Vehicle Antenna Footprint Optimization for Efficient MIMO V2X Communications

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***Abstract*—Improving efficiency of upcoming vehicle communication networks is one of the main goals in near-future wireless systems. In addition, multi-antenna configurations are known as the main technique to improve the system performance with current constrains, such as the limited spectrum. They are an unlimited and non-lasting resource, but they imply a more complex implementation. In this context, the design of this type of geometries must be optimized considering the entire scenario and the final propagation conditions. Due to the relation between the propagation environment and the correlation between elements, the antenna inter-element spacing has to be adjusted to reach the maximum performance at the minimum possible footprint size. This work investigates the impact of correlation on channel capacity and also proposes a proper separation of the elements when they are mounted on a vehicle for two different urban scenarios: communication between two vehicles (V2V) and car connected to the cellular network (V2I).**

Keywords–MIMO systems, Urban propagation, Vehicles.

I. INTRODUCTION

Vehicle communications have become a recurring topic over the last years due to the increasing interest on creating an efficient and reliable network of connected cars, Vehicle to Everything (V2X). The goal ranges from providing driving aids to the user to self-driving cars. Then, energy efficiency and low latency are two main factors to consider.

In the following work, the focus will be put on the car antenna configuration in order to improve the whole performance of the system by means of numerical simulations for two main situations: Vehicle to Vehicle (V2V), in which two cars try to communicate, and Vehicle to Infrastructure (V2I), where a Base Station (BS) is introduced. For both cases, Multiple Input Multiple Output (MIMO) geometries will be compared with respect to the Single Input Single Output (SISO) case, especially focusing on the impact of the inter-element spacing on the system performance [1]. Conventional MIMO systems for automotive applications are already detailed in [2]. Otherwise, related work in [3] also analyzed the beamforming capabilities of such structures using monopole arrays.

In particular, the study is based in the experimental validation of the specified configurations in a simulated urban environment, in which the cars and the BS will be placed to emulate a realistic situation. A district of the city of Barcelona has been chosen to provide an approach close to reality. The operating frequency is located in the upper side of the S-band, from $3.4\,\mathrm{GHz}$ to $3.8\,\mathrm{GHz}$, with better propagation properties as compared to higher bands, and which the automotive industry has also become interested in [4].

Next sections are organized as follows: Section II introduces some theoretical concepts that will be useful for the following discussion, Section III describes the environment and numerical tools, Section IV defines the methodology used to evaluate the results, Section V presents the results for the V2I simulations, whereas Section VI does the same for the case of V2V, and, finally, Section VII summarizes the previous work in some major statements deduced from the study.

II. THEORETICAL BACKGROUND

A. Capacity in MIMO Channels

One of the most used figures of merit at physical layer in the analysis of communications systems is the channel capacity. For a MxN MIMO system, being M the number of transmitting units and N the receiving ones, capacity may be obtained as [5]:

$$C = \log_2\left(\det\left[\boldsymbol{I}_N + \frac{P_T \boldsymbol{H}\boldsymbol{H}^*}{P_N}\right]\right), \quad (1)$$

where I_N is the identity matrix, $\mathbf{H}$ is the channel matrix, whose entries correspond to the addition of all multipaths between each input and output port, P_T is the transmission power and P_N, the noise level. The operator (.)* denotes the conjugate transpose operator, i.e., Hermitian matrix.

$$\|\boldsymbol{H}\|_{\mathrm{F}} = \left(\sum_{i,j=1}^{N,M} |h_{ij}|^2\right)^{1/2} \quad (2)$$

$$\boldsymbol{H_C} = \frac{\boldsymbol{H}\boldsymbol{H}^*}{\|\boldsymbol{H}\|_F^2} \quad (3)$$

Otherwise, we can express the same equation as a function of the channel eigenvalues, $\lambda_i(\boldsymbol{H_C})$. In this case, the channel matrix is normalized using the Frobenius norm, in (2), and the eigenvalues are those corresponding to the product between both $\mathbf{H}$ and its Hermitian, as in (3).

$$C = \sum_{i=1}^{N} \log_2\left(1 + \frac{P_R \lambda_i(\boldsymbol{H_C})}{P_N}\right) \quad (4)$$

In (4), capacity is defined by means of two main concepts in multi-element cellular communications: the Signal to Noise Ratio (SNR) at the receiver, defined as the ratio between

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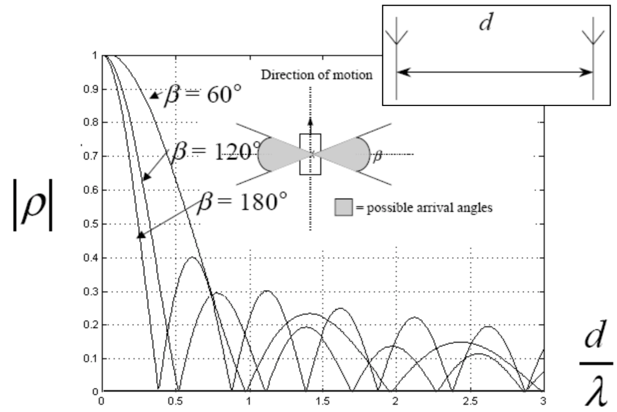

Figure 1. Correlation for two dipoles with changing inter-element spacing and three distinct angle of arrival [7].

received power and noise level ($SNR_{RX} = P_R/P_N$), and the channel richness, determined by the number of relevant eigenvalues. In this analysis, multi-user interference is not considered, but it would affect the noise term (if it is assumed uncorrelated with respect to desired signal), degrading the system performance.

B. Correlation and Spatial Diversity

In a MIMO system, the distance between antennas has a direct impact on the channel capacity through the correlation between the antenna elements. This fading correlation was researched by Shiu et al. [6]. The smaller the angle spread becomes, the higher is the correlation and the lower the responding channel capacity [5]. Therefore, a higher inter-element spacing is needed for small angle spreads.

Figure 1 shows the correlation for three different kind of possible arrival angles for two dipoles with varying inter-element spacing. Furthermore, mutual coupling between the antennas is another penalty on the channel capacity, which is not studied in this work.

III. Simulation Environment

The study of vehicle communications implies complex and large environments, which require the support of numerical tools to model the performance of the system in a realistic situation. This section is dedicated to detail the elements involved in the process of design and simulation of both the scenario and the antennas. The latter is considered to be the entire vehicle when mounted on the car due to its impact in the field distribution.

A. Software simulation

Initially, *FEKO* [8] is used to model the vehicle, as well as the BS for the V2I case, together with the antenna structure. It considers the effect of all the structure when calculating the field. The resulting radiation pattern is imported in a second tool, *WinProp* [9], that is used to simulate the propagation environment. It is possible to create the scenario for the case of study, with a geometrical approximation of buildings, trees and any other element and simulate using the ray tracing method the interaction of all them when one or more radiators are activated. In this case, a car (V2V) or a BS (V2I) are used as transmitting elements and several points over a virtual trajectory are assumed to calculate the received fields. At the receiving points, the effect of the car is considered, as the radiation pattern calculation is including its structure. It is important to mention that all receiving points assume a still vehicle located on them, which is neglecting any Doppler effect.

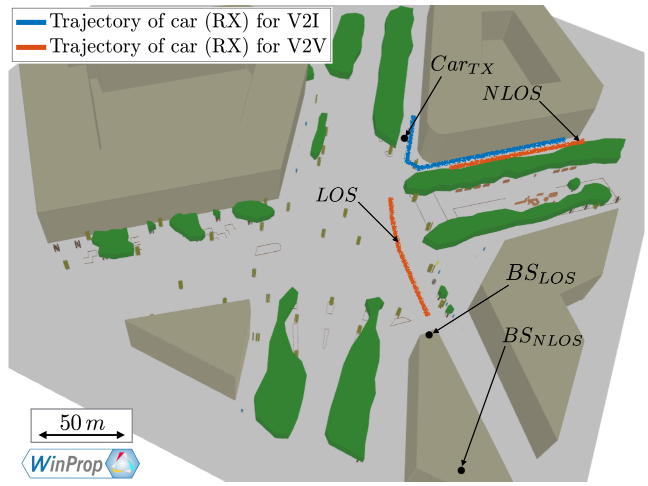

Figure 2. Scenario representation with the location of transmitting vehicle (V2V), transmitting BS (V2I) and trajectories used in the simulations.

B. Scenario

The chosen scenario is an urban area with medium-height buildings, some trees and streetlights. In particular, it is a model of an intersection in a district of Barcelona called as *L'Eixample*, which is known for its rectangular shape and corners close to $90\,\mathrm{deg}$. In Figure 2, the 3-D view of the scenario is shown.

All buildings are made of concrete walls of $30\,\mathrm{cm}$ thickness and $18\,\mathrm{m}$ height, some of them including a courtyard. The ground is made of asphalt, streetlights are modelled as metallic cylinders and trees include a solid wooden trunk and the top is assumed to be a foliage semi-transparent to the rays (only a certain attenuation applied as they pass through).

C. Vehicle configuration

For the vehicle model, a prototype of a conventional car is used. It includes two types of materials: metal for the body and laminated glass for the windows. Wheels and internal elements are excluded to simplify the design and to reduce computational complexity and time consumption during the simulations.

As shown in Figure 3a, the antenna is mounted on the car rooftop. For V2V communications, both transmitter and receiver will have the same height and, for the case of V2I, if large distances are assumed, the angle of arrival is close to the horizontal plane. In consequence, the ideal radiation pattern should be maximum for angles close to the horizontal plane and minimum in the vertical axis. Thus, the chosen antenna is a monopole. In case of MIMO configurations, two or four antennas are placed in a straight line, appropriated to fit in a shark-fin footprint.

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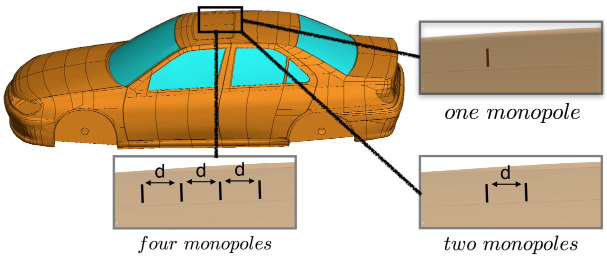
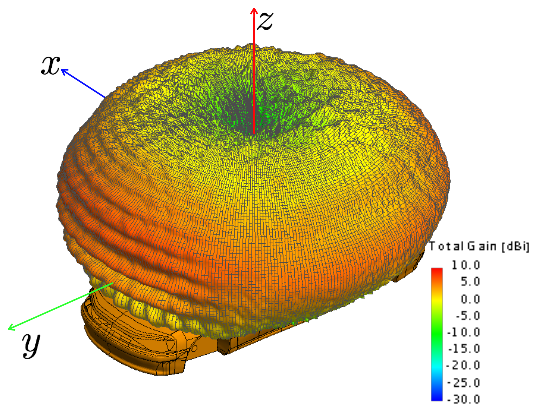


(a) Antenna configurations on the car.



(b) Radiation pattern of a monopole mounted on the car rooftop.

Figure 3. Model of the vehicle and antennas.

D. Base Station

It consists of a set of omnidirectional elements placed on the top of a building as shown in Figure 2. The total height is 21 m over the ground, or 3 m over the rooftop. Depending on the case, one, two, or four antennas are used (for SISO and MIMO 2x2 or 4x4, respectively), with a constant spacing in all cases.

IV. Methodology

The figure of merit to estimate the system performance is the average capacity for the set of points used in each specific path. For each one, the capacity is calculated using (4), once the channel matrix is obtained by the numerical simulation. The noise level is not fixed in the calculation, but a mean SNR is assumed for the overall trajectory. Its value is set to 10 dB. In addition, in order to determine the achievable performance and validate the results, a theoretical maximum is calculated with ideal channel eigenvalues, i.e., $\sigma_i = 0.5$ (i=1,2) for MIMO 2x2 and $\sigma_j = 0.25$ (j=1,2,3,4), for MIMO 4x4.

The spacing between the antenna elements (monopoles) on top of the car is chosen to be in the range of 0.1 to 4 times the wavelength, in steps of 0.1λ. For each one, the average capacity over a given trajectory is calculated and then compared with respect to the SISO case.

V. Impact of the Inter-Element Spacing in V2I MIMO Communications

In this section, the performance in terms of capacity is studied for MIMO V2I systems. The analysis distinguishes between two different situations: Line of Sight (LOS) and Non Line of Sight (NLOS). In the first case, the BS is placed at the edge of the building, whereas, in the latter, the direct view is blocked by placing it some meters backwards (see Figure 2).

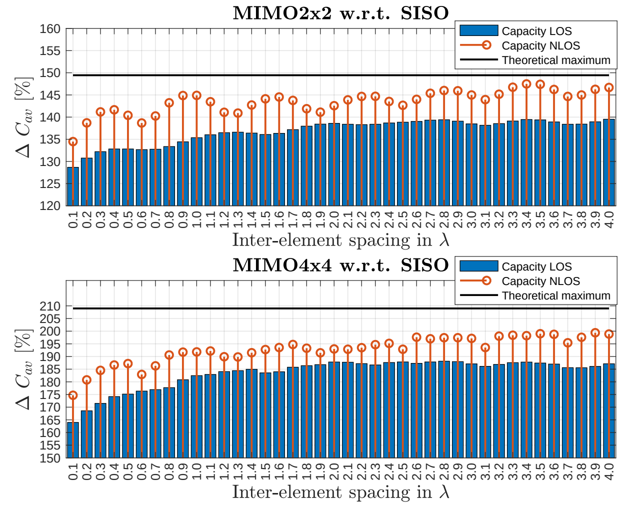


Figure 4. V2I channel capacity for different inter-element spacing for MIMO 2x2 and MIMO 4x4 with respect to the SISO channel capacity in percent and a fixed SNR of 10 dB.

Figure 4 shows the average channel capacity obtained for distinct inter-element spacing with respect to the SISO case in percentage. It illustrates the MIMO 2x2 case (upper figure) for the LOS in blue, the NLOS in red and the theoretical maximum in black. The same illustration is shown in the lower figure for MIMO 4x4.

First, if MIMO 2x2 is analyzed, it is observed a theoretical maximum channel capacity 149% respect to SISO. The minimum for LOS case is 129 % and, in NLOS, it is 135%, both obtained with an inter-element spacing of 0.1 wavelength. The maximum with 147% for NLOS is achieved with a spacing of 3.4 λ and is almost reaching the theoretical maximum of 149%. In the case of LOS, the maximum of 139% although the channel capacity is almost flat after inter-element distances of 1.9λ. The evolution for NLOS is expected as in the theoretical graph (see Figure 1). Regarding MIMO 4x4, the theoretical maximum channel capacity is now 209%. The lowest channel capacity is again obtained for both LOS and NLOS when inter-element spacing is 0.1 wavelengths (164% and 175%, respectively). On the other hand, the greatest capacity is achieved at the spacing of 2.8λ, with 188%, for LOS and 3.9λ, and 198% for NLOS.

From the previous results, it is deduced that MIMO 2x2 is almost reaching the theoretical maximum for NLOS communication, whereas MIMO 4x4 has a bigger step until its maximum. It can be determined that the channel is not rich enough, even increasing the inter-element spacing. Otherwise, it is also true that MIMO 4x4 provides a larger improvement with respect to SISO in terms of capacity although the channel rank is low.

Additionally, in MIMO 4x4 case, there is a more significant increment when the spacing is increased if the values are compared from the lowest distances to the largest. As stated in [10], “the specific behavior is also depending on the amount of elements in the car, which seems to indicate that higher is the number of elements, higher may be the necessary inter-element distance to obtain the optimal performance.”

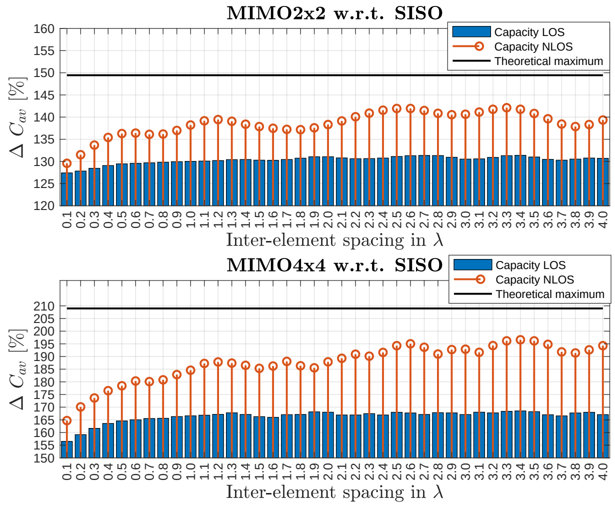


Figure 5. V2V channel capacity for different inter-element spacing for MIMO 2x2 and MIMO 4x4 with respect to the SISO channel capacity in percent and a fixed SNR of 10 dB.

VI. Impact of inter-element spacing in V2V MIMO communications

The goal now is to analyze the communication between two equal vehicles (V2V). This situation has some major differences as compared to previous case: both transmitter and receiver have the same height, their spacing is modified at the same time and both use monopole antennas.

The transmitting vehicle is fixed in a still position. Otherwise, two trajectories are considered for the receiver: one in LOS in which the car is driving along the same path as the transmitter and another in NLOS behind the building close to the corner (Figure 2).

Figure 5 compares both situations when MIMO 2x2 or 4x4 are used. In contrast with V2I model, the increment in capacity is much more evident for NLOS. It is necessary to remind at this point that the SNR is fixed to 10 dB and the performance is only affected by the eigenvalues distribution. Then, we can deduce that the rank of the channel matrix is clearly increasing when there is no direct path.

In NLOS, the average capacity is very similar to previous case. There is a maximum of 123% at 3.3λ for MIMO 2x2 and 194% at 3.4λ for MIMO 4x4. In any case, the oscillation is considerably stable above 2λ. Otherwise, for the LOS situation, capacity is much more reduced. This behavior indicates a very strong path, corresponding to the direct view, and low power reflections. Now, the behavior is almost stable after 0.5λ and maximum values are 132% and 168% for MIMO 2x2 and 4x4, respectively.

VII. Conclusions

Based on the realistic numerical modeling of a V2X urban environment, two main conclusions may be extracted. In terms of antenna footprint, it has been shown that higher the order of the MIMO system, larger has to be the inter-element distance to obtain optimal performance. Furthermore, the increment of the distance improves capacity in both LOS and NLOS for V2I; whereas, for V2V, a significant improvement is only obtained in NLOS.

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References

[1] C.-N. Chuah, D. N. C. Tse, J. M. Kahn, and R. A. Valenzuela, "Capacity scaling in mimo wireless systems under correlated fading," IEEE Transactions on Information Theory, vol. 48, no. 3, Mar 2002, pp. 637–650.

[2] A. Paier, L. Bernado, J. Karedal, O. Klemp, and A. Kwoczek, "Overview of vehicle-to-vehicle radio channel measurements for collision avoidance applications," in 2010 IEEE 71st Vehicular Technology Conference, May 2010, pp. 1–5.

[3] T. Kopacz, A. Narbudowicz, D. Heberling, and M. J. Ammann, "Evaluation of automotive mimo antennas for v2v communication in urban intersection scenarios," in Antennas and Propagation (EUCAP), 2017 11th European Conference on. IEEE, 2017, pp. 2907–2911.

[4] "Frequency bands for v2x," ACEA Position Paper, no. 8, 2016.

[5] G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," Wireless personal communications, vol. 6, no. 3, 1998, pp. 311–335.

[6] D. S. Shiu, G. J. Foschini, M. J. Gans, and J. M. Kahn, "Fading correlation and its effect on the capacity of multielement antenna systems," IEEE Transactions on communications, vol. 48, no. 3, 2000, pp. 502–513.

[7] W. C. Jakes and D. C. Cox, Eds., Microwave Mobile Communications. Wiley-IEEE Press, 1994.

[8] Altair Hyperworks, FEKO User Manual 2017, Altair Hyperworks.

[9] Altair Engineering Inc., WinProp Software for Wave Propagation and Radio Planning, Altair Engineering Inc.

[10] A. Pfadler, C. Ballesteros, J. Romeu, and L. Jofre, "Multi-antenna configuration modeling for massive mimo v2i," in Antennas and Propagation (EUCAP), 2018 12th European Conference on. IEEE, 2018, pp. 215–219.