Numerical and Experimental Anaysis of Massive MIMO Channel Characteristics in a Rectangular Highway Tunnel at 5.9 GHz

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***Abstract*— To increase channel capacity, MIMO techniques are often used, and now, with the development of the 5G technique, massive transmitting arrays become to be widely implemented. For vehicular communication, the dedicated frequency band is around 5.9 GHz, and, to our knowledge, there are very few contributions to massive MIMO in tunnels and especially in road tunnels. In this paper, the case of a highway rectangular tunnel is treated, being its width much larger than its height. The Tx array is a square array of 64 elements and the correlation between array elements, deduced from simulation and measurements, is first presented. Due to the shape of the tunnel cross-section, it appears that the correlation between vertically aligned elements is much greater than that occurring between elements situated on a horizontal line, and, as an example, the correlation between elements 7.5 cm apart, can be equal to 0.9 and 0.7, respectively. Consequently, the way of partitioning the massive array is studied to find the best compromise between channel capacity and complexity of the transmission scheme, taking the number of radio frequency chains into account. Illustrations are given for transmission techniques based either on beamforming or singular values decomposition of the transfer matrix. Lastly, for a MIMO transmission, the precoding matrices must be periodically updated when the mobile moves along the tunnel, due to changes in the transfer matrix. The longitudinal correlation distance and the channel stationarity are thus calculated for correlation values equal to 0.7 or 0.9.**

Keywords- tunnel; propagation; massive MIMO; correlation; vehicular communication; beamforming; singular value decomposition; stationary distance.

I. Introduction

Wireless communications in confined areas, as in road and railway tunnels have already been widely studied and a survey examining current advancements for modeling the propagation of waves in tunnels is presented in [1]. The frequency band under consideration often extends from about 1 GHz up to mm waves but, for road tunnels, special emphasis is placed on the 5.9 GHz band which is the allocated band in Europe dedicated to intelligent transport systems (ITS). Ray tracing simulation tools are often used, as in [2], to predict channel characteristics such as path loss, delay spread, direction of departure/arrival of the waves, and polarization ellipse at the receiver. For curved tunnels, a ray-tube tracing method is presented in [3], ray tubes taking multiple reflections and diffractions into account, diffractions occurring when a ray tube illuminates the edges of the tunnel. The influence of traffic and the shape of the tunnel cross-section on path loss and fading is studied in [4], wave propagation being modeled with a shooting and bouncing ray (SBR) image method, while vehicles are simulated by metallic rectangular boxes. Theoretical and experimental results show that path loss in an arched tunnel is smaller than in a rectangular tunnel and that traffic produces faster fading than in the case of an empty tunnel.

Previous works have also shown that multiple-input multiple-output (MIMO) techniques such as space-time block code applied to tunnel environments present better performances than a single-input single-output (SISO) transmission, despite the small angular spread of the rays in this environment, performances of various transmission schemes being presented in [5]. This can be explained from a waveguide approach, and more precisely from the weight of the various propagation modes, the tunnel behaving as an oversized waveguide, [6], [7]. To evaluate the impact of tunnel curvature on MIMO channel capacity, an approach combining modal analysis and a ray tracing scheme was used, [8]. It is shown that the decrease of channel capacity in the presence of curvatures in the horizontal plane can be partly offset by increasing the MIMO system size. Furthermore, if the cross-section of the tunnel has an arched shape, Wang et al., [9] show that the delay spread and Doppler spread increase with the tunnel radius increment, with frequencies of 3.5 GHz and 28 GHz being considered. Measurements of the observable capacity of a 2x2 MIMO system at 5.8 GHz are described in [10]. It appears that the polarization diversity technique improves the capacity but mainly in the case of a rectangular tunnel, the benefits of such a technique become poor in an arched tunnel.

More recently, the massive MIMO technique was introduced and will be widely used for 5G communication networks to increase capacity and throughput. Many papers deal with the implementation and performance of such a technique in the urban or suburban environments but only very few of them discuss the case of tunnel environment. Li et al. describe in [11] a 3D Geometry-Based channel model for massive MIMO vehicular-to-vehicular communication in a curved tunnel, while in [12] channel parameters as delay spread, angular spread, and condition number of the *H* channel transfer matrix are deduced from measurements carried out at 3.5 GHz in a subway tunnel with a transmitting rectangular array (Tx) of 32 elements, and a cylindrical receiving array (Rx) of 64 elements.

The objective of this paper is to present and analyze the channel properties in a highway tunnel, the expected capacity being strongly related to the correlation between elements of the massive Tx array. Indeed, the width of such a tunnel is usually much larger than its height; this may introduce dissymmetry in the characteristics of the Tx array and have a strong impact on the need or not to partition the massive array into sub-arrays. In this paper, both theoretical and experimental results of massive MIMO characteristics in a straight rectangular tunnel are presented. The carrier frequency is 5.9 GHz, the square Tx array has 64 elements while Rx is a uniform linear array (ULA) of 8 elements. The main contributions of this paper are: i) Determine the correlation between elements of Tx by distinguishing the correlation between elements situated on the same horizontal line from that between elements vertically aligned, ii) Study the influence of road traffic on the previous characteristics, iii) Point out the influence of the way of partitioning the massive array into sub-arrays to increase capacity, taking the complexity of the implementation of the transmission scheme into account and lastly, iv) Study the longitudinal correlation and the channel stationarity along the tunnel.

The paper is organized as follows: The geometrical configuration of the tunnel with or without traffic, the main features of the channel sounder used for measurements, and those of the propagation model are described in Section II. Section III refers to the variation of the mean received power versus the distance Tx-Rx depending on the road traffic, while in Section IV the correlation between elements of the Tx massive array is studied. Section V presents examples of the partition of the massive array to improve capacity for a Single user-MIMO (Su-MIMO) and lastly, in Section VI, longitudinal correlation and channel stationarity are treated.

II. Experimental Configuration and Main Features of the Simulation Tool

A. *Geometrical Characteristics*

Measurements have been carried out in a one-way 2-lane tunnel situated near Anvers (Belgium). This tunnel, about 1 km long is straight and its cross section is nearly rectangular. Its width and its height are 10 m and 6 m, respectively. The traffic inside the tunnel of course depends on the hour of the day. At night it is nearly empty; in the middle of the day, trucks proceed in a single file on the right lane (Fig. 1a) while during rush hours, traffic jams occur. Results deduced from measurements presented in this paper refer to the second configuration (Fig. 1a) while the theoretical modeling also includes the case of an empty tunnel for the sake of comparison.

(a) (b)

Fig. 1. a) Photo of the tunnel, b) Massive array situated near the exit of the tunnel

The Tx massive array is situated at a height of 3 m near the tunnel exit (Fig. 1b). It is a uniform 8x8 square patch array with an element spacing dtx = 2.5 cm, i.e. about half a wavelength (λ) at 5.9 GHz. Each patch is vertically polarized. The mobile Rx array is located on the roof of a small van moving on the left lane and situated 2.5 m above ground. It is a horizontal uniform linear array (ULA) formed by a set of 8 wideband vertical biconical antennas, and the element spacing between two successive elements drx = 7.5 cm, about $3\lambda/2$.

B. *Channel Sounder*

The propagation channels are measured with the MaMIMOSA radio channel sounder, [13]. Data are modulated using orthogonal frequency-division multiplexing (OFDM) with 8192 subcarriers using a 12.21 kHz subcarrier spacing. The streaming mode of MaMIMOSA is selected for the vehicular context. It corresponds to the frame structure emitted every 510 ms and starts with a 51.2 µs preamble, followed by 4096 OFDM symbols. This yields a duration of around 500 ms. Each Tx antenna transmits a pilot every eight sub-carriers, with one sub-carrier per antenna shift to interleave the Tx antenna signals. Note that one OFDM symbol out of 32 was recorded for this campaign. The channel sounder is configured to measure a 64 x 16 massive radio channel measurements at 5.9 GHz with a transmission bandwidth of 80 MHz. If the mobile supporting the Rx array moves at a speed of 72 km/h, the displacement of the mobile during 1 ms would be 2 cm and one can thus expect that the channel would remain stationary. More details on the channel sounder can be found in [13].

C. *Propagation Model*

Simulations have been done with Opal, a ray-tracing propagation simulator based on Graphics Processing Units (GPU). It uses the SBR method, electromagnetic waves being simulated by rays launched from the transmitter. This tool has already been applied for the simulation of the propagation of 1.3 GHz waves in tunnels, [14]. The received field is obtained by summing the contributions of the rays hitting a reception sphere around the receiving point. The conductivity and relative permittivity of the tunnel walls are chosen equal to 10^{-2} S/m and 5, respectively. In the presence of a file of trucks (Fig. 1a), each truck is roughly modeled by a metallic parallelepiped, 12 m long, 2 m wide, and 4 m high. The trucks are supposed to be uniformly distributed in the tunnel, the distance between them being 40 m.

III. Experimental Mean Received Power along the Tunnel

Curves in Fig. 2 represent the variation of the average Rx power along the tunnel, referred to an arbitrary value, on the one hand, calculated in an empty tunnel or the presence of a line of trucks, and, on the other hand, deduced from measurements.

The averaging was made over the 64 Tx elements, the 8 Rx elements, and 32 frequencies within the 80 MHz bandwidth. If we compare the theoretical median value of the power received between 600 m and 1000 m, in the presence or not of trucks, it appears that the additional attenuation due to the presence of trucks is 8 dB.

In the presence of trucks, we see from the shape of these curves, that a two-slope model can be used for path loss variation, the total interval being divided into 2 zones: 50 - 600 m and 600 – 900 m. Table I gives the slope of the regression lines in these 2 zones deduced either from simulation or from measurements. We see a rather good agreement between these values.

IV. Correlation between Tx Array Elements

Since the tunnel has a rectangular shape but with a width much larger than its height, it can be interesting to divide the square Tx array into sub-arrays, corresponding to any column or any horizontal line. The average correlation at Tx has first been calculated between elements belonging to the same line and then between elements vertically aligned. Tunnels either empty or in the presence of trucks will be successively considered.

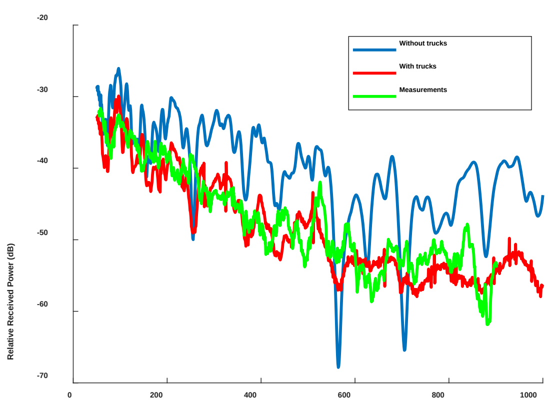

Fig. 2. Mean received power referred to an arbitrary value: i) simulation of an empty tunnel (without trucks) or in presence of a file of trucks, ii) Measurements in presence of trucks.

TABLE I. Presence of a truck convoy: slopes of the regression line deduced either from experiments or from simulation.

Distance Tx - Rx	50-600 m	600-900 m
Simulation (dB/100m)	3.4	1.2
Measurement (dB/100m)	3.3	1.7

A. *Empty Tunnel*

In Fig.3, the predicted value of the correlation between Tx elements, deduced from the *H* transfer matrix, is given for a spacing between them of 2.5 cm, 5 cm, and 7.5 cm, and a distance between Tx and Rx varying from 50 to 1000 m. Let us recall that the spacing between two successive elements is 2.5 cm.

These curves show that the correlation between elements increases with the distance Tx-Rx. Indeed, near Tx, the contribution of waves reflecting on the tunnel walls with a large angle of incidence is important, while at a large distance, only rays propagating with a grazing angle of incidence play a role in the total field, decreasing spatial diversity. Curves in Fig. 4 give the correlation for the same geometrical configuration but for array elements vertically aligned.

By comparing curves in Figs. 3 and 4, it appears that the correlation between elements on a vertical line is very high since, even for a spacing of 7.5 cm, it often remains larger than 0.9.

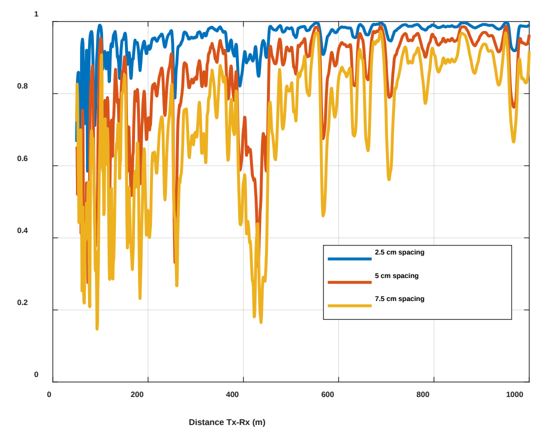

Fig. 3. Empty tunnel. Predicted correlation between Tx elements belonging to the same horizontal line, the spacing between them being 2.5 cm, 5 cm or 7.5 cm.

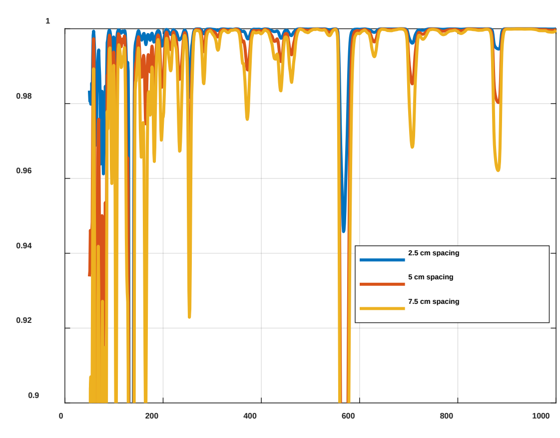

Fig. 4. Same as in Fig. 3, but for array elements vertically aligned.

TABLE II. MEDIAN VALUE OF THE CORRELATION COEFFICIENT BETWEEN TX ARRAY ELEMENTS FOR VARIOUS SPACING, DIRECTION OF THE SUB-ARRAYS, AND DISTANCE TX-RX

Spacing between array elements	Direction of the sub-arrays	Position of Rx inside the tunnel	
		200-400 m	400-600 m
2.5 cm	H	0.97	0.97
	V	0.99	0.99
5 cm	H	0.81	0.90
	V	0.99	0.99
7.5 cm	H	0.66	0.80
	V	0.99	0.99

To summarize these results, Table II gives the median value of the correlation coefficient between Tx array elements if the spacing between them is either 2.5, 5, or 7.5 cm and depending on the direction of the sub-arrays, horizontal (H) or vertical (V). Since correlation increases with distance, 2 zones have been envisaged: firstly, for a distance Tx-Rx varying from 200 to 400 m and, secondly, between 400 to 600 m. Table II shows that the median value of the correlation between horizontally aligned elements varies from 0.66 to 0.80 along the tunnel, while it remains equal to 0.99 for vertical sub-arrays.

B. Presence of a File of Trucks

In Table III, an element spacing of 7.5 cm is assumed and results of the median value of the correlation in the presence of trucks deduced either from simulation or experiments are given. A rather good agreement between prediction and measurements is obtained. Furthermore, we see from Table III that the presence of a line of trucks does not change the previous conclusions on the influence of the direction of the sub-arrays.

Concerning correlation at Rx, let us first recall that at Rx, the array is a horizontal ULA, the spacing between elements being 7.5 cm. To lighten the presentation, we only mention that, in the presence of trucks, the median value of the correlation deduced from measurement or modeling is on the order of 0.73, for a distance Tx-Rx between 200 and 400 m, and of 0.82 between 400 and 600 m. These values are similar to those calculated at Tx between horizontally aligned elements. Furthermore, as at Tx, the presence of trucks does not significantly change this correlation.

V. SINGLE USER-MIMO: PARTITION OF THE MASSIVE ARRAY

Since the correlation between vertically or horizontally aligned elements is quite different, one can wonder if the partition of the massive array into sub-arrays could be an interesting solution for increasing the capacity, taking the complexity of the implementation of the transmission scheme into account.

In the following, the calculation of the ergodic capacity is based either on beamforming (BFTx) or on singular value decomposition of the H transfer matrix (SVD). Since the tunnel is straight, BFTx is obtained by considering the whole square array of 64 elements, fed in phase, such that its main lobe is directed toward the tunnel axis. The array gain of such a network is 64 or 18 dB. In this case, only one radio-frequency (RF) chain is needed. At Rx, the received signals

TABLE III. COMPARISON OF THE MEDIAN VALUE OF THE TX CORRELATION, FOR AN ELEMENT SPACING OF 7.5 CM, DEDUCED EITHER FROM MODELING OR FROM MEASUREMENTS

Configuration	Direction of the sub-arrays	Position of Rx inside the tunnel	
		200-400 m	400-600 m
Convoy of trucks Theory	H	0.70	0.82
	V	0.96	0.97
Convoy of trucks Measurements	H	0.73	0.87
	V	0.90	0.94

are combined to maximize the signal-to-noise ratio (SNR). SVD allows sending simultaneously different information on several equivalent orthogonal channels, the increase in capacity depending on the channel multipath richness. This capacity can be much higher than that obtained with BFTx but at the cost of increased complexity.

To point out, on an example, the interest or not to partition the Tx array, two configurations will be successively treated. Firstly, it is assumed that each array element is connected to an RF chain meaning that 64 RF chains are needed and, secondly, that the whole array is partitioned into 8 vertical sub-arrays, each sub-array being fed by one RF chain, leading to a total of 8 RF chains.

At Rx, the number of ULA elements is limited to 4 instead of 8 as previously, to fit a more practical configuration. Spacing between elements being 7.5 cm leads to a ULA 22.5 cm long. The two previous SVD configurations are thus noted (4x64), and (4x8), respectively. Only the case of an empty tunnel is presented, with similar results both theoretically and experimentally, being obtained in the presence of trucks. Curves in Fig. 5 show the variation of capacity versus the distance Tx-Rx in the 3 configurations, namely: BFTx, (4x64) SVD, and (4x8) SVD. To overcome the effect of the longitudinal attenuation, a constant SNR of 20 dB is assumed.

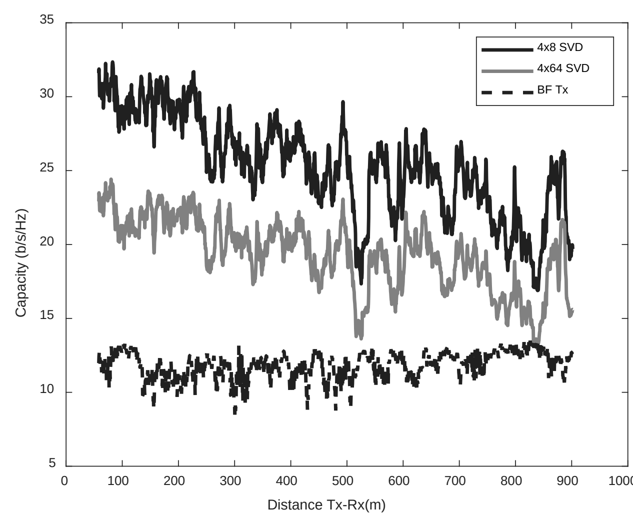

Fig. 5. Ergodic capacity for a constant SNR of 20 dB and calculated for 3 transmission schemes..

For BFTx, capacity varies between 11.6 and 12.5 b/s/Hz, thus quite comparable to 14 b/s/Hz which would be obtained in free space. It also appears that SVD using 64 RF chains gives worst results than that with 8 RF chains.

Indeed, the median correlation between elements vertically aligned is near 1 (Table II) and one cannot take full advantage of using the 64 elements of the square Tx array. On the contrary, if this array is partitioned into 8 vertical sub-arrays, the elements of each sub-array being fed in phase (one RF chain), an additional array gain of 8, or 9 dB, is obtained. For SVD, whatever the configuration, capacity decreases with distance. This is due to an increase in the correlation between elements as shown in Fig. 3. At a large distance when only one mode of the SVD plays a leading part, SVD becomes equivalent to BFTx.

VI. Axial Correlation and Distance of Stationarity.

Firstly, let us consider any element of the Rx array of the user equipment (UE). When Rx moves along the tunnel, a correlation ρ can be calculated between the signal received by this element at an abscissa z and that at $z+dz$, the principle of calculation of the correlation along the longitudinal axis being the same as for the correlation in the transverse plane. One can thus deduce a correlation distance D_c defined as the displacement dz to reach a given value of ρ, equal for example to 0.7 or 0.9, and noted $D_c(0.7)$ or $D_c(0.9)$, respectively. If we want to take the full Rx array into account to quantify the change in the spatial structure of the MIMO channel between z and $z+dz$, the concept of stationarity region has been introduced by Herdin et al., [15].

It is defined as the region in which the channel statistics remain approximately constant. In this case, a transmission scheme can take advantage of the channel statistics by estimating it and adapting the transmission accordingly. As detailed in [15], a simplified metric for measuring the stationarity of the MIMO channel is the correlation matrix distance (CMD). Let us mention that this concept of CMD was also applied to study the stationarity of the scatterer contributions in wideband car-to-car channels, [16]. The coefficient characterizing the distance between the two correlation matrices *R(z)* and *R(z+dz)* calculated from the *H* transfer matrix, is defined as :

$$C\_CMD = \frac{\langle \mathrm{vec}\{R(z)\}, \mathrm{vec}\{R(z+dz)\} \rangle}{\|\mathrm{vec}\{R(z)\}\|_f \|\mathrm{vec}\{R(z+dz)\}\|_f} \quad (1)$$

where f is the Froebenius norm.

With this definition, *C_CMD* varies between 0 and 1, 1 corresponding to the case of a maximum correlation. As previously, a stationarity distance D_s is defined by the distance dz to reach a given value of *C_CMD*, 0.7 or 0.9 for example and noted $D_s(0.7)$ or $D_s(0.9)$. The cumulative distribution function (cdf) of D_c and D_s calculated over the entire tunnel is given in Fig. 6. For a correlation coefficient $\rho = 0.7$, the median values of the correlation distance and of the stationary distance are: $D_c(0.7) = 2$ m and $D_s(0.7) = 3.5$ m. To reach a more important correlation of 0.9, these distances are reduced to $D_c(0.9) = 1$ m and $D_s(0.9) = 1.5$ m.

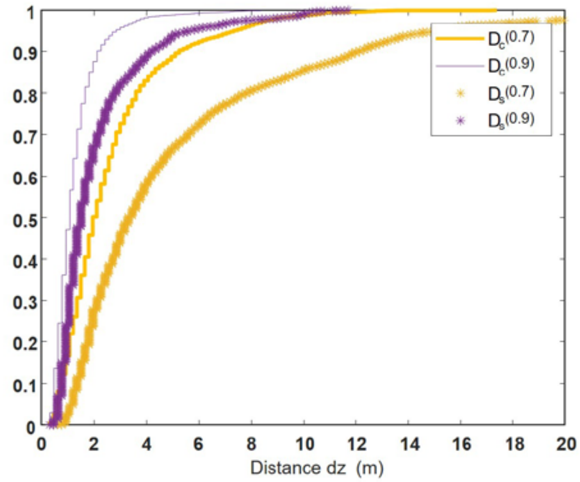

Fig. 6. Cdf of the correlation distance and of the stationarity distance for 2 correlation values, 0.7 and 0.9.

In any case, D_s is larger than D_c. Indeed, D_s is based on the spatial structure of the channel and can be interpreted, for example, as the region in which the number of possible layers supported by the channel remains constant. However, even if the mobile moves in this region, it could be necessary to update periodically the precoding matrices, this periodicity being certainly related to the correlation distance. Nevertheless, further work is needed to detail this point.

VII. Conclusion.

It was shown that in a highway rectangular tunnel whose width is much larger than its height, the correlation between vertically aligned elements of a massive array remains always high, on the order or greater than 0.9, even for an element spacing of 3λ/2, contrary to what happens for elements situated on the same horizontal line.

The presence of a file of trucks in one lane of the tunnel does not change this conclusion. This characteristic of the massive array has a strong impact on the performance of a MIMO link. To illustrate this point, communication between a square Tx array of 64 elements and a mobile Rx array of 4 elements has been considered. We have shown that an SVD based on the whole array with 64 RF chains gives worst results than those obtained by partitioning the array into 8 vertical sub-arrays needing only 8 RF chains. Indeed, due to the high correlation between Tx elements vertically aligned, it is not possible to take full advantage of the massive array. Of course, this conclusion applies to a tunnel whose width is nearly twice greater than its height, as in our examples.

Practically, for any geometrical configuration of the tunnel, a simulation is needed to find the optimum transmission scheme, taking also the needed number of RF chains into account. This transmission scheme is often based on precoding matrices which must be periodically updated, depending on the changes of the channel matrices when the mobile moves in the tunnel. Therefore, longitudinal correlation distance and channel stationarity have been introduced. It was shown that, for a correlation coefficient of 0.7, the median values of these two distances are equal to 2 m and 3.5 m, respectively. In the next step, it will be interesting to study the degradation of the MIMO performances if the precoding matrix is not correctly updated, and thus to quantify, for a given speed of the vehicle, the link between the periodicity of updating the precoding and the correlation time or the stationarity time.

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