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Abstract

This work presents a capacity analysis of Space-Time Block Codes (STBC) for Vehicle-to-Vehicle (V2V) communication in Line-of-Sight (LOS). The aim is to assess how this type of coding performs when the V2V LOS channel is influenced by ground reflections. STBCs of various coding rates are evaluated using antenna elements distributed over the surface of two contiguous vehicles. A multi-ray tracing tool is used to model the multiple constructive/destructive interference patterns of the transmitted/received signals by all pairs of Tx-Rx antenna links. Simulation results show that STBCs are capable of counteracting fades produced by the destructive self-interference components across a range of inter-vehicle distances. Notably, the effectiveness in deep fades is shown to outperform schemes with exclusive receive diversity. Higher-order STBCs with rate losses are also evaluated, showing interesting gains even for low coding rate performance, particularly, when accompanied by a multiple antenna receiver. Overall, these results can shed light on how to exploit transmit diversity in slow fading vehicular channels.

Orthogonal Space-Time Block Coding for V2V LOS Links with Ground Reflections

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***Abstract*—This work presents a capacity analysis of space-time block codes (STBC) for vehicle-to-vehicle (V2V) communication in modified line-of-sight (LOS) scenarios. The aim is to assess how performance of the V2V LOS channel is influenced by ground reflections. STBCs of various coding rates are evaluated using antenna elements distributed over the surface of two contiguous vehicles. A multi-ray tracing tool is used to model the multiple constructive/destructive interference patterns of the transmitted/received signals by all pairs of Tx-Rx antenna links. The results show that STBCs are capable of counteracting the fades produced by the destructive self-interference components across a range of inter-vehicle distances. Notably, the effectiveness of STBCs in deep fades is shown to outperform schemes with exclusive receive diversity. Higher-order STBCs with rate losses are also evaluated, showing interesting gains even for low coding rate performance, particularly, when accompanied by a multiple antenna receiver. Overall, these results can shed light on how to exploit transmit diversity in slow fading vehicular channels.**

***Index Terms*—LOS, MIMO, STBC, Two-ray model, V2V.**

I. Introduction

Vehicle-to-vehicle (V2V) communication is a promising yet challenging aspect of vehicular networks and Intelligent Transportation Systems (ITS) [1]. V2V communication performance is crucial for several safety-critical vehicular applications, e.g., platooning [2], which rely on vehicles networking capabilities to improve transportation efficiency and road safety.

Multiple-input and multiple-output (MIMO) antenna systems are one of the prospective upgrades to be implemented in future connected vehicles [3] (including platoons), aiming at improving channel capacity and reliability with minimum spectrum efficiency losses. MIMO theory and its applications is a well-known subject in wireless communication [4], offering vast practical and theoretical knowledge with proven success in the vehicular realm.

Space-time block codes (STBC) are a classical approach to achieve transmit diversity in MIMO systems. STBCs started with the pioneering work of Alamouti in [5] who proposed an effective and low-complex pre-coding/decoding scheme over space-time dimensions. The work paved the way for several other coding techniques achieving diversity at the transmitter side. Notably, achieving results equivalent to a maximum-ratio combining (MRC) receiver [6]. While the advantages of STBCs in conventional stochastic fading channels remains well understood, its potential to counteract deterministic fading due to ground reflections has not been fully exploited for vehicular applications with time-invariant channels.

In this work, we investigate the performance of STBCs in V2V MIMO LOS links scenarios with steady traffic (see e.g. [7], [8] for further motivations), or scenarios with reduced stochastic scattering, i.e., characterized by a time-invariant LOS channel, but also highly influenced by (deterministic) ground signal reflections. This is unlike the more typical approach to counteract stochastic fading in scenarios with scattering prevalence (see e.g. [9]). The deterministic analysis is built upon our prior work in [10] where we established the V2V channel model to account for self-interference patterns that appear when using multiple antennas with ground reflections. Specifically, STBCs of various coding rates are evaluated across a range of inter-vehicle distances. Interestingly, the capacity results reveal gains that outperform schemes of exclusive receive diversity. These results suggest STBCs can be used as a valid option to mitigate deterministic fades in V2V MIMO LOS channels showing slow or time-invariant statistics.

II. Related Work & Motivation

MIMO technology lies at the core of improved connectivity towards the next generation of wireless communication systems [11]. STBCs are a simple but rather powerful MIMO solutions with a still unexplored performance in vehicular

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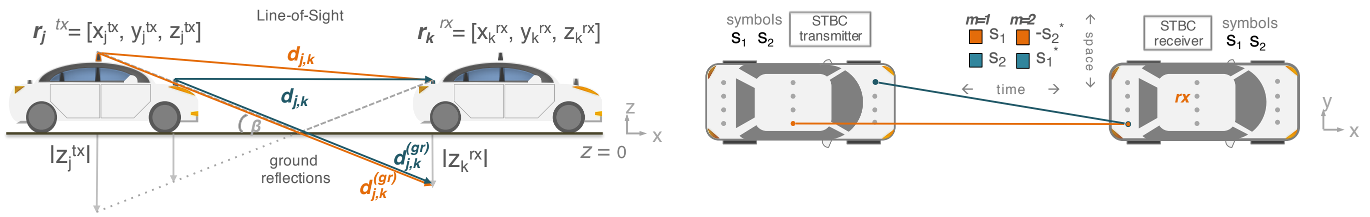

Figure 1. V2V LOS link showing: (left) the geometrical basis of the two-ray model with both the LOS and ground reflected paths; and (right) an aerial view of the V2V LOS channel for a 2×1 configuration using a transmit diversity scheme based on an Alamouti space-time block codes.

applications. Despite vehicular channels being typically highly time-varying and rich in scattering, motivations for V2V communication in steady traffic scenarios are also relevant [7], [8], and thus require further attention. A particular example for this situation is discussed in [7], where vehicles move in a steady traffic flow, and thus with an average (steady) traffic speed. This implies the vehicular group is steady in a certain duration, and thereby also its underlying properties, as the vehicular topology and propagation channel. A similar situation is assumed in [8] where both vehicles and scatterers around the Tx-Rx pairs have the same velocity and direction. This situation can be further challenged by characteristic ground signal reflections of V2V LOS scenarios [10], which is of further concern in our research. As previously stated, this work shows how STBCs of varying coding rates can bring benefits as a way to mitigate slow fading dynamics in V2V LOS MIMO channels. To the best of our knowledge, this has been addressed partially in [12], without considering its impact on the capacity performance.

III. V2V Channel Model

Consider the V2V scenario depicted in Figure 1 where each vehicle contains two horizontal linear arrays of N antennas. The first array is at the rooftop of each vehicle while the other is at the corresponding front (or rear) part (bumper) of the vehicle. The arrays are thus mirrored in the contiguous vehicle, having $2N = N_{Tx} = N_{Rx}$ antennas by car; where N_{Tx} and N_{Rx} are, respectively, the total number of transmit and receive antennas. The channel between any of the j^{th} and k^{th} antenna elements is denoted as $h_{j,k}$, and is defined as the contribution of the LOS and the NLOS components, i.e., $h_{j,k} = h_{j,k}^{LOS} + h_{j,k}^{NLOS}$. Since this work is concerned with the LOS channel performance, we focus on the former component only, specifically, when affected by ground signal reflections. To this purpose, we assume $h_{j,k}$ is well described by the classical two-ray propagation model. In the literature, this method has been recognized as a good predictor of the received signal strength in V2V LOS links [13], [14].

Formally, we consider the V2V channel as in [10]:

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

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 ground reflected electric distances computed as a function of $d_{j,k}$ and $d_{j,k}^{(gr)}$, the distance of the respective LOS and ground reflected path. P_T is the average Tx power per symbol and G_T and G_R are the respective Tx and Rx antenna gains. λ is the operational wavelength, $i = \sqrt{-1}$ and $\Gamma_{j,k}$ is the reflection coefficient which can be formally expressed as follows (modification of [15]):

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

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, n_r and n_i denote, respectively, the real and imaginary parts of the complex refractive index of ground n_{gr}, given by $n_{gr} = n_r + i n_i = \sqrt{\epsilon_r - i \frac{\sigma \lambda}{\epsilon_0 2\pi c}}$, where c is speed light, and ϵ_r and σ denote, respectively, the relative permittivity and conductivity of the asphalt pavement [16].

IV. MIMO Model

Considering a space-time block code mapping a set of N_{Tx} symbols to N_{Tx} transmit antennas over a set of M time slots, the MIMO model in the time slot m considering N_{Tx} transmit antennas and N_{Rx} receiving antennas can be defined as

$$\mathbf{x}(m) = \mathbf{H}\mathbf{s}(m) + \mathbf{v}(m), \tag{3}$$

where $\mathbf{s}(m) = [s_0(m), s_1(m), \ldots, s_{N_{Tx}-1}(m)]^T$ is the vector of transmitted symbols across the different antennas, and $\mathbf{v}(m)$ the vector of zero-mean additive circular complex Gaussian noise $\mathbf{v}(m) \sim \mathcal{CN}(\mathbf{0}_{N_{Rx}}, \sigma_v^2 \mathbf{I}_{N_{Rx}})$. $\mathbf{H}_{N_{Rx} \times N_{Tx}}$ is the MIMO channel matrix of size $N_{R_x} \times N_{T_x}$ which corresponds to the transpose matrix formed by the elements $h_{j,k}$ and $\mathbf{x}(m)$ is the vector of received symbols in the time slot m.

Given the code rate R defined as $R = N_{Tx}/M$, the mapping of the symbols to the antennas in different time slots can also be represented with a single matrix $\mathbf{S}_{N_{Tx},R}$ of individual elements $s_{j,m}$, where m and j denote the respective time and Tx antenna indexes. Then, by assuming the channel matrix $\mathbf{H}$ as invariant across the duration of the block code, the MIMO model in (3) can be re-written as

$$\mathbf{X} = \mathbf{H}\mathbf{S}_{N_{Tx},R} + \mathbf{V}, \tag{4}$$

where $\mathbf{X} = [\mathbf{x}(1), \ldots, \mathbf{x}(m)]$ and $\mathbf{V} = [\mathbf{v}(1), \ldots, \mathbf{v}(m)]$ are the respective stacked array of the received and noise vectors across the duration of the block code. The received signal is then processed at the receiver to obtain the estimates of the transmitted symbols as follows: $\hat{\mathbf{s}} = \mathbf{G}_r\mathbf{X}+\mathbf{G}_i\mathbf{X}^H$, where $\mathbf{G}_r$ and $\mathbf{G}_i$ are decoding matrices designed to remove inter-symbol interference. The particular case of Alamouti [5] coding for a 2×1 system uses the following decoding matrix:

$$\mathbf{S} = \begin{pmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{pmatrix}^T .$$

Considering the channel matrix for this case as $\mathbf{H} = [h_1 \quad h_2]$, the received signal is then given by

$$\mathbf{X} = [h_1 s_1 + h_2 s_2 + v_1 \qquad -h_1 s_2^* + h_2 s_1^* + v_2]$$

The decoder yields the following estimates of the transmitted symbols: $\hat{s}_1 = h_1^* X(1) + h_2 X(2)^*$ and $\hat{s}_2 = h_2^* X(1) - h_1 X(2)^*$. This operation is followed by hard symbol detection. The main property of STBC to be used in this work can be found by substituting the values of the received signal $\mathbf{X}$ in the previous expression, and obtain the signal-to-noise-ratio (SNR), which yields $\eta = \frac{|h_1|^2+|h_2|^2}{\sigma_v^2}$. In this paper we consider that higher order orthogonal STBCs, for example $\mathbf{S}_{4,3/4}$, comply with the same property as the Alamouti code expression for SNR, and therefore it can be expressed as the orthogonal contribution of all pairs of antennas:

$$\eta = \sum_{j=1}^{N_{Tx}} \sum_{k=1}^{N_{Rx}} |h_{j,k}|^2/\sigma_v^2.$$

V. Performance model & Metrics

The STBC receiver decodes the signals stored over the M time slots of duration of the space time block coding scheme. Since the block code is assumed to be orthogonal, the symbols can be decoded without inter-symbol interference with an average signal-to-noise ratio (SNR) given by:

$$\eta = \alpha \sum_{k=1}^{N_{Rx}} \sum_{j=1}^{N_{Tx}} \left| e^{2\pi i \tilde{d}_{j,k}}/\tilde{d}_{j,k} + \Gamma_{j,k}\, e^{2\pi i \tilde{d}_{j,k}^{(gr)}}/\tilde{d}_{j,k}^{(gr)} \right|^2, \quad (5)$$

where $\alpha = \frac{P_T G_T G_R}{N_{Tx}(4\pi)^2\sigma_v^2}$. The instantaneous capacity is thus given by

$$C = R \log_2(1+\eta), \quad (6)$$

where the code rate R is approximated by the boundary given in [17], i.e., $R = \frac{n_0}{n_0+1}$, and $n_0 = 2N$.

For the purposes of benchmark analysis, the average SNR of the maximum-ratio combining (MRC) and equal-gain combining (EGC) receivers are given by [10]:

$$\eta_{MRC} = \alpha \sum_{j=1}^{N_{Rx}} \left| \sum_{k=1}^{N_{Tx}} \left(\frac{e^{2\pi i \tilde{d}_{j,k}}}{\tilde{d}_{j,k}} + \Gamma_{j,k} \frac{e^{2\pi i \tilde{d}_{j,k}^{(gr)}}}{\tilde{d}_{j,k}^{(gr)}} \right) \right|^2, \quad (7)$$

and

$$\eta_{EGC}{}^1 = \frac{\alpha}{N_{Rx}} \left| \sum_{k=1}^{N_{Tx}} \sum_{j=1}^{N_{Rx}} \left(\frac{e^{2\pi i \tilde{d}_{j,k}}}{\tilde{d}_{j,k}} + \Gamma_{j,k} \frac{e^{2\pi i \tilde{d}_{j,k}^{(gr)}}}{\tilde{d}_{j,k}^{(gr)}} \right) \right|^2. \quad (8)$$

A. Performance Metrics

Let us define the outage probability of V2V LOS MIMO channel as the probability that the ratio of the capacity to the free-space loss (FSL) value falls below a threshold (ξ) in the range of inter-vehicle distances $[d_{min}, d_{max}]$:

$$\Theta = \Pr\{C/C_{FSL} \leq \xi\} = \frac{\int_{d_{min}}^{d_{max}} \text{ind}(C/C_{FSL} \leq \xi) dy}{d_{max} - d_{min}}, \quad (9)$$

where y is the auxiliary variable denoting the inter-vehicle distance, and C_{FSL} is the capacity of the FSL link without ground reflections, and $ind(\cdot)$ is the indicator function. The expression is also the cumulative distribution function (CDF) of the ratio of the instantaneous capacities of the STBC and FSL solution. The outage probability in (9) provides us with the performance of the link by measuring the degradation of the signal below the threshold ξ, averaged over a given range of distances. However, the analysis of this first order statistical metric could hide some of the dynamics in the performance of the proposed multiple antenna systems, particularly when they suffer fading or nulls. To address this issue, let us now define the *average gain in fading* as the average gain of the space-time diversity algorithm when the reference solution is in outage:

$$G = \frac{\int_{d_{min}}^{d_{max}} \text{ind}(C_{FSL} \leq \xi) C/C_{FSL} dy}{d_{max} - d_{min}}. \quad (10)$$

VI. Evaluation

A. Simulation Setup

Consider a 2-vehicle configuration with variable number of antennas N and a range of inter-vehicular distances $d \in [1, 20]$m. The antennas are vertically polarized distributed in two uniform linear arrays with equal number of antennas each, i.e. $N_{Tx} = N_{Rx} = 2N$. The arrays are parallel on the y-axis and 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 also separated by 1m on the x-axis, i.e. shifted 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 $N \leq 12$, and for the rest of parameters we assume $\lambda = 0.125$, $\epsilon_r = 4$, $\sigma = 0.02$.

B. *Simulation Results*

Fig. 2 shows the capacity performance versus inter-vehicular distance for different STBC algorithms and the FSL solution for reference. All solutions consider an abstraction of STBC schemes based on full diversity and the theoretical rate limit for that coding order. Note that the results in Fig. 2 consider only one antenna at the receiver, i.e. $N_{Rx} = 1$. From this, we can observe a slight improvement when we use higher order codes despite the rate loss characteristic of this type of codes. The improvement is in terms of a reduction of the span between the minimum and maximum achievable instantaneous capacity. This can be seen, e.g., in code S_{4x1} which shows less peaks and fades than lower-order codes.

Fig. 3 shows capacity performance results similar to the previous case but now for higher numbers of antennas. Since the idea is to improve the relatively low gain obtained with only one receive antenna, we explore here the case of maximum space diversity, i.e., $N_{Rx} = N_{Tx}$. Moreover, we compare STBC performance with equivalent exclusive receive diversity schemes, particularly, MRC and EGC algorithms. Interestingly, these results show that MRC and EGC show lower and higher peaks than STBC.

Fig. 4 presents the cumulative density function (CDF) of the capacity performance of STBC in comparison with conventional multiple antenna combining solutions with symbol repetition across the transmit antennas (i.e., MRC and EGC). The formula used for this outage probability is given in the previous subsection in (9) and is calculated using well known numerical methods for integration. The results show that STBC seems to behave worse than MRC and EGC. In addition, MRC outperforms EGC, an observation which contradicts the results in our previous paper in [10], where EGC shows a higher signal excursion than MRC. The explanation lies on the omission of the accumulation of noise in the performance of EGC in our previous paper in [10], which leads EGC to show higher signal excursions than MRC. In this paper, it is shown that with a correct formulation of the noise component of EGC, MRC seems to outperform both EGC and STBC. However, EGC still shows the lower signal excursions with more pronounced fades as found in the original paper. Note that the results of our previous paper in [10] still apply for the behaviour of the signal strength (ignoring the noise component). Despite these advances, the average results tend to hide some specific aspects of the performance of the solutions. In fact, our prior work also shows that EGC and MRC can be the worst solutions in terms of the depth of the fades at given values of inter-vehicular distance. That is to say, while EGC or MRC can experience the largest signal values,

[1]In our previous work in [10], the formula of EGC did not consider the accumulation of noise across the receiving antennas. Under this consideration, MRC outperforms EGC in terms of SNR. However, in terms of signal strength, the deterministic nature of the multi-ray channel causes EGC to experience higher signal excursions than MRC, which is the main outcome of the study in [10].

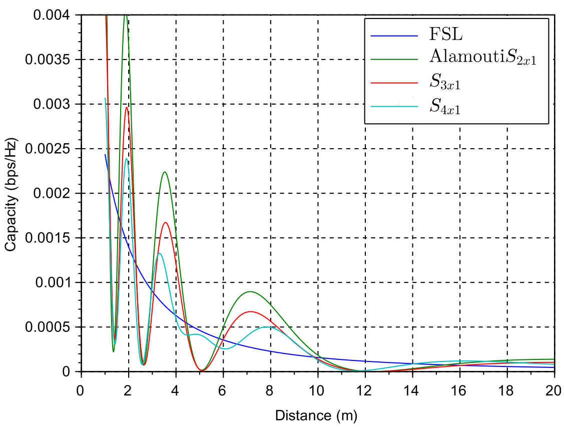

Figure 2. Capacity performance versus inter-vehicular distance for different STBC algorithms and the FSL solution for reference.

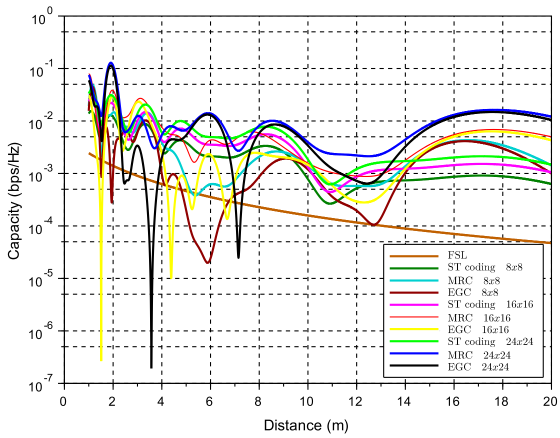

Figure 3. Capacity versus inter-vehicular distance of different STBC over LOS channels with ground reflection when compared to the MRC and EGC solutions ($N_{Rx} = N_{Tx}$)

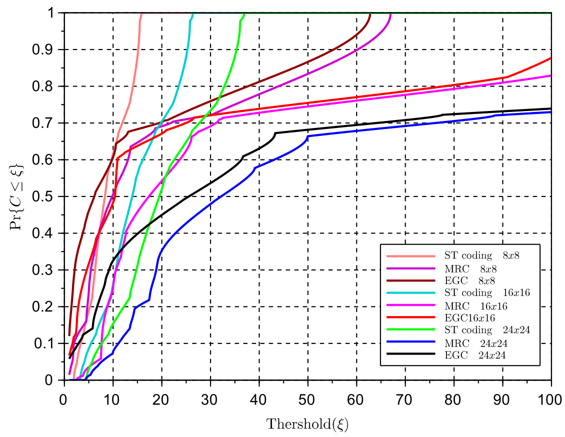

Figure 4. Capacity ratio of different STBCs and SIMO solution to the capacity of the FSL case.

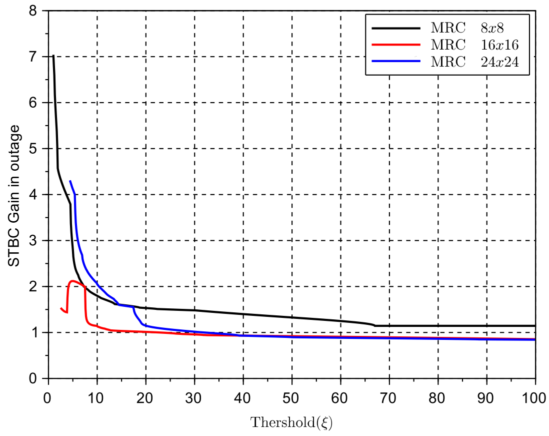

Figure 5. Capacity gain (G) in outage of STBCs over MRC multiple antenna schemes.

they can also show the deepest fades or lowest values of signal strength and also SNR.

To better investigate the behavior above mentioned, we investigate the metric *average gain in outage* (or average gain in fading) as defined in (10) in the previous subsection. Specifically, Fig. 5 and Fig. 6 show the performance of this gain w.r.t. the MRC and EGC solutions, respectively, for various values of the threshold used in the definition of outage probability in (9). Note that for better visualization, the observed gain over the MRC solution are in linear scale and the gains over EGC are in dB. These results clearly show that STBC outperforms both types of combining SIMO solutions when these solutions are in outage. From this result, we can therefore conclude that while space time diversity can limit the maximum peak of the received signal, it provides a very good countermeasure against fading or signal nulls for various ranges of inter-vehicular distance.

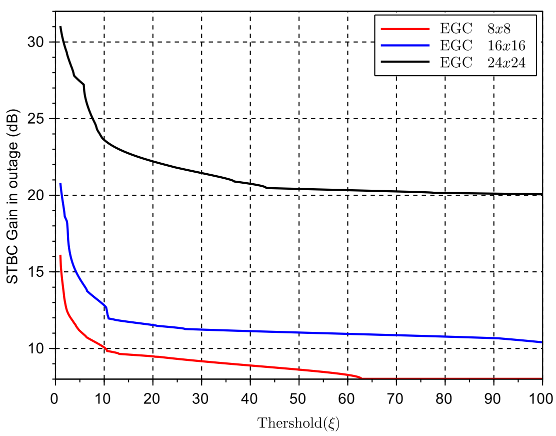

Figure 6. Capacity gain (G) in outage of STBCs over EGC multiple antenna schemes.

VII. Conclusion

This paper has presented the capacity performance analysis of orthogonal space time block codes in V2V MIMO LOS (time-invariant) channels with ground reflection. The results show that, in general, STBCs can provide capacity gains over single antenna systems as well as reduce the effects of self interference produced by ground reflections. Moreover, when compared to conventional SIMO solutions using EGC and MRC schemes, STBC seems to perform rather poor (on average) regarding outage probability for different values of performance ratio with respect to the FSL solution. However, a closer look at the performance of the solutions in case of outage reveals that STBC provides gains in performance with respect to MRC and, particularly, with respect to EGC when these solutions are in outage. This implies STBC is an attractive candidate to counteract deep fades and provide a more stable signal level (here against self-interference patterns), but at the same time it cannot provide the maximum signal peaks as compared to MRC or EGC. Another conclusion is that despite losses in code rates, STBC in combination with multiple antenna receivers can provide important capacity gains for the LOS components when affected by ground reflections.

Future work remains to be done to clarify if the capacity gains reported here for the LOS channel are preserved in time-varying scenarios with increased scattering components.

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