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Abstract

This paper investigates the improvement in terms of outage probability of a vehicle-to-vehicle (V2V) communication link with respect to the density of antennas used at each vehicle end. The objective is to find a trade-off between system complexity and communication performance considering that the deterministic component of the link is affected explicitly by multiple ground reflections (self-interference). The antennas are assumed to be located at regularly distributed positions across the surface of contiguous vehicles. Part of the work assumes symbol repetition at the transmitter side, and different signal combining mechanisms at the receiver side, namely, maximum-ratio and equal-gain combining (MRC and EGC, respectively). The objective is to minimize outage probability of the link with deterministic and stochastic channel components (Rice-distributed), where the line-of-sight (LOS) is affected by multi-ray ground reflections as an extension of the well-known two-ray model. This scenario is considered more realistic for V2V scenarios due to the potential proximity of ground to the antenna elements. The outage probability is calculated over a range of inter-vehicle distances with respect to the free-space loss solution. The results show that performance is improved even for a relatively small number of antennas and that a critical point is reached beyond which improvement is only differential. This suggests that an optimum trade-off can be obtained to ensure a value of outage probability with a complexity constraint over a range of inter-vehicle distances.

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***Abstract*—This paper investigates the outage probability of a vehicle-to-vehicle (V2V) multiple antenna communication link with respect to the density of antennas. The objective is to study the trade-off between complexity (number of antennas) and link performance considering explicit ground reflections. The antennas are assumed to be located at regularly distributed positions across the surface of contiguous vehicles. Under the assumption of symbol repetition across Tx antennas, we also focus on well-known mechanisms such as maximum-ratio and equal-gain combining (MRC and EGC, respectively). The objective is to minimize the outage probability of the V2V link with deterministic and stochastic channel components (i.e., Rice-distributed), where the line-of-sight (LOS) is affected by ground reflections (as an extension of the two-ray model). This scenario is more realistic for V2V applications due to the proximity of the antennas to the ground. The outage probability is averaged over a range of inter-vehicle distances with respect to the free-space loss solution. The results show that performance is improved even for a relatively small number of antennas, and that a point is reached beyond which improvement becomes differential. This suggests an optimum trade-off between outage probability and complexity can be reached over a range of inter-vehicle distances.**

***Index Terms*—antenna arrays, design optimization, MIMO, RF communications, scattering problems, signal processing.**

I. Introduction

Multiple-Input Multiple-Output (MIMO) systems lie at the core of improved wireless connectivity. In V2X (vehicle-to-everything), MIMO design is particularly challenging due to propagation and distortion issues [1], [2]. Propagation models in V2X can be broadly grouped in deterministic ray tracing and geometric stochastic. The simplest deterministic model is the line-of-sight (LOS) model, which ignores ground reflections (e.g., [3]). Ground reflections can be studied with the well-known two-ray model (see [4]), while stochastic solutions consider randomized scatterer distributions (e.g, [5]).

To the best of our knowledge, existing V2X models have not considered the explicit interaction of ground reflections and stochastic components. Thus, the present work aims to partially fill this gap by introducing a hybrid model that considers Rice fading links enriched with a LOS component with explicit ground reflections. This component is an extension of the well-known two-ray model to a scenario with multiple antennas with multiple reflections.

The work here presented is an extension of the paper in [6] where the analysis was conducted with a V2V LOS MIMO model with ground reflections and without stochastic scattering. This model had been previously proposed in [7] as an extension of the two-ray model for V2V MIMO transceivers. The main contribution of this paper on top of the past work in [6] is the inclusion of stochastic channel components for the full analysis of the V2V MIMO environment. This provides a more realistic framework for the convergence of deterministic and stochastic components of V2X links.

Different approaches are considered to model the stochastic links. We use both conventional Rice and also double Rice statistics that capture scenarios with different types of interactions between scatterers. Spatial correlation is also introduced in two different ways: using differences in the angle of arrival (AoA), and with constant spatial correlation.

The overall performance is compared (as outage) to the case of the free-space path loss (FSPL) without reflections and without scattering. The outage probability is averaged over a range of inter-vehicle distances to study the trade-off between the number of antennas and the average link performance. The objective is to reach an optimum number of antennas for a range of inter-vehicular distances. The effects of antenna position on capacity have been studied before, for example in [8] and in [9]. Our work differs from these works in the use of outage probability as a target metric.

The results show that performance is improved even for a relatively low number of antennas and that a critical point is reached beyond which improvement is only marginal. This suggests a trade-off between outage and complexity can be reached over a range of inter-vehicle distances. This outcome can help in the design of vehicular networks to estimate the number of antennas that can ensure a minimum outage probability to prevent safety, reliability or security issues (e.g., [10], [11]) of high-level applications such as platoons.

The rest of the paper is organized as follows. Section II and Section III introduce the description of the scenario and signal model, respectively. Multiple antenna processing algorithms are presented in Section IV and the proposed trade-off analysis in Section V. Section VI summarizes and discusses the main results of our work. Finally, Section VII concludes the paper.

II. System Model

Consider the V2V multiple antenna model depicted in Figure 1 where each vehicle contains two horizontal arrays of antennas. The first array is placed at the rooftop of each vehicle, and the second at the corresponding front (or rear) part or bumper of the car. Both arrays are thus mirrored in the contiguous vehicle, i.e., $N_{Tx} = N_{Rx} = 2N$, where N is the number of antennas per array.

The distance between antenna j in the transmitter ($j \in \mathcal{T}_x$) and antenna k in the receiver ($k \in \mathcal{R}_x$) is denoted by $d_{j,k}$. $\mathcal{T}_x$ denotes the set of Tx antennas and R_x is the set of Rx antennas. The distance for the ground reflected ray is denoted by $d_{j,k}^{(gr)}$. The channel between the j^{th} transmitter antenna and the k^{th} receiver antenna is denoted by $h_{j,k}$ and will be defined as the contribution of the line-of-sight (LOS) *deterministic* component and the non-line-of sight (NLOS) *stochastic* component $h_{j,k} = h_{j,k}^{LOS} + h_{j,k}^{NLOS}$.

All LOS channels will be described by an extension of the two-ray model. We also considered equivalent channel variables that absorb the transmit power P_T, normalization factors, as well as the Tx (G_T) and Rx (G_R) antenna gains. This can be expressed mathematically as follows [4]:

$$h_{j,k}^{LOS} = \sqrt{\frac{P_T G_T G_R \kappa}{(4\pi)^2 N_{Tx}(\kappa+1)}} \left(\frac{e^{2\pi i \tilde{d}_{j,k}}}{\tilde{d}_{j,k}} + \Gamma_{j,k} \frac{e^{2\pi i \tilde{d}_{j,k}^{(gr)}}}{\tilde{d}_{j,k}^{(gr)}} \right) \quad (1)$$

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 ground reflected electric distances, $\Gamma_{j,k}$ is the reflection coefficient for link (k, j), λ is the operational wavelength and $i = \sqrt{-1}$. The reflection coefficient for vertical polarization can be written as follows [12]:

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

where $\beta_{j,k}$ is the angle of reflection for ray (k, j), while n_r is the ground refractive index $n_r = \sqrt{\epsilon_r}$, and ϵ_r the relative permittivity of asphalt [13].

The NLOS channels will be modelled as random processes with two types of statistics. The first type considers conventional Rice statistics modelling the channel as a non-zero-mean circular complex Gaussian random processes with variance $\sigma_{j,k}^2$: $h_{j,k} \sim \mathcal{CN}(h_{j,k}^{LOS}, \sigma_{j,k}^2)$. The Rice factor is defined as the ratio of the power of the LOS to the NLOS component: $\kappa = \frac{|h_{j,k}^{LOS}|^2}{\sigma_{j,k}^2}$, where $\sigma_{j,k}^2 = \frac{P_T G_T G_R}{(4\pi)^2 N_{Tx}(\kappa+1)\tilde{d}_{j,k}^2}$.

The second type of statistics for the scattering component considers double Rice random variables that are used in some V2V channel models. Two correlation models will be used for the V2V MIMO system. The first model is used exclusively for the case of simple Rice statistics and consists of a constant correlation model described by the following equation:

$$h_{j,k}^{NLOS} = \sigma_{j,k}(\sqrt{1-\rho} Z_{j,k} + \sqrt{\rho}\nu), \quad (3)$$

where $Z_{j,k}$ and ν are two independent circular complex Gaussian random variables with unit variance, and ρ is the constant correlation coefficient between any pair of antenna links of the V2V model. The second correlation model employs a sum of sinusoids of a set of uniformly distributed scatterers around one or both of the vehicles and the difference in the angle of arrivals (AoAs) to different antenna elements defines the correlation statistics of the multiple antenna model (phase correlation). We consider the following channel models:

$$h_{j,k}^{NLOS}(t) = \sum_{w=1}^{N_s} C_w e^{i\pi F_d \cos(\nu_w) t + r_w}, \quad (4)$$

for simple interaction of scatterers, where F_d is the Doppler frequency, ν_w is the AoA of ray w in antenna k, r_w is a random phase for ray w and C_w a normalization factor. In the case of double interaction of scatterers we use:

$$h_{j,k}^{NLOS}(t) = \sum_{u=1}^{N_s} \sum_{w=1}^{N_s} C_{u,w} e^{i\pi F_d(\cos(\xi_{u,j}) + \cos(\nu_{w,k}))t + r_{u,w}}, \quad (5)$$

where $\xi_{u,j}$ is the angle of departure (AoD) for ray u from antenna j, $\nu_{w,k}$ is the AoA of ray w in antenna k, and $r_{u,w}$ is a random phase.

III. MIMO Model

Considering the transmit and receive beam-forming arrays, denoted by $\mathbf{G}_{tx}$ and $\mathbf{G}_{rx}$, respectively, the received signal can be written as follows:

$$\mathbf{x} = \mathbf{G}_{rx}\mathbf{H}\mathbf{G}_{tx}\mathbf{s} + \mathbf{v}, \quad (6)$$

where $\mathbf{s} = [s(0), s(1), \ldots, s(N_{Tx} - 1)]^T$ is the vector of transmitted symbols across the different antennas, and $(\cdot)^T$ is the transpose operator. The vector $\mathbf{v}$ represents a zero-mean additive circular complex Gaussian noise with variance σ_v^2. $\mathbf{H}$ is the MIMO channel matrix of size $N_{Rx} \times N_{Tx}$.

A. Capacity and SVD analysis

The capacity of MIMO systems is defined as [14]:

$$C = \log_2 \det \left|\mathbf{I} + \mathbf{H}\mathbf{H}^H/N_{Tx}\right|, \quad (7)$$

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:

$$\mathbf{H} = \mathbf{U}\boldsymbol{\Sigma}\mathbf{V}, \quad (8)$$

where $\mathbf{U}$ and $\mathbf{V}$ are the unitary matrices containing the receive and transmit optimum beam-forming vectors. The diagonal matrix $\boldsymbol{\Sigma}$ contains the singular values of the channel. These singular values allow us to study the feasibility of the MIMO channel created by direct and ground reflected components.

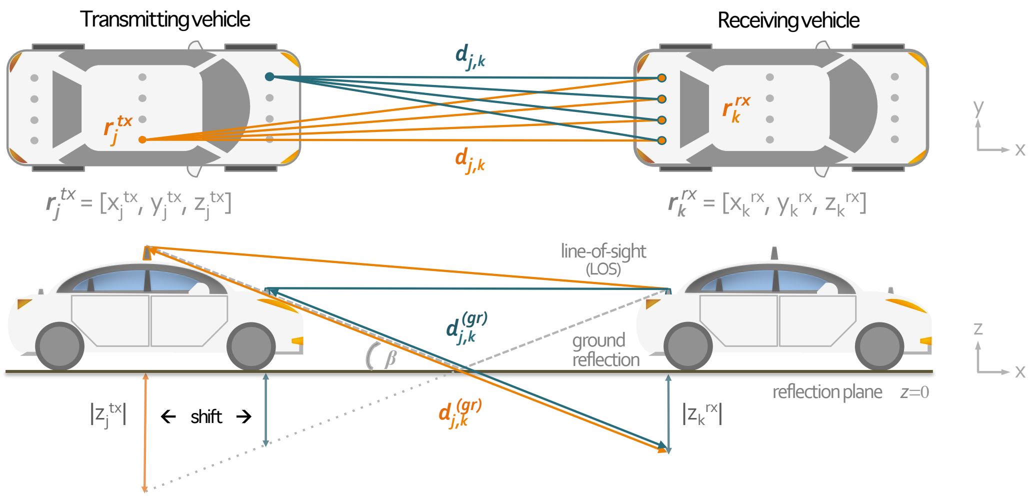


Fig. 1: V2V link showing: (bottom) both the LOS and ground reflected paths followed by the signals from two transceivers mounted on the transmitting vehicle (left) when sent to the antennas on the receiving vehicle (right), according to the two-ray model; and (top) an aerial view of this V2V channel [6].

IV. Diversity Combining

Let us assume for simplicity a single symbol repeated across all active Tx antennas. The received signal in (6) becomes a SIMO (single input multiple output) problem as described in our previous work in [7]. The pre-processed received signal in the kth antenna of the receiver is given by:

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

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

A. MRC diversity

Maximum-ratio combining (MRC) at the receiver side is implemented by using as receiver beam-forming vector the complex conjugate of the wireless channel. This leads to the following post-processing signal:

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

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

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

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. Let us now substitute the expression given by (1) into the expression of the SNR given by (11). This leads to:

$$\eta = \alpha_{MRC} \sum_{k \in \mathcal{R}_x} | \sum_{j \in \mathcal{T}_x} (\hat{h}_{j,k}^{LOS} + \hat{h}_{j,k}^{NLOS})|^2 \tag{12}$$

where $\alpha_{MRC} = \frac{P_T G_T G_R}{N_{Tx}(4\pi)^2 \sigma_v^2}$, while $\hat{h}_{j,k}^{LOS}$ and $\hat{h}_{j,k}^{NLOS}$ are the normalized values of the LOS and NLOS components, respectively. From this expression we can observe that the instantaneous SNR is a sum of the squares of non-zero mean circular complex and correlated Gaussian random variables. The Cumulative Density Function (CDF) of the instantaneous SNR expression in (12) is denoted by $F_\eta(y) = \Pr\{\eta \leq y\}$ which is also the outage probability of the link.

B. Rice fading

In the case of conventional Rice fading with the linear correlation model in (3), the expression in (12) becomes: $\eta = \alpha_{MRC} \sum_{k \in \mathcal{R}_x} | \sum_{j \in \mathcal{T}_x} (\hat{h}_{j,k}^{LOS} + \hat{\sigma}_{j,k}(\sqrt{1-\rho} Z_{j,k} + \sqrt{\rho}\nu))|^2$. Based on this expression, it is possible to write the characteristic function of the instantaneous SNR conditioned on the value of the r.v. ν as follows:

$$\Psi_{\eta|\nu}(i\omega) = \prod_{k \in \mathcal{R}_x} \frac{1}{1 - i\omega\sigma_k^2} e^{\sum_{k \in \mathcal{R}_x} \dfrac{i\omega\mu_k^2}{1 - i\omega\sigma_k^2}}, \tag{13}$$

where $\mu_k = \sum_{j \in \mathcal{T}_x} (h_{j,k}^{LOS} + \sqrt{\rho}\nu_{j,k})$, $\nu_{j,k} = \sigma_{j,k}\nu$, $\sigma_k^2 = \sum_{j \in \mathcal{T}_x} \sigma_{j,k}^2$, and $\Psi_X(i\omega) = \int_x f_X(x) e^{i\omega x} dx$ for any r.v. X with Probability Density Function (PDF) given by $f_X(x)$ and CDF given by $F_X(x) = \int_{-\infty}^{x} f_X(w) dw$.

C. Symmetric scattering

The solution given in the previous subsection can be further simplified by assuming the random components experienced by all the antennas are symmetrical in power distribution. This suggests the scatterers are located uniformly distributed and a relatively the same distance (far-field) from all the antennas.

$$\Psi_{\eta|\nu}(i\omega) = \frac{1}{(1 - i\omega\sigma^2)^{N_{Rx}}} e^{\dfrac{i\omega N_{Rx}\mu^2}{1 - i\omega\sigma^2}}, \tag{14}$$

where σ^2 is the symmetrical power of all scattered signals.

D. EGC diversity

Equal Gain combining refers to the scheme where all the received signals are simply averaged instead of being weighted by each measured channel component. The received signal is therefore given by

$$x = \sum_{k\in\mathcal{R}_x} \tilde{x}_k = \sum_{k\in\mathcal{R}_x} (\sum_{j\in\mathcal{T}_x} h_{j,k}s + \tilde{v}_k),$$

The SNR can be therefore written as:

$$\eta = |\sum_{k\in\mathcal{R}_x}\sum_{j\in\mathcal{T}_x} \hat{h}_{j,k}|^2/(N_{Rx}\sigma_v^2), \tag{15}$$

which can also be written as follows::

$$\eta = \alpha_{EGC}|\sum_{k\in\mathcal{R}_x}\sum_{j\in\mathcal{T}_x}\left(\hat{h}_{j,k}^{LOS} + \hat{h}_{j,k}^{NLOS}\right)|^2, \tag{16}$$

where $\alpha_{EGC} = \frac{P_T G_T G_R}{N_{Tx}N_{Rx}|(4\pi)^2\sigma_v^2}$. Since the scattering components $h_{j,k}^{NLOS}$ are all circular complex Gaussian random variables the summation is also a Gaussian variable with variance equal to the sum of the variances. This means the SNR η is a non-central chi-square random variable with variance equal to $\sigma^2 = \sum_{j\in\mathcal{R}_x,k\in\mathcal{T}_x}\sigma_{j,k}^2$. The characteristic function can be therefore written as follows.

$$\Psi_\eta(i\omega) = \frac{1}{1-i\omega\sigma^2} e^{\frac{i\omega\left|\sum_{j\in\mathcal{T}_x,k\in\mathcal{R}_x} h_{j,k}^{LOS}\right|^2}{1-i\omega\sigma^2}}. \tag{17}$$

The back-transform of the CF can be written in the standard form for non-central chi-square distributions.

E. 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: $\eta = \sum_{k\in\mathcal{R}_x}\sum_{j\in\mathcal{T}_x}|h_{j,k}|^2/\sigma_v^2$. Let us substitute the expression given by (1) into the expression of the SNR. This leads to:

$$\eta = \alpha_{fd}\sum_{k\in\mathcal{R}_x}\sum_{j\in\mathcal{T}_x}|h_{j,k}^{LOS} + h_{j,k}^{NLOS}|^2. \tag{18}$$

where $\alpha_{fd} = \frac{P_T G_T G_R}{N_{Tx}|(4\pi)^2\sigma_v^2}$. The characteristic function of this random variable can be written as follows

$$\Psi_{\eta|\nu}(i\omega) = \prod_{k\in\mathcal{R}_x,i\in\mathcal{T}_x}\frac{1}{1-i\omega\sigma_{j,k}^2} e^{\sum_{k\in\mathcal{R}_x,j\in\mathcal{T}_x}\frac{i\omega\mu_{j,k}^2}{1-i\omega\sigma_{j,k}^2}}, \tag{19}$$

where $\mu_{j,k} = h_{j,k}^{LOS} + \sqrt{\rho}\nu_{j,k}$, and $\nu_{j,k} = \sigma_{j,k}\nu$.

V. Optimum Trade-off

Let us define the outage probability of the V2V link as the probability that the ratio of the SNR to the free-space loss (FSL) solution falls below a threshold (ψ) in the range of inter-vehicle distances $[d_{min}, d_{max}]$. This can be written as the ratio of the average of the outage probability in the defined distance range to the length of the range:

$$\Theta = \Pr\{\eta/\eta_{FSL} \leq \psi\} = \frac{\int_{d_{min}}^{d_{max}} F_{\eta/\eta_{FSL}}(\beta)dy}{d_{max} - d_{min}}, \tag{20}$$

where y is the auxiliary variable denoting the inter-vehicle distance, and η_{FSL} is the performance of the FSL link without ground reflections. Therefore, the performance of the V2V MIMO LOS link can be expressed as the complement to one of the outage probability $\gamma = 1 - \Theta$. The trade-off analysis can be expressed as an optimization problem:

$$N_{opt} = \arg\min_N \Theta \qquad \text{s.t.} \quad N \leq N_{max}, \tag{21}$$

where N_{opt} and N_{max} denotes the optimal and maximum number of antennas per array, respectively. The constraint serves as a complexity control in the optimization.

Alternatively, the problem can be expressed also as:

$$\min(N_{Tx} + N_{Rx}) \qquad \text{s.t.} \quad \gamma = \xi, \tag{22}$$

which indicates the minimization of system complexity subject to a constant relative performance denoted by ξ. In this paper we plot the CDF for various values of numbers of antennas to search for the optimum trade-off between these two values.

VI. Evaluation

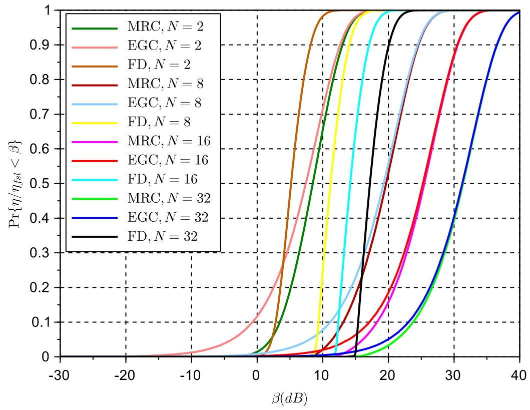
A. Setup

Consider a 2-vehicle configuration with varying number of antennas $2N$ on each car, and a range of inter-vehicular distance $d \in [50, 500]$m. The antennas are distributed in two horizontal linear arrays with an equal number of vertically polarized antennas on each vehicle, i.e. $2N = N_{Tx} = N_{Rx}$.

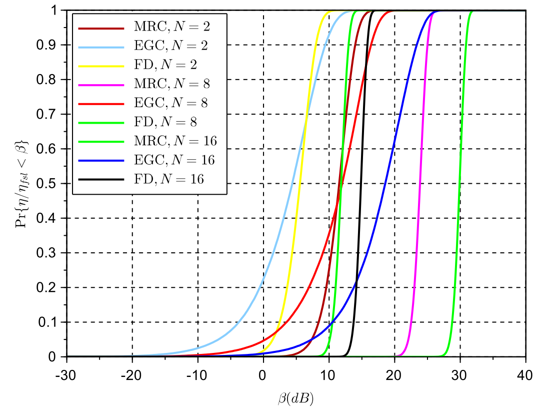
The arrays are positioned at two different heights w.r.t. the ground plane, $z_1 = 1.2$m and $z_2 = 0.6$m. Both arrays are parallel on the y-axis, and separated by 1m on the x-axis, i.e. a shift towards the front/back of the following/lead car, as depicted in Fig. 1. The width of the cars is set to 2m, over which the position of the antennas in the array is regularly spaced according to N. As feasibility constraint, we assume $N \leq 40$. This constraint meets the current state of the art of multiple antenna transceivers. A number of antenna elements above 50 or 100 is considered as massive MIMO, which is a

TABLE I: List of main variables.

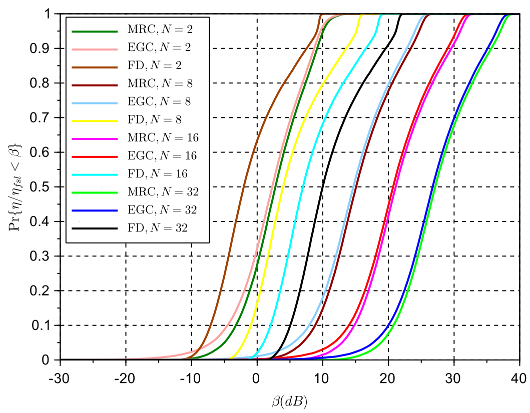
Variable	Meaning
$h_{j,k}$	Channel between Tx antenna j and Rx antenna k
N_{Tx}	Number of Tx antennas
N_{Rx}	Number of Rx antennas
P_T	Tx Power
Γ	Reflection coefficient
$\mathbf{s}$	Transmitted signal across antennas
$\mathbf{r}_k$	Rx Signal in antenna k
$\mathbf{v}_k$	Noise vector in antenna k
G_T, G_R	Tx and Rx Antenna gains
$\mathcal{R}_x$	Set of antennas used at the Rx side
$\mathcal{T}_x$	Set of antennas used at the Tx side



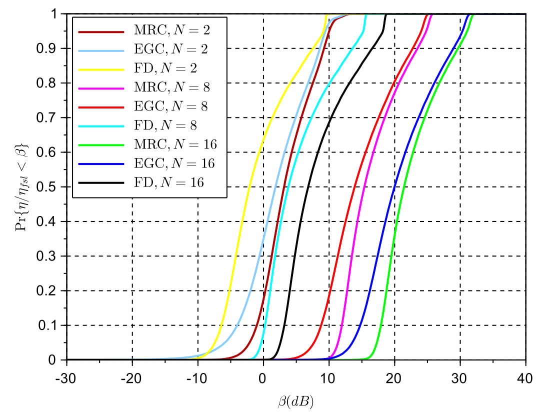
(a) $\kappa_{dB} = -15dB$, Rice fading constant correlation.



(c) $\kappa_{dB} = -15dB$, Rice fading phase correlation.



(b) $\kappa_{dB} = 15dB$, Rice fading constant correlation.



(d) $\kappa_{dB} = 15dB$, Rice fading phase correlation.

Fig. 2: CDF of η/η_{fsl} (average outage probability) for different number of antennas under MRC and EGC receivers in presence of ground reflection: (left) Rice fading constant correlation and (right) Rice fading phase correlation.

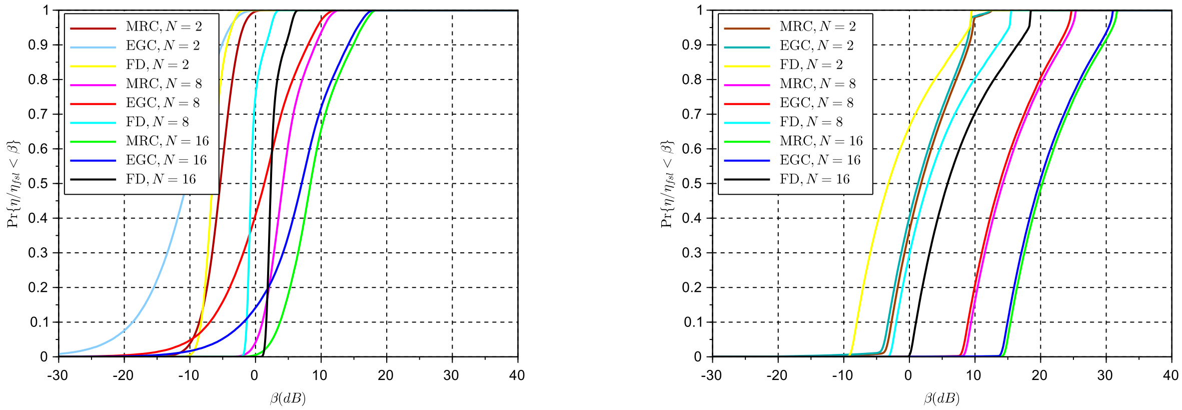
technology mainly intended for base stations or access points. By contrast, at the vehicle side, the number of antennas will be considered limited, but still higher than for conventional mobile terminals. In addition, the size of vehicles can also pose a constraint on how many antennas can be placed. It is worth pointing put out that future antenna technology could lead to the feasibility of massive MIMO also at the vehicle end. As for the the rest of parameters, we assume: $\lambda = 0.125$, and $\epsilon_r = 4$. The chosen wavelength meets the frequency allocation of ISM systems in the 2.4GHz band, while the electrical parameters of the ground are consistent with the values used for pavement in dry conditions [13].

B. Results

Fig. 2(a) shows the CDF of the performance of the V2V MIMO link with ground reflection w.r.t. the FSL case (without reflection). This is also the outage probability in (20). The results were obtained for a simple Rice fading channel with constant correlation coefficient $\rho = 0.5$ and Rice factor $\kappa_{dB} = -15$. The results in Fig 2(b) show a scenario with higher Rice factor $\kappa_{dB} = 15$. It can be observed that the performance of MRC and full diversity are higher than EGC. However, when the correlation and the rice factor increase, EGC starts gaining momentum. This is because the channel becomes more deterministic.

Fig. 2(c) and Fig. 2(d) mimic the results presented in the previous two figures, but this time using a phase correlation Rice fading model. The results show a similar trend, but the difference between EGC and MRC is smaller, particularly in the case of $\kappa_{dB} = -15$. Finally, Fig. 3(a) and 3(b) show the results with a Double rice fading model with phase correlation. In all cases, the difference is observed mainly in the figure with decreased line of sight. In the regime with high LOS, the results seem very similar in all cases.

Moreover, in all cases the rate of improvement is much higher at low numbers of antennas than at higher ranges. This suggests the existence of a trade-off between performance and complexity that can be used to solve the constrained optimization problems in (21) and (22). For example, the



(a) $\kappa_{dB} = -15dB$, Double Rice fading phase correlation
.

(b) $\kappa_{dB} = 15dB$, Double Rice fading phase correlation
.

Fig. 3: CDF of η/η_{fsl} (average outage probability) for different number of antennas under MRC and EGC receivers in presence of ground reflection: (left) Double Rice fading constant correlation and (right) Double Rice fading phase correlation.

gain obtained by increasing the number of antennas from $N = 2$ to $N = 8$ is limited as compared to when we increase from $N = 16$ to $N = 32$. Therefore, there is no need to increase dramatically system complexity by adding large numbers of antennas. The addition of a few antennas is much more effective than an indiscriminate complexity escalation.

VII. Conclusions

This paper complements our prior work in [6] by extending the V2V MIMO link multiple ray tracing analysis with ground reflection to consider stochastic channel components. This makes the outage probability analysis to be more realistic. The results show that classical reception diversity techniques, namely EGC and MRC, can be used to effectively mitigate fades, including those created by multiple ground reflections, as well as stochastic fading occurrences. Particularly, the CDF of the reception probability of the link shows MRC improvements dominating over EGC under varying configurations. Yet, suggesting the existence of a trade-off region where the number of antennas could be optimized. In future work, we aim at extending the analysis to several cars within a platoon, as well as to specific road infrastructures, e.g. tunnels.

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