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Wave propagation in tunnels in a MIMO context—a theoretical and experimental study

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Abstract

MIMO (Multiple-Input Multiple-Output) techniques, based on multiple antennas at both the transmitting and receiving sites, use multipath propagation to transform the overall channel into numerous independent virtual channels. However, when the link is made in a long tunnel, the number of reflecting objects between, or near, the transmitter and the receiver is often quite low. In addition, due to the large transverse dimensions of the tunnel compared to the wavelength, the tunnel acts like a lossy oversized waveguide. In such situations, the concept of spatial diversity must be replaced by the concept of modal diversity. This article uses theoretical and experimental results to show the conditions in which MIMO techniques allow the ergodic capacity of the channel to be increased. ***To cite this article: M. Lienard et al., C. R. Physique 7 (2006).***

Résumé

Propagation des ondes (MIMO) dans un tunnel—une étude théorique et expérimentale. Les techniques multi-antennes en émission et en réception (MIMO) consistent à utiliser la propagation par trajets multiples de manière à transformer le canal global en un certain nombre de canaux virtuels indépendants les uns des autres. Cependant, si la liaison est effectuée dans un long tunnel, le nombre d'objets réfléchissants distribués entre l'émetteur et le récepteur ou au voisinage de ceux-ci, risque souvent d'être faible. De plus, compte tenu des dimensions transversales du tunnel vis-à-vis de la longueur d'onde, le tunnel se comportera comme un guide d'ondes à pertes surdimensionné. Dans ce cas, le concept de diversité spatiale doit être remplacé par celui de diversité modale. L'objet de cette présentation est de montrer, en s'appuyant sur une démarche théorique et expérimentale, les conditions dans lesquelles les techniques MIMO permettront d'augmenter la capacité ergodique du canal. ***Pour citer cet article : M. Lienard et al., C. R. Physique 7 (2006).***

Keywords: MIMO; Propagation channel; Tunnel

Mots-clés : MIMO ; Canal de propagation ; Tunnel

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1. Introduction

For many applications, primarily in the road or rail sectors, the ability to maximize the data rate while avoiding increases in transmitting power and/or the transmission bandwidth is important. For example, in ground-to-train communication, image transmission from a subway car can be an essential part of a system design that aims to increase passenger safety. In addition, a high data transmission rate can facilitate pre-diagnosis from the ground when mechanical or electrical malfunctions occur, which may in turn to prevent a precipitous return of the wagon to the workshop if such drastic action is unnecessary. As normalization is currently carried out, the bandwidth associated with this kind of communication link is 200 kHz for a carrier frequency close to 900 MHz, which corresponds to that used for GSM-R. Since the applications under study require a wider bandwidth, we decided to examine the possible improvements that could be obtained using a MIMO system.

Foschini et al. [1] have already shown that the well-known Shannon formula for determining the maximum capacity C can be extended to determine the capacity of the MIMO channel for a given signal-to-noise ratio (SNR). This capacity is expressed in terms of the Wishart matrix, defined by HH^H, as follows:

$$\mathrm{C} = \log_2\left[\det\left(I + \frac{\rho}{n_\mathrm{T}} HH^H\right)\right] \text{ bit/s/Hz} \tag{1}$$

where ρ is the average SNR (which is assumed identical for each receiving antenna), I is the identity matrix, and H is the channel transfer matrix. To highlight the efficiency of MIMO techniques, the total transmitting power is assumed to remain constant, whatever the number of transmitting antennas, which causes the $1/n_\mathrm{T}$ factor seen in formula (1) to appear.

In a multipath environment, it is often assumed that the channels connecting the transmitting and receiving antennas are uncorrelated and that the field amplitude variations display a Rayleigh distribution. In a building, these assumptions are usually justified, given the numerous obstacles between the transmitter and the receiver. Still, it is important to remember that a correlation between the fading of each channel can degrade the link's performance considerably [2].

In a tunnel, on the other hand, the symmetry of the translation can only generate a low spread of the directions of arrival (DoA) of the rays on the receiving array, meaning a low correlation between the channels can only be due to the different hybrid modes [3] propagating in the tunnel. Among these hybrid modes, the high-order modes are highly attenuated at great distances from the transmitter, which is important to keep in mind. Still, a low spatial correlation of the transmitting and receiving antennas is not enough to guarantee a high capacity with a MIMO system, because the capacity also depends on the rank of the channel transfer matrix H. For example, given a large number of reflectors in the immediate area of the transmitting and receiving arrays, and a single dominant tunnel propagation mode, the H matrix will be degenerated. This phenomenon is often called 'a modal key hole' [4]. In general, the maximum number of degrees of freedom of the channels cannot exceed the number of modes supported by the tunnel. Consequently, the question that must be asked is whether or not the diverse modes present in the particular context of a tunnel produce a distribution of the singular values of H, and a sufficiently low spatial correlation near the antennas, to allow a space–time coding algorithm to increase the channel capacity significantly. It must be clearly emphasized that there is no change in the fundamental concept of diversity introduced by Foschini et al. [1]. The important point to outline is that in a tunnel, the properties of the H matrix depend on the modes and not on the angular spread of the rays.

In the initial stage of experimentation, the channel transfer matrix was measured in certain tunnels of the RATP (Paris metro) network in order to optimize the geometric configuration of the array elements. Preliminary results, given in [5] and [6], have shown that MIMO may improve the channel capacity for short range communication. In this article, additional experimental work is first presented. Then, the proposed approach combining ray theory and modal theory is described. Lastly, the influence of the number and weight of the modes on the correlation between the array elements and on the expected capacity of the link is demonstrated theoretically.

2. Evaluating ergodic capacity from an experimental characterization of the channel

2.1. Tunnel configuration and measurement principles

Given the complicated vertical and horizontal geometric structure of a subway tunnel, such as that studied in Paris, a purely experimental approach was first used to demonstrate the potential usefulness of MIMO techniques in such a

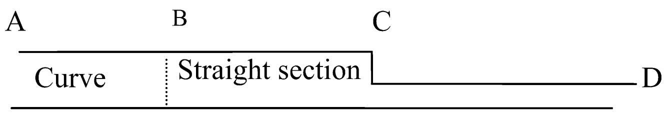

Fig. 1. Schematic configuration of the tunnel.

context. The tunnel in which the measurements took place is shown schematically in Fig. 1. This tunnel can be divided into two segments:

- A two-track tunnel that is 8 m wide and about 300 m long, with a significant curve from point A to point B (200 m) followed by a straight section from point B to point C (about 100 m).
- A one-track tunnel that is 4 m wide and about 300 m long from point C to point D.

The transmitting antennas are located on one of the two platforms, A or D, and are directed towards either the 2-track or the 1-track tunnel.

For these experiments, a system with 4 transmitting antennas and 4 receiving antennas was studied. The channel sounder used in the experiment, is based on the standard correlation principle, with a center frequency of 900 MHz and an analysis bandwidth of 35 MHz, which is much higher than the bandwidth that can be occupied by the final MIMO system. Since the channel is flat in this bandwidth, the elements of the H matrix, deduced from the impulse response, are complex numbers.

In order to benefit fully from the propagation diversity, the elements of each of the mobile and fixed arrays must be omnidirectional in the horizontal plane and have low directivity. However, since most of the energy propagates in the direction of the tunnel axis, an increase in the channel capacity, which could probably be obtained using a MIMO system and antennas with low directivity, can also be obtained with a SISO (Single Input Single Output) system by using high-gain antennas. For this reason, a compromise between directivity and diversity must be found. Other research about the spread of the direction of arrival of the rays (DoA) indicates that using antennas whose main lobe aperture is roughly the same as the spread of the direction of arrival/departure of the rays (i.e., antennas with a gain of 6 to 8 dBi) provides a compromise solution [5].

In order to avoid introducing phase shifts while the H matrix elements were being measured, the train was kept immobile during data acquisitions; with no one on the platform or the track, the channel also remains stationary. This constraint is due to the principle of measurements since the transmitting and receiving elements are successively scanned, contrary to what happens in practical applications.

To avoid the effect of path loss when the range of the link increased, each H matrix is normalized so that the average SNR remains constant.

2.2. *Positioning the array elements*

To minimize the correlations between antenna elements, a variety of tests were conducted for 2 orientations of the array axis, one running parallel to the tunnel axis and the other perpendicular. A third configuration, in which the angle between the array axis and the tunnel axis is approximately 45°, was also tested (in Fig. 2, this third configuration is denoted 'diagonal'). According to the calculation of the channel capacity deduced from formula (1), the array axis running parallel to the tunnel axis produces the worst results [5]. In an attempt to confirm this theoretical result, even approximately, the electromagnetic field radiating from a vertical electric dipole placed in rectangular tunnel measuring 6 m × 8 m was calculated using ray theory. The graphs in Fig. 2 show the variation of the capacity between the transmitter and receiver for the three orientations of the transmission array. For these calculations, a SNR of 10 dB and a 4-element MIMO network was assumed.

Modal theory provides one possible explanation of these results, since the direction of arrival of the rays is nearly the same as the tunnel axis. Consider the simple example of the interference between 2 hybrid modes EH_{mn}. In the transverse plane, this interference causes variations in the amplitude and the phase of the received signal, insuring a very low correlation between the antennas situated in this plane. However, in the longitudinal plane, the field variations from one abscissa to another depend on the difference between the phases of the propagation constants associated with each mode, which leads to very large pseudo-periods depending on the tunnel axis. In the rest of the experiment

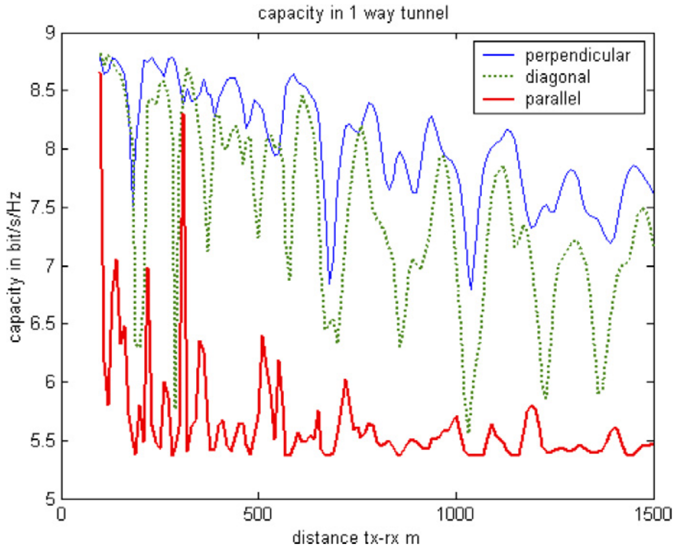

Fig. 2. Theoretical variation of the maximum capacity versus the distance and for various orientations of the fixed linear array.

Table 1
Mean capacity for various communication techniques (SNR = 10 dB)

	SISO	SIMO	MIMO
Rayleigh channel	3 bits/s/Hz	5 bits/s/Hz	11 bits/s/Hz
Tunnel	3 bits/s/Hz	#5 bits/s/Hz	8.5 bits/s/Hz

discussed here, the fixed array elements are placed 1 m apart and the mobile on-board array elements are placed 70 cm apart, or at a distance of 2λ.

2.3. An example with a short range and a uniform tunnel

First, let us consider a uniform tunnel, one whose cross-section does not vary. This could be either the 2-track tunnel between points A and C, or the 1-track tunnel from point C to Point D (Fig. 1). In both cases, the maximum range is 300 m. Table 1 provides the average ergodic capacity, for a SISO system (a single transmitting antenna and a single receiving antenna), a SIMO system (with a Maximum Ratio Combining technique) or a MIMO system with 4 transmitting and 4 receiving antennas.

Two configurations were considered: a Rayleigh channel (iid channels) or a tunnel configuration. For such short distances, the results obtained for both tunnel segments (2-track and 1-track) were practically identical. According to the information reported in Table 1, MIMO is a potentially interesting solution in tunnels, at least for ranges of several hundred meters.

2.4. An example with a narrowing tunnel

Let us now consider a transmission from point A in Fig. 1. The curve in Fig. 3 shows the variation of the received power, expressed in dB above an arbitrary level. Along the first 200 m—the large curve occurring between points A and B (Fig. 1)—the attenuation per unit length is quite high, reaching 25 dB/100 m. Just after the bend, the signal amplitude increases due to the fact that the train is moving on a track that is quite close to the internal curvature of the bend; this increase can be justified theoretically using a ray launching model applied to a curved tunnel. Attenuation drops again once the array reaches the 1-track segment of the tunnel, for a mean attenuation hovering around 10 dB/100 m.

In addition to the increased path loss, the high-order hybrid modes are rapidly attenuated in the narrow tunnel segment, which causes a reduction in the channel capacity, as is shown in Fig. 4. In fact, as soon as the mobile

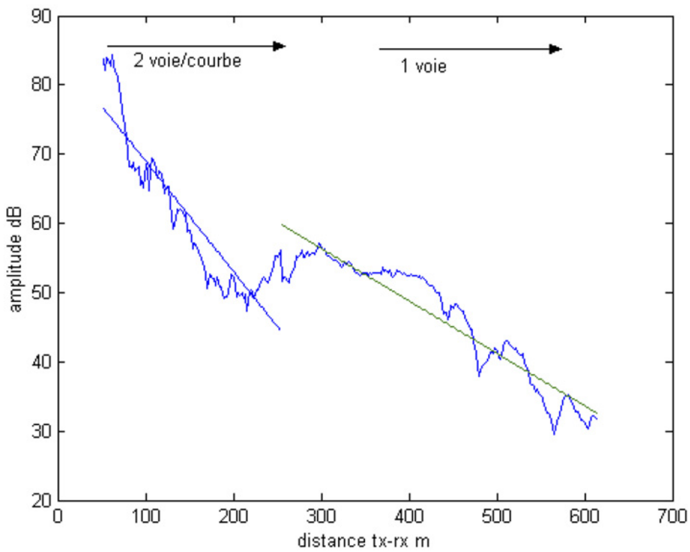

Fig. 3. Variation of the received power, the mobile moving from a 2-track tunnel to a 1-track tunnel.

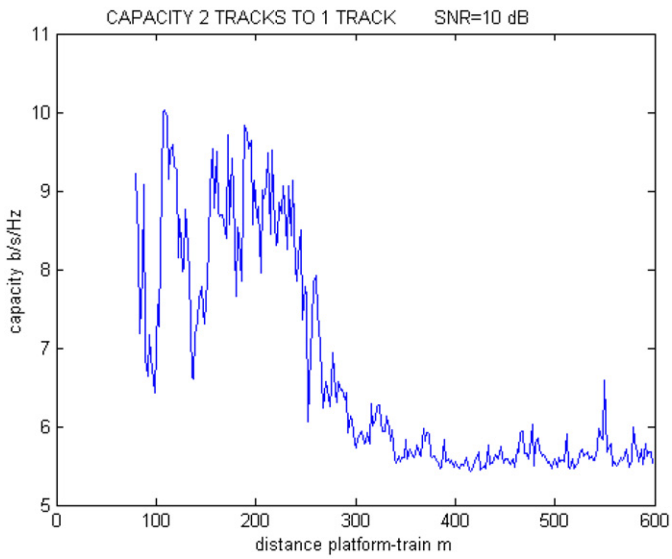

Fig. 4. Variation of the ergodic capacity. Transmission from the 2-track tunnel, reception first in the 2-track tunnel (0–300 m), and then in the 1-track tunnel (300–600 m).

array reaches the 1-track tunnel, the capacity drops to 5.5 bits/s/Hz—the value for a SIMO transmission—and stays practically constant.

At this point, studying how the correlation coefficients between the antennas evolve provides interesting information. Initially limiting the analysis to a qualitative interpretation of the behavior of these coefficients makes it possible to observe the evolution of the average values.

For a given abscissa, an average correlation coefficient—obtained either between the stationary antennas on the platform ($\bar{\rho}_{\text{platform}}$) or between the mobile antennas on the train ($\bar{\rho}_{\text{train}}$)—is introduced. The former is calculated using $\bar{\rho}_{\text{platform}} = E(\rho_{p,q})$, and the latter using $\bar{\rho}_{\text{train}} = E(\rho^{p,q})$, where $p \neq q$ and $\rho_{p,q}$ and $\rho^{p,q}$ are, respectively, the correlation coefficient between the p and q antennas, either situated on the platform or on the train.

The curve in Fig. 5 represents the variation of $\bar{\rho}_{\text{train}}$ over the link range. Its average value is between 0.7 and 0.8 in the 2-track tunnel, but moves rapidly towards 1 once the tunnel narrows, which, of course, could explain the decreased

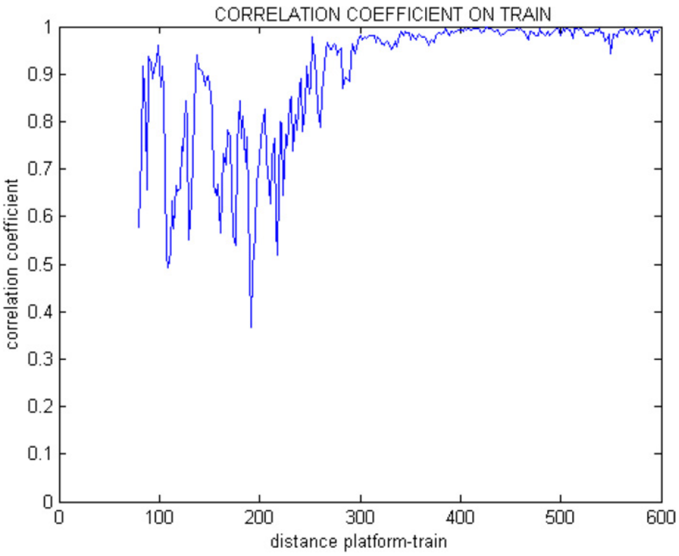

Fig. 5. Mean correlation coefficient $\bar{\rho}_{\text{train}}$ between the mobile array elements versus the distance between the transmitter and the receiver.

channel capacity [6]. However, in general, it is not possible to attribute the reduced capacity over large distances to this variation alone. In fact, two explanations are possible. The first is that the diversity order, related to the number of modes existing in the transverse plane of the tunnel in the receiving zone, becomes smaller than the number of array elements (4 in this experiment). This is the so-called 'key hole' effect, which occurs when only the lowest-order mode is dominant at large distances. The second possibility is that, though the number of modes remains greater than the number of array elements, the number is not sufficient to ensure a low correlation between the array elements. In this case, simply increasing the inter-element spacing will recover the lost capacity. In addition, since the 'key hole' effect does not really exist in this case, modifying the environment near the antenna in order to create multiple reflections would improve the diversity.

To resolve these issues, an analytic method that would provide the weight of each mode over the distance between the transmitter and the receiver would be useful. The next section describes an approach that combines modal method and ray theory technique, and several examples are given.

3. Theoretical modeling

Analytical expressions of the modes that propagate in an oversized lossy waveguide have, until now, only been possible for simple geometric configurations: rectilinear waveguide configurations of rectangular or circular cross-sections. In this discussion, the tunnel cross-section is assumed to be rectangular. Even though this ideal configuration is never achieved in real tunnels, the results obtained will increase understanding of the phenomena under study.

Applying boundary conditions to the walls of the tunnel allows the basis functions $\bar{e}_{m,n}$ associated with each mode m, n to be determined, which provides both the field distribution of the given mode in the transverse plane and the propagation constant [7]. However, determining the weight of each mode excited by the transmitting antenna also requires that boundary conditions be imposed in the plane in which the excitation takes place. Because this is quite complicated, a much simpler approach based on ray theory was adopted.

It must be stressed that, given the finite conductivity of the tunnel walls, the modes are not precisely orthogonal. Nevertheless, numerical applications indicate that, when considering the first 60 modes with orders $m \leqslant 11$ and $n \leqslant 7$, the modes can be considered as practically orthogonal [8]. In this case, if the electric field $E(x, y, z)$ in a plane of the cross-section—with an abscissa z parallel to the tunnel axis—is calculated numerically using ray theory, the weight $\alpha_{m,n}(z)$ of any mode m, n for this abscissa can be obtained by projecting the electric field on the basis $\bar{e}_{m,n}$.

$$\alpha_{m,n}(z) = \int_{-a/2}^{a/2} \int_{-b/2}^{b/2} E(x, y, z) \cdot \bar{e}_{m,n}(x, y) \, \mathrm{d}x \, \mathrm{d}y \tag{2}$$

where a and b, respectively, denote the width and the height of the tunnel, parallel to the x and y axes.

3.1. Mode weight over distance

In the following numerical applications, an 8 m-wide, 4.5 m-high tunnel, corresponding to the 2-track segment shown in Fig. 1, is assumed. The equivalent conductivity and the relative permittivity of the walls are assumed to be 10^{-2} S/m and 5, respectively. As in the actual experiments, the transmission frequency is 900 MHz. The radiating element is a vertical dipole situated 50 cm from the ceiling, at 1/4 of the tunnel width. The six modes with the highest energies at a distance of 300 m and 600 m are provided in Table 2.

Due the position of the transmitting dipole, the most energetic mode is the mode 2,1. The other columns in Table 2 show the relative weight of the other modes, normalized for each distance in terms of the highest mode weight.

At 300 m, numerous other modes are still contributing significantly to the total field, since the 6th mode presents only a relative attenuation of 5 dB in relation to the strongest mode. On the other hand, at 600 m, only a few higher-order modes remain.

The notion of 'active modes'—those modes that contribute most significantly to the signal power in the receiving plane at a given distance from the transmitter—is quite important to understanding the MIMO results. The number of active modes, N_a ($x\%$), is defined as the number of modes whose powers, at a given abscissa z, are equal to at least $x\%$ of the power of the strongest mode [8]. Since the weight of each mode depends on the position of the transmitting dipole, in order to obtain statistically exploitable results, 12 successive positions of the dipole in the transverse plane of the tunnel were tested to produce an average value for the number of active modes over the distance between the transmitter and the receiver. Consequently, the average value of N_a is no longer a whole number.

Fig. 6 shows the variation of N_a for a tunnel that is 5 m wide and 4.5 m high, corresponding to the 1-track tunnel (segment C–D) in Fig. 1. For a 4×4 MIMO system, at least 4 active modes are needed to obtain optimal results. If the weight of the least powerful mode has at least 20% of the power of the dominant mode, the maximum distance between the transmitter and the receiver must not exceed 200 m, as the curve in Fig. 6 illustrates. For a narrower tunnel, the

Table 2
Relative weights of the modes at 300 and 600 m

Modes	2,1	1,1	3,1	5,1	6,1	2,2
300 m	0 dB	−2 dB	−3 dB	−4 dB	−4 dB	−5 dB
600 m	0 dB	−2 dB	−4 dB	−9 dB	−9 dB	−15 dB

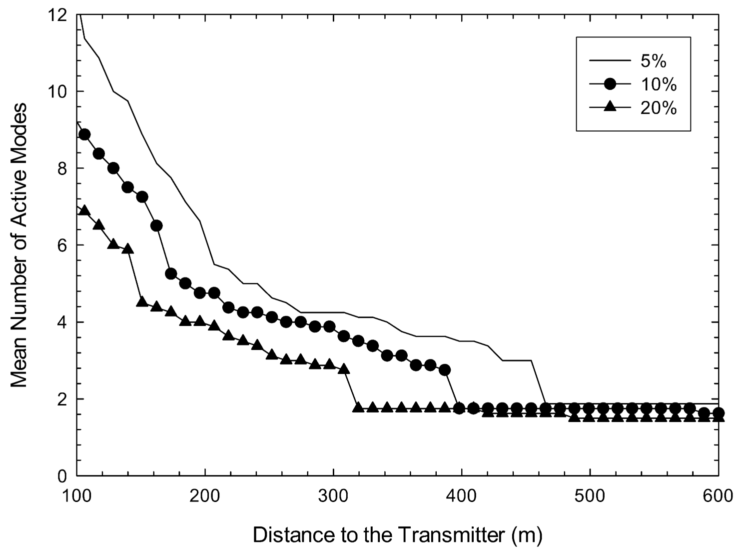

Fig. 6. Average number of active modes whose powers are equal to at least $x\%$ of the most powerful mode.

maximum distance would have to be 400 m. Over 400 m, the transfer matrix is no longer full rank, and its capacity will begin to decrease, regardless of the number of reflections caused by obstacles located near the receiver. Fig. 6 also shows that, beyond 300 m into the 1-track tunnel, the number of active modes is between 1 and 2, depending on the position of the receiving array. This confirms the results depicted in Fig. 4, which demonstrate the rapid decrease in the channel capacity at large distances from the transmitter.

3.2. Correlation

In this section, the correlation between the receiving array elements and the correlation of the transmitting array elements are considered in succession.

3.2.1. Correlation distance at the receiver

If the receiving array elements are correlated, the ergodic capacity of the channel will decrease. Previous studies [2] have shown that the amplitude of the correlation coefficient must remain under 0.7 to avoid degrading the performance of the MIMO system as compared to the ideal case, in which there is no correlation between the elements. The approach described in the beginning of this section was used to determine the minimum required distance between the elements that will satisfy these conditions in a 1-track and 2-track tunnel. Table 3 summarizes these results.

As the receiver moves further away from the transmitter, the correlation distance increases. This is obviously connected to the number of active modes in the receiving zone, since some of these modes provoke slow variations of the signal in the transverse plane, which lead to large correlation distances. The same reasoning can be used to explain the differences in the results obtained for the 1- and 2-track tunnels. In the narrow 1-track tunnel, the correlation distance increases rapidly, around 1 m for a range exceeding 400 m; such a distance would be prohibitive for practical applications involving 4 receiving elements. This result also helps to explain, at least qualitatively, the form of the curve in Fig. 5, which represents the variation of the average correlation coefficient over distance.

3.2.2. Correlation between the transmitting elements

For the MIMO system to be efficient, the different sets of modes generated by each transmitting element must also be not highly correlated. This means that the weights of the modes m, n generated by an element j_1 must not be identical or proportional to those generated by another element j_2. The average correlation coefficient $r_{j_1,j_2}^{\mathrm{Modes}}$ for the modes generated by any two elements j_1 and j_2 can be introduced [8], using the ratio below:

$$r_{j_1,j_2}^{\mathrm{Modes}}(z) = \left| \frac{\mathrm{E}_{m,n}[\alpha_{m,n}(z, j_1)\alpha_{m,n}^*(z, j_2)]}{\sqrt{\mathrm{E}_{m,n}[\alpha_{m,n}(z, j_1)\alpha_{m,n}^*(z, j_1)]}\sqrt{\mathrm{E}_{m,n}[\alpha_{m,n}(z, j_2)\alpha_{m,n}^*(z, j_2)]}} \right| \tag{3}$$

where $\mathrm{E}_{m,n}[\,]$ denotes the average value for the set of modes m, n whose weights are $\alpha_{m,n}(z)$. Table 4 presents the values of $r_{j_1,j_2}^{\mathrm{Modes}}$ for the 1-track tunnel, both for three transmitter–receiver distances and for two intervals d between the array elements: 2λ (i.e., 67 cm) and 4λ (i.e., 1.34 m).

As the distance increases, the higher-order modes become more and more attenuated, which implies that the transmitting elements must be placed further and further apart in order to maintain a low correlation between them.

Table 3
Distance needed between the elements to obtain a correlation coefficient of 0.7

Distance	200 m	400 m	600 m
1-track tunnel	0.7 m	0.9 m	1.1 m
2-track tunnel	0.4 m	0.6 m	0.8 m

Table 4
Average correlation between the two transmitting elements separated by a distance d

Distance	200 m	400 m	600 m
Mean correlation for $d = 67$ cm	0.7	0.8	0.9
Mean correlation for $d = 1.34$ m	0.2	0.5	0.7

4. Conclusion

The experimental studies described in the first part of this article clearly highlight the advantages of using MIMO systems in tunnels: the spatial diversity that normally results from the multiple reflections and diffractions that occur in buildings are replaced here by modal diversity. However, for narrower tunnels, system performance degenerates when the range of the link exceeds several hundred meters. To explain this phenomenon, at least qualitatively, an approach based on modal theory was developed. This approach both helps to determine the variation of the number of active modes over the transmitter–receiver distance, and demonstrates its consequences on the correlation between the transmitting and receiving elements.

In conclusion, one can also outline that the bit error rate (BER) is of course the final and the most useful metric in digital communication, but the gain in terms of BER obtained with MIMO techniques is strongly dependent on the signal processing which has been chosen.

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