polar configuration.

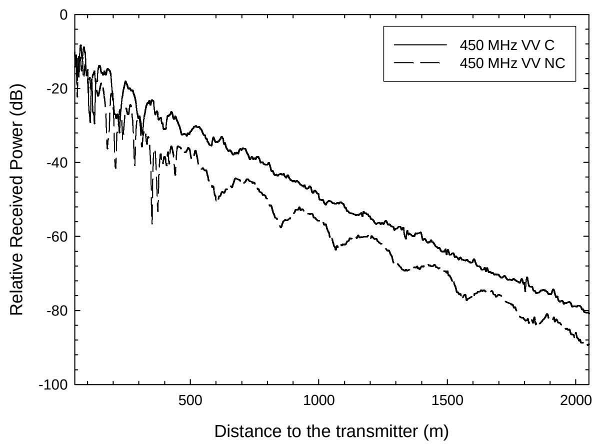


Figure 3: Received Power (dB) in the arched tunnel for two polarizations at 450 MHz.

B. Interpreting the experimental results from modal theory

If we first consider the propagation inside a simple straight rectangular tunnel, no exact analytical solution is available, due to the difficulty coming from the boundary conditions near the four corners. However, approximate expressions of the modal eigenfunctions of the hybrid modes $EH_{m,n}^{x\,or\,y}$ and of the propagation constant are given in the literature [21], assuming that the waves remains polarized. The upper index *x* or *y* refers to the case of a vertical or horizontal polarization, respectively. The electric field at any point can be expressed with the following form:

$$E(x,y,z)=\sum_{m}\sum_{n}\alpha_{m,n}\, e_{m,n}(x,y)\, e^{-jk_{m,n}z} \qquad (1)$$

where $\alpha_{m,n}$ is the complex amplitude or the weight of the *m,n* mode excited by a transmitting antenna situated at (x_{tx},y_{tx}), $e_{m,n}(x,y)$ is the normalized modal function calculated at the receiving point (*x*, *y*), and $k_{m,n}$ is the complex propagation constant. The mathematical expressions of the modal functions can be found in [21] and [22].

The problem of the excitation of a tunnel by an electric dipole can be solved by applying the boundary conditions in the cross section of the tunnel which contains the transmitting antenna. For a circular tunnel, the solution has been given by Wait and Hill [23], while for a rectangular tunnel, Emslie et al. [10] have calculated the insertion loss of a half wave dipole, but considering only the excitation of the fundamental mode (1,1). Since the tunnel has lossy walls, all of the modes have some attenuation and therefore, there is no clear distinction between propagating and evanescent modes, as outlined by Holloway et al. [8]. If solutions of the tunnel excitation can be obtained for a Hertzian dipole, the approach would be much more difficult for any type of antenna than for a patch antenna used in the experimental approach. Furthermore, in order to predict the field distribution inside a tunnel, only the knowledge of the relative weight of the modes is needed.

The relative weight of the mode (*m,n*) excited by a transmitting dipole situated at (x_{tx},y_{tx}) is given by the value of the eigenmode function at this point, i.e. $e_{m,n}(x_{tx},y_{tx})$. Equation (1) can thus be written as:

$$E(x,y,z)=\sum_{m}\sum_{n}e_{m,n}(x_{tx},y_{tx})\, e_{m,n}(x,y)\, e^{-jk_{m,n}z} \qquad (2)$$

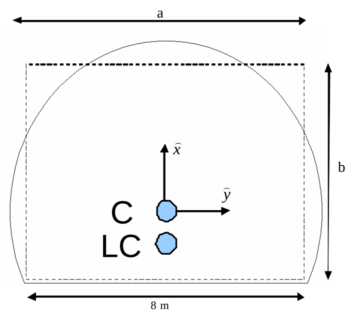
It must be recalled that the distance between the transmitter and the receiver is large enough so that the contribution of the continuous spectrum of modes is negligible. Furthermore, as we shall see later, only a few discrete modes will be needed for the field reconstruction, taking the frequency range and the transverse dimensions of the tunnel into account. The validity of this approach was checked by comparing the field variation versus axial distance deduced either from (2) or calculated from the well-known ray theory. It must be noted that such a comparison implies adjusting the power reference level of the theoretical curves calculated from the modal approach described above, excluding the insertion loss of the antennas from the formulation.

In order to apply the theory of the propagation inside a rectangular tunnel so as to interpret the experimental results obtained in an arched tunnel, the preliminary step is to find the dimensions of the rectangular tunnel. This tunnel would be equivalent to the actual arched tunnel, whose dimensions seem optimum in the sense that it minimizes the difference between theoretical and experimental results. It seems reasonable to choose the transverse surface of the rectangular tunnel as nearly equal to the surface of the actual tunnel, its width and height approximating the exact shape. To choose the equivalent tunnel, the following configuration was considered: VV polarization, centered position of the transmitter and the receiver (Position C in Fig. 2a) and a frequency of 510 MHz. The optimization was made by minimizing the difference between the attenuation constant of the dominant mode (EH_{11}) and the mean slope of the field decay at large distance. It turns out that the rectangular tunnel must have the electrical and geometrical parameters: $\sigma = 10^{-2}$ S/m, $\varepsilon_r = 5$, a = 8m and b = 5.6m (see Fig. 1). We have kept these dimensions for all simulations, thus assuming that the complex permittivity of the tunnel does not vary appreciably in the 500 - 900 MHz frequency range.

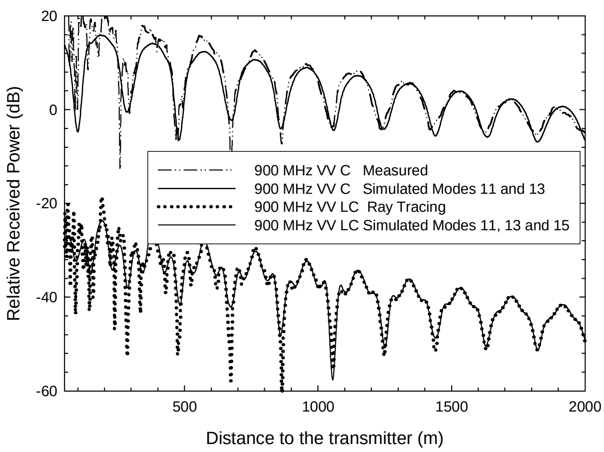
From the modal theory based on this simple tunnel geometry, one can first try to quantitatively justify the offset observed between the two curves in Fig. 3 and related to configurations C and NC at 450 MHz. Indeed, at a large distance (the dominant mode being EH_{11}), the decrease of the received power when the transmitting and receiving antennas move from centered to off-centered positions is due to a smaller excitation/reception of this mode. The power loss, referred to the centered case, is thus given by $e_{1,1}\left(x_{tx}, y_{tx}\right).e_{1,1}\left(x_{rx}, y_{rx}\right)$. This leads to an additional attenuation (for NC) of 6 dB which is close to the 8 dB value experimentally observed.

The variation of the received power shown in Fig. 2b behaves as a damped sinusoid around the mean path loss. This can be interpreted as a beating between the first two modes. Considering the equivalent rectangular tunnel, it can be shown that the pseudo period of this beating (160 m for HH and 106 m for VV) can be well predicted by the modal theory.

Let us now consider a frequency of 900 MHz and two positions of the vertical antennas in the transverse plane of the tunnel: position “C” as previously, and position “LC” (Low centered). In this last case, the antennas remain placed along the vertical *x* axis, but at a height of 50cm above ground. The upper two curves in Fig. 4 (for C) correspond to the measured values and to the theoretical results respectively, assuming an equivalent rectangular tunnel. They are calculated from the modal theory by taking into account only the first two modes (EH_{11} and EH_{13}). We see the good agreement between these curves, high order modes being strongly attenuated beyond 500 m. We have also compared the approaches based either on the ray theory or on the modal theory for LC.



a)



b)

Figure 4: a) Position of the antennas and b) Measured relative received power (dB), simulated and reconstructed received power in an arched tunnel at 900 MHz.

For the same equivalent rectangular tunnel as before, the comparison between the two lowest curves in Fig. 4 shows that the variation of the received power deduced from the first 3 modes in the modal theory is quite comparable to the variation calculated through the ray theory.

III. MIMO CHANNEL CAPACITY

Let us now consider a *M*x*N* MIMO system, where *M* and *N* are the number of transmitting and receiving antennas, and let $\boldsymbol{H}$ be the transfer matrix. The capacity of such a system is given by [15], [16]:

$$C = \log_2\left(\det\left|\boldsymbol{I}_N + \frac{SNR}{M}\boldsymbol{H}\boldsymbol{H}^H\right|\right) \qquad (3)$$

where $\mathbf{I}_N$ is the *N*x*N* identity matrix, $(\ )^H$ is the transpose conjugate operation and *SNR* is the signal-to-noise ratio at the receiver. By using a single value decomposition, it has been shown that the MIMO channel is equivalent to a number of independent channels whose power gains are the eigenvalues λ_i of $\boldsymbol{H}\boldsymbol{H}^H$. In a tunnel, this mathematical concept can be physically interpreted. Indeed, in the absence of random scatterers, the channel diversity is only due to the excitation of orthogonal modes by the transmitting elements, leading to a so-called modal diversity.

To observe the possible improvement of the channel capacity when using MIMO techniques, let us consider a numerical example with a rectangular tunnel, 7 m wide and 4 m high. In this tunnel three configurations of antennas will be successively studied, the number of antenna elements being equal to 4, 3 or 2. We assume that the Tx and Rx antennas are always identical and placed in the center of the tunnel. Furthermore, the total length of the antenna arrays is equal to 90 cm, whatever the number of elements. The MIMO channel capacity can be deduced from (3), the transfer matrix being calculated from the ray theory or from the modal theory. It must be emphasized that capacity *C* can be strongly dependent on the position of the antenna in the transverse planes of the tunnel.

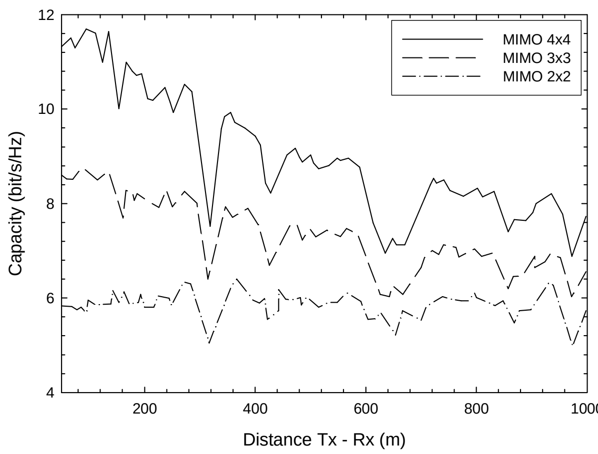


Figure 5: Capacity versus distance between Tx and Rx at 2GHz for 4x4, 3x3 and 2x2 antenna arrays.

Therefore, *C* was calculated for two positions of the Tx array and 50 positions of the Rx array in successive cross sections. This leads to an average value C_{av} of C, for a given distance Tx -Rx, and whose variation is represented in Fig.5, for a SNR of 10 dB. For a 4x4 MIMO system, good performances are obtained at short distances since the capacity reaches 11 bits/s/Hz instead of 3.5 bits/s/Hz for the SISO (Single Input Single Output) case. However, as soon as the distance increases, the capacity decreases nearly linearly, and it becomes equal to 7 bits/s/Hz at 1 km. For a 2x2 MIMO configuration the capacity is obviously smaller, on the order of 6 bits/s/Hz, but it remains nearly constant in the whole range of distance. This result can be interpreted in terms of the number of modes significantly contributing to the received power. Indeed, this number, corresponding to the order of diversity, must remain greater than the number of array elements; otherwise the $\boldsymbol{H}$ matrix becomes degenerate. Furthermore, it must be outlined that a high number of modes give rise to an important variation of the amplitude and phase of the field in a transverse plane, and therefore to a low correlation coefficient between the antenna elements. It is thus interesting to analyze the variation of the relative weights of the modes along the tunnel axis, and to have a measure of the multipath richness versus frequency and distance. To characterize the tunnel itself and thus to avoid the influence of the number of antenna elements, a reference scenario corresponding to a uniform excitation of the tunnel is studied in the next section.

IV. Multipath Richness in a Reference Scenario

We assume in this scenario that the electromagnetic field has the same phase and amplitude everywhere in the excitation plane and, consequently, each mode is equally excited. Following this approach, each eigenvalue λ_i of $\boldsymbol{HH}^H$ must correspond to the power of a mode EH_{mn} in the receiving plane and can thus be calculated from the modal theory, as it will be shown in the next paragraphs.

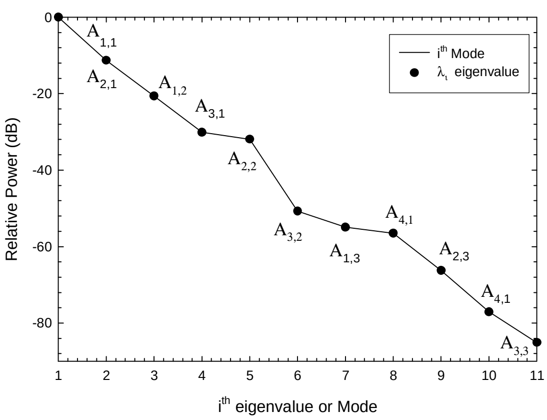


Figure 6: Relative weight of the modes and amplitude of MIMO eigenvalues in a 4 m x 5 m rectangular tunnel at 1000 m for f = 900 MHz.

If λ_1 is the highest eigenvalue, it would be associated to the lowest order mode EH_{11} propagating with the smallest attenuation. If at any abscissa z, λ_i is normalized to λ_1, all eigenvalues can be calculated from (4) and are thus easily deduced from the available closed-form expressions of the attenuation constants α_{mn}.

$$\lambda_i / \lambda_1 = \exp\left(-2\left(\alpha_{mn} - \alpha_{11}\right) z\right) \quad (4)$$

To numerically check the validity of this approach, let us consider a 4 m wide and 5 m high rectangular tunnel, whose electrical parameters of the walls are $\sigma = 10^{-2}$ S/m and $\varepsilon_r = 5$, and a distance of 1000 m between the transmitting and receiving planes. As suggested in [20], the reference configuration also corresponds to a link between transmitting and receiving planar arrays whose element spacing is very small. For a frequency of 900 MHz, a $\boldsymbol{H}$ transfer matrix of dimensions (775,775) was chosen. The dots in Fig. 6 refer to the eigenvalues deduced from the $\boldsymbol{H}$ matrix and normalized to λ_1. The values $A_{i,j,}$ deduced from (4), i.e. from the modal theory with the propagation constants calculated from formulas given in [21], exactly superimpose the eigenvalues calculated from $\boldsymbol{H}$. In order to clearly show this point and thus to clarify Fig. 6, the modal eigenvalues $A_{i,j,}$ where i,j is the order of the mode, have been joined to one another by a straight line.

For dense planar transmitting and receiving arrays, the channel capacity can then be analytically deduced from the set of eigenvalues given by (4), assuming a given signal to noise ratio. However, it must be emphasized that, contrary to the case of a lossless waveguide, such a uniform excitation will not lead to an upper bound of the channel capacity because in the receiving plane, the weights of the modes are not identical anymore.

It can also be of interest to introduce a simple relationship or curve, which expresses the multipath richness (or more precisely the diversity richness in our case) of the channel matrix without reference to the *SNR*.

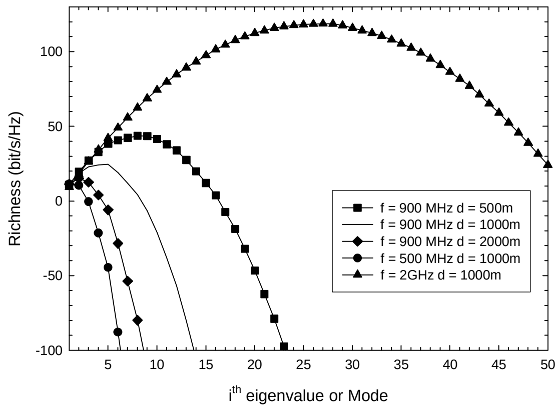


Figure 7: Multipath Richness in a 4 m x 5 m rectangular tunnel at different distances and frequencies

As explained in [20], a richness curve $R(k)$ can be defined from the cumulative sum of the log of the eigenvalues.

$$R(k) = \sum_{i=1}^{k} \log_2(\lambda_i) \quad k = 1, N \quad (5)$$

Curves in Fig. 7 have been plotted for the same tunnel configuration as previously, and for different distances between the transmitter and the receiver (500 m, 1000 m and 2000 m at 900 MHz), and different frequencies (500 MHz, 900 MHz and 2 GHz at 1000 m). Fig. 7 shows the mean richness degradation when either decreasing the frequency or increasing the distance. At 1 km, for example, there are only two eigenvalues playing a leading part for a transmitting frequency of 900 MHz. This will lead to a degeneracy of the ***H*** matrix for a MIMO system with more than 2 transmitting/receiving elements. On the contrary, at 2 GHz, a full rank matrix would be obtained, even for a large number of antenna elements.

V. Conclusion

In this work we have shown that the modal theory is an interesting tool to explain the variation either of the field along the tunnel axis for the SISO case or of the channel capacity for MIMO systems. Narrowband SISO measurements at different frequencies have shown that some hundreds of meters away from the transmitter only a few modes determine the spatial variation of the electric field. Consequently, a simple theoretical model theory can be directly used to interpret and predict propagation in tunnels. We have also shown that MIMO performances can be interpreted by means of the weights of the modes excited and propagated in the tunnel. This approach allows determining the multipath richness in a reference scenario assuming that all modes are equally excited and can be entirely recovered.

Acknowledgment

This work has been supported by the European FEDER funds, the Region Nord Pas de Calais and the French ministry of research in the frame of a program on research for transportation system (CISIT project).

References

[1] M. Lienard and P. Degauque, “Natural Wave Propagation in Mine Environments”, *IEEE Trans. on Antennas and Propag.*, vol. 48, no. 9, pp. 1326-1339, September 2000 .

[2] M. Ndoh and G. Y. Delisle, “Undergorund mines wireless propagation modeling”, *60th IEEE Vehicular Techno. Conf.,* Los Angeles, CA, pp. 3584-3588, 2004

[3] M. Boutin, A. Benzakour, C. Despins and S. Affes, “Radio wave characterization and modeling in underground mine tunnels”, *IEEE Trans. on Antennas and Propag.*, vol. 56, n°2, pp. 540-549, Feb. 2008.

[4] T.-S. Wang and C.-F. Yang, “Simulations and Measurements of Wave Propagations in Curved Road Tunnels for Signals From GSM Base Stations”, *IEEE Trans.s on Antennas and Propag.*, vol. 54, no. 9, pp. 2577-2584, September 2006.

[5] D. Didascalou, J. Maurer and W. Wiesbeck, “Subway Tunnel Guided Electromagnetic Wave Propagation at Mobile Communications Frequencies”, *IEEE Trans. on Antennas and Propag.*, vol. 49, no. 11, pp 1590-1596 , November 2001.

[6] D. Didascalou, T. M. Schäfer, F. Weinmann, and W. Wiesbeck, “Ray-Density Normalization for Ray-Optical Wave Propagation Modeling in Arbitrarily Shaped Tunnels”, *IEEE Trans. on Antennas and Propag.*, vol. 48, no. 9, pp, 1316-1325, September 2000.

[7] A. V. Popov and N. Yan Zhu, “Modeling Radio Wave Propagation in Tunnels with a Vectorial Parabolic Equation , *IEEE Trans. on Antennas and Propag.*, vol. 48, no. 9, pp. 1403-1412, September 2000.

[8] C. L. Holloway, D. A. Hill, R. A. Dalke and G. A. Hufford, “Radio wave propagation characteristics in lossy circular waveguises such as tunnels, mine shafts and boreholes”, *IEEE Trans on Antennas and Propag.*, vol. 48, pp 1354-1366, Sept. 2000.

[9] D. G. Dudley and S. F. Mahmoud, “Linear Source in a Circular Tunnel”, *IEEE Trans.s on Antennas and Propag.*, vol. 54, no. 7, pp. 2034-2047, July 2006.

[10] A. G. Emslie, R. L. Lagace, and P. F. Strong, “Theory of the propagation of UHF radio waves in coal mine tunnels”, *IEEE Trans.s on Antennas and Propag.*, vol. AP-23, pp. 192–205, 1975.

[11] S. F. Mahmoud and J. R. Wait, “Geometrical optical approach for electromagnetic wave propagation in rectangular mine tunnels”, *Radio Science*, vol. 9, pp. 1147–1158, 1974.

[12] Y.P. Zhang and Y. Hwang, “Characterization of UHF radio propagation channels in tunnel environments for microcellular and personal communications”, *IEEE Transactions on Vehicular Technologies*, vol. 47, issue 1, pp. 283-296, Feb 1998.

[13] Luis Correia, Mobile Broadband Multimedia Networks: Techniques, Models and Tools for 4G, Elsevier 2006.

[14] J.-M. Molina-Garcia-Pardo, Martine Lienard and Pierre Degauque, “Propagation in Tunnels: Experimental Investigations and Channel Modeling in a Wide Frequency Band for MIMO Applications”, accepted for publication in EURASIP JWCN 2009.

[15] G. J. Foschini and J. Gans, “On Limits of Wireless Communications in a Fading Environment when Using Multiple Antennas”, *Wireless Personal Communications*, vol. 6, no. 3, pp. 315-335, March, 1996.

[16] I. E. Telatar, “Capacity of Multi-Antenna Gaussian Channel”, *European Trans. on Telecommunications*, vol. 10, no. 6, pp 585-595, 1999.

[17] P. Kyritsi and D. Cox, “Expression of MlMO capacity in terms of waveguide modes”, *Electronics Letters*, vol. 38, No. 18, pp. 1056-1057, 2002.

[18] M. Lienard, P. Degauque, J. Baudet and D. Degardin, D, “Investigation on MIMO channels in subway tunnels”, *IEEE J. on Selected Areas in Communications*, vol. 21, N° 3, pp. 332 – 339, April 2003

[19] S. Loyka, “Multiantenna capacities of waveguide and cavity channels”, *IEEE Trans. on Vehicular Technology*, vol. 54, pp. 863–872, 2005

[20] J. Bach Andersen, “Array Gain and Capacity for Known Random Channels with Multiple Element Arrays at Both Ends”, *IEEE J. on Selected Areas in Communications*, vol. 18, No. 11, November 2000

[21] K. D. Laakmann and W. H. Steier, “Waveguides: characteristic modes of hollow rectangular dielectric waveguides,” *Appl. Opt.*, vol. 15, pp. 1334–1340, 1976.

[22] A. G. Emslie, R. L. Lagace, and P. F. Strong, “Theory of the propagation of UHF radio waves in coal mine tunnels”, *IEEE Trans. on Antennas and Propag.*, vol. AP-23, pp. 192–205, 1975.

[23] J. R. Wait and D. A. Hill, “Impedance of an Electric Dipole Located in a Cylindrical Cavity in a Dissipative Medium”, *Applied Physics*, vol. 11, pp. 351-356, 1995.

Jose-Maria Molina-Garcia-Pardo (M'99) was born in Orihuela, Alicante, Spain, in 1977. He received the Telecommunications Engineer degree from the Universidad Politécnica de Valencia (UPV), Spain, in 2000, the MSc in Communication and Signal Processing from the University of Newcastle, UK, in 2001 and the Ph.D. in Telecommunications Engineering from the Universidad Politécnica de Cartagena (UPCT), Spain, in 2004.

In 2000, he joined the Communications and Signal Processing department of the University of Newcastle, UK, where he was involved in Blind Source Separation. In 2001, he joined the Information Technologies and Communications Department of the Universidad Politécnica de Cartagena, Spain, where has been an Associate Professor. His research activities have been centred on propagation studies for Multiple-Input and Multiple-Output systems, measurement campaigns in special environments and ray-launching in the area of mobile personal communications systems.

Martine Lienard received the M.S and Ph.D. degrees from the University of Lille, Lille, France in 1988 and 1993, respectively.

In 1990, she joined the TELICE (Telecommunications, Interference and Electromagnetic Compatibility) Laboratory, University of Lille, which became a group of the Institut d Electronique, Microelectronique et de Nanotechnologies (IEMN) in 2004. She is presently a Professor at the University of Lille.

Her current research deals with both the theoretical and experimental prediction of propagation characteristics in confined areas, as in tunnels, and the optimization and performances of modulation and diversity schemes, such as MIMO, OFDM and Spread Spectrum Techniques, for wireless local area network and power line communications.

Paul Stefanut received the M.S. degree from the University of Lille, France, in 2006. He joined the TELICE (Telecommunications Interferences and Electromagnetic Compatibility) Laboratory in 2006 where he is presently pursuing a PhD degree. His current research deals with the optimization of localization systems in environments related to transportation systems, employing antenna arrays and high resolution parameter estimation algorithms.

Pierre Degauque (M'76) received the M.S and Ph.D. degrees from the University of Lille, Lille, in 1966 and 1970, respectively. He also received the engineer degree from the Institut Superieur d Electronique du Nord, Lille, in 1967.

Currently, he is a Professor at the University of Lille and head of the TELICE group. Since 1967, he has been working in the field of electromagnetic wave propagation and radiation from various antenna configurations. He was involved in research on radiation of antennas situated in absorbing media for geophysical applications. His primary interest is now in radio propagation in confined areas, mines and tunnels. He is also active in research on Electromagnetic Compatibility, including wave penetration into structures and coupling to transmission lines.

He was Vice Chairman of URSI Commission E, Electromagnetic Noise and Interference, from 1999 to 2002 and Chairman from 2002 to 2005.