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CISTER-TR-241201

2024/10/07

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Abstract

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2024 IEEE 100th Vehicular Technology Conference (VTC2024-Fall) | 979-8-3315-1778-6/24/$31.00 ©2024 IEEE | DOI: 10.1109/VTC2024-Fall63153.2024.10757902

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***Abstract*—The problem of optimum antenna separation for a vehicle-to-vehicle (V2V) multiple antenna system is addressed here by considering the combined effects of line-of-sight (LOS), path loss, and ground reflections. Our work extends previous approaches that were based exclusively on LOS assumptions. It is shown that by introducing the new impairments, the LOS solution no longer complies with the orthogonality condition, thus being sub-optimal in more general settings. A more accurate solution is proposed, which is based on a series expansion model that numerically boils down to a polynomial root problem. To reduce the complexity of this solution we propose a reformulation of the problem as the minimization of a cost function. A two-stage approach is employed to address this optimization: 1) the LOS solution is used as an initial approximation to the optimum separation, and 2) the approximation is improved using a gradient descent iterative tool. The LOS solution is shown to improve its accuracy for the more realistic scenario when the inter-vehicular distance increases. The solutions presented here partially fill a gap in V2V antenna design by increasing robustness under changing propagation/configuration settings.**

***Index Terms*—V2V, MIMO, LOS, Ground Reflection**

I. Introduction

Vehicle communications will proliferate in the coming years with the advent of 5G/6G standards [1]. These new technologies target higher reliability, increased bandwidth, and reduced fading. A key solution to achieve these goals is known as multiple-input multiple-output (MIMO) [2].

Vehicular MIMO channel modeling has been addressed extensively in the literature. Solutions include: 1) deterministic *two-ray or multiple rays* that capture the effects of ground reflections [3], 2) *geometry-based stochastic models* [4], and 3) *line-of-sight* (LOS) models [5]. Despite these advances, V2V antenna design remains with several open issues, as solutions must be robust to the highly changing vehicular environment, particularly in dense urban scenarios.

Optimization of the number of antennas usually becomes a complex integer problem. For example, the work in [6] targets optimum antenna density considering LOS and ground reflections. By contrast, optimum antenna separation constitutes a more tractable problem. The authors in [5] have derived an expression for the optimum antenna separation in a V2V scenario based on channel orthogonality in LOS scenarios for different inter-vehicular distances.

This paper addresses the optimization of the antenna separation in V2V MIMO systems using a channel model that combines three effects: 1) a *LOS component*, 2) explicit *path-loss* per link, and 3) *ground reflections*. Our paper extends the work in [5] by using a more realistic setting. This extension shows that the solution for LOS V2V MIMO antenna separation of [5] is sub-optimum for more general and realistic channel models. The channel vector orthogonality condition is no longer achieved accurately as in the case of LOS environments. We propose an exact solution based on a series expansion model that numerically boils down to a polynomial root problem resulting in a resource-intensive solution. To address this issue we reformulate the channel orthogonality condition used in [5] and express it as a minimization problem. The analysis reveals that the minimum points that result from this optimization, correspond to the maximum capacity curve. It has also been shown that local optima can be found via gradient steepest descent that uses as initial approximation the LOS solution from [5]. It is also verified that the LOS solutions become more accurate when the inter-vehicular distance increases under a fixed value of antenna height. The results are obtained for different values of the inter-vehicular distance.

This paper is organized as follows. Section II provides a review of relevant works. Section III describes the scenario and signal model for V2V links with multiple antennas. Section IV proposes the optimization problem. Section V presents the results of our proposals. Finally, Section VI draws conclusions.

II. Related works

LOS MIMO capacity can be optimized by adjusting antenna placement [7], [8], [9], [10]. With uniform linear arrays (ULAs), optimum performance is achieved by adjusting antenna separation [11], [12]. In [13], the effects of optimum antenna separation and communication distance on eigenvalues are investigated for sub-terahertz (Sub-THz) LOS-MIMO. Horizontal and vertical antenna spacing that maximizes the capacity for LOS MIMO is obtained in [14]. To mitigate the issue of distance-dependent design, [15], [16] employed non-uniform linear arrays.

In comparison with previous LOS-modelling approaches, this work introduces two additional effects in the problem of antenna separation of V2V MIMO: path loss and ground

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reflections. We explicitly extend the work in [5], showing how the LOS solutions can be used as initial approximation to the solution that are subsequently refined via gradient descent optimization. This means we provide a method to achieve optimum V2V design that adapts to changing conditions.

Notation. Scalar variables are denoted by lowercase letters. The variable i is the imaginary number $i = \sqrt{-1}$. Vector and matrix variables are denoted, respectively by lowercase and capital bold letters. $(\cdot)^T$ and $(\cdot)^H$ denote, respectively, transpose and Hermitian transpose operators. $|\cdot|$ denotes absolute value or vector norm operator. $\mathcal{R}^+$ and $\mathcal{Z}^+$ denote the set of real and integer positive numbers, respectively. $det(\cdot)$ is the determinant matrix operator.

III. System model

A. Scenario description

Fig. 1 shows a V2V system with an array placed on the rooftop of each vehicle. They are located at the same height (denoted by z_{ant}) with the same antenna separation, denoted here by d_{ant}. The distance between arrays is denoted by d_{veh}, which is the inter-vehicular distance. The objective is to calculate the optimum d_{ant} that maximizes capacity. The list of main variables can be found in Table I. The number of Tx antennas is denoted by N_{Tx}, while the number of Rx antennas is denoted by N_{Rx}. The position of the jth transmit antenna is denoted by $\mathbf{r}_j^{(tx)} = [x_j^{(tx)}, y_j^{(tx)}, z_j^{(tx)}]$ while the position of the kth receive antenna is denoted by the vector $\mathbf{r}_k^{(rx)} = [x_k^{(rx)}, y_k^{(rx)}, z_k^{(rx)}]$. The distance between antenna j in the transmitter and antenna k in the receiver is denoted by $d_{j,k}$ and is given by: $d_{j,k} = |\mathbf{r}_j^{(tx)} - \mathbf{r}_k^{(rx)}|$. The ground reflection distance is given by: $d_{j,k}^{(g)} = |\mathbf{r}_j^{(tx)} - \tilde{\mathbf{r}}_k^{(rx)}|$, where $\tilde{\mathbf{r}}_k^{(rx)} = [x_k^{(rx)}, y_k^{(rx)}, -z_k^{(rx)}]$ denotes the mirror image over reflection plane ($z = 0$). The coordinates for the j-th Tx and the k-th RX antennas (see Fig. 1), can be written, respectively, as: $\mathbf{r}_j^{(tx)} = [(j-1)d_{ant}, 0, z_{ant}]$ and $\mathbf{r}_k^{(rx)} = [(k-1)d_{ant}, d_{veh}, z_{ant}]$.

B. Channel model

The channel gain between the j-th Tx antenna and the k-th Rx antenna is denoted by $h_{j,k}$, and it will be described by a two-ray model, which considers that both the LOS signal and the ground reflection arrive within the duration of an information symbol [17]. This means the channel is given by:

$$h_{j,k} = \sqrt{P_T}(e^{2\pi i \tilde{d}_{j,k}}/\tilde{d}_{j,k} + \Gamma_{j,k} e^{2\pi i \tilde{d}_{j,k}^{(g)}}/\tilde{d}_{j,k}^{(g)}), \quad (1)$$

where P_T is the average channel power including effects of antenna gains and the Tx power, $\tilde{d}_{j,k} = d_{j,k}/\lambda$ and $\tilde{d}_{j,k}^{(g)} = d_{j,k}^{(g)}/\lambda$, are respectively, the direct and the ground reflected electric distances, $\Gamma_{j,k}$ is the reflection coefficient, and λ is the operational wavelength. From this point onwards, the notation $\tilde{d}$ indicates an electrical distance. The reflection coefficient can be written as follows (modification of [18]):

$$\Gamma_{j,k} = \frac{A \sin\beta_{j,k} + B(\sqrt{n_r^2 - \cos{\beta_{j,k}}^2} + i n_i)}{n_r^2 \sin\beta_{j,k} + (\sqrt{n_r^2 - \cos{\beta_{j,k}}^2} + i n_i)}, \quad (2)$$

where $A = n_r^2$ and $B = 1$ for vertical polarization, $A = 1$ and $B = -1$ for horizontal polarization, $\beta_{j,k}$ is the angle of reflection, n_r is the real part of the ground refraction index n_g, and n_i is the imaginary part: $n_g = n_r + i n_i = \sqrt{\epsilon_r - i\frac{\sigma\lambda}{\epsilon_0 2\pi c}}$. c is light speed, while ϵ_r and σ denote, respectively, the relative permittivity and conductivity of asphalt pavement [19].

TABLE I
List of variables

Parameter	Variable
Number of Tx antennas	N_{T_x}
Number of Rx antennas	N_{R_x}
Distance between jth Tx and kth Rx antennas	$d_{j,k}$
Distance of ground reflection between antennas j and k	$d_{j,k}^{(g)}$
Antenna height	z_{ant}
Antenna separation	d_{ant}
Inter-vehicular distance	d_{veh}
Channel between antennas j and k	$h_{j,k}$
Reflection coefficient between antennas j and k	$\Gamma_{j,k}$
Operational wavelength	λ
Reflection angle between antennas j and k	$\beta_{j,K}$
Ground refraction index	n_g
Ground relative permittivity	ϵ_r
Ground conductivity	σ
Azimuth Angle between antennas j and k	$\phi_{j,k}$

C. MIMO model and Capacity

The MIMO signal model can be written as $\mathbf{x} = \mathbf{H}\mathbf{s} + \mathbf{v}$, where $\mathbf{s}$ and $\mathbf{x}$ denote, respectively, the transmitted and received symbols, $\mathbf{v}$ is the zero-mean noise with unit variance $\sigma_v^2 = 1$, and $\mathbf{H}$ is the MIMO channel matrix of size $N_{Rx} \times N_{Tx}$ which corresponds to the transpose of the matrix formed by elements $h_{j,k}$. This matrix can also be written as follows:

$$\mathbf{H} = [\quad \mathbf{h}_1,\ \mathbf{h}_2, \cdots, \mathbf{h}_j, \cdots, \mathbf{h}_{N_{Tx}} \quad], \quad (3)$$

where the j-th column of $\mathbf{H}$, i.e. $\mathbf{h}_j$, corresponds to the channel vector from the j-th Tx antenna to the k-th Rx antenna. The capacity of the MIMO system using a high SNR approximation is given by [20]:

$$C \approx B_w \log_2\left(\det\left((P_T/N_{Tx}\sigma_v^2)\mathbf{H}^H\mathbf{H}\right)\right) \quad (4)$$

where B_w is the system bandwidth.

IV. Optimization of antenna separation

To design the channel matrix $\mathbf{H}$ of the LOS MIMO system to have orthogonal columns, from (3) we need to have [5]:

$$\mathbf{h}_j^H \mathbf{h}_l = 0 \quad \text{for} \quad j \neq l;\ j, l = 1, \cdots, N_{Tx}. \quad (5)$$

Let us now obtain an explicit expression of the orthogonality condition by substituting the channel model given by (1) into the previous expression (5), which results in:

$$\mathbf{h}_j^H \mathbf{h}_l = P_T \sum_{k=1}^{N_{Rx}} \left\{ \frac{e^{i2\pi(\tilde{d}_{j,k} - \tilde{d}_{l,k})}}{\tilde{d}_{j,k}\tilde{d}_{l,k}} + \frac{\Gamma_{j,k}}{\tilde{d}_{j,k}^{(g)}\tilde{d}_{l,k}} e^{i2\pi(\tilde{d}_{j,k}^{(g)} - \tilde{d}_{l,k})} \right.$$
$$\left. + \frac{\Gamma_{l,k}}{\tilde{d}_{j,k}\tilde{d}_{l,k}^{(g)}} e^{i2\pi(\tilde{d}_{j,k} - \tilde{d}_{l,k}^{(g)})} + \frac{\Gamma_{j,k}\Gamma_{l,k}}{\tilde{d}_{j,k}^{(g)}\tilde{d}_{l,k}^{(g)}} e^{i2\pi(\tilde{d}_{j,k}^{(g)} - \tilde{d}_{l,k}^{(g)})} \right\} \quad (6)$$

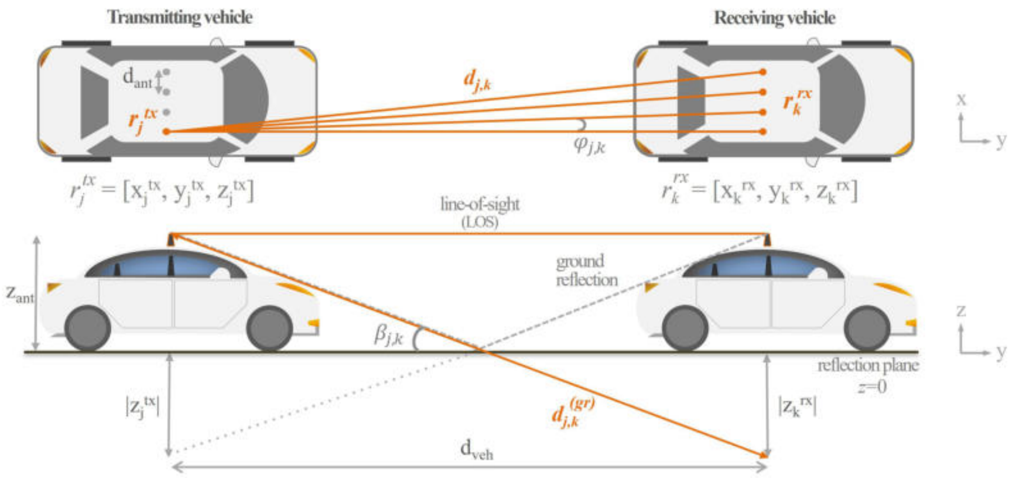

Fig. 1. V2V system showing: (bottom) LOS and ground reflected components, and (top) an aerial view of the V2V channel.

From the structure of the previous expression in (6), we can observe that the first term belongs to the original LOS problem, while the rest of the terms belong to the extended problem with ground reflections. Consider now the following Taylor's series expansions $e^d/d = \sum_{q=0}^{\infty} d^{q-1}/q!$ and $d^n = a^n(1+x)^{n/2} = a^n \sum_{q=0}^{\infty} C_q^{n/2} x^q$, where C_q^m is the binomial coefficient. Combining these series expansions, the individual terms of (6) can each be written as follows:

$$\frac{e^{\alpha d}}{d} = \sum_{i=0}^{\infty} \frac{\alpha^i d^{i-1}}{i!} = \sum_{i=0}^{\infty} \frac{\alpha^i a^{i-1}}{i!} \sum_{q=0}^{\infty} C_q^{\frac{i-1}{2}} x^q. \qquad (7)$$

For the particular case of the LOS distances, i.e.,$d_{j,k}$ the terms to be used in the previous expression are given by $x = (j-k)^2 \tilde{d}_{ant}^2 / \tilde{d}_{veh}^2$ and $a = d_{veh}$. In the case of the ground reflected ray distance $d_{j,k}^{(g)}$, the parameters are given by: $x = (j-k)^2 \tilde{d}_{ant}^2 / \sqrt{\tilde{d}_{veh}^2 + 4z_{ant}^2}$, and $a = \sqrt{d_{veh}^2 + 4z_{ant}^2}$. When the above expansion in (7) is used in the expression in (6), and the series is constrained to a finite number of terms, the result is a polynomial root problem, whose solution can be resource intensive.

Let us now reduce the complexity of the resulting polynomial root problem by considering the following expressions (see also Fig.1): $\tilde{d}_{j,k} = \tilde{d}_{veh}/\cos\phi_{j,k}$, $\tilde{d}_{j,k}^{(g)} = \tilde{d}_{veh}/\cos\beta_{j,k}\cos\phi_{j,k}$ and the triangle inequality $\tilde{d}_{j,k}^{(g)} \leq \tilde{d}_{j,k} + 2\tilde{z}_{ant}$, where $\phi_{j,k}$ is the angle between the x axis in Fig. 1 and the j,k links. By substituting these expressions in (6) we obtain:

$$\mathbf{h}_j^H \mathbf{h}_l \approx \hat{P}_T \sum_{k=1}^{N_{Rx}} e^{i2\pi(\tilde{d}_{j,k} - \tilde{d}_{l,k})} \sum_{q=1}^{4} \alpha_{j,k,l}^{(q)} \cos\phi_{j,k} \cos\phi_{l,k}, \quad (8)$$

where

$$\alpha_{j,k,l}^{(1)} = 1, \quad \alpha_{j,k,l}^{(4)} = \Gamma_{j,k}\Gamma_{k,l} e^{i4\tilde{z}_{ant}} \cos\beta_{j,k}\cos\beta_{l,k}$$

$$\alpha_{j,k,l}^{(2)} = \Gamma_{j,k} e^{i2\tilde{z}_{ant}} \cos\beta_{j,k}, \quad \alpha_{j,k,l}^{(3)} = \Gamma_{k,l} e^{i2\tilde{z}_{ant}} \cos\beta_{l,k},$$

The expression in (8) consists of the LOS term given by $\sum_{k=1}^{N_{Rx}} e^{i2\pi(\tilde{d}_{j,k} - \tilde{d}_{l,k})}$ and the deviation caused by path-loss and ground reflection components given by $\sum_{q=1}^{4} \alpha_{j,k,l}^{(q)} \cos\phi_{j,k}\cos\phi_{l,k}$. From the structure of the expressions in (6) and the deviation terms, it is possible to draw some useful conclusions about the orthogonality condition in (5). The deviation terms are all dependent on the antenna indexes and the angles $\phi_{j,k}$ and $\beta_{j,k}$. This index dependency means that it directly influences the structure and the result of the LOS term on the left side of (6). This observation is sufficient to claim that the LOS solution is no longer accurate in the general case with explicit path-loss and ground reflections. However, when the inter-vehicular distance increases, all the angles $\phi_{j,k}$ and $\beta_{j,k}$ tend to be zero, which means the deviation terms all become equal to one, and therefore the LOS solution becomes asymptotically (for $d_{veh} \to \infty$) the solution of the system with path loss and ground reflections. The fact that the orthogonality function for each term of (6) has a different solution denotes that the optimum antenna separation for the summation of all these terms is more difficult to obtain than in the LOS case.

Let us now ignore the path loss terms in (6), for which each one of the terms can be addressed using the methodology proposed in [5]. This leads to a similar expression for each term ($q = 1, 2, 3, 4$), which is given by:

$$\frac{1 - e^{2\pi\delta^{(q)} N_{Rx} u}}{1 - e^{2\pi\delta^{(q)} u}}, \qquad q = 1, \ldots, 4,$$

where $\delta^{(q)} = \tilde{d}_{ant}^2/\lambda d_q$, $d_1 = \tilde{d}_{ant}^2$, $d_4 = \sqrt{4\tilde{z}_{ant}^2 + \tilde{d}_{ant}^2}$, and $\{d_2, d_3\} \in \{d_1, d_4\}$. The solution of the previous expression as derived in [5] is given, in our context, by:

$$d_{ant}^{opt,(q)} = \sqrt{p\lambda d_q / N_{Rx}}. \qquad \forall p \in \mathcal{Z}^+$$

$$\left\{ p' : p' = \frac{p_1 N_{Rx}}{u}, \{p_1, p'\} \in \mathcal{Z}^+, u \in \{1, 2, \ldots, N_{Tx}\} \right\}. \quad (9)$$

This result confirms again that the solution for each term is slightly different, being the first term the case of LOS propagation. This means the LOS solution is no longer the exact solution when considering ground reflections. To address this deviation problem with a lower complexity than the full polynomial solution previously presented, let us reformulate the orthogonality function as a minimization problem, where the objective function can be written as:

$$U = |\sum_{j,l} \mathbf{h}_j^H \mathbf{h}_l|^2. \quad j \neq l; \; j,l = 1, \cdots, N_{Tx} \tag{10}$$

Therefore, the optimization problem can be formulated as:

$$\min_{d_{ant}} \quad U, \quad \text{s.t} \quad d_{ant} \in \mathcal{R}^+. \tag{11}$$

Since this type of optimization usually shows local optima, we propose to use the LOS solution in (9) as the initial approximation, which is subsequently refined via gradient steepest descent:

$$d_{ant}(n) = d_{ant}(n-1) - \xi \frac{\partial U}{\partial d_{ant}}, \tag{12}$$

where ξ is the learning rate. The algorithm stops when the difference between iterations, denoted by $\Delta = |d_{ant}(n) - d_{ant}(n-1)|$, is below a threshold η, which means the improvement in future iterations is marginal and the local optimum has been reached. The algorithm is described in more detail in Algorithm 1.

Algorithm 1 Optimum antenna spacing for V2V MIMO with ground reflections

Require: $N_{tx} = N_{rx}$; d_{veh}; z_{ant}; λ; ξ; η; P_T
Ensure: $d_{ant}^{LOS} = \sqrt{p\lambda d_{veh}/N_{tx}}, \quad \forall p \in \mathcal{Z}^+$ from (9)
Ensure: $\left\{p' : p' = \frac{p_1 N_{Rx}}{u}, \{p_1, p'\} \in \mathcal{Z}^+, u \in \{1,.,N_{Tx}\}\right\}$
  $n \leftarrow 0$
  while $\Delta \geq \eta$ **do**
    $U \leftarrow |\sum_{j,l} \mathbf{h}_j^H \mathbf{h}_l|^2. \quad j \neq l; \; j,l = 1,.,N_{Tx}$ from (10)
    $d_{ant}(n) \leftarrow d_{ant}(n-1) - \xi \frac{\partial U}{\partial d_{ant}}$ from (12)
    $\Delta \leftarrow |d_{ant}(n) - d_{ant}(n-1)|$
    $n \leftarrow n+1$
  end while

V. Results

Let us first focus on showing the behaviour of the capacity function in (4) and the orthogonality objective function in (5) versus the antenna separation d_{ant} considering LOS, path-loss, and ground reflections. For all the results we assume a fixed antenna height $z_{ant} = 1.6$m. The operational wavelength is set to $\lambda = 0.125$, and the dielectric parameters for ground reflection are set to $\epsilon_r = 4$ and $\sigma_c = 0.02$, which are consistent with asphalt used on road construction. In all experiments, the number of transmit and receive antennas was set to $N_{Tx} = N_{Rx} = 4$. Capacity values were obtained by assuming $Bw =$ 10MHz and $\frac{P_T}{\sigma_v^2} = 40$dB.

Fig. 2 shows the results for an inter-vehicular distance equal to $d_{veh} = 4$m and Fig. 3 using a value of $d_{veh} = 15$m. The figures show the exact objective function in (10) and the curve of capacity in (4). The results are the following:

1) A system with LOS, path-loss, and ground reflections, which is labelled ***LOS+ground ref.-MIMO+path-loss***.
2) A LOS-MIMO system with path-loss and no ground reflections, which is labelled ***LOS-MIMO+path loss***.
3) A curve labelled ***Capacity*** that shows the match between the roots of (5) and the capacity-curve peaks.

Two other types of results are also shown in both figures:

1) The red dots with a vertical red dotted line show the roots of the ideal LOS-MIMO system as obtained from the expression in (9) which was derived in [5] and which is labelled here ***LOS-MIMO [5]***.
2) The blue dots show the roots obtained by the exact solution (e.s) of the curve of the ideal LOS-MIMO system without path-loss and without ground reflections, which is labelled as ***LOS-MIMO (e.s)***.

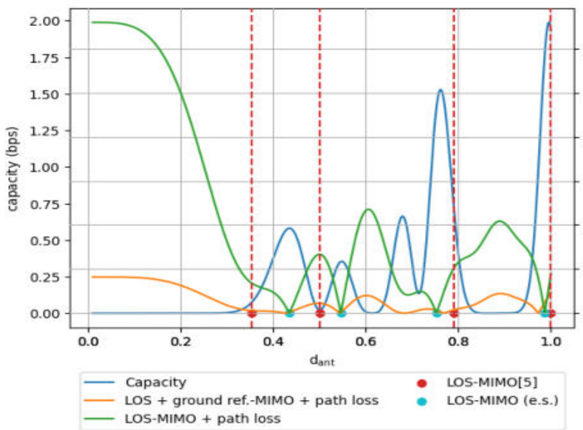

Fig. 2. Orthogonality (10) and capacity (4) versus antenna separation for V2V MIMO using an inter-vehicular distance of $d_{veh} = 4$ meters.

These figures confirm our findings in previous sections: the roots of the orthogonality function are modified due to the effects of path-loss and ground reflections. Additionally, when the inter-vehicular distance increases from $d_{veh} = 4$ to $d_{veh} = 15$ meters, as shown in Fig. 3 the roots of the two curves are almost indistinguishable, as also predicted in the previous sections: the LOS-MIMO solution becomes accurate for high values of d_{veh}. An interesting result is that the solution from the literature in [5] for the roots of the ideal LOS-MIMO system without path-loss and without ground reflections, is slightly inaccurate even when increasing the inter-vehicular distance. We attribute this difference to the approximations made in the derivation of the expressions in ideal conditions. However, they still provide a convenient starting point for our proposed gradient descent optimization. Our proposed solution uses the LOS-MIMO solution as the first approximation, which is subsequently refined via gradient steepest descent, thus obtaining a more accurate optimum antenna separation that minimizes the objective function in (11). The results of our algorithm versus the LOS solution for the first roots of the objective function are shown in Table II using $d_{veh} = 4$m. The table shows the accuracy of our solution compared to the conventional LOS-MIMO ideal assumption.

TABLE II
V2V MIMO OPTIMUM ANTENNA SEPARATION ($d_{veh} = 4$M)

p	LOS MIMO (e.s.)	Gradient descent	Full (e.s)	LOS MIMO [5]	d_{veh} (m)
1	0.425	0.4375	0.435	0.35	4
2	0.546	0.534	0.544	0.5	4
5	0.752	0.756	0.769	0.754	4
1	0.73	0.72	0.73	0.6846	15
2	0.915	0.931	0.915	0.9682	15

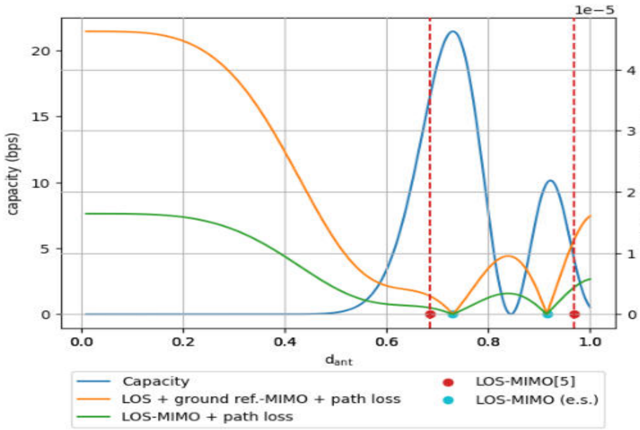

Fig. 3. Orthogonality (10) and capacity (4) versus antenna separation for V2V MIMO using an inter-vehicular distance of $d_{veh} = 15$ meters.

VI. CONCLUSIONS

This paper addressed the derivation of the optimum antenna separation for V2V MIMO under the influence of LOS, ground reflections, and path loss. The exact solution was formulated as a polynomial root problem, that allowed us to demonstrate that path loss and ground reflections generate a different solution from the conventional LOS case. This has also been proved by showing that the solution using the method developed for LOS MIMO is different for each term of the orthogonality condition. However, this difference tends to disappear when the inter-vehicular distance increases. To resolve the accuracy issue for shorter values of d_{veh} we proposed a gradient steepest descent optimization that minimizes the absolute square value of the overall orthogonality objective function. We also show by plotting the exact function versus antenna separation that convergence to the desired local optima can be ensured by setting the initial value as the LOS MIMO solution of the literature and refining it via gradient descent. This method shows robustness to changes in configuration and propagation settings and thus achieves optimum V2V antenna design.

ACKNOWLEDGMENTS

This work was supported by the CISTER Research Unit (UIDP/UIDB/04234/2020), financed by National Funds through FCT/MCTES (Portuguese Foundation for Science and Technology) and within project POCI-01-0145-FEDER-032218 (5GSDN); financed through National Funds from FCT and European funds through the EU ECSEL JU. This document reflects only the author's view and the Commission is not responsible for any use that may be made of the information it contains. This work was also developed under project INSECT (ECSEL/0002/2019 - JU grant nr. 876038) and also by FCT under PhD grant PRT/BD/154912/2023.

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