A Cooperative Relay Selection Scheme in V2V Communications under Interference and Outdated CSI

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***Abstract*—Vehicle-to-vehicle communication systems are characterized by a highly time varying channel. For this reason, many relay selection schemes demand the continuous monitoring of all available channel links, resulting to an unnecessary increase of the system overhead processing. In this paper, an alternative (lower complexity) cooperative relaying selection scheme is adopted. For this new scheme, the influence of interference as well as the existence of outdated channel state information in a decode-and-forward relaying scenario is investigated. To this aim the bivariate double-Nakagami probability density function is introduced and used to model the correlation between the channel states during the selection and the data transmission instances. The performance is analysed using the criteria of outage probability and the average symbol error probability. It is shown that with the proposed approach a significant reduction in feedback load processing is achieved, with only a slight loss in performance.**

***Index Terms*- Co-channel interference, outdated channel estimates, relay selection, vehicle-to-vehicle communications.**

I. Introduction

Cooperative communications have been considered as a promising solution for extending coverage and enhancing reliability in contemporary communication networks. The performance of these systems is directly related with the relaying protocol and the selection mechanism that has been considered. As far as the employed protocol is concerned, two major approaches exist, namely decode-and-forward (DF) and amplify-and-forward (AF). With a small cost on the complexity, DF offers better performance as compared to AF, due to the decoding process that is employed in the first phase and guarantees a minimal good *source-to-relay* link. Moreover, regarding the relay selection mechanism, best relay selection (BRS) has been proposed as an efficient technique for improving performance [1]. In BRS, the best relay, from a set of N available ones, is selected and used for cooperation between the source and the destination. As a result, BRS requires increased processing and feedback load overhead, since in each packet transmission, full channel state information (CSI) is necessary for all relays, while also more relay switches are expected. This is especially important in ad-hoc networks because, the required fast relay switching rates impair system stability and/or lead to inaccurate channel estimations, [2].

Vehicular ad-hoc networks (VANET)s represent an integral part of the intelligent transportation systems (ITS)s that has gained an important interest by the scientific community and the industry over the past several years. These systems enable the vehicle-to-vehicle (V2V) communications and can be applied in a variety of communication scenarios ranging from road-safety and energy-saving improvements to comfort and infotainment. However, in contrast to the traditional cellular-mobile radio link, the V2V propagation channel is much more dynamic, since it consists of two non-stationary transceivers, closely located to the ground level. In this context, many works have investigated V2V cooperative scenarios, e.g., [3]–[6]. A common observation in previous works is the assumption of noise limited environment. However, in many practical situations, e.g., in the presence of hidden terminals, the performance of these systems can be significantly affected by co-channel interference (CCI), e.g., [7]. Moreover, to the best of the authors' knowledge, previous works in this area assume that perfect CSI is available at the system for relay selection. However, due to channel estimation errors and feedback delays, such an ideal assumption cannot be established in practice and has only theoretical importance [8].

In this paper, an analytical investigation of the influence that interfering effects as well as outdated CSI have to the performance of a V2V cooperative system is performed. In particular, the analysis is based on a well-established channel model for mobile-to-mobile communications such as double-Nakagami (DN) [9]. For this fading model, the bivariate probability density function (PDF) is presented for the first time and used to model the correlation between the exact and the outdated versions of the received signal to noise ratio (SNR). Moreover, a new relay selection scheme is adopted, which reduces feedback load processing, while achieves almost similar performance to BRS. The rest of the paper is organized as follows. Section II contains the system and channel model under investigation. In Section III, a stochastic analysis is performed for the received signal to interference ratio (SIR) statistics, which is used to analyse the outage probability (OP) and the average symbol error probability (SEP) performances in Section IV. In Section V, several numerical performance results are presented and in Section VI the concluding remarks are provided.

II. System and Channel Model

We consider a V2V cooperative communication scenario with one source (S), N relays $R_n = \{1, 2, \dots, N\}$ and one destination (D). We assume that all nodes are equipped with a single antenna and the transmission is realized in two phases. All hops in the scheme under consideration, including the interfering links, experience DN fading with channel gains, h_X, having PDF given by [9]

$$f_{h_x}(x) = \frac{2}{x\Gamma(m_{x,k})\Gamma(m_{x,\ell})}\mathcal{G}_{0,2}^{2,0}\left(\frac{m_{x,k}m_{x,\ell}x^2}{\Omega_{x,k}\Omega_{x,\ell}}\Big|_{m_{x,k},m_{x,\ell}}^{-}\right) \quad (1)$$

where $m_{x,y}$ denote the shaping parameter related with the severity of the fading and $\Omega_{x,y} = E\left\langle |h_x|^2\right\rangle$, with $x \in \{s_n, r_n, I_n, I_d\}$, when referring to S-$R_n$, $R_n - D$, interfering source to R_n, interfering source to D, respectively and $y, \ell \in \{1,2,3,4\}$ being related with the DN double-bounce interaction [10]. Moreover, in (1), $\Gamma(\cdot)$ is the gamma function and $\mathcal{G}_{p,q}^{m,n}[\cdot|\cdot]$ is the Meijer's G-function [11, eq. (9.301)]. The DN distribution is adopted since it provides a realistic description of the V2V channel in situations where both transmitter and receiver are moving. Moreover, similar to previous studies, e.g., [4], we have also assumed that all underlying channels are quasi-static, which can be justified for vehicular communication scenarios in rush-hour traffic.

In addition, R_ns as well as D are also subject to interfering signals under the assumption that (in general) the level of interference is such that the effect of thermal noise on system's performance can be ignored, i.e., interference limited scenario. Similar to other cases in the past, e.g., [12], for analytical simplification purposes, and without losing the generality, the analytical results are derived for the case of one interferer.

At the first phase, the source transmits a signal to all potential available relays (N), which form a set of relays. It is noted that the direct link between S and D is assumed to be heavy shadowed and thus not used. As a result, the received SIR at the nth relay is given by

$$\gamma_{\mathrm{out}_{s_n}} = \frac{\gamma_{s_n}}{\gamma_{I_n}} \quad (2)$$

where $\gamma_{s_n} = E_S|h_{s_n}|^2/\sigma_{s_n}^2$ is the instantaneous received SNR received at R_n, with E_S denoting the transmitter signal energy, $\sigma_{s_n}^2$ the variance of the additive white Gaussian noise (AWGN), and $\gamma_{I_n} = E_{I_n}|h_{I_n}|^2/\sigma_{I_n}^2$ denotes the instantaneous interference to noise ratio (INR) also received at R_n. Moreover, let $\mathcal{C}$ denoting the decoding set of the active relays that have correctly decoded the source message [13]. This set will form the basis for the relay that will be selected in the next phase.

A. Relay Selection Scheme

In this paper, a new relay-selection scheme is employed that aims at reducing complexity and feedback load processing. The mode of operation of the new scheme is as follows. The relay that was selected in the previous round of communications (tagged relay), sends a request to send (RTS) packet to the final destination. From this packet, the destination estimates the received instantaneous SNR, which is compared with a predefined threshold, γ_{th}, and if it exceeds it, then this relay is selected and no further processing is required. Otherwise, a flag packet is send to all relays that successfully received the original message (including the tagged relay) asking for the initialization of a best relay selection mechanism similar to the one given in [14]. In particular, all relays belonging to the set ignite a timer, which is related with the quality of their second-hop link. The time of the best relay, in terms of the SNR, expires first and hence this relay is selected for the second hop transmission.

From the mathematical point of view, under the assumption of independent and identically distributed (i.i.d.) fading, the CDF of the received instantaneous SNR for the link between R_n and D, $\tilde{\gamma}_{\mathrm{sel}}$, given $\mathcal{C}$, can be expressed as [15]

$$F_{\tilde{\gamma}_{\mathrm{sel}}|\mathcal{C}}(x) = \begin{cases} F_{\gamma_{r_n}}(x) - F_{\gamma_{r_n}}(\gamma_{\mathrm{th}}) \\ +F_{\gamma_{r_n}}(\gamma_{\mathrm{th}})F_{\gamma_{r_n}}(x)^{|\mathcal{C}|-1}, & x \geq \gamma_{\mathrm{th}} \\ F_{\gamma_{r_n}}(x)^{|\mathcal{C}|}, & x < \gamma_{\mathrm{th}} \end{cases} \quad (3)$$

where $\gamma_{r_n} = E_R|h_{r_n}|^2/\sigma_{r_n}^2$, with $f_{\gamma_x}(x)$ obtained by employing a change of variables in (1) and CDF given by

$$F_{\gamma_x}(x) = \frac{1}{\Gamma(m_{x,1})\Gamma(m_{x,2})}\mathcal{G}_{1,3}^{2,1}\left(\frac{m_{x,1}m_{x,2}x}{\Omega_{x,1}\Omega_{x,2}}\Big|_{m_{x,1},m_{x,2},0}^{1}\right). \quad (4)$$

The corresponding expression for the PDF of $\tilde{\gamma}_{\mathrm{sel}}|\mathcal{C}$ is

$$f_{\tilde{\gamma}_{\mathrm{sel}}|\mathcal{C}}(x) = \begin{cases} f_{\gamma_{r_n}}(x) + (\mathcal{C}-1)F_{\gamma_{r_n}}(\gamma_{\mathrm{th}}) \\ \times f_{\gamma_{r_n}}(x)F_{\gamma_{r_n}}(x)^{\mathcal{C}-2}, \ x \geq \gamma_{\mathrm{th}} \\ \mathcal{C}f_{\gamma_{r_n}}(x)F_{\gamma_{r_n}}(x)^{\mathcal{C}-1}, \ x < \gamma_{\mathrm{th}}. \end{cases} \quad (5)$$

After the selection is made, the relay forwards the initial message to the final destination and the received SIR at the destination, given set $\mathcal{C}$, can be expressed as

$$\gamma_{\mathrm{out}} = \frac{\tilde{\gamma}_{\mathrm{sel}}}{\gamma_{I_d}} \quad (6)$$

where $\gamma_{I_d} = E_{I_d}|h_{I_d}|^2/\sigma_{I_d}^2$ denotes the received instantaneous INR at destination. The behavior of the proposed scheme depends on the selected switching threshold γ_{th}, which is related with the instantaneous SNR. More specifically, with an increase on γ_{th}, its performance improves, approaching that of BRS, with the cost of a higher feedback load processing.

B. CSI Model

In a V2V communication scenario, it is very likely that the fading behavior will change rapidly. Hence, in this work, the CSI of the $R_n - D$ links is assumed to be outdated, due to the delay existing between the relay selection and data transmission phases as well as the fast time varying nature of the medium. Thus, the CSI model employed in [16] will be also adopted. More specifically, at the data transmission instance, the level of imperfection between the actual SNR, γ_{sel}, and $\tilde{\gamma}_{\mathrm{sel}}$, which is available at the selection instance, can be measured based on a correlation coefficient. In that case, the PDF of the actual received SNR of the *selected* user at the data transmission instance can be expressed as [17]

$$f_{\gamma_{\mathrm{sel}}|\mathcal{C}}(y) = \int_0^\infty f_{\gamma_{\mathrm{sel}},\tilde{\gamma}_{\mathrm{sel}}}(y,x)\frac{f_{\tilde{\gamma}_{\mathrm{sel}}|\mathcal{C}}(x)}{f_{\gamma_{r_n}}(x)}dx. \quad (7)$$

For evaluating (7), the bivariate DN distribution is required, which, to the best of the authors' knowledge, has not been presented in the past. Here, the following expression for the joint PDF between γ_{sel} and $\tilde{\gamma}_{\text{sel}}$ has been obtained as

$$
\begin{aligned}
f_{\gamma_{\text{sel}},\tilde{\gamma}_{\text{sel}}}(x,y) &= \sum_{h=0}^{\infty}\sum_{q=0}^{\infty} \frac{\frac{4\rho_1^h \rho_2^q/[\Gamma(m_{r_n,1})\Gamma(m_{r_n,2})]}{\left(\prod_{i=1}^{4}\overline{\gamma}_{r_n,i}\right)^{\frac{m_{r_n,1}+m_{r_n,2}+q+h}{2}}}}{\Gamma(m_{r_n,1}+h)\Gamma(m_{r_n,2}+q)h!q!} \\
&\times \frac{(xy)^{\frac{m_{r_n,1}+m_{r_n,2}+h+q}{2}-1}}{(1-\rho_1)^{m_{r_n,2}+h+q}(1-\rho_2)^{m_{r_n,1}+h+q}} \\
&\times K_{m_{r_n,1}-m_{r_n,2}+h-q}\left[\frac{2x^{1/2}}{\sqrt{\overline{\gamma}_{r_n,1}\overline{\gamma}_{r_n,3}(1-\rho_1)(1-\rho_2)}}\right] \\
&\times K_{m_{r_n,1}-m_{r_n,2}+h-q}\left[\frac{2y^{1/2}}{\sqrt{\overline{\gamma}_{r_n,2}\overline{\gamma}_{r_n,4}(1-\rho_1)(1-\rho_2)}}\right]
\end{aligned} \quad (8)
$$

where $0 \leq \rho_1, \rho_2 < 1$ are the power correlation coefficients of the underlying fading processes of the first and second bounces, respectively. Moreover, in (8), $\overline{\gamma}_{r_n,i} = \Omega_{r_n,i}/m_{r_n,1}, \forall i \in \{1,2\}$, $\overline{\gamma}_{r_n,i} = \Omega_{r_n,i}/m_{r_n,2}, \forall i \in \{3,4\}$ and $K_v(\cdot)$ is the second kind modified Bessel function of vth order [11, eq. (8.407/1)]. It is noted that (8) is new and its analytical derivation will be provided in the journal version of this work due to limited space. It is also noted that the power pdf of [18, eq. (6.69)] is a special case of (8).

III. SIR Statistics

In this section, the CDF of the system's output SIR is derived, while a high SNR analysis is also provided.

A. 1st Link Statistics

The first phase is characterized by the probability that the nth relay decodes the signal incorrectly, P_{off}, which actually represents the SEP of R_n. In particular, P_{off} can be evaluated as

$$
P_{\text{off}} = a\int_0^{\infty} \operatorname{erfc}\left(\sqrt{b\gamma}\right) f_{\gamma_{\text{out}_{s_n}}}(\gamma)d\gamma \quad (9)
$$

where (a,b) depend on the modulation scheme employed, e.g., for binary phase shift keying (BPSK), $a=1/2, b=1$. Next, in order to simplify the analysis, it is assumed that $|m_{s_n,2}-m_{s_n,1}| = 1/2$ as well as $|m_{I_n,2}-m_{I_n,1}| = 1/2$, i.e., quite similar fading conditions exist for the scattering environments around both S and R_n. Thus, substituting the PDFs of γ_{s_n} and γ_{I_n} in $f_{\gamma_{\text{out}_{s_n}}}(\gamma) = \int_0^{\infty}\gamma f_{\gamma_{s_n}}(x\gamma) f_{\gamma_{I_n}}(x)dx$ using [19, eq. (07.34.03.0606.01)] as well as [11, eq. (3.326)], the PDF of $\gamma_{\text{out}_{s_n}}$ is given by[1]

$$
\begin{aligned}
f_{\gamma_{\text{out}_s}}(\gamma) &= \frac{\Gamma\left(2m_{s,1}+2m_{I,1}\right)}{\Gamma(m_{s,1})\Gamma(m_{s,2})}\frac{2^{1-2m_{s,1}-2m_{I,1}}\pi}{\Gamma(m_{I,1})\Gamma(m_{I,2})} \\
&\times \left[\prod_{i=1}^{2}\left(\frac{1}{\overline{\gamma}_{s,i}}\right)^{m_{s,1}}\left(\frac{1}{\overline{\gamma}_{I,i}}\right)^{m_{I,1}}\right] \\
&\times \gamma^{m_{s,1}-1}\left(\sqrt{\frac{\gamma}{\overline{\gamma}_{s,1}\overline{\gamma}_{s,2}}}+\sqrt{\frac{1}{\overline{\gamma}_{I,1}\overline{\gamma}_{I,2}}}\right)^{-2m_{s,1}-2m_{I,1}}
\end{aligned} \quad (10)
$$

[1] Since the analytical results presented in this and the next sections refer to i.i.d. statistics, the relay index n will be omitted.

where $\overline{\gamma}_{I,i} = \Omega_{I,i}/m_{I,i}$ and $\overline{\gamma}_{s,i} = \Omega_{s,i}/m_{s,i}$. Moreover, substituting (10) in (9), using [20, eq. (10)], [19, eq. (06.27.26.0006.01)] and [20, eq. (21)], the following closed-form expression for P_{off} is obtained

$$
\begin{aligned}
P_{\text{off}} &= \frac{a/\sqrt{\pi}}{\Gamma(m_{s,1})\Gamma(m_{s,2})\Gamma(m_{I,1})\Gamma(m_{I,2})} \\
&\times \mathcal{G}_{3,4}^{4,2}\left(\frac{b\overline{\gamma}_{s,1}\overline{\gamma}_{s,2}}{\overline{\gamma}_{I,1}\overline{\gamma}_{I,2}}\middle|_{0,\frac{1}{2},m_{I,1},\frac{2m_{I,1}+1}{2}}^{\frac{1-2m_{s,1}}{2},1-m_{s,1},1}\right).
\end{aligned} \quad (11)
$$

B. 2nd Link Statistics

In the second communication phase, the CDF of the output SIR given $\mathcal{C}$, $\gamma_{\text{out}|\mathcal{C}}$, can be expressed as

$$
\begin{aligned}
F_{\gamma_{\text{out}|\mathcal{C}}}(\gamma) &= \pi^2\Gamma(2m_{r,1})\sum_{h,q=0}^{\infty}\sum_{j_1,j_2=0}^{\left|h-\frac{1}{2}-q\right|-\frac{1}{2}} \\
&\times \left[\prod_{i=1}^{2}\frac{\left(j_i+|h-\frac{1}{2}-q|-\frac{1}{2}\right)!(1-\rho_i)^{m_{r,i}}\left(\frac{1}{\overline{\gamma}_{I_d,i}}\right)^{m_{I_d,1}}}{j_i!\left(-j_i+|h-\frac{1}{2}-q|-\frac{1}{2}\right)!\Gamma(m_{r,i})^2\Gamma(m_{I_d,i})}\right] \\
&\times \frac{\rho_1^h\rho_2^q 2^{3-\theta_1-\theta_2-2m_{I_d,1}}\Gamma\left(2m_{I_d,1}+\theta_1\right)}{\Gamma(h+m_{r,1})\Gamma(q+m_{r,2})h!q!\theta_1}\mathcal{A}\left(\frac{\gamma}{\overline{\gamma}_{13}\rho_{12}}\right)^{\frac{\theta_1}{2}} \\
&\times \frac{{}_2F_1\left(1,2m_{I_d,1}+\theta_1,1+\theta_1,\frac{\frac{\sqrt{\gamma}}{\sqrt{\overline{\gamma}_{13}\rho_{12}}}}{\frac{\sqrt{\gamma}}{\sqrt{\overline{\gamma}_{13}\rho_{12}}}+\sqrt{\frac{1}{\overline{\gamma}_{I_d,1}\overline{\gamma}_{I_d,2}}}}\right)}{\left(\frac{\sqrt{\gamma}}{\sqrt{\overline{\gamma}_{13}\rho_{12}}}+\sqrt{\frac{1}{\overline{\gamma}_{I_d,1}\overline{\gamma}_{I_d,2}}}\right)^{2m_{I_d,1}+\theta_1}}
\end{aligned} \quad (12)
$$

where $\overline{\gamma}_{x,y} = \overline{\gamma}_{r,x}\overline{\gamma}_{r,y}, \rho_{12} = (1-\rho_1)(1-\rho_2)$, $\theta_i = h+q+2m_{r,1}-j_i$, for $i \in \{1,2\}$, ${}_2F_1(\cdot)$ denotes the Gauss hypergeometric function [11, eq. (9.100)] and $\mathcal{A}$ is given in (13) (shown at the top of the next page). Moreover, in (13), $\beta_\ell = \frac{\ell}{\sqrt{\overline{\gamma}_{24}\rho_{12}}} + \ell i\sqrt{\frac{1}{\overline{\gamma}_{13}}}$, $\overline{\gamma}_{I_d,i} = \Omega_{I_d,i}/m_{I_d,i}$, $\gamma(.,.)$ and $\Gamma(.,.)$ denote the lower and the upper incomplete gamma functions [11, eqs. (8.350/1-2)], respectively. The proof for (12) is provided in the Appendix.

1) Asymptotic Analysis: The exact expression for $F_{\gamma_{\text{out}|\mathcal{C}}}(\gamma)$ does not provide a clear physical insight of the system's performance. In order to provide a simplified expression, the main concern is to derive an asymptotic closed-form expression for $F_{\gamma_{\text{out}|\mathcal{C}}}(\gamma)$. Therefore, assuming $\rho = \rho_1 = \rho_2$, higher values of $\overline{\gamma}_{r_i}$ and based on the approach presented in the Appendix, a closed-form asymptotic expression for the CDF of $\gamma_{\text{out}|\mathcal{C}}$ is obtained in (14) (shown at the top of the next page), where $\beta_3 = \overline{\gamma}_{13}\rho$.

IV. Performance Evaluation

In this section using the previously derived results, important performance metrics of the scheme under consideration will be analytically study. More specifically, the performance will be studied using the criteria of OP and the SEP.

$$\mathcal{A}=\frac{\Gamma(m_{r,1})\Gamma(m_{r,2})}{\sqrt{\pi}\Gamma(2m_{r,1})}\Gamma\left(\theta_2,\frac{2\sqrt{\gamma_{\rm th}}}{\sqrt{\overline{\gamma}_{24}\rho_{12}}}\right)+\sum_{t=1}^{2}\frac{2^{1-2m_{r,1}}(\mathcal{C}-t+1)}{(\overline{\gamma}_{24}\rho_{12})^{\frac{\theta_2}{2}}}\sum_{i=0}^{\mathcal{C}-t}\binom{\mathcal{C}-t}{i}\sum_{\substack{n_1,\dots,n_{2m_{r,1}-1}=0\\ n_1+\cdots+n_{2m_{r,1}-1}=i}}^{i}\frac{i!(-1)^i}{n_1!\cdots n_{2m_{r,1}-1}!}$$
$$\times\frac{\left(\prod_{j=1}^{2m_{r,1}-1}\frac{1}{\left(\overline{\gamma}_{13}^{j/2}j!\right)^{n_{j+1}}}\right)}{\beta_1^{\theta_2+\sum_{j=1}^{2m_{r,1}-1}jn_{j+1}}}\left[(2-t)\gamma\left(\theta_2+\sum_{j=1}^{2m_{r,1}-1}jn_{j+1},\beta_2\sqrt{\gamma_{\rm th}}\right)+(t-1)F_{\gamma_x}(\gamma_{\rm th})\Gamma\left(\theta_2+\sum_{j=1}^{2m_{r,1}-1}jn_{j+1},\beta_2\sqrt{\gamma_{\rm th}}\right)\right]. \tag{13}$$

$$F_{\gamma_{\rm out|\mathcal{C}}}(\gamma)=\left[\Gamma\left(2m_{r,1},\frac{2\sqrt{\gamma_{\rm th}}}{\sqrt{\beta_3}}\right)+\sum_{i=1}^{2}(\mathcal{C}+1-i)\left(\frac{\sqrt{\pi}/m_{r,1}}{\Gamma(m_{r,1})\Gamma(m_{r,2})}\right)^{\mathcal{C}-i}\left[(2-i)\left(\frac{2}{\beta_3}\right)^{2(\mathcal{C}-1)m_{r,1}}\gamma\left(2\mathcal{C}m_{r,1},\frac{2\sqrt{\gamma_{\rm th}}}{\sqrt{\beta_3}}\right)+(i-1)\right.\right.$$
$$\left.\left.\times F_{\gamma_x}(\gamma_{\rm th})\left(\frac{2}{1-\rho}\right)^{2(2-\mathcal{C})m_{r,1}}\Gamma\left(2m_{r,1}(\mathcal{C}-1),\frac{2\sqrt{\gamma_{\rm th}}}{\sqrt{\beta_3}}\right)\right)\right]\left[\prod_{i=1}^{2}\frac{\left(\frac{1}{\overline{\gamma}_{I_d,i}}\right)^{\frac{1-2m_{r,2}}{2}}}{\Gamma(m_{I_d,i})}\frac{\Gamma\left(m_{r,2}+m_{I_d,i}-\frac{1}{2}\right)}{\Gamma(m_{r,i})^2\overline{\gamma}_{r,3-i}^{\frac{2m_{r,2}-1}{2}}}\right]\frac{\pi(1-\rho)^{1/2}}{m_{r,1}2^{2m_{r,1}-1}}\gamma^{\frac{2m_{r,2}-1}{2}}. \tag{14}$$

A. Outage Probability

The OP is defined as the probability that the instantaneous received SIR falls below a predetermined threshold $\gamma_{\rm T}$. Therefore, the OP can be evaluated as

$$P_{\rm out}=P_{\rm off}^N+\sum_{k=1}^{N}\binom{N}{k}P_{\rm off}^{N-k}\left(1-P_{\rm off}\right)^kF_{\gamma_{\rm out|k}}(\gamma_{\rm T}). \tag{15}$$

B. Symbol Error Probability

The SEP can be evaluated as

$$\overline{P}_{\rm se}=P_{\rm off}^N+\sum_{k=1}^{N}\binom{N}{k}P_{\rm off}^{N-k}\left(1-P_{\rm off}\right)^kP_{\rm se|k} \tag{16}$$

where

$$P_{\rm se|k}=\sqrt{2\pi}\Gamma(2m_{r,1})\sum_{h,q=0}^{\infty}\sum_{j_1,j_2=0}^{\left|h-\frac{1}{2}-q\right|-\frac{1}{2}}\frac{\rho_1^h\rho_2^q}{h!q!}$$
$$\times\left[\prod_{i=1}^{2}\frac{\left(j_i+\left|h-\frac{1}{2}-q\right|-\frac{1}{2}\right)!(1-\rho_i)^{m_{r,i}}\left(\frac{1}{\overline{\gamma}_{I_d,i}}\right)^{1/2}}{j_i!\left(-j_i+\left|h-\frac{1}{2}-q\right|-\frac{1}{2}\right)!\Gamma(m_{r,i})^2\Gamma(m_{I_d,i})}\right]\mathcal{A}$$
$$\times\frac{\Gamma\left(2m_{I_d,1}+\theta_1\right)a\sqrt{b}/\theta_1}{\Gamma(h+m_{r,1})\Gamma(q+m_{r,2})}\sum_{k=0}^{2m_{I_d,1}-1}\frac{\sqrt{\overline{\gamma}_{13}\rho_{12}}/k!}{2^{\theta_1+3j_1+j_2+2m_{I_d,1}-k}}$$
$$\times\frac{(1-2m_{I_d,1})_k(\theta_1)_k}{(\theta_1+1)_k\Gamma(\theta_1+k)}\mathcal{G}_{2,3}^{3,2}\left(\frac{b\overline{\gamma}_{13}\rho_{12}}{2\overline{\gamma}_{I_d,1}\overline{\gamma}_{I_d,2}}\middle|\begin{matrix}\frac{-\theta_1-k}{2},\frac{1-\theta_1-k}{2}\\-\frac{1}{2},0,0\end{matrix}\right). \tag{17}$$

For deriving (17), the following procedure was followed. First, (12) is substituted in $P_{\rm se|k}=\int_0^\infty\frac{a\sqrt{b}}{2\sqrt{2\pi}\sqrt{\gamma}}\exp\left(-\frac{b\gamma}{2}\right)F_{\gamma_{\rm out|k}}(\gamma)d\gamma$. Then, [19, eq. (07.23.03.0142.01)] is employed, followed by [20, eqs. (10 and 11)]. Finally, using [20, eq. (21)] and after some mathematical manipulations yields to (17).

V. Numerical Results

In this section, several numerically evaluated performance results are provided. These results include the OP investigation, based on (15) and (16), which can be evaluated with the aid of (11), (12) ((14) for the asymptotic case) and (17). In all cases, the following assumptions have been made for the various parameters of the system under consideration. For the first link, the number of relays is $N=4$ (if not otherwise stated), shaping parameter of the desired link $m_{s,1}=1.5$, mean values $\Omega_{s,i}=10$dB, shaping parameter of the interfering links $m_{I,1}=1.5$, average INR $\overline{\gamma}_{I,i}=4$dB. For the second link, shaping parameter of the desired link $m_{r,1}=1.5$, shaping parameter of the interfering links $m_{I_d,1}=1$, average INR $\overline{\gamma}_{I_d,i}=4$dB. Moreover, the processing complexity of the proposed scheme is also evaluated based on the approach provided in [21]. More specifically, as a performance indicator for the complexity, the average number of active relays (NAR) ($N_{\rm out}$) is adopted. It is obvious that as the NAR, which must be examined in the second phase of communications, increases, the processing and feedback load will also increase. In the proposed scheme, NAR can be evaluated using $N_{\rm out}=P_{\rm off}^N+\sum_{k=1}^{N}\binom{L}{k}P_{\rm off}^{N-k}\left(1-P_{\rm off}\right)^k\left[1+(k-1)F_{\gamma_{rn}}(\gamma_{\rm th})\right]$.

In Fig. 1, assuming $\Omega_{r,i}=10$dB, switching threshold $\gamma_{\rm th}=10$dB, the OP is plotted as a function of the correlation coefficients $\rho_1=\rho_2=\rho_i$ for different values of the outage threshold γ_T. In this figure, it is shown that the OP decreases with the decrease of γ_T. It is noted that as ρ_i increases, i.e., the SNR at the selection instance approaches the one at the reception instance, the performance improves, i.e., OP decreases. This performance improvement is higher for $\rho_i\to 1$, while it seems that for lower values of γ_T, the performance gain due to the increase of ρ_i is higher.

In Fig. 2, assuming $\gamma_T=10$dB, $\gamma_{\rm th}=20$dB, the OP is plotted as a function of $\Omega_{r,i}=\overline{\gamma}_{r,i}m_j$, where j depends on i as shown below (8), for different values of ρ_i. In this figure it is depicted a gap among performances exists for

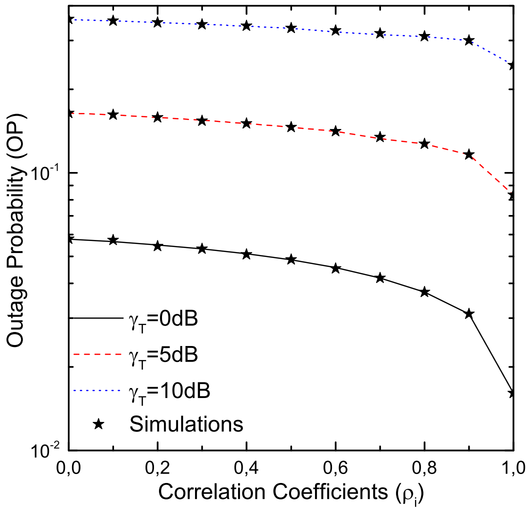

Fig. 1. OP vs ρ_i for different values of γ_T.

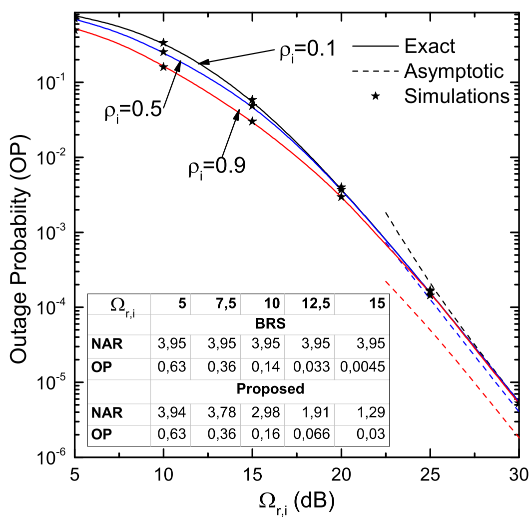

Fig. 2. OP vs the average SNR of the 2nd hop for different values of ρ_i.

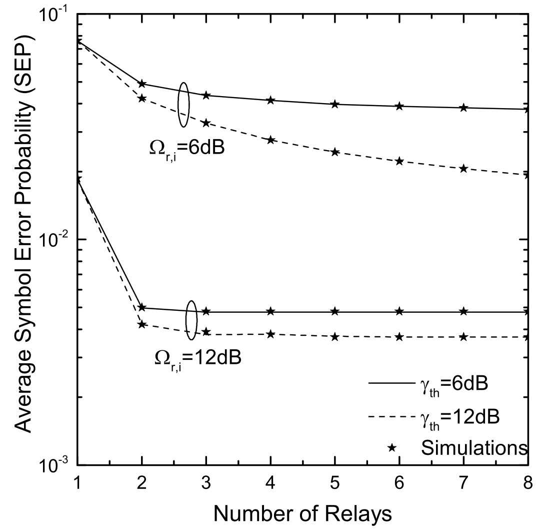

Fig. 3. SEP vs number of relays for different values of $\Omega_{r,i}$.

$\overline{\gamma}_{r,i} < \gamma_{\rm th}$, which decreases as $\overline{\gamma}_{r,i}$ increases. This behavior is due to the mode of operation of the new scheme, since for $\overline{\gamma}_{r,i} > \gamma_{\rm th}$ it is very likely that all second hop links satisfy the switching threshold and thus the number of switches is expected to decrease. Moreover, the asymptotic curves, which are also included in the same figure, approximate quite well the exact ones even for moderate values of the average SNR, i.e., 20dB, while the approximation improves for lower values of ρ_i. In addition, in the same figure, the average NAR is also included for the proposed scheme as well as the corresponding one with BRS. For the BRS the OP has been also evaluated and included in the table. It is shown that for lower values of $\overline{\gamma}_{r,i}$, the proposed scheme offers an excellent compromise between performance and complexity as compared to BRS.

In Fig. 3, assuming $\rho_i = 0.75$, $\gamma_T = 10$dB, the SEP of BPSK is plotted as a function of the number of relays N for different values of $\overline{\gamma}_{r,i}$ and $\gamma_{\rm th}$. It is depicted in this figure that the performance improves with an increase on $\overline{\gamma}_{r,i}$, $\gamma_{\rm th}$ and N. More specifically, for lower values of $\overline{\gamma}_{r,i}$, by setting a larger value for the switching threshold, results to an important improvement on the system performance, which further improves with the increase of N. However, for higher values of $\overline{\gamma}_{r,i}$ the gain offered due to the increase of $\gamma_{\rm th}$ is smaller. Moreover, it is not necessary to employ more than 2 relays since for $N > 2$ the gain achieved is minor. Finally, simulation performance results are also included in all figures, verifying the validity of the proposed theoretical approach.

VI. Conclusions

The influence of the interference as well as outdated CSI on the performance of a cooperative V2V relaying scenario has been analytically investigated. The bivariate DN distribution has been presented for the first time and used to model the correlation between the channel gains of the received signals at the selection and the data transmission instances. Based on the DF protocol, a new threshold-based relay selection scheme has been adopted, which reduces the overhead processing that the conventional BRS approach induces to the system. For this new scheme, analytical expressions for the SIR statistics were derived and used to provide the CDF of the output SIR. In addition, its performance has been evaluated, using well-known performance metrics, namely OP and SEP. It is depicted that in many cases the new scheme, outperforms BRS in terms of the performance versus complexity trade-off.

Appendix
Proof for Equation (12)

Firstly, a convenient expression for $\left(F_{\gamma_{r_j d}}(x)\right)^{\mathcal{C}}$ should be provided. In this context and based on (4), by employing [19, eq. (07.34.03.0732.01)] as well as [11, eq. (8.352/1)], the following mathematically tractable expression is derived

$$\left(F_{\gamma_{r,n}}(x)\right)^{\mathcal{C}} = \left\{ \frac{\sqrt{\pi}2^{\frac{3}{2}-m_{r,1}-m_{r,2}}\Gamma(2m_{r,1})}{\Gamma\left(m_{r,1}\right)\Gamma\left(m_{r,2}\right)} \right.$$
$$\left. \times \left[1 - \exp\left(-2\sqrt{\frac{x}{\overline{\gamma}_{13}}}\right) \sum_{j=1}^{2m_{r,1}-1} \frac{2^j}{j!} \left(\frac{x}{\overline{\gamma}_{13}}\right)^{\frac{j}{2}} \right] \right\}^{\mathcal{C}}$$

$$\stackrel{(1)}{=} \frac{\sqrt{\pi}2^{\frac{3}{2}-m_{r,1}-m_{r,2}}\Gamma(2m_{r,1})}{\Gamma(m_{r,1})\Gamma(m_{r,2})}\sum_{i=0}^{\mathcal{C}}\binom{\mathcal{C}}{i}\sum_{\substack{n_1,\ldots,n_{2m_{r,1}-1}=0\\ n_1+\cdots+n_{2m_{r,1}-1}=i}}^{i}(-1)^i$$
$$\times\frac{i!\prod_{j=1}^{2m_{r,1}-1}\left(\frac{2}{\overline{\gamma}_{13}^{j/2}j!}\right)^{n_{j+1}}}{n_1!\cdots n_{2m_{r,1}-1}!}x^{\sum_{j=1}^{2m_{r,1}-1}\frac{j}{2}n_{j+1}}\exp\left(-2i\frac{\sqrt{x}}{\sqrt{\overline{\gamma}_{13}}}\right) \quad \text{(A-1)}$$

where (1) holds due to the use of the binomial and the multinomial identities. Now, based on (A-1) and by substituting (5), (8) in (7), the following type of integrals appear

$$\begin{aligned}\mathcal{I}_1 &= \int_0^{\gamma_{\text{th}}} x^{a_1}\exp\left(b_1x^{1/2}\right)dx\\ \mathcal{I}_2 &= \int_{\gamma_{\text{th}}}^{\infty} x^{a_2}\exp\left(b_2x^{1/2}\right)dx.\end{aligned} \quad \text{(A-2)}$$

These integrals can be solved with the aid of [11, eqs. (8.350/1-2)] and after some mathematics, the following expression for the PDF of γ_{sel} is obtained

$$f_{\gamma_{\text{sel}}|\mathcal{C}}(y)=\pi^{\frac{3}{2}}\Gamma(2m_{r,1})\sum_{h,q=0}^{\infty}\sum_{j_1,j_2=0}^{\left|h-\frac{1}{2}-q\right|-\frac{1}{2}}\frac{\rho_1^h\rho_2^q}{h!q!}$$
$$\times\left[\prod_{i=1}^{2}\frac{(j_i+|h-1/2-q|-\frac{1}{2})!(1-\rho_i)^{\frac{j_1-h-q}{2}}}{j_i!\left(-j_i+|h-\frac{1}{2}-q|-1/2\right)!\Gamma(m_{r,i})^2}\right]$$
$$\times\frac{2^{1-2j_1-2j_2-\theta_2}(1-\rho_2)^{1/2}}{\Gamma(h+m_{r,1})\Gamma(q+m_{r,2})\overline{\gamma}_{13}^{\frac{\theta_1}{2}}}\mathcal{A}y^{\frac{\theta_1}{2}-1}\exp\left(-\frac{2y^{1/2}}{\sqrt{\overline{\gamma}_{13}\rho_{12}}}\right) \quad \text{(A-3)}$$

with the corresponding CDF given by

$$F_{\gamma_{\text{sel}}|\mathcal{C}}(y)=\pi^{3/2}\Gamma(2m_{r,1})\sum_{h,q=0}^{\infty}\sum_{j_1,j_2=0}^{\left|h-\frac{1}{2}-q\right|-\frac{1}{2}}\frac{\rho_1^h\rho_2^q}{h!q!}$$
$$\times\left[\prod_{i=1}^{2}\frac{(j_i+|h-1/2-q|-\frac{1}{2})!(1-\rho_i)^{\frac{j_1-h-q}{2}}}{j_i!\left(-j_i+|h-1/2-q|-\frac{1}{2}\right)!\Gamma(m_{r,i})^2 2^{\theta_i}}\right] \quad \text{(A-4)}$$
$$\times\frac{(1-\rho_2)^{1/2}\rho_{12}^{\frac{\theta_1}{2}}/2^{2(j_1+j_2-1)}}{\Gamma(h+m_{r,1})\Gamma(q+m_{r,2})}\mathcal{A}\gamma\left(\theta_1,\frac{2\sqrt{\gamma}}{\sqrt{\overline{\gamma}_{13}\rho_{12}}}\right).$$

Moreover, based on (6), the CDF of $\gamma_{\text{out}|\mathcal{C}}$ can be evaluated by $F_{\gamma_{\text{out}|\mathcal{C}}}(\gamma)=\int_0^{\infty}F_{\gamma_{\text{sel}}|\mathcal{C}}(y\gamma)f_{I_d}(y)dy$. Substituting (A-4) and the PDF of I_d, i.e.,

$$f_{I_d}(y)=\frac{\left(\frac{1}{\overline{\gamma}_{I_d,1}\overline{\gamma}_{I_d,2}}\right)^{\frac{m_{I_d,1}+m_{I_d,2}}{2}}}{\Gamma(m_{I_d,1})\Gamma(m_{I_d,2})}$$
$$\times y^{\frac{m_{I_d,1}+m_{I_d,2}}{2}-1}K_{m_{I_d,2}-m_{I_d,1}}\left(2\sqrt{\frac{y}{\overline{\gamma}_{I_d,1}\overline{\gamma}_{I_d,2}}}\right) \quad \text{(A-5)}$$

in the above definition and using first [11, eq. (8.469/3)], then [11, eq. (6.455/2)] and after some mathematical manipulation yields (14) and also completes this proof.

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