Optimized Amplify-and-Forward Relaying for Vehicular Ad-Hoc Networks[1]

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***Abstract*— Cooperative communication techniques promise the advantages of MIMO (multi-input multi-output) communications for wireless scenarios with single-antenna terminals. In this paper, we investigate the performance of a vehicle-to-vehicle cooperative scheme where another vehicle in the vicinity of the source vehicle acts as a relay. The underlying source-to-relay, relay-to-destination, and source-to-destination links are modeled as cascaded (double) Rayleigh fading. This statistical model provides a realistic description of inter-vehicular channel where two or more independent Rayleigh fading processes are assumed to be generated by independent groups of scatterers around the two mobile terminals. We derive a pairwise error probability (PEP) expression for the inter-vehicular cooperative scheme under consideration and show that the full distributed spatial diversity is extracted. Based on the derived PEP expressions, we obtain union bounds on the bit error rate performance which are then minimized to optimally allocate power between broadcasting and relaying phases. Optimum power allocation brings performance gains up to 3dB depending on the relay location and deployed modulation scheme.**

I. Introduction

Vehicular ad-hoc networks (VANETs) involve vehicle-to-vehicle (V2V) and vehicle-to-road (V2R) communications enabling a vehicle to communicate with other vehicles and sensors/access-points installed along the road. Information gathered through V2V and V2R communications can help improve the road traffic safety and efficiency, providing drivers with timely information on road and traffic conditions and achieving smooth traffic flow on the roads. Besides these main navigation safety functionalities, potential in-vehicle applications have recently emerged such as audio/video streaming, high-speed internet access, cooperative downloading, multiplayer gaming, mobile commerce as a result of ever-increasing dependence on internet and multimedia services.

The current literature in VANETs has mainly focused on networking aspects, but has not yet fully explored physical layer issues in inter-vehicular communication which inherently differs from well-studied traditional cellular or WLAN (wireless local area network) applications. In this paper, we study cooperative diversity [1]-[3] in the context of VANETs. Although cooperative diversity has been extensively investigated in the literature, the current results are mainly limited to Rayleigh fading channel model. This statistical model typically assumes a wireless communication scenario with a stationary base station antenna above roof-top level and a mobile station at street level. On the other hand, in V2V communication systems, both the transmitter and receiver are in motion and their antennas are relatively at lower elevations invalidating the Rayleigh fading assumption [4]. *Cascaded (double) Rayleigh* fading channel model [5], [6] is accepted to be a more realistic description of inter-vehicular channel where two or more independent Rayleigh fading processes are assumed to be generated by independent groups of scatterers around the two mobile terminals.

In a recent paper of ours [7], we have studied the performance of a cooperative V2V system where the source vehicle is assisted by a roadside access point (AP). In [7], the channel between source and destination vehicles is modeled by cascaded Rayleigh fading while source-to-relay AP and relay AP-to-destination channels are modeled by Rayleigh fading channel. In this paper, we consider a scenario where the source vehicle is assisted by another vehicle. Therefore, all underlying channels are modeled as cascaded Rayleigh fading. We consider "receive diversity" protocol of [1], [8] with amplify-and-forward (AF) relaying. We first derive the achievable diversity order for this vehicle-assisted scenario through the derivation of pairwise error probability (PEP). Then, building upon a union bound on the bit error rate (BER), we formulate a power allocation problem to determine how overall transmit power should be shared between broadcasting and relaying phases.

The rest of the paper is organized as follows: In Section II, we introduce the vehicle-assisted V2V transmission model. In Section III, we derive the PEP expressions and discuss the achievable diversity order. In Section IV, we present union bounds on BER which are used as objective functions for optimization and results of the optimization procedure. In Section V, we present simulation results to compare the performance of optimum and equal power allocation schemes. We finally conclude in Section VI.

II. System Model

We consider a single-relay AF vehicular cooperative network with half-duplex nodes each of which is equipped with a single pair of transmit and receive antennas. We assume an aggregated channel model which takes into account both long-term path loss and short-term fading. This lets us to explicitly consider the effects of relay location in our transmission model.

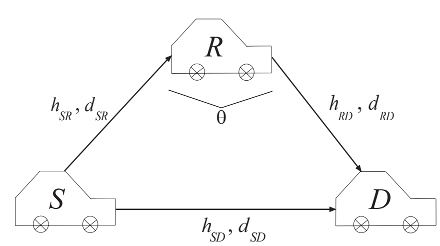

Fig. 1. System model.

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In Fig.1, d_{SD}, d_{SR}, and d_{RD} are the distances of source-to-destination (S→D), source-to-relay (S→R), and relay-to-destination (R→D) links, respectively, and θ is the angle between S→R and R→D links. Assuming the path loss between S→D to be unity, the relative gain of S → R and R→ D links are defined, respectively, as $G_{SR} = (d_{SD}/d_{SR})^{\upsilon}$ and $G_{RD} = (d_{SD}/d_{RD})^{\upsilon}$ [8]. We further define the *relative geometrical gain* $\mu = G_{SR}/G_{RD}$ (in dB) which is an indicator of relay location with respect to the source and destination. More negative this ratio is, more closely the relay is placed to destination terminal. On the other hand, positive values of this ratio indicate that the relay is more close to source terminal. The particular case of $\mu = 0$dB means both source and destination nodes have the same distance to the relay.

In Fig.1, h_{SR}, h_{RD} and h_{SD} represent S→R, R→D, and S→D link fading coefficients. These coefficients are modeled as the product of two independent complex Gaussian random variables [6], i.e., $h_{SD} = \alpha_1.\gamma_1$, $h_{SR} = \alpha_2.\gamma_2$, $h_{RD} = \alpha_3.\gamma_3$, where α_1, α_2, α_3, γ_1, γ_2 and γ_3 have zero mean and variance of 0.5 per dimension. Therefore, their magnitudes $|h_{SD}|$, $|h_{SR}|$ and $|h_{RD}|$ follow cascaded Rayleigh distribution, i.e., $f(|h|) = 4|h|K_0(2|h|)$ where the subscript is dropped for convenience. Here, K_0 is the modified Bessel function of second kind of zero order [13]. We assume that all underlying channels are quasi-static which are well justified for vehicular communication scenarios in rush-hour traffic.

The transmission model under consideration builds upon receive diversity (RD) cooperation protocol[2] [1]. This protocol effectively implements a SIMO (single-input multiple-output) scheme in a distributed fashion realizing receive diversity advantages. In RD protocol, the source node communicates with the relay and destination nodes over the first transmission phase. In the second transmission phase, only the relay node communicates with the destination node. Therefore, the signal transmitted both to the relay and destination nodes over the two transmission phases is the same. Let x denote the transmitted signal chosen from an *M*-PSK or *M*-QAM constellation. Considering path-loss effects, the received signals at the relay and destination are given as

$$r_R = \sqrt{2G_{SR}KE}h_{SR}x + n_R, \tag{1}$$

$$r_{D1} = \sqrt{2KE}h_{SD}x + n_{D1} \tag{2}$$

where n_R and n_{D_1} are the independent samples of zero-mean complex Gaussian random variables with variance $N_0/2$ per dimension. Here, the total energy (to be used by both source and relay terminals) is $2E$ during two time slots yielding an average power in proportion to E per time slot, i.e., assuming unit time duration. K is an optimization parameter which controls the fraction of power reserved for the broadcasting phase. The relay terminal normalizes the received signal r_R by a factor of $\sqrt{E[|r_R|^2]} = \sqrt{2G_{SR}KE + N_0}$ and re-transmits the resulting signal during the second time slot. After proper normalizations and mathematical manipulation, we obtain [10]

$$r_{D2} = \sqrt{aE}h_{SR}h_{RD}x + n_{D2} \tag{3}$$

where $a = (2G_{SR}K)/(A + |h_{RD}|^2)$ with $A = [1 + 2G_{SR}K(E/N_0)]/[2G_{RD}(1-K)(E/N_0)]$ and n_{D2} is the zero-mean complex Gaussian random variable with variance $N_0/2$ per dimension. Writing (2) and (3) in a matrix notation, we have

$$\underbrace{\begin{bmatrix} r_{D_1} \\ r_{D_2} \end{bmatrix}}_{\mathbf{r}} = \underbrace{\begin{bmatrix} \sqrt{2KE}x & 0 \\ 0 & \sqrt{aE}x \end{bmatrix}}_{\mathbf{X}} \underbrace{\begin{bmatrix} h_{SD} \\ h_{SR}h_{RD} \end{bmatrix}}_{\mathbf{h}} + \underbrace{\begin{bmatrix} n_{D_1} \\ n_{D_2} \end{bmatrix}}_{\mathbf{n}}. \tag{4}$$

III. Derivation of Union Bounds on the BER

In our work, we aim to optimize the BER performance for the cooperative vehicular scheme under consideration. A union bound on the BER is given by [11]

$$P_b \le \frac{1}{n}\sum_{\mathbf{X}} p(\mathbf{X}) \sum_{\mathbf{X}\neq\hat{\mathbf{X}}} q(\mathbf{X},\hat{\mathbf{X}})P(\mathbf{X},\hat{\mathbf{X}}) \tag{5}$$

where $p(\mathbf{X})$ is the probability that codeword $\mathbf{X}$ is transmitted, $q(\mathbf{X},\hat{\mathbf{X}})$ is the number of information bit errors in choosing another codeword $\hat{\mathbf{X}}$ instead of the original one, $P(\mathbf{X},\hat{\mathbf{X}})$ is the corresponding PEP, and n is the number of information bits per transmission. As revealed by (5), PEP is the building block for the derivation of union bound. A Chernoff bound on the conditional PEP is given by [12]

$$P(\mathbf{X},\hat{\mathbf{X}}|\mathbf{h}) \le \exp\left(-\frac{\mathbf{h}(\mathbf{X}-\hat{\mathbf{X}})(\mathbf{X}-\hat{\mathbf{X}})^H\mathbf{h}^H}{4N_0}\right). \tag{6}$$

Substituting $\mathbf{X}$ and $\mathbf{h}$ in (6), we have

$$\begin{aligned} P(\mathbf{X},\hat{\mathbf{X}}|h_{SD},h_{SR}h_{RD}) \quad &\le \quad \exp\left(-\tfrac{2K|x-\hat{x}|^2}{4}\tfrac{E}{N_0}|h_{SD}|^2\right) \\ &\times \quad \exp\left(-\tfrac{a|x-\hat{x}|^2}{4}\tfrac{E}{N_0}|h_{SR}|^2|h_{RD}|^2\right). \end{aligned} \tag{7}$$

Replacing $|h_{SD}| = |\alpha_1||\gamma_1|$, $|h_{SR}| = |\alpha_2||\gamma_2|$ and $|h_{RD}| = |\alpha_3||\gamma_3|$ in (7) and averaging the resulting expression over $|\alpha_1|^2$ and $|\gamma_1|^2$ which are both exponentially distributed, we obtain

$$\begin{aligned} &P(\mathbf{X},\ \hat{\mathbf{X}}|\alpha_2\gamma_2,\alpha_3\gamma_3) \le A_1 \\ &\times\exp\left(-\tfrac{a|x-\hat{x}|^2}{4}\tfrac{E}{N_0}|\alpha_2|^2|\gamma_2|^2|\alpha_3|^2|\gamma_3|^2\right). \end{aligned} \tag{8}$$

where $\Gamma(.,.)$ is the Gamma function [13] and A_1 is given by

$$\begin{aligned} A_1 \quad &= \quad \left(\tfrac{K|x-\hat{x}|^2}{2}\tfrac{E}{N_0}\right)^{-1}\exp\left(\left(\tfrac{K|x-\hat{x}|^2}{2}\tfrac{E}{N_0}\right)^{-1}\right) \\ &\times \quad \Gamma\left(0,\left(\tfrac{K|x-\hat{x}|^2}{2}\tfrac{E}{N_0}\right)^{-1}\right) \end{aligned}$$

Now we define y_1 and y_2 as $y_1 = |\alpha_2|^2|\gamma_2|^2$ and $y_2 = |\alpha_3|^2|\gamma_3|^2$ whose probability density (pdf) functions are given by

$$p(y) = \frac{1}{2\sigma_y\sqrt{y}}G_{0,2}^{2,0}\left(\left(4\sigma_y^2\right)^{-1}y\left|_{\frac{1}{2},\frac{1}{2}}^{-}\right.\right), \tag{9}$$

where $G_{p,q}^{m,n}(.|:)$ is the Meijer-G function [14] and $\sigma_y^2 = \sigma_\alpha^2\sigma_\gamma^2$ where $\sigma_\alpha^2 = \sigma_\gamma^2 = 0.5$ (See Appendix for the derivation of this pdf). Averaging (8) with respect to y_1 and using [13, Eq. 7.813.1], we obtain

$$\begin{aligned} &P(\mathbf{X},\ \hat{\mathbf{X}}|y_2) \le A_1\left(a|x-\hat{x}|^2(E/4N_0)y_2\right)^{-\frac{1}{2}} \\ &\times G_{1,2}^{2,1}\left(\tfrac{1}{a|x-\hat{x}|^2(E/4N_0)y_2}\left|_{\frac{1}{2},\frac{1}{2}}^{\frac{1}{2},-}\right.\right). \end{aligned} \tag{10}$$

Further averaging (10) over y_2, we obtain the PEP as

$$\begin{aligned} &P(\mathbf{X},\ \hat{\mathbf{X}}) \le A_1\left(G_{SR}K\tfrac{|x-\hat{x}|^2}{2}\tfrac{E}{N_0}\right)^{-\frac{1}{2}} \\ &\times\int_0^\infty \tfrac{\sqrt{A+y_2}}{y_2}G_{1,2}^{2,1}\left(\tfrac{1}{(G_{SR}K\frac{|x-x|^2}{2}\frac{E}{N_0})}(1+\tfrac{A}{y_2})\left|_{\frac{1}{2},\frac{1}{2}}^{\frac{1}{2},-}\right.\right) \\ &\times G_{0,2}^{2,0}\left(y_2\left|_{\frac{1}{2},\frac{1}{2}}^{-}\right.\right)dy_2 \end{aligned} \tag{11}$$

A closed-form solution for (11) is unfortunately not available, but this single integral can be easily evaluated through commercially available mathematics software such as Matlab or Mathematica.

[2]This is referred as orthogonal amplify-and-forward relaying (OAF) in [9].

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To have further insight into system performance, we plot in Fig. 2 the effective (instantaneous) diversity order [15] which is simply the slope of derived PEP as a function of the average signal-to-noise ratio (SNR=E/N_0) on a log-log scale. As benchmarks, we include the performance of maximal ratio combining (MRC) with two receive antennas over Rayleigh and cascaded Rayleigh fading channels.

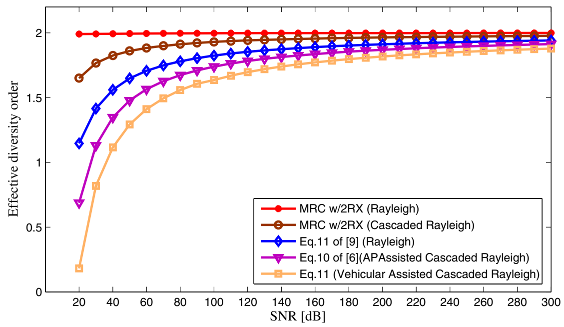

Fig. 2. Effective diversity order over conventional and cascaded Rayleigh fading.

It is obvious from Fig. 2 that for MRC scheme the instantaneous diversity order converges to its asymptotical value of two immediately over conventional Rayleigh fading. The convergence gets slower for the same scheme under cascaded Rayleigh fading channel. Another benchmark is the performance of the RD cooperation protocol over Rayleigh fading channel[3] . It is observed that the presence of co-operation (therefore introduction of a cascaded channel over source-relay-destination link) slows down the convergence. This can be also seen from the performance of AP-assisted cooperative scheme of [7]. In our scenario, the convergence of diversity order to its asymptotical value becomes the slowest since both nature of cooperation and cascaded Rayleigh channels severely degrade the performance in the lower SNR values.

IV. Optimum Power Allocation (OPA)

The specific form of BER bounds depends on the modulation scheme. Introducing $f(\Delta = |x - \hat{x}|^2) \hat{=} P(\mathbf{X}, \hat{\mathbf{X}})$, union bounds on BER for various modulation schemes are given by

$$P_{b,BPSK} \leq f\left(\Delta = 4\right), \tag{12}$$

$$P_{b,4-PSK} \leq f\left(\Delta = 2\right) + f\left(\Delta = 4\right), \tag{13}$$

$$\begin{aligned} P_{b,16-PSK} &\leq 0.5 f\left(\Delta = 0.1523\right) + f\left(\Delta = 0.5858\right) \\ &+ f\left(\Delta = 1.2347\right) + f\left(\Delta = 2\right) + 1.25 f\left(\Delta = 2.7655\right) \\ &+ 1.5 f\left(\Delta = 3.4122\right) + 1.25 f\left(\Delta = 3.8479\right) + 0.5 f\left(\Delta = 4\right) \end{aligned} \tag{14}$$

$$\begin{aligned} P_{b,16QAM} &\leq 0.75 f\left(\Delta = 0.4\right) + f\left(\Delta = 1.6\right) \\ &+ 0.25 f\left(\Delta = 3.6\right) + 1.125 f\left(\Delta = 0.8\right) + f\left(\Delta = 3.2\right) \\ &+ 2.25 f\left(\Delta = 2\right) + 0.75 f\left(\Delta = 4\right) + 0.125 f\left(\Delta = 7.2\right) \\ &+ 0.75 f\left(\Delta = 5.2\right) \end{aligned} \tag{15}$$

The resulting BER expressions need to be minimized with respect to the power allocation parameter K ($0 \leq K \leq 1$). It can be readily checked that these expressions are convex functions with respect to K. See for example Fig. 3 where we plot (13) with respect to K for various values of SNR.

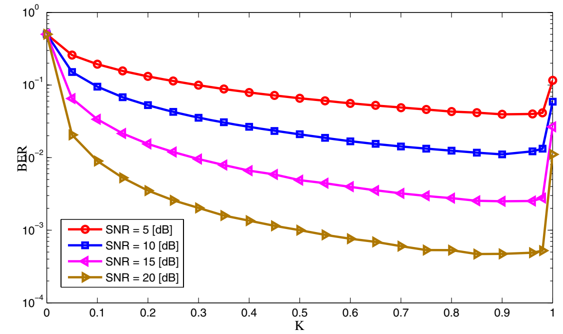

Fig. 3. BER versus K ($\mu = -30$dB, 4-PSK, $\theta = \pi$, and $\upsilon = 2$).

Convexity of the functions under consideration guarantees that local minimum found through optimization will be indeed a global minimum. Since no closed-form solution is available, we resort to numerical methods to solve this optimization problem. It should be also emphasized that this problem needs not to be solved in real-time for practical systems, because the optimization does not depend on the instantaneous channel information or the input data. This means that the optimum power allocation values can be obtained apriori for given values of operating SNR and propagation parameters, and can be stored for use as a lookup table in practical implementation.

In Table I, we present optimum values for BPSK, 4-PSK, 16-PSK and 16-QAM modulations. We assume $\theta = \pi$ and path loss coefficient $\upsilon = 2$. We consider various values of relative geometrical gain $\mu = G_{SR}/G_{RD}$ (in dB). For $\mu = -30$dB (i.e, relay is close to destination), we observe that $\sim 97\%$ of power should be used in broadcasting phase. For $\mu = 0$dB (i.e., relay is located midway between the source and destination nodes), the power dedicated to broadcasting phase drops. The exact value depends on the modulation type. For example, for BPSK and 4-PSK, $\sim 67\%$ of power should be reserved for broadcasting phase. On the other hand, $\sim 69\%$ of power is required by the source to achieve optimum performance in case of 16-PSK and 16-QAM. For $\mu = 30$dB (i.e., relay is close to the source), our results show that $\sim 53\%$ of power should be used in broadcasting phase for BPSK/4-PSK while $\sim 54\%$ of power would be sufficient in the case of 16-PSK and 16-QAM.

In Fig. 4, we demonstrate power savings (as predicted by the derived union bounds) achieved by optimum power allocation for a target BER of 10^{-3}. We assume 4-PSK, 16-PSK and 16-QAM modulations.

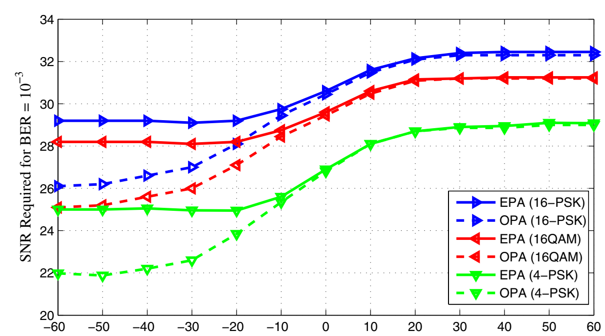

Fig. 4. Power efficiency gains for a target BER of 10^{-3}.

From Fig. 4, we observe performance improvements of $\sim$ 3dB, $\sim$ 2.8dB $\sim$ 3.1dB for 4-PSK, 16-PSK and 16-QAM modulations respectively assuming negative values of μ. For positive values of μ, it

[3]The corresponding PEP can be found in [10].

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TABLE I

OPTIMUM POWER ALLOCATION PARAMETERS

SNR	BPSK			4-PSK			16-PSK			16-QAM		
	μ			μ			μ			μ		
	-30dB	0dB	30dB	-30dB	0dB	30dB	-30dB	0dB	30dB	-30dB	0dB	30dB
[dB]	K	K	K	K	K	K	K	K	K	K	K	K
5	0.9030	0.6660	0.5530	0.9720	0.6510	0.5990	0.9280	0.6700	0.5530	0.9640	0.6720	0.5630
10	0.9460	0.6760	0.5350	0.9720	0.6730	0.5580	0.9600	0.6840	0.5420	0.9720	0.6900	0.5530
15	0.9590	0.6770	0.5270	0.9720	0.6770	0.5410	0.9690	0.7050	0.5360	0.9710	0.6940	0.5420
20	0.9620	0.6780	0.5240	0.9720	0.6780	0.5340	0.9700	0.7020	0.5370	0.9720	0.6930	0.5410
25	0.9630	0.6780	0.5230	0.9260	0.6780	0.5320	0.9710	0.6990	0.5370	0.9720	0.6920	0.5400
30	0.9630	0.6780	0.5230	0.9730	0.6780	0.5320	0.9710	0.6970	0.5290	0.9720	0.6920	0.5370
35	0.9630	0.6780	0.5230	0.9730	0.6780	0.5310	0.9710	0.6970	0.5290	0.9720	0.6920	0.5370
40	0.9630	0.6780	0.5230	0.9730	0.6780	0.5310	0.9710	0.6970	0.5290	0.9720	0.6910	0.5360
45	0.9630	0.6780	0.5230	0.9730	0.6780	0.5310	0.9710	0.6970	0.5290	0.9720	0.6910	0.5360

is observed that OPA and EPA (equal power allocation) performance curves converge to each other indicating the optimality of EPA. We also observe that EPA and OPA schemes require higher SNRs for 16-PSK and 16-QAM modulations in order to provide same performance of 4-PSK.

V. SIMULATION RESULTS

In this section, we present Monte-Carlo simulation results to elaborate on our analytical results in the previous section. BER performance of relay-assisted V2V scheme is simulated for various relay locations and modulation schemes. We assume $\theta = \pi$ and $v = 2$ in our simulations.

In Fig. 5, we assume 4-PSK modulation for the cooperative scheme and consider a scenario where the relay vehicle is close to the destination (i.e., $\mu = -30$dB). Considering that two time slots are required to transmit one symbol in the considered cooperation protocol, this scheme achieves a throughput rate of 1bits/sec/Hz. The benchmark schemes are non-cooperative direct transmission (i.e., no relaying) and MRC with two receive antennas. To maintain the same throughput rate with the cooperative scheme, they are simulated with BPSK.

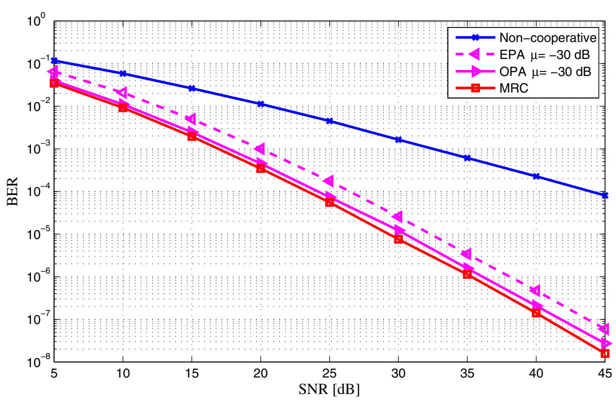

Fig. 5. Performance results of RD protocol for $\mu = -30$ dB (4-PSK).

As seen from the figures, the relay-assisted V2V scheme under both EPA and OPA significantly outperform the direct transmission. The performance of OPA is about 2.8dB better than that of EPA at BER = 10^{-3}, confirming our earlier observations on power savings (c.f., Fig. 4). We also observe from Fig. 5 that the performance of cooperative scheme with EPA is 2.9dB from that of MRC scheme which can be seen as a lower bound on the performance of the virtual receive diversity scheme under consideration. Through OPA, the gap reduces to 0.55dB.

In Fig. 6, we assume 16-PSK and 16-QAM modulations for the cooperative scheme while the benchmarking direct transmission and MRC schemes are simulated with 4-PSK. OPA provides 2.8dB power savings and outperforms EPA counterpart. However, even with OPA, performance curves are still about 5dB far away from the MRC bound. This is rather as a result of the crowded nature of signal constellations under consideration.

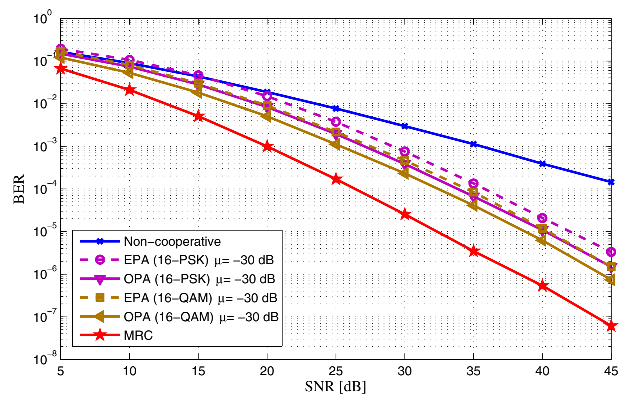

Fig. 6. Performance results of RD protocol for $\mu = -30$ dB (16-PSK and 16-QAM).

In Fig. 7, we compare the performance of AP-assisted [7] and vehicular-assisted V2V cooperative schemes for $\mu = -30, 0, 30$dB assuming 16-PSK. We observe that AP-assisted V2V scheme provides better performance than vehicular-assisted counterpart since AP-assisted scheme takes advantage of the underlying (more mild) Rayleigh links in S→R and R→D links. Specifically, at BER=10^{-3} AP-assisted scheme outperforms vehicle-assisted scheme by 4.1dB for $\mu = 30$dB. The performance gap decreases to 3.5dB for $\mu = -30$dB.

VI. CONCLUSIONS

In this paper, we have studied a cooperative inter-vehicular transmission scheme where all underlying channels are modeled as cascaded Rayleigh fading. We have derived a PEP expression which demonstrates that the asymptotical diversity order is two for the single-relay scenario under consideration. Although this scheme achieves full diversity, the available diversity order is only partially extracted in practical SNR range due to the nature of underlying cascaded Rayleigh fading. Building upon the derived PEP, we have

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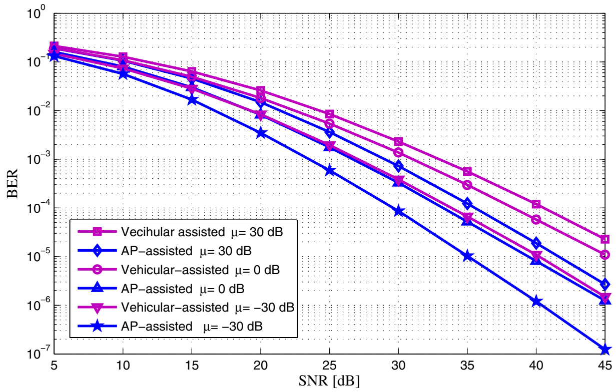

Fig. 7. Comparison of vehicle-assisted and access-point assisted V2V cooperative schemes for various relay locations.

obtained union bounds on BER which are used as an objective function for formulation of optimum power allocation between broadcasting and relaying phases. Through numerical optimization, we have determined optimum power allocation values which have brought performance improvements up to 3dB depending on relay location. Extensive Monte-Carlo simulations have been further presented to confirm the analytical findings.

APPENDIX

This appendix presents the derivation of pdf for $y = |\alpha|^2|\gamma|^2$ where α and γ are zero mean complex Gaussian with variance of $\sigma_\alpha^2 = \sigma_\gamma^2 = 0.5$ per dimension. Let z be the product of $|\alpha|$ and $|\gamma|$. The pdf of $z = |\alpha||\gamma|$ is given by [14, Eq. 8]

$$p(z) = 2G_{0,2}^{2,0}\left(z^2\left|_{\frac{1}{2},\frac{1}{2}}^{-}\right.\right). \tag{16}$$

Noting $y = z^2$, we have [16] $p(y) = p(z)/(2\,z)$ which yields (9) as

$$p(y) = \frac{1}{\sqrt{y}}G_{0.2}^{2,0}\left(y\left|_{\frac{1}{2},\frac{1}{2}}^{-}\right.\right) \tag{17}$$

It can be noted that by using [17, pp. 420, Eq. 11.17], i.e.,

$$G_{0,2}^{2,0}\left(y\left|_{a,b}^{-}\right.\right) = 2y^{\frac{a+b}{2}}K_{a-b}\left(2\sqrt{y}\right) \tag{18}$$

we can rewrite (17) as

$$p(y) = 2K_0\left(2\sqrt{y}\right) \tag{19}$$

which is the pdf for y obtained in [18] in terms of modified Bessel function of second kind of zero order.

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