# Conference Paper

## A Multi-Ray Analysis of LOS V2V Links for Multiple Antennas with Ground Reflection

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## Abstract

This paper presents a vehicle-to-vehicle (V2V) geometric multi-ray tracing model for an improved line-of-sight (LOS) estimation. This model is especially suited for distributed antenna transceivers in the presence of ground reflections. The multiple antennas are assumed to be spaced regularly in horizontal and vertical directions over contiguous vehicles. The main focus of our study is the ability of the multiple antenna system to counteract or exploit, respectively, the destructive or constructive interference of multiple rays in the LOS channel component. This work is a complement to existing V2V channel models by providing more details on how ground reflections affect the LOS channel. The analysis is framed in the context of MIMO (multiple-input multiple-output) systems to investigate general aspects such as capacity limits and singular value distribution. The work then focuses on symbol repetition across the transmit antennas and two different strategies for signal combining at the receiver end: maximum ratio and equal gain combining (MRC and EGC, respectively). These solutions are compared with a full diversity solution as well as with the information theoretical limits. An adaptive antenna selection mechanism is finally proposed that outperforms all other solutions. The paper shows both vertical and horizontal polarization results with corrected complex Fresnel reflections coefficients for lossy materials. Moreover, it is shown that multiple antenna design in V2V systems can be useful to counteract the destructive interference created by multiple rays on the LOS channel component.

# A Multi-Ray Analysis of LOS V2V Links for Multiple Antennas with Ground Reflection

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***Abstract*—This paper presents a vehicle-to-vehicle (V2V) geometric multi-ray tracing model for an improved line-of-sight (LOS) estimation. The model is especially suited for distributed antenna transceivers in the presence of ground reflections. The multiple antennas are assumed to be spaced regularly in horizontal and vertical directions over contiguous vehicles. The main focus of our study is the ability of the multiple antenna system to counteract or exploit, respectively, the destructive or constructive interference of multiple rays in the LOS channel component. This work is a complement to existing V2V channel models by providing more details on how ground reflections affect the LOS channel. The analysis is initially framed in the context of MIMO (multiple-input multiple-output) systems to investigate general aspects such as capacity limits and singular value distribution. The work then focuses on a scheme with single symbol repetition across the transmit antennas and two different strategies for signal combining at the receiver: maximum-ratio and equal-gain combining (MRC and EGC, respectively). These solutions are compared with a full diversity solution as well as with the information theoretical limits. An adaptive antenna selection mechanism is finally proposed that outperforms all other solutions. The paper shows both vertical and horizontal polarization results with corrected complex Fresnel reflection coefficients for lossy materials. Moreover, it is shown that multiple antenna design in V2V systems can be useful to counteract the destructive interference created by multiple rays on the LOS channel component.**

***Index Terms*—MIMO, V2V, line of sight, Two ray model**

## I. INTRODUCTION

The number of "things" connected to the cloud is growing exponentially. Wireless technology is a natural enabler of the concept of *Internet-of-Things* (IoT) due to its flexible infrastructure, pervasiveness, and over-the-air management capabilities. Improvements on wireless technology have paved the way for new critical IoT applications [1]–[3].

Vehicular networks have been gaining particular importance over the last few years. Vehicle subsystems are becoming more specialized, adaptive and connected to the cloud. Additionally, the advent of autonomous vehicles calls for a new generation of reliable, real-time, dependable and ultra-low latency wireless links to ensure road and user safety. Vehicle-to-everything (V2X) technology will therefore play a key role in future applications such as vehicle platooning [4].

Propagation aspects have been largely studied for V2V and (more recently) vehicle platoons under a variety of models (e.g. ray tracing, geometric stochastic, etc.) [5]–[7]. However, in general V2V models are more focused on aspects such as shadowing by obstacles, scattering, multi-path and delay spread distribution. To the best of our knowledge, there is a gap in the understanding of the behavior of the line-of-sight (LOS) components under the effects of ground reflections, particularly using multiple distributed antennas across the surface of vehicles. This paper aims to explore a simplified geometric multiple ray tracing model to analyze the potential effects of destructive/constructive interference between multiple direct and ground reflected rays on the performance of V2V LOS communications using distributed antennas. More specifically, we aim to investigate how multiple antenna algorithms can reduce the fades in the LOS channel. Unlike previous approaches we consider the corrected Fresnel complex reflection coefficients that arise in lossy dielectric materials implementing the concepts presented in [8]. The results in this paper suggest that not only conventional distributed multiple-input multiple-output (MIMO) algorithms can help in reducing the destructive interference of multiple reflected rays, but also antenna selection can be used to further improve resistance to fades due to ground reflections.

This paper is organized as follows. Section II presents a non-exhaustive review of related works. Section III presents the description of the scenario and signal reception model for V2V links with multiple antennas. Section IV provides the general MIMO model. Section V introduces specific antenna processing algorithms. Section VI presents results of our proposals. Finally, Section VII draws conclusions.

## II. RELATED WORK AND CONTRIBUTIONS

In recent years, significant effort has been placed to characterize V2V channels. In [9], ray-tracing simulations and three dimensional (3D) models of the vehicular environment were used to optimize antenna location for V2V communications. Several works have investigated MIMO V2V systems. The work in [10] studied the effects of antenna position on the channel capacity. In comparison with this work, our paper focuses on the variations of the LOS component under different MIMO algorithms. The work aims to evaluate the effects of multiple ray components of ground reflections on the average signal-to-noise ratio (SNR) of the MIMO transceiver. Our work considers corrected Fresnel reflection coefficients to account for dielectric losses of asphalt. In addition, we propose antenna selection proving that for different values of inter-

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vehicle distance, antenna selection contributes to improve the post-processing SNR of the transceiver.

In [14], a channel model that characterizes the non-stationarities of small-scale MIMO-V2V channels was proposed. Our work is complementary to these stochastic channels as we focus on the LOS component and the effects of ground reflection. Our work is more relevant in cases where V2V channels are dominated by the LOS component.

The study of the reliability of V2V links is essential to properly evaluate the performance of vehicular communications [11]. In [12], this issue has been recently studied by a measurement-based analysis in urban and suburban scenarios for car platoon formations. Our work aims to give more details on the LOS variations between the vehicles of platoons due to ground reflections in scenarios with reduced scattering contributions. Summarizing, our contributions are:

1) A multi-ray geometrical model is used to provide more details on how the LOS is affected by the reflected ground components of V2V channels with multiple distributed antennas and cross-polarization.
2) Improved reflection coefficients using the corrected complex Fresnel coefficients for lossy materials.
3) Use of different RX combining strategies for spatial and cross-polarization diversity with Tx single symbol repetition.
4) Antenna selection for V2V MIMO transceivers is shown to provide gains in terms of reduction of destructive interference in the LOS component of V2V channels.

## III. System model

Fig. 1 depicts the distributed antenna system in a two-vehicle setup. Each vehicle can host multiple antennas in different positions, usually on the rooftop or on the sides of the vehicle. The objective of placing multiple antenna transceivers as widely spaced as possible over different locations of a vehicle is to achieve diversity and thus help in reducing the effect of destructive interference that is commonly seen in links with ground reflected components. In all cases, we consider both vertically, horizontal and cross-polarization performance. The target is to improve the reliability of the link between two vehicles and thus reduce the latency of higher-level configurations such as vehicle platoons or autonomous vehicles assisted by cloud/edge information management. The number of Tx antennas is denoted by $N_{Tx}$, while the number of receive antennas is denoted by $N_{Rx}$. The position of the $j$th transmit antenna is denoted by $\mathbf{r}_j^{tx} = [x_j^{tx}, y_j^{tx}, z_j^{tx}]$ while the position of the $k$th receive antenna is denoted by the vector $\mathbf{r}_k^{rx} = [x_k^{rx}, y_k^{rx}, z_k^{rx}]$. The direct distance between antenna $j$ in the transmitter and antenna $k$ in the receiver is denoted by $d_{j,k}$ and is given by:

$$d_{j,k} = |\mathbf{r}_j^{tx} - \mathbf{r}_k^{rx,}|, \tag{1}$$

which, in Cartesian coordinate system, boils down to $d_{j,k} = \sqrt{(x_j^{tx} - x_k^{rx})^2 + (y_j^{tx} - y_k^{rx})^2 + (z_j^{tx} - z_k^{rx})^2}$. The distance for the ground reflected ray, denoted by $d_{j,k}^{(gr)}$, is given by:

$$d_{j,k}^{(gr)} = |\mathbf{r}_j^{tx} - \tilde{\mathbf{r}}_k^{rx}| = |\tilde{\mathbf{r}}_j^{tx} - \mathbf{r}_k^{rx}|, \tag{2}$$

where $|\cdot|$ is the absolute value operator, and the notation $\tilde{\mathbf{a}}$ indicates the mirror image of vector $\mathbf{a}$ over the plane of reflection. This means that:

$$\tilde{\mathbf{r}}_j^{tx} = \mathbf{r}_{j||}^{tx} - \mathbf{r}_{j-}^{tx},$$

where $\mathbf{r}_{j||}^{tx}$ and $\mathbf{r}_{j-}^{tx}$, denote, respectively, the parallel and perpendicular component of vector $\mathbf{r}_j^{tx}$ with respect to the reflection plane. Since we define the reflection plane as $z = 0$ (see Fig.1), then $\mathbf{r}_{j||}^{tx} = [x_j^{rx}, y_j^{rx}, 0]^T$ and $\mathbf{r}_{j-}^{tx} = [0 \quad 0, \quad z_j^{tx}]^T$. Therefore, the expression in (2) becomes $d_{j,k}^{(gr)} = \sqrt{(x_j^{tx} - x_k^{rx})^2 + (y_j^{tx} - y_k^{rx})^2 + (z_j^{tx} + z_k^{rx})^2}$, which is equivalent to the formula given in [16]. We do not consider additional reflections due to the body of the vehicles. The channel between the $j$th Tx antenna and the $k$th Rx antenna is denoted by $h_{j,k}$ and will be defined as the contribution of the Line-of-Sight (LOS) component and the non-line-of sight (NLOS) component $h_{j,k} = h_{j,k}^{LOS} + h_{j,k}^{NLOS}$. For convenience, we will focus our analysis mainly on the LOS component to evaluate the performance of distributed MIMO solutions to counteract the destructive interference of the multiple ray components mainly created by multiple ground reflections between the pairs of Tx and Rx antennas.

All channels will be described by the two-ray model. We consider the exact formulation of two plane waves travelling two different distances and concurring in the same destination point. Each ray experiences an attenuation proportional to the inverse of the squared distance (path loss exponent equal to two) and a phase-shift proportional to the distance of each trajectory. This model assumes the two rays arrive within the boundaries of a symbol duration. This can be expressed mathematically as follows [17]:

$$h_{j,k}^{LOS} = \sqrt{P_T G_T G_R}/(4\pi) \left( e^{2\pi i \tilde{d}_{j,k}} / \tilde{d}_{j,k} + \Gamma e^{2\pi i \tilde{d}_{j,k}^{(gr)}} / \tilde{d}_{j,k}^{(gr)} \right) \tag{3}$$

where $\tilde{d}_{j,k} = d_{j,k}/\lambda$ and $\tilde{d}_{j,k}^{(gr)} = d_{j,k}^{(gr)}/\lambda$, are respectively, the direct and the ground reflected electric distance, $\Gamma$ is the reflection coefficient, $G_T$ and $G_R$ are the gains of the Tx and Rx antennas, respectively, $\lambda$ is the operational wavelength and $i = \sqrt{-1}$. The reflection coefficient can be written as follows (modification of [8]):

$$\Gamma = \frac{A \sin\beta + B(\sqrt{n_r^2 - \cos\beta^2} + i n_i)}{n_r^2 \sin\beta + (\sqrt{n_r^2 - \cos\beta^2} + i n_i)}, \tag{4}$$

where $A = n_r^2$ and $B = 1$ for vertical polarization and $A = 1$ and $B = -1$ for horizontal polarization. $\beta$ is the angle of reflection, $n_r$ is the real part of the complex refractive index of ground $n_{gr}$ and $n_i$ is the imaginary part of $n_{gr}$, so $n_{gr} = n_r + i n_i = \sqrt{\epsilon_r - i \frac{\sigma\lambda}{\epsilon_0 2\pi c}}$. $c$ is speed light, while $\epsilon_r$ and $\sigma$ denote, respectively, the relative permittivity and conductivity of asphalt pavement [15].

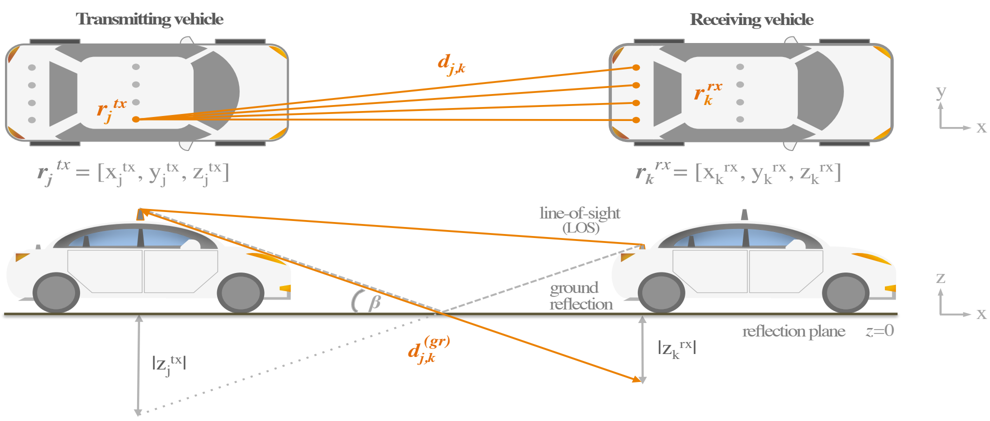


Fig. 1: V2V communication link showing: (bottom) both the LOS and ground reflected path components that the signals from the transceiver mounted on the transmitting vehicle (left) follow when sent to the receiving vehicle (right), according to the two-ray model; and (top) an aerial view of the V2V channel.

## IV. MIMO Model

The general MIMO model considering the set of transmit antennas $\mathcal{T}_x$ and the set of receiving antennas $\mathcal{R}_x$, as well as their respective transmit and receive beam-forming arrays $\mathbf{G}_{tx}$ and $\mathbf{G}_{rx}$, can be written as follows:

$$\mathbf{x} = \mathbf{G}_{rx}\mathbf{H}\mathbf{G}_{tx}\mathbf{s} + \mathbf{v}, \tag{5}$$

where $\mathbf{s} = [s(0), s(1), \ldots, s(|\mathcal{T}_x|-1)]^T$ is the vector of transmitted symbols across the different antennas, and $(\cdot)^T$ denotes the transpose operator, and $|\cdot|$ denotes the set cardinality operator. The vector $\mathbf{v}$ represents a zero-mean additive circular complex Gaussian noise $\mathbf{v} \sim \mathcal{CN}(\mathbf{0}_{|\mathcal{R}_x|}, \sigma_v^2 \mathbf{I}_{|\mathcal{R}_x|})$, where $\mathcal{CN}(\mathbf{m}, \mathbf{\Delta})$ denotes a complex circular Gaussian distribution with mean $\mathbf{m}$ and covariance matrix $\mathbf{\Delta}$, $\mathbf{I}_n$ denotes the identity matrix of order $n$, and $\mathbf{0}_n$ and $\mathbf{1}_n$, the respective column vectors of zeroes and ones of length $n$. $\mathbf{H}$ is the MIMO channel matrix of size $|\mathcal{R}_x| \times |\mathcal{T}_x|$ which corresponds to the transpose of the matrix formed by the elements $h_{j,k}$, and $\mathbf{x}$ is the vector of received symbols.

### A. Capacity and SVD analysis

The capacity of MIMO systems is defined as [16]

$$C = \log_2 \det \left|\mathbf{I} + \mathbf{H}\mathbf{H}^H / |\mathcal{T}_x|\right|, \tag{6}$$

where $\det|\cdot|$ is the determinant operator and $(\cdot)^H$ the Hermitian transpose operator. The singular value decomposition (SVD) of the channel matrix can be expressed as:

$$\mathbf{H} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}, \tag{7}$$

where $\mathbf{U}$ and $\mathbf{V}$ are the unitary matrices containing the receive and transmit optimum beamforming vectors. The diagonal matrix $\mathbf{\Sigma}$ contains the singular values of the channel. These singular values allow us to study the feasibility of the MIMO deterministic channel created by direct and ground reflected components. We will focus on some simple cases of how conventional MIMO algorithms affect the constructive/destructive interference of multiple ground reflected rays.

## V. Performance model

Let us assume a single symbol repeated across all active Tx antennas. This means that the transmit beam-forming array becomes a vector of ones ($\mathbf{1}_{|\mathcal{T}_x|}$), the transmit symbol vector reduces to a single scalar $s$ with symbol power constraint $E[s^*s] = 1$, and the beamforming matrix array $\mathbf{G}_{rx}$ becomes a single vector denoted by $\mathbf{g}_{rx}$ of size $N_{Rx} \times 1$. The received signal in (5) becomes SIMO (single input multiple output) problem:

$$x = \mathbf{g}_{rx}\tilde{\mathbf{x}} = \mathbf{g}_{rx}(\mathbf{h}s + \tilde{\mathbf{v}}), , \tag{8}$$

where $\tilde{\mathbf{x}}$ is the pre-processed received signal, $\mathbf{h} = \mathbf{H}\mathbf{1}_{|\mathcal{T}_x|}$ is the equivalent channel vector for transmit symbol repetition across antennas and $\tilde{\mathbf{v}}$ is the pre-processed noise at the receiver. The pre-processed received signal in the $k$th antenna of the receiver is given by:

$$\tilde{x}_k = \sum_{j \in \mathcal{T}_x} h_{j,k} s / \sqrt{|\mathcal{T}_x|} + \tilde{v}_k, \tag{9}$$

where $\tilde{v}_k$ is the pre-processed noise component in antenna $k$.

### A. MRC receive diversity

Maximum-ratio combining (MRC) at the receiver side is implemented by using in (8) $\mathbf{g}_{rx} = \mathbf{h}^H$. This leads to the following post-processing signal:

$$x = \sum_{k \in \mathcal{R}_x} (\sum_{j \in \mathcal{T}_x} h_{j,k} s / \sqrt{|\mathcal{T}_x|})^* \tilde{x}_k. \tag{10}$$

By substituting the received signal of the $k$th antenna given by (9) into (10) we obtain the following: $x = \sum_{k \in \mathcal{R}_x} \left(\sum_{j \in \mathcal{T}_x} h_{j,k} s / \sqrt{|\mathcal{T}_x|}\right)^* \left(\sum_{j \in \mathcal{T}_x} h_{j,k} s / \sqrt{|\mathcal{T}_x|} + \tilde{v}_k\right)$. This leads to the formula of signal to noise ratio (SNR) :

$$\eta = \sum_{k \in \mathcal{R}_x} |\sum_{j \in \mathcal{T}_x} h_{j,k}|^2 / (|\mathcal{T}_x| \sigma_v^2). \tag{11}$$

MRC receivers are particularly designed for fading scenarios, by ensuring that even if one of the branches has a deep fade, the combining operation with the other branches that do not experience a deep fade can lead to correct signal detection

[18]. Let us assume that all the antennas at the transmitter are used for symbol transmission, as well as all the antennas at the receiver are used for decoding the information. The magnitude of the large scale channel component at the receiver vehicle can be obtained by substituting the expression given by (3) into the expression of the SNR given by (11). This leads to:

$$\eta = \alpha \sum_{j\in\mathcal{R}_x} | \sum_{k\in\mathcal{T}_x} (e^{2\pi i\tilde{d}_{j,k}}/\tilde{d}_{j,k} + \Gamma e^{2\pi i\tilde{d}^{(gr)}_{j,k}}/\tilde{d}^{(gr)}_{j,k})|^2, \quad (12)$$

where $\alpha = \frac{P_T G_T G_R}{|\mathcal{T}_x|(4\pi)^2\sigma_v^2}$.

*B. Equal gain diversity*

Equal Gain combining refers to the scheme where all the received signals are simply averaged $\mathbf{g}_{rx} = \mathbf{1}$, instead of being weighted by each measured channel component. The SNR expression for the ECG technique results to be:

$$\eta = \alpha | \sum_{k\in\mathcal{R}_x} \sum_{j\in\mathcal{T}_x} h_{j,k}|^2. \quad (13)$$

Let us now substitute the expression given by (3) into the expression of the SNR given by (13). This leads to:

$$\eta = \alpha | \sum_{k\in\mathcal{R}_x} \sum_{j\in\mathcal{T}_x} \left(e^{2\pi i\tilde{d}_{j,k}}/\tilde{d}_{j,k} + \Gamma e^{2\pi i\tilde{d}^{(gr)}_{j,k}}/\tilde{d}^{(gr)}_{j,k}\right)|^2. \quad (14)$$

*C. Full diversity*

As benchmark of the proposed schemes, we detail here a solution where all channel components are used ideally for diversity combining. This scheme is called here “full diversity” (FD). This leads to the following formula for the SNR:

$$\eta = \sum_{k\in\mathcal{R}_x} \sum_{j\in\mathcal{T}_x} |h_{j,k}|^2/|\mathcal{T}_x|\sigma_v^2. \quad (15)$$

Let us substituting the expression given by (3) into the expression of the SNR given by (15). This leads to:

$$\eta = \alpha \sum_{k\in\mathcal{R}_x} \sum_{j\in\mathcal{T}_x} |e^{2\pi i\tilde{d}_{j,k}}/\tilde{d}_{j,k} + \Gamma e^{2\pi i\tilde{d}^{(gr)}_{j,k}}/\tilde{d}^{(gr)}_{j,k}|^2. \quad (16)$$

*D. Antenna selection*

We propose a modified scheme based on antenna selection. The idea behind this proposal is that not always having all the available Tx and Rx antennas is beneficial for improved LOS performance. There could be configurations of multiple antennas that can experience deeper fades than other configurations. Therefore, in the proposed scheme, both the optimum transmit and receive antenna sets can be calculated to maximize performance as follows:

$$\eta_{max} = \max_{\mathcal{T}_x,\mathcal{R}_x} \eta, \quad (17)$$

where

$$\eta = \tilde{\alpha} \sum_{k\in\mathcal{R}_x} \delta_k \sum_{j\in\mathcal{T}_x} \xi_{j,k} h_{j,k}.$$

The values $\tilde{\alpha} = \alpha$, $\delta_k = 1$ and $\xi_{j,k} = h^*_{j,k}$ refer to full diversity. The values $\tilde{\alpha} = \alpha$, $\delta_k = \sum_{j\in\mathcal{T}_k} h^*_{j,k}$ and $\xi_{j,k} = 1$ correspond to MRC. Finally, the values $\tilde{\alpha} = \alpha \sum_{k\in\mathcal{R}_x}\sum_{j\in\mathcal{T}_x} h^*_{j,k}$, $\delta_k = 1$ and $\xi_{j,k} = 1$ correspond to EGC. The optimization in (17) is conducted using an exhaustive search algorithm. In practice, antenna selection can be activated when two connected vehicles have a good estimation of the average distance between them or when channel estimation allows the system to know accurate propagation conditions between vehicles. The objective of the multiple antenna transceiver approach is to minimize the fading or destructive interference that is typical of two-ray model propagation. By combining different locations of receive and transmit antenna and processing at the receiver, the intention is to obtain less probability of low LOS signal quality at the receiver end.

## VI. Results

Consider a 2-vehicle configuration with $N_{Tx} = N_{Rx} = 4$ antennas with variable distance between vehicles. Two sets of antennas will be placed at different heights on each vehicle. The highest position will be given by $z_1 = 2$ meters while the lowest position will be $z_2 = 0.7$ meters. The width of the vehicles is set to 1.5 meters. The lower antennas will be placed 0.2 meters shifted towards the front/back of the following/lead car. Simulation settings are given in Table I.

The results of the different combinations of transmit and receive antennas with different processing algorithms (MRC, EGC and FD) as well as the selective antenna processing approach are displayed from Fig. 2 to Fig. 4. Some of the results include the performance without ground reflection to evaluate how fades or peaks in received signal are produced by destructive/constructive interference of the multiple ground reflections (denoted by “1-ray”). Fig. 2 shows the maximum and minimum eigenvalues, as described in Eq. (7), for the channel matrix versus distance between vehicles using 6GHz center frequency. The figure shows that there is a relative good diversity of the MIMO system to achieve parallel information transmission. However, the minimum eigenvalues seem to be very low, which suggest that due to the configuration of the system, full rank might not be achieved. We also recall that these MIMO analysis tools are more intended to fading channels, and that the analysis here presented uses deterministic multiple rays.

Fig. 3 depicts the received signal strength in dB versus distance between vehicles for various MIMO transmission options with different receiver combining strategies. As it can be seen in this figure, antenna selection configuration shows better signal quality observed at the receiver side. Moreover, to evaluate the performance considering polarization of the antenna, we changed the polarization of antennas in both sides of communication from vertical to horizontal polarization and observe the consequences of this setup modification (horizontal denoted by “h” and vertical by “v”). In general, horizontal polarisation is not much different to vertical polarization. However, the cross-polarization results (denoted by “x”) show a promising reduction (smoothing) of fades for 4x4 configuration. The figure also shows that the effect of dielectric losses of asphalt on 4x4 EGC horizontal solution (denoted by “4x4EGCh*”) seem to be visible but minimum.

TABLE I: Simulation parameters

| Variable | Meaning | value |
|---|---|---|
| $d_{veh}$ | Intra-vehicular distance | 1-10 |
| $h_1$ | height of top antennas | 2 |
| $h_2$ | height of bottom antennas | 0.7 |
| $v_w$ | vehicle width | 1.5 |
| $\epsilon_r$ | relative permittivity (asphalt) [15] | 4 |
| $\lambda$ | wavelength | 0.05m (6GHz) |
| $\sigma$ | conductivity (asphalt) [15] | 0.02 |
| $h_{j,k}$ | Channel between antenna $j$ and antenna $k$ | |
| $N_{Tx}$ | Number of Tx antennas | |
| $N_{Rx}$ | Number of Rx antennas | |
| $P_T$ | Tx Power | |
| $\Gamma$ | Reflection coefficient | |
| $\mathbf{s}$ | Transmitted signal across antennas | |
| $G_T, G_R$ | Tx and Rx Antenna gains | 1 |
| $\mathcal{R}_x$ | Set of antennas used at the Rx side | |
| $\mathcal{T}_x$ | Set of antennas used at the Tx side | |

To evaluate the capacity of channel (bps/Hz) as described in Eq.(6), several antenna configuration at both sides versus distance between vehicles are plotted in Fig. 4. In comparison with ground reflected wave propagation, the capacity decreased significantly, while full diversity model have been considered. Once again the results seem to show that diversity combining techniques that are successful in fading environments, in our particular settings they reduce sometimes their performance. This figure also presents the effect of scattering using the V2V stochastic model in [14] with a Rice factor of 3dB showing that our LOS model provides good approximation when Rice factors are relatively low. Fig. 5 shows the results for SNR versus distance in the range of 10 to 1000m using a logarithmic scale for the x-axis.

In some of the figures presented, the EGC solution overlaps antenna selection as the highest performance solution. The reason is that, in general, EGC provides higher gains in deterministic channel settings, while MRC performs better in randomized fading channel conditions. In our case, channels are deterministic so as to better analyse the impact of destructive or constructive interference between the multiple rays resulting from the multiple Tx and Rx antennas with ground reflected components. Thus our selective antenna approach and ECG, perform better for most of the evaluated cases.

## VII. Conclusions

This paper has presented an extension of the two ray model by considering multiple antennas at both transmitter and receiver side for V2V communication. The results show that by using transmit and receive diversity, particularly equal gain combining strategy performs well for smoothing the fades created by multiple rays (including ground reflections) being received by the multiple antennas of the configuration. An antenna selection algorithm was observed to provide the best performance. We figured out from our investigation that EGC and in general averaging operations outperform full diversity solutions that are commonly the best solution in settings with random fading variations. The reason why the tools for fading distributions tend to perform worse is our deterministic channel with multi-ray components.


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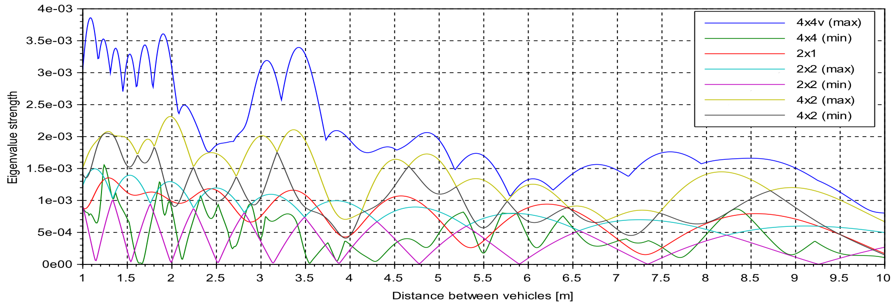


Fig. 2: Maximum and minimum singular values for the channel matrix versus distance between vehicles.

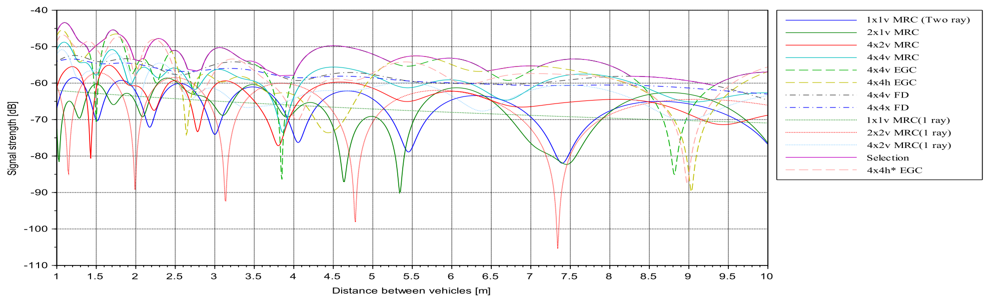


Fig. 3: Received signal strength (dB) vs distance between vehicles for several configurations of multiple antennas at the transmitter and receiver side, considering ground reflected wave propagation, EGC and full diversity.

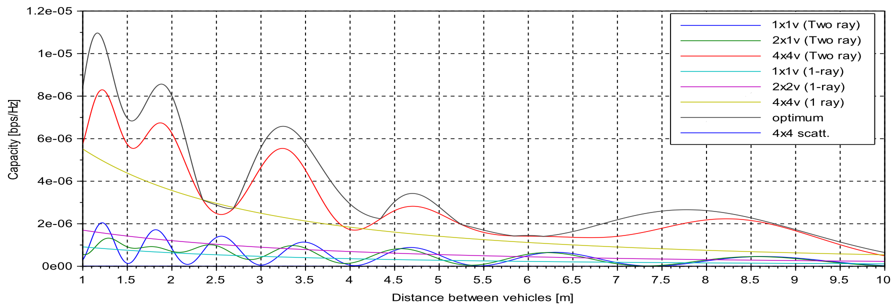


Fig. 4: Capacity (bps/Hz) vs distance between vehicles for several configurations of multiple antennas at the transmitter and receiver side, considering ground reflected wave propagation, EGC and full diversity.

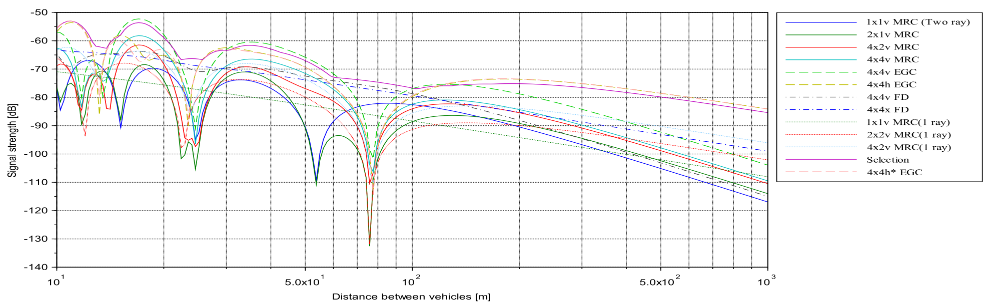


Fig. 5: Received signal strength (dB) vs distance between vehicles for several configurations of multiple antennas at the transmitter and receiver side, considering ground reflected wave propagation, EGC and full diversity.