On the Optimum Number of Antennas for V2V LOS Links with Ground Reflection

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Abstract

This paper investigates the rate of improvement of a vehicle-to-vehicle (V2V) line-of-sight (LOS) communication link with respect to the density of antennas used at each vehicle. The objective is to find a trade-off between system complexity and communication performance considering that the link is affected by multiple ground reflections (self-interference). The antennas are assumed to be located at regularly distributed positions across the surface of contiguous vehicles. 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 main objective of the optimization investigated here is to minimize the outage probability of the LOS link affected by multi-ray ground reflections (obtained over a range of inter-vehicle distances) with respect to the free-space loss case. 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, suggesting 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 rate of improvement of a vehicle-to-vehicle (V2V) line-of-sight (LOS) communication link with respect to the density of antennas used at each vehicle. The objective is to find a trade-off between system complexity and communication performance considering that the link is affected by multiple ground reflections (self-interference). The antennas are assumed to be located at regularly distributed positions across the surface of contiguous vehicles. 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 main objective of the optimization investigated here is to minimize the outage probability of the LOS link affected by multi-ray ground reflections (calculated over a range of inter-vehicle distances) with respect to the free-space loss case. 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.**

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

I. INTRODUCTION

The automotive industry is experiencing a digital revolution. Future vehicles will be connected to cloud/edge infrastructure, thus enabling applications such autonomous control, energy optimization, traffic management, etc. This concept requires a communication infrastructure that supports critical decision making, ultra-low latency transmission, and real time control. New wireless technologies are being developed to comply with these requirements and thus ensure road, user, and pedestrian safety. Vehicle-to-everything (V2X) technology will thus play a key role in smart city applications (see [1]).

Multiple antennas lie at the core of improved wireless connectivity. Therefore, a crucial aspect in modern V2X design is propagation modelling for this new technology. Propagation in vehicular networks has been addressed under a variety of models (e.g. ray tracing, geometric stochastic, etc.) [2]–[4] under single and multiple antenna settings. Optimization of the antenna position for V2V (vehicle-to-vehicle) links has been addressed in [5]. Stochastic V2V models can be found, e.g., in [6], and the effects of antenna position on capacity in [7].

Despite these advances, existing results have not covered the issue of the optimum number of antennas needed to compensate the destructive interference of ground reflections in V2X links. This works aims to partially fill this gap, by investigating how the number of antennas in vehicles can compensate the fades produced by ground reflected rays on the line-of-sight (LOS) component. This paper complements our previous work in [8] where we established the model used for V2V MIMO (multiple-input multiple-output) systems with ground reflections as an extension of the two-ray model. The study used different receiver processing algorithms such as maximum-ratio and equal-gain combining (MRC and EGC, respectively). This previous work addressed configurations with a fixed number of antennas.

This paper extends our prior work to a scenario with variable numbers of antenna elements. The overall performance is compared to the case of free space path loss model without reflections. The outage probability is calculated over a range of inter-vehicle distances. The antennas of both leading and following vehicles are assumed to be distributed in two horizontal lines over the surface of each vehicle and their density is changed to investigate the differential increase of performance against the reference model. The results show that performance of the V2V LOS link is improved even for a relatively small number of antennas and that a critical point is reached beyond which the improvement is only marginal, thus suggesting an optimum trade-off between performance and complexity over a range of inter-vehicle distances.

This paper is organized as follows. Section II presents the description of the scenario and signal reception model for V2V links with multiple antennas. Section III introduces the multiple antenna processing algorithms. Section IV proposes the antenna optimization. Section V presents results of our proposals. Finally, Section VI draws conclusions.

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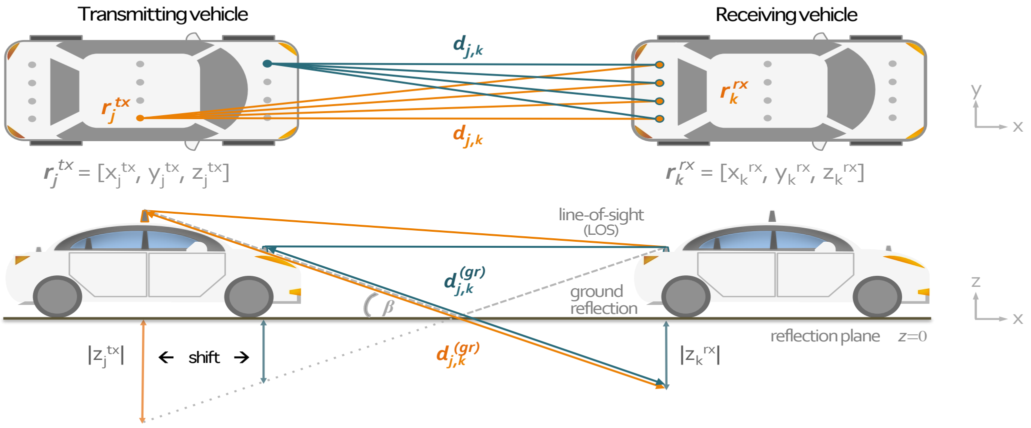

Fig. 1. V2V link showing: (bottom) both the LOS and ground reflected paths followed by the signals from two transceivers mounted on the transmitting vehicle (left) when sent to the antennas on the receiving vehicle (right), according to the two-ray model; and (top) an aerial view of this V2V channel.

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 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. All transmitter antennas are assumed to be used for symbol repetition, while all the antennas at the receiver vehicle are used for decoding the information. This reduces the problem to a single-input multiple-output (SIMO) system.

The distance between antenna j in the transmitter and antenna k in the receiver is denoted by $d_{j,k}$. 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) 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 in the presence of ground reflections.

All channels will be described by a multiple ray model. This can be expressed mathematically as follows [9]:

$$h_{j,k}^{LOS} = \sqrt{P_T G_T G_R}/4\pi(e^{2\pi i\tilde{d}_{j,k}}/\tilde{d}_{j,k} + \Gamma e^{2\pi i\tilde{d}_{j,k}^{(gr)}}/\tilde{d}_{j,k}^{(gr)}) \tag{1}$$

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 the ground reflected electric distances, Γ is the reflection coefficient, P_T/σ_v^2 is the average Tx power to noise ratio, G_T and G_R are the gains of the Tx and Rx antennas, respectively, λ is the operational wavelength and $i = \sqrt{-1}$. The reflection coefficient can be written as follows (modification of [10]):

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

where $A = n_r^2$ and $B = 1$ for vertical polarization, and $A = 1$ and $B = -1$ for horizontal polarization. β is the angle of reflection, while n_r and n_i are the real and imaginary parts, respectively of the complex ground refractive index $n_{gr} = n_r + in_i = \sqrt{\epsilon_r - i\frac{\sigma\lambda}{\epsilon_0 2\pi c}}$, c is speed light, and ϵ_r and σ denote, respectively, the relative permittivity and conductivity of asphalt [11].

III. PERFORMANCE MODEL

A. MRC diversity

Maximum-ratio combining (MRC) receivers are suited for fading scenarios using redundancy between branches [12]. The signal-to-noise ratio (SNR) for this receiver is given by [8]:

$$\eta = \alpha\sum_{j=1}^{N_{Rx}}|\sum_{k=1}^{N_{Tx}}(e^{2\pi i\tilde{d}_{j,k}}/\tilde{d}_{j,k} + \Gamma e^{2\pi i\tilde{d}_{j,k}^{(gr)}}/\tilde{d}_{j,k}^{(gr)})|^2, \tag{3}$$

where $\alpha = \frac{P_T G_T G_R}{N_{Tx}(4\pi)^2\sigma_v^2}$, and $|\cdot|$ is the absolute value operator.

B. ECG diversity

Equal gain combining (EGC) refers to the scheme where all the received signals are simply averaged. The SNR expression for the ECG technique results to be [8]:

$$\eta = \alpha|\sum_{k=1}^{N_{Tx}}\sum_{j=1}^{N_{Rx}}\left(e^{2\pi i\tilde{d}_{j,k}}/\tilde{d}_{j,k} + \Gamma e^{2\pi i\tilde{d}_{j,k}^{(gr)}}/\tilde{d}_{j,k}^{(gr)}\right)|^2. \tag{4}$$

IV. OPTIMIZATION

Let us define the outage probability of the LOS MIMO channel as the probability that the ratio of the signal strength 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 mathematically written as the ratio of the integral of all cases where the signal-ratio surpasses the threshold in the defined distance range to the length of the range:

$$\Theta = \Pr\{\eta/\eta_{FSL} \leq \psi\} = \frac{\int_{d_{min}}^{d_{max}} \text{ind}(\eta/\eta_{FSL} \leq \psi)dy}{d_{max} - d_{min}}, \tag{5}$$

where ind$(\cdot)$ is the indicator function, i.e. ind$(C) = 1$ if "C" is true or 0 otherwise, 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 optimization can be then expressed as follows:

$$N_{opt} = \arg\max_{N} \gamma \qquad \text{s.t.} \quad N \leq N_{max}, \tag{6}$$

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 optimization can be expressed also as:

$$\min(N_{Tx} + N_{Rx}) \qquad \text{s.t.} \quad \gamma = \xi, \tag{7}$$

which indicates the minimization of system complexity subject to a constant relative performance of the link denoted by ξ.

V. EVALUATION

Setup. Consider a 2-vehicle configuration with varying number of antennas on each car, and 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 $N \leq 10$. As for the the rest of parameters, we assume: $\lambda = 0.125$, $\epsilon_r = 4$, and $\sigma = 0.02$.

Results. Fig. 2 shows the cumulative distribution function (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 (5). The results show that as the number of antennas increases, the link performance is also improved. It can also be observed that the gain in the EGC case escalates much faster than the MRC case. 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 (6) and (7). For example, the gain obtained by increasing the number of antennas from $N = 7$ to $N = 10$ is limited as compared when we increase from $N = 4$ to $N = 7$. 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 in improvement than an indiscriminate complexity escalation.

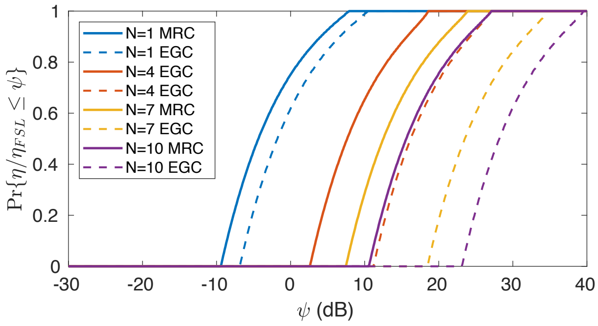

Fig. 2. CDF of the reception probability for different number of antennas under MRC and EGC receivers in presence of ground reflection w.r.t FSL.

VI. CONCLUSIONS & NEXT STEPS

This paper complements our prior work in [8] by extending the V2V MIMO link analysis with ground reflection to a variable number of antennas. Moreover, it investigates the performance of the V2V LOS channel from the perspective of outage probability due to ground reflections, over a range of inter-vehicle distances. The results show that classical reception diversity techniques, namely ECG and MRC, can be used to effectively mitigate fades, including those created by multiple ground reflections. Particularly, the CDF of the reception probability of the link shows ECG improvements dominating over MRC under varying configurations. Yet, suggesting the existence of a trade-off region where the number of antennas could be optimized. In future, we will build upon these observations to provide a comprehensive solution for the optimization problem here defined, assessing the performance of ECG and MRC, as well as by considering additional diversity techniques, e.g., full diversity and antenna selection.

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