V2V Cooperative Relaying Communications Under Interference and Outdated CSI

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***Abstract*—In this paper, we study a cooperative vehicle-to-vehicle (V2V) interference-limited communication system with decode-and-forward relaying operating over double-Nakagami (DN) fading channels. This distribution has been proposed as a fading model for scenarios where both the transmitter and the receiver are in motion, as is the case in V2V communications. For the purposes of our analysis, we introduce the bivariate DN distribution and derive statistical metrics for this distribution, such as the probability density function, the cumulative distribution function, and the moments. The new expressions have been employed to model the outdated channel state information (CSI) that is due to the fast time varying nature of the wireless medium and the delay naturally existing between relay selection and data transmission instances. The analysis considers two relay selection schemes, according to the relay-destination channel quality, namely the well-known best relay selection (BRS) and a new one termed as threshold-based relay selection, which offers lower complexity than BRS. Using our analytical framework, exact and asymptotic performance results are obtained for the outage and the average symbol error probabilities, while the diversity order has been also evaluated. The numerical and simulation results corroborate our theoretical ones and quantify the impact of outdated CSI, level of interference, and varying distances between the relay nodes and the final destination on the system's performance.**

***Index Terms*—Best relay selection, co-channel interference, correlated double-Nakagami (DN) statistics, decode-and-forward, outdated channel estimates, PDF of the sum of DN RVs, vehicle-to-vehicle communications.**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 to 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 minimum good *source-to-relay* link. Regarding the relay selection mechanism, best relay selection (BRS) has been proposed as an efficient technique for improving performance [2]. In BRS, the relay with the best relay-to-destination channel quality, among a set of N available ones, is selected and used for cooperation between the source and the destination. However, BRS requires increased processing and feedback load overhead since estimations for the channel state information (CSI) are necessary for all relay links in each packet transmission. Moreover, additional relay switching operations are required that may lead to fast relay switching rates, which is known to impair system stability and/or lead to performance loss in ad-hoc networks, e.g., [3], [4].

Vehicular ad-hoc networks represent an integral part of the intelligent transportation systems (ITSs) that have 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. Recently, ITS techniques have been adopted in the envisioned autonomous driving in road trains, which is implemented via the concept of platooning [5]. In particular, platoons form cooperative V2V communication networks, where important information, e.g., velocity, exact position, is distributed among vehicles throughout the platoon. 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, the transmitted signal can propagate to the receiver via a keyhole and thus the envelope of the resulting narrow-band impulse response is modeled using a cascaded distribution [6]. Depending upon the propagation environment characteristics, various statistical (cascaded) models have been proposed, with the most notable being the double-Rayleigh (DR), double-Nakagami (DN) [7], and double-Rice [8], with the first one representing a special case of the other two. It is noteworthy that the cascaded distributions include as limiting case the constitute distributions, e.g., the DN distribution converges to Nakagami-m. Thus, using these generic distributions, it is possible to model various propagation conditions, ranging from worse than Rayleigh, appearing in V2V communication scenarios [9], to non-fading conditions [10].

Many works have investigated V2V cooperative communications, e.g., [11]–[17]. For example in [11], assuming

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Part of this work has been presented in [1].

DF relaying in a V2V communication scenario, the symbol error rate performance is evaluated. Moreover, in [16], the performance of a two-way AF multi-relay cooperative V2V communication network is analyzed, assuming DR fading conditions. A common observation in previous works is that noise limited environments have been assumed. However, in many practical situations, e.g., in the presence of hidden terminals [18], the performance of these systems can be significantly affected by co-channel interference (CCI), e.g., [19]. Moreover, previous works in this area assume that perfect CSI is available for relay selection and data transmission. However, due to feedback delays and the fast time-varying nature of the fading channels, such an ideal assumption has only theoretical importance and cannot be established in practice, especially in vehicular networks [4], [20], [21]. Thus, to the best of the authors' knowledge, no other work has considered relay selection for V2V communications in the presence of outdated CSI and CCI. The main reason for this, was the absence of exact expressions for the bivariate statistics of cascaded distributions until very recently [22].

In this paper, an analytical study of the impact of CCI and outdated CSI on the performance of a V2V cooperative system is performed. The analysis is based on the DN distribution for modeling the V2V channel fading conditions [7]. In particular, the contributions of the paper are as follows:

- The bivariate DN distribution is introduced and important statistical metrics of this distribution, namely the joint probability density function (PDF), cumulative distribution function (CDF), and the moments are introduced;
- The new expressions are used to model the correlation between the exact and outdated versions of the received signal-to-noise ratio (SNR) in a V2V cooperative communication scenario;
- Assuming non-identically distributed fading conditions and an interference limited scenario, a generic analytical framework for evaluating the performance of BRS has been developed, which allows different distances among the mobile nodes to be considered;
- A new relay selection scheme is adopted, which reduces feedback load processing, while achieving almost similar performance to BRS;
- A closed-form approximated expression for the PDF of the sum of L DN distributed random variables (RVs) is derived and used to investigate the impact of the accumulated interference;
- The performance of both relay selection schemes has been evaluated using the criteria of outage probability (OP) and average symbol error probability (SEP).

The results are obtained in exact analytical expressions that allow fast and efficient evaluations of the performance, thereby avoiding the time consuming simulations.

The paper is organized as follows. In Section II, the bivariate statistics of the DN distribution are presented. In Section III, the system and channel model of the cooperative relaying scheme are presented, while is Section IV a stochastic analysis is performed for the received signal-to-interference ratio (SIR). In Section V, this analysis is used to study the OP and the SEP performances. In Section VI, several numerical performance results are presented and Section VII provides the conclusions.

II. Double-Nakagami Bivariate Statistics

Let X_j, X_{j+2}, $j \in \{1,2\}$, be two correlated Nakagami-m RVs with joint PDF given by [10, eq. (6.1)]

$$\begin{aligned} f_{X_j,X_{j+2}}(x_1,x_2) = & \frac{4(x_1x_2)^{m_j}/\Gamma(m_j)}{\Omega_j\Omega_{j+2}(1-\rho_j)\left(\Omega_j\Omega_{j+2}\rho_j\right)^{\frac{m_j-1}{2}}} \\ & \times \exp\left[-\frac{\Omega_{j+2}x_1^2+\Omega_j x_2^2}{\Omega_j\Omega_{j+2}(1-\rho_j)}\right] I_{m_j-1}\left[\frac{2\sqrt{\rho_j}x_1x_2}{\sqrt{\Omega_j\Omega_{j+2}}(1-\rho_j)}\right], \end{aligned} \tag{1}$$

with $m_j > 0.5$, $\Omega_j = \mathbb{E}\left\langle X_j^2\right\rangle/m_j$, $\Omega_{j+2} = \mathbb{E}\left\langle X_{j+2}^2\right\rangle/m_j$, where $\mathbb{E}\langle\cdot\rangle$ denotes expectation, $\Gamma(\cdot)$ is the Gamma function [23, eq. (8.310/1)], and $I_v(\cdot)$ is the modified Bessel function of the first kind and order v [23, eq. (8.445)]. Moreover, in (1), $0 \le \rho_j < 1$ is the power correlation coefficient defined as

$$\rho_j \triangleq \frac{\operatorname{cov}\left(X_j^2, X_{j+2}^2\right)}{\sqrt{\operatorname{var}\left(X_j^2\right)\operatorname{var}\left(X_{j+2}^2\right)}}, \tag{2}$$

where $\operatorname{cov}(\cdot)$ and $\operatorname{var}(\cdot)$ are the covariance and variance, respectively. Let Z_1, Z_2 denote two DN RVs that are defined as the product of two independent Nakagami-m RVs, i.e.,

$$\begin{array}{c} Z_1 = X_1 \times X_2 \\ \rho_{DN}\Big\downarrow \quad \rho_1\Big\downarrow \quad \rho_2\Big\downarrow \\ Z_2 = X_3 \times X_4. \end{array} \tag{3}$$

In (3), ρ_j denotes the correlation coefficient between the Nakagami RVs, defined in (2), and ρ_{DN} is the correlation coefficient of the DN RVs. It is noted that the analysis of the multiplicative fading channel models has received a great deal of attention during the last years as it is proved by the numerous of contributions that exist, e.g., [22], [24], [25].

As shown in Appendix A, for non-identically distributed DN RVs, the PDF of the bivariate DN distribution is given by

$$\begin{aligned} f_{Z_1,Z_2}(x,y) = & \sum_{h,q=0}^{\infty} \frac{16/[\Gamma(m_1)\Gamma(m_2)]}{\Gamma(m_1+h)h!\Gamma(m_2+q)q!} \\ & \times \frac{\rho_1^h\rho_2^q(xy)^{p_1-1}}{(\Omega_1\Omega_2\Omega_3\Omega_4)^{\frac{p_1}{2}}(1-\rho_1)^{h+q+m_2}(1-\rho_2)^{h+q+m_1}} \\ & \times K_{p_2}\left(\frac{2x}{\sqrt{\Omega_1\Omega_3\hat{\rho}}}\right)K_{p_2}\left(\frac{2y}{\sqrt{\Omega_2\Omega_4\hat{\rho}}}\right), \end{aligned} \tag{4}$$

where $\hat{\rho} = (1-\rho_1)(1-\rho_2), p_1 = h+q+m_1+m_2, p_2 = h-q+m_1-m_2$, and $K_v(\cdot)$ is the modified Bessel function of the second kind and vth order [23, eq. (8.432/1)]. In Appendix B, it is proved that the error truncating the infinite series in (4) converges and thus (4) also converges. Moreover, in Appendix C, it has been proved that (4) is a valid PDF. It is worth noting that by setting $m_1 = m_2 = 1$, $\rho_1 = \rho_2$, $\Omega_1 = \Omega_2$, and $\Omega_3 = \Omega_4$, (4) simplifies to the joint PDF of the bivariate DR distribution given in [26, eq. (6.69)]. The joint CDF of Z_1 and Z_2 is given by $F_{Z_1,Z_2}(x,y) = \int_0^x\int_0^y f_{Z_1,Z_2}(x,y)dxdy$. Substituting (4) in this definition, representing Bessel function as in [27, eq. (14)], and then using

[27, eq. (26)], the following generic expression for the joint CDF can be obtained as

$$F_{Z_1,Z_2}(x,y)=\sum_{h,q=0}^{\infty}\frac{1/[\Gamma(m_1)\Gamma(m_2)]}{\Gamma(m_1+h)h!\Gamma(m_2+q)q!}\times\frac{\rho_1^h\rho_2^q(xy)^{p_1}}{(\Omega_1\Omega_2\Omega_3\Omega_4)^{\frac{p_1}{2}}(1-\rho_1)^{h+q+m_2}(1-\rho_2)^{h+q+m_1}}\, G_{1,3}^{2,1}\left(\frac{x^2/\hat{\rho}}{\Omega_1\Omega_3}\bigg|_{\frac{p_2}{2},-\frac{p_2}{2},-\frac{p_1}{2}}^{1-\frac{p_1}{2}}\right)G_{1,3}^{2,1}\left(\frac{y^2/\hat{\rho}}{\Omega_2\Omega_4}\bigg|_{\frac{p_2}{2},-\frac{p_2}{2},-\frac{p_1}{2}}^{1-\frac{p_1}{2}}\right). \quad (5)$$

In (5), $G_{p,q}^{m,n}[\cdot|\cdot]$ denotes the Meijer's G-function [23, eq. (9.301)], which is a built-in function in many mathematical software packages, e.g., Mathematica, Maple, and thus can be directly evaluated. By setting $m_1=m_2=1$, (5) simplifies to the joint CDF of the bivariate DR distribution given in [22, eq. (6)]. The joint moments of Z_1, Z_2 can be derived by substituting (4) in $\mathbb{E}\langle Z_1^{n_1}Z_2^{n_2}\rangle$ and using [23, eq. (6.561/16)], yielding to

$$\mathbb{E}\langle Z_1^{n_1}Z_2^{n_2}\rangle=\sum_{h,q=0}^{\infty}\frac{\rho_1^h\rho_2^q(\Omega_1\Omega_3)^{n_1/2}(\Omega_2\Omega_4)^{n_2/2}}{\Gamma(h+m_1)\Gamma(q+m_2)h!q!}\times\frac{(1-\rho_1)^{m_1+\frac{n_1+n_2}{2}}(1-\rho_2)^{m_2+\frac{n_1+n_2}{2}}}{\Gamma(m_1)\Gamma(m_2)}\Gamma\left(h+m_1+\frac{n_1}{2}\right)\times\Gamma\left(q+m_2+\frac{n_1}{2}\right)\Gamma\left(h+m_1+\frac{n_2}{2}\right)\Gamma\left(q+m_2+\frac{n_2}{2}\right). \quad (6)$$

Furthermore, using [23, eq. (9.100)] and after some mathematical analysis, (6) simplifies to the following closed-form expression

$$\mathbb{E}\langle Z_1^{n_1}Z_2^{n_2}\rangle=\prod_{j=1}^{2}\frac{\Gamma\left(m_j+\frac{n_1}{2}\right)\Gamma\left(m_j+\frac{n_2}{2}\right)}{\Gamma(m_j)^2}(\Omega_j\Omega_{j+2})^{\frac{n_j}{2}}\times(1-\rho_j)^{m_j+\frac{n_1+n_2}{2}}{}_2F_1\left(m_j+\frac{n_1}{2},m_j+\frac{n_2}{2};m_j;\rho_j\right), \quad (7)$$

with ${}_2F_1(\cdot,\cdot;\cdot;\cdot)$ denoting the Gauss hypergeometric function [23, eq. (9.100)]. In order to investigate the relation between m_1, m_2, ρ_1, ρ_2, and the DN correlation coefficient ρ_{DN}, (2) is employed as follows

$$\rho_{DN}=\frac{E\langle Z_1^2Z_2^2\rangle-E\langle Z_1^2\rangle E\langle Z_2^2\rangle}{\sqrt{\left(E\langle Z_1^4\rangle-E\langle Z_1\rangle^4\right)\left(E\langle Z_2^4\rangle-E\langle Z_2\rangle^4\right)}}, \quad (8)$$

with

$$\mathbb{E}\langle Z_j^n\rangle=\left(\frac{1}{\Omega_x\Omega_{x+1}}\right)^{-n/2}\frac{\Gamma(m_1+n/2)\Gamma(m_2+n/2)}{\Gamma(m_1)\Gamma(m_2)}, \quad (9)$$

where if $j=1\rightarrow x=1$ else if $j=2\rightarrow x=3$. Substituting (7) and (9) in (8), using ${}_2F_1(a,b;b-1;z)=\frac{(1-z)^{-a-1}[b+(a-b+1)z-1]}{b-1}$ [28, eq. (07.23.03.0081.01)], and after some algebra, the following expression for ρ_{DN} is obtained

$$\rho_{DN}=\frac{(m_1+\rho_1)(m_2+\rho_2)-m_1m_2}{(m_1+1)(m_2+1)-m_1m_2}. \quad (10)$$

In Fig. 1, using (10) and assuming $m_1=0.8, m_2=1.2$, ρ_{DN} is plotted as a function of ρ_1 and ρ_2. It is clear, that ρ_{DN} also ranges between zero and unity. Moreover, in the same figure, it is shown that as m_1, m_2 increase, ρ_{DN} approaches ρ_j.

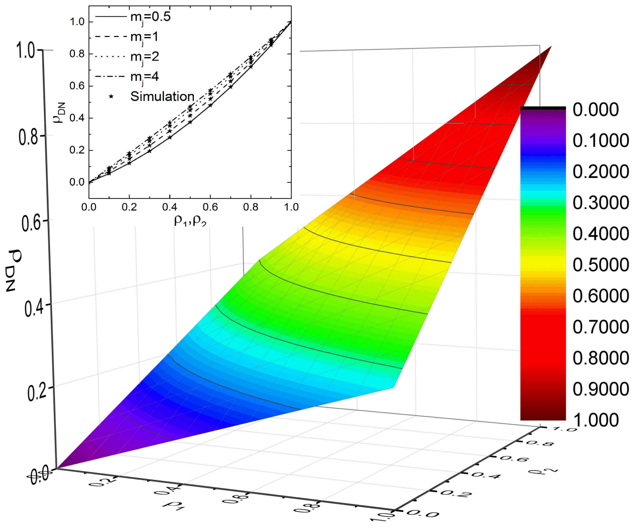

Fig. 1. The DN correlation coefficient ρ_{DN} as a function of the correlation coefficients of the underlying Nakagami RVs ρ_j, with $j\in\{1,2\}$.

In Fig. 2, assuming the same parameters for the DN RVs, i.e., $m_j=m, \Omega_i=\Omega\,(\forall i\in\{1-4\}), \rho_j=\rho$, the bivariate CDF, given by (5), is plotted as a function of x, with $y=x$, for different values of ρ. Moreover, simulated results are also included in this figure, verifying in all cases the agreement between the analytical and the simulated CDFs. It is noted that correlated DN RVs have been generated using (3) and the approach presented in [29]. In addition, the rate of convergence of the infinite series given in (5) has been also investigated. More specifically, the minimum number of terms, which guarantees accuracy better than $\pm 0.5\%$ is presented in the Table included in Fig. 2, for different values of x, Ω, m, and ρ. From this Table, it is clear that a relatively small number of terms is necessary to achieve an excellent accuracy. Moreover, this number of terms increases as x and/or ρ and/or m increase as well as with the decrease of Ω. It should be also noted that similar rate of convergence has been also observed for all the infinite series expressions presented in this paper.

III. V2V Cooperative Relaying Communications: System and Channel Model

We consider a V2V cooperative communication system with one source (S), N relays $R_n=\{1,2,\ldots,N\}$, 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 fading amplitudes, Z_X, having marginal PDF given by [7]

$$f_{Z_x}(y)=\frac{2G_{0,2}^{2,0}\left(\frac{y^2}{\Omega_{x,i}\Omega_{x,i+1}}\bigg|_{m_{x,1},m_{x,2}}^{-}\right)}{y\Gamma(m_{x,1})\Gamma(m_{x,2})}. \quad (11)$$

In this section, the subscript notations of the DN shaping and scaling parameters have changed. Therefore, in (11), $x\in\{s_n,r_n,I_n,I_d\}$, when referring to $S-R_n$, R_n-D,

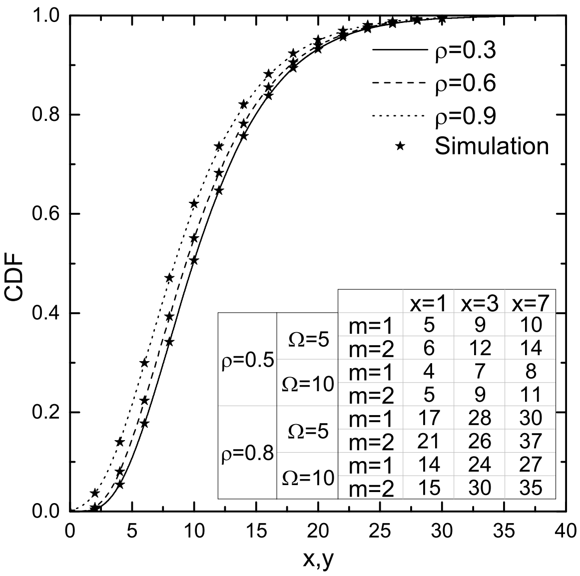

Fig. 2. CDF of DN for different values of ρ.

interfering source to R_n, interfering source to D, links, respectively, while $i \in \{1,3\}$, which is related with the DN double-bounce interaction [6]. The DN distribution is adopted since it provides a realistic description of various V2V channel conditions, in situations where both the transmitter and the receiver are moving [11]. In particular by modifying the values of the distribution's shaping parameters $m_{x,1}, m_{x,2}$, different fading conditions can be described, e.g., lower values of $m_{x,i}$ correspond to severe fading. In addition, R_ns as well as D are also subject to interfering signals under the assumption that the level of interference is such that the effect of thermal noise on system's performance can be ignored, i.e., interference limited scenario. In general, in order to simplify the analysis, the analytical results are derived for the case of single interferer. Undoubtedly, such a scenario is less generic; however, it has clear practical interest and importance. More specifically, in ITS-G5, which is the standard for V2V communications, simultaneous transmissions are sensed and avoided, based on the carrier sensing multiple access with collision avoidance mechanism that is supported. Thus, it is very likely most of the hidden nodes (if any) will be located outside the sensitivity range of the receiver, and thus the aggregated interference can be considered as low enough to be negligible, resulting to a *single dominant interferer*. This is the reason why this assumption has been also adopted by many researchers in the past, e.g., [30]–[32]. However, for comparison purposes, an analytical framework has been also developed for the scenario where L interfering signals are received at the destination D, as it is shown in Appendix F.

At the first phase, the source transmits a signal to all potential available relays, which form the set of available relays. The direct link between S and D is assumed to be unavailable due to heavy shadowing channel condition. As a result, the received SIR at the nth relay is given by

$$\gamma_{\text{out}_{s_n}} = \frac{\gamma_{s_n}}{\gamma_{I_n}}, \tag{12}$$

where $\gamma_{s_n} = P_{s_n} Z_{s_n}^2 / N_0$ is the instantaneous SNR received at R_n, P_{s_n} is the transmit power value, N_0 is the power spectral density of the additive white Gaussian noise (AWGN), and $\gamma_{I_n} = P_{I_n} Z_{I_n}^2 / N_0$ is the instantaneous interference-to-noise ratio (INR) also received at R_n. Moreover, let $\mathcal{C}$ denote the *decoding set* of the active relays that have correctly decoded the source message [33]. This set will form the basis for the relay which will be selected in the next transmission phase.

A. Relay Selection Schemes

Here, two different relay selection schemes are considered.

1) Best Relay Selection: In the first one, a single relay, belonging to the decoding set, with the best instantaneous $R_n - D$ channel quality is selected to forward the information to the destination. This scheme is called here BRS and its mode of operation is analytically described in [34]. It is noted that BRS may be implemented in both centralized and distributed manner and thus it is a good candidate for ad-hoc networks. From the mathematical point of view, assuming non-identically distributed fading conditions, the CDF of the instantaneous SNR for the link between the selected relay and D, $\tilde{\gamma}_{\text{sel}}$, given $\mathcal{C}$, can be expressed as

$$F_{\tilde{\gamma}_{\text{sel}}|\mathcal{C}}(x) = \prod_{n=1}^{|\mathcal{C}|} F_{\gamma_{r_n}}(x), \tag{13}$$

where $\gamma_{r_n} = P_{r_n} Z_{r_n}^2 / N_0$ and $F_{\gamma_{r_n}}(x)$ is given by

$$F_{\gamma_{r_n}}(x) = \frac{G_{1,3}^{2,1}\left(\frac{x}{\overline{\gamma}_{r_n,i}\overline{\gamma}_{r_n,i+1}}\middle|\begin{smallmatrix}1\\ m_{r_n,1},m_{r_n,2},0\end{smallmatrix}\right)}{\Gamma(m_{r_n,1})\Gamma(m_{r_n,2})}. \tag{14}$$

In (14), $\overline{\gamma}_{r_n,i} = P_t \Omega_{r_n,i}$, with P_t denoting the transmit SNR, which for simplicity is considered to be equal for all relay nodes, and $|\mathcal{C}|$ is the cardinality of $\mathcal{C}$. The corresponding PDF expression is given by

$$f_{\tilde{\gamma}_{\text{sel}}|\mathcal{C}}(x) = \sum_{n=1}^{|\mathcal{C}|} f_{\gamma_{r_n}}(x) \prod_{\substack{\ell=1\\ \ell\neq n}}^{|\mathcal{C}|} F_{\gamma_{r_\ell}}(x), \tag{15}$$

with $f_{\gamma_{r_n}}(x)$ obtained by employing a change of variables in (11). For identically distributed RVs, (13) simplifies to

$$F_{\tilde{\gamma}_{\text{sel}}|\mathcal{C}}(x) = F_{\gamma_{r_n}}(x)^{|\mathcal{C}|} \tag{16}$$

and (15) simplifies to

$$f_{\tilde{\gamma}_{\text{sel}}|\mathcal{C}}(x) = |\mathcal{C}| f_{\gamma_{r_n}}(x) F_{\gamma_{r_n}}(x)^{|\mathcal{C}|-1}. \tag{17}$$

2) Threshold-Based Relay Selection: A new relay-selection scheme, called threshold-based relay selection (t-RS)[1], that aims at reducing complexity and feedback load processing, is also employed. 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 packet to the 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

[1]Part of the analysis related with t-RS is also included in [1].

flag packet is sent to all relays that successfully received the original message (including the tagged relay) asking for the initialization of the BRS mechanism. In particular, all relays belonging to the decoding set ignite a timer, which is related to the quality of their second-hop link. The timer of the best relay, in terms of the estimated SNR, expires first and hence this relay is selected for the second-hop transmission.

To simplify the analysis, only identically distributed fading conditions have been assumed for the t-RS. The CDF of the received instantaneous SNR for the link between the selected R_n and D, $\tilde{\gamma}_{\rm sel}$, given $\mathcal{C}$, can be expressed as [35]

$$F_{\tilde{\gamma}_{\rm sel}|\mathcal{C}}(x) = \begin{cases} F_{\gamma_{r_n}}(x) - F_{\gamma_{r_n}}(\gamma_{\rm th}) & \\ +F_{\gamma_{r_n}}(\gamma_{\rm th}) F_{\gamma_{r_n}}(x)^{|\mathcal{C}|-1}, & x \geq \gamma_{\rm th} \\ F_{\gamma_{r_n}}(x)^{|\mathcal{C}|}, & x < \gamma_{\rm th}. \end{cases} \tag{18}$$

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

$$f_{\tilde{\gamma}_{\rm sel}|\mathcal{C}}(x) = \begin{cases} f_{\gamma_{r_n}}(x) + (|\mathcal{C}|-1) F_{\gamma_{r_n}}(\gamma_{\rm th}) & \\ \times f_{\gamma_{r_n}}(x) F_{\gamma_{r_n}}(x)^{|\mathcal{C}|-2}, & x \geq \gamma_{\rm th} \\ |\mathcal{C}| f_{\gamma_{r_n}}(x) F_{\gamma_{r_n}}(x)^{|\mathcal{C}|-1}, & x < \gamma_{\rm th}. \end{cases} \tag{19}$$

The behavior of the proposed scheme depends on the selected switching threshold $\gamma_{\rm th}$, which is related with the instantaneous SNR. More specifically, with an increase on $\gamma_{\rm th}$, its performance improves, approaching that of BRS, with the cost of a higher feedback load processing [35].

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

$$\gamma_{\rm out} = \frac{\tilde{\gamma}_{\rm sel}}{\gamma_{I_d}}, \tag{20}$$

where $\gamma_{I_d} = P_{I_d} Z_{I_d}^2 / N_0$ denotes the received instantaneous INR at D.

B. CSI Model

In a V2V communication scenario, it is very likely that the fading behavior changes rapidly. Hence, in this work, the CSI of the $R_n - D$ links is assumed to be outdated, due to the delay between the relay selection and data transmission phases as well as the fast time varying nature of the wireless channel, similar to many works in the past, e.g., [4], [21], [36]. More specifically, the imperfection between γ_{s_n}, which is the actual SNR at the data transmission phase, and $\tilde{\gamma}_{s_n}$, which is the estimated SNR at the selection phase, is quantified using correlation coefficient ρ_{DN}. In that case, the PDF of the actual received SNR of the *selected relay* at the data transmission instance can be expressed as [36]

$$f_{\gamma_{\rm sel}|\mathcal{C}}(y) = \int_0^\infty f_{\gamma_{r_n},\tilde{\gamma}_{r_n}}(y,x) \frac{f_{\tilde{\gamma}_{\rm sel}|\mathcal{C}}(x)}{f_{\gamma_{r_n}}(x)} dx. \tag{21}$$

For evaluating (21), $f_{\gamma_{r_n},\tilde{\gamma}_{r_n}}(y,x)$ is required. Capitalizing on the results presented in Section II, making a change of variables in (4), the following expression for the joint PDF between γ_{r_n} and $\tilde{\gamma}_{r_n}$ can be obtained

$$\begin{aligned} f_{\gamma_{r_n},\tilde{\gamma}_{r_n}}(y,x) = \sum_{h,q=0}^{\infty} & \frac{\dfrac{4\rho_1^h \rho_2^q / [\Gamma(m_{r_n,1})\Gamma(m_{r_n,2})]}{\left(\prod_{i=1}^4 \overline{\gamma}_{r_n,i}\right)^{\frac{m_{r_n,1}+m_{r_n,2}+q+h}{2}}}}{\Gamma(m_{r_n,1}+h)\Gamma(m_{r_n,2}+q) h! q!} \\ & \times \frac{(xy)^{\frac{m_{r_n,1}+m_{r_n,2}+h+q}{2}-1}}{(1-\rho_1)^{m_{r_n,2}+h+q}(1-\rho_2)^{m_{r_n,1}+h+q}} \\ & \times K_{m_{r_n,1}-m_{r_n,2}+h-q}\left[\frac{2x^{1/2}}{\sqrt{\overline{\gamma}_{r_n,1}\overline{\gamma}_{r_n,3}\hat{\rho}}}\right] \\ & \times K_{m_{r_n,1}-m_{r_n,2}+h-q}\left[\frac{2y^{1/2}}{\sqrt{\overline{\gamma}_{r_n,2}\overline{\gamma}_{r_n,4}\hat{\rho}}}\right]. \end{aligned} \tag{22}$$

Based on the above expression, in the next section, the SIR statistics for the schemes under consideration will be studied.

IV. V2V Cooperative Relaying Communications: SIR Analysis

In this section, an analytical framework for evaluating the CDF of the system's output SIR is derived, for both relay selection schemes under consideration.

A. Statistics of the 1st Link

The first communication phase is characterized by the probability that the nth relay decodes the signal incorrectly, $P_{{\rm off}_n}$, which actually represents the SEP at R_n. In particular, for both schemes, $P_{{\rm off}_n}$ can be evaluated as

$$P_{{\rm off}_n} = a \int_0^\infty {\rm erfc}\left(\sqrt{b\gamma}\right) f_{\gamma_{{\rm out}_{s_n}}}(\gamma) d\gamma, \tag{23}$$

where (a,b) depend on the employed modulation scheme, e.g., for binary phase shift keying (BPSK), $a = 1/2, b = 1$. Next, in order to simplify the analysis, it is assumed that $|m_{s_n,2} - m_{s_n,1}| = 1/2$ and $|m_{I_n,2} - m_{I_n,1}| = 1/2$. Such an assumption corresponds to a propagation scenario where quite similar fading conditions exist for the scattering regions around both S and R_n. Thus, substituting the PDFs of γ_{s_n} and γ_{I_n}, which are of the form given in (D-8), in $f_{\gamma_{{\rm out}_{s_n}}}(\gamma) = \int_0^\infty \gamma f_{\gamma_{s_n}}(x\gamma) f_{\gamma_{I_n}}(x) dx$, using [28, eq. (07.34.03.0606.01)] as well as [23, eq. (3.326/2)], the PDF of $\gamma_{{\rm out}_{s_n}}$ is given by

$$\begin{aligned} f_{\gamma_{{\rm out}_{s_n}}}(\gamma) = & \frac{\Gamma\left(2(m_{s_n,1}+m_{I_n,1})\right) 2^{1-2(m_{s_n,1}-m_{I_n,1})}}{\Gamma(m_{s_n,1})\Gamma(m_{s_n,2})\Gamma(m_{I_n,1})\Gamma(m_{I_n,2})} \\ & \times \pi \left[\prod_{j=1}^2 \left(\frac{1}{\overline{\gamma}_{s_n,j}}\right)^{m_{s_n,1}} \left(\frac{1}{\overline{\gamma}_{I_n,j}}\right)^{m_{I_n,1}}\right] \gamma^{m_{s_n,1}-1} \\ & \times \left(\sqrt{\frac{\gamma}{\overline{\gamma}_{s_n,1}\overline{\gamma}_{s_n,2}}} + \sqrt{\frac{1}{\overline{\gamma}_{I_n,1}\overline{\gamma}_{I_n,2}}}\right)^{-2m_{s_n,1}-2m_{I_n,1}}, \end{aligned} \tag{24}$$

where $\overline{\gamma}_{s_n,j} = P_t \Omega_{s_n,j}$ and $\overline{\gamma}_{I_n,j} = P_I \Omega_{I_n,j}$, with P_I denoting the transmit INR. Moreover, substituting (24) in (23), using [27, eq. (10)], [28, eq. (06.27.26.0006.01)], and [27, eq. (21)], the following closed-form expression for $P_{{\rm off}_n}$ is obtained

$$P_{{\rm off}_n} = \frac{a G_{3,4}^{4,2}\left(\frac{b\overline{\gamma}_{s_n,1}\overline{\gamma}_{s_n,2}}{\overline{\gamma}_{I_n,1}\overline{\gamma}_{I_n,2}} \middle| \begin{matrix} \frac{1-2m_{s_n,1}}{2}, 1-m_{s_n,1}, 1 \\ 0, \frac{1}{2}, m_{I_n,1}, \frac{2m_{I_n,1}+1}{2} \end{matrix}\right)}{\Gamma(m_{s_n,1})\Gamma(m_{s_n,2})\Gamma(m_{I_n,1})\Gamma(m_{I_n,2})\sqrt{\pi}}. \tag{25}$$

1) Asymptotic Analysis: The exact expression for P_{off_n} does not provide a clear physical insight of the system's performance. In order to provide a simplified expression, we derived an asymptotic closed-form expression for P_{off_n}. Using the same approach as the one for deriving (25), together with an asymptotic expression for the modified Bessel function, i.e., $K_v(z) \simeq \frac{1}{2}\Gamma(v)\left(\frac{1}{2}z\right)^{-v}$ [37, eq. (9.6.9)] as well as [23, eq. (6.561/16)], [28, eq. (06.27.21.0132.01)], the following simplified approximated expression has been obtained

$$\begin{aligned}P_{\text{off}_n} \simeq & \left(\frac{\overline{\gamma}_{I_n,1}\overline{\gamma}_{I_n,2}}{b\overline{\gamma}_{s_n,1}\overline{\gamma}_{s_n,2}}\right)^{m_{s_n,1}} a\Gamma\left(m_{s_n,2}-m_{s_n,1}\right) \\ & \times \frac{\Gamma\left(m_{s_n,1}+m_{I_n,1}\right)\Gamma\left(m_{s_n,1}+m_{I_n,2}\right)}{\Gamma\left(m_{s_n,1}\right)\Gamma\left(m_{s_n,2}\right)\Gamma\left(m_{I_n,1}\right)\Gamma\left(m_{I_n,2}\right)}.\end{aligned} \tag{26}$$

B. Statistics of the 2nd Link

For the second communication phase, the statistics of BRS scheme are derived first and then the corresponding ones of t-RS.

1) Best Relay Selection: The CDF of the output SIR given $\mathcal{C}$, $\gamma_{\text{out}|\mathcal{C}}$, can be expressed as

$$\begin{aligned}F_{\gamma_{\text{out}|\mathcal{C}}}(\gamma) = & \sum_{n=1}^{|\mathcal{C}|}\left[\prod_{\substack{\ell=1\\ \ell\neq n}}^{|\mathcal{C}|}\frac{\sqrt{\pi}\Gamma\left(2m_{r_\ell,1}\right)2^{1-2m_{r_\ell,1}}}{\Gamma\left(m_{r_\ell,1}\right)\Gamma\left(m_{r_\ell,2}\right)}\right]\sum_{h,q=0}^{\infty} \\ & \sum_{g_1,g_2=0}^{\left|h-\frac{1}{2}-q\right|-\frac{1}{2}} \pi^{3/2}\mathcal{A}_1\frac{\rho_1^h\rho_2^q(1-\rho_2)^{1/2}\Gamma\left(p_{4,2}+2m_{r_n,1}\right)}{h!q!\Gamma(m_{r_n,1}+h)\Gamma(m_{r_n,2}+q)p_{4,2}} \\ & \times\frac{\left(\overline{\gamma}_{I_d,1}\overline{\gamma}_{I_d,2}\right)^{p_{4,2}}2^{2-p_{4,2}-2m_{r_n,1}}\left(\mathcal{D}_1+\mathcal{B}_1\mathcal{D}_2\right)}{\Gamma(m_{r_n,1})\Gamma(m_{r_n,2})\Gamma\left(m_{I_d,1}\right)\Gamma\left(m_{I_d,2}\right)}\gamma^{p_{4,2}/2} \\ & \times {}_2F_1\left(p_{4,2},p_{4,2}+2m_{r_n,1};p_{4,2}+1;-\left(\frac{\gamma\overline{\gamma}_{I_d,1}\overline{\gamma}_{I_d,2}}{\overline{\gamma}_{r_n,2}\overline{\gamma}_{r_n,4}\hat{\rho}}\right)^{\frac{1}{2}}\right).\end{aligned} \tag{27}$$

where

$$\begin{aligned}\mathcal{A}_1 = & \prod_{j=1}^{2}\frac{\left(g_j+\left|h-q-\frac{1}{2}\right|-\frac{1}{2}\right)!}{g_j!\left(-g_j+\left|h-q-\frac{1}{2}\right|-\frac{1}{2}\right)!} \\ & \times\frac{1/(1-\rho_j)^{h+q+m_{r_n,1}-(g_1+g_2)/2}}{2^{2g_j}\left(\overline{\gamma}_{r_n,j}\overline{\gamma}_{r_n,j+2}\right)^{\frac{p_{4,j}}{2}}\Gamma\left(m_{r_n,j}\right)},\end{aligned}$$

$$\begin{aligned}\mathcal{B}_1 = & \sum_{k=1}^{|\mathcal{C}|-1}(-1)^k\sum_{\substack{\ell_1=1\\ \ell_1\neq n}}^{|\mathcal{C}|-k+1}\sum_{\substack{\ell_2=\ell_1+1\\ \ell_2\neq\ell_1}}^{|\mathcal{C}|-k+2}\cdots\sum_{\substack{\ell_k=\ell_{k-1}+1\\ \ell_k\neq\ell_{k-1}}}^{|\mathcal{C}|} \\ & \sum_{d_{k,1}=0}^{2m_{\ell_1,1}-1}\sum_{d_{k,2}=0}^{2m_{\ell_2,1}-1}\cdots\sum_{d_{k,k}=0}^{2m_{\ell_k,1}-1}\prod_{t=1}^{k}\frac{\left(2\sqrt{p_{5,t}}\right)^{d_{k,t}}}{d_{k,t}!},\end{aligned}$$

$$\mathcal{D}_1 = f\left(\frac{p_{4,1}}{2}-1,\frac{1}{\sqrt{\overline{\gamma}_{r_n,1}\overline{\gamma}_{r_n,3}\hat{\rho}}}\right),$$

$$\mathcal{D}_2 = f\left(\sum_{t=1}^{k}\frac{d_{k,t}+p_{4,1}}{2}-1,\sum_{t=1}^{k}p_{5,t}^{1/2}+\frac{1}{\sqrt{\overline{\gamma}_{r_n,1}\overline{\gamma}_{r_n,3}\hat{\rho}}}\right),$$

with $f\left(x,y\right)=\frac{\Gamma(2+2x)}{2^{2x+1}y^{2(x+1)}}$, $p_{4,j}=2m_{r_n,1}+h+q-g_j$, and $p_{5,t}=\frac{1}{\overline{\gamma}_{\ell_t,1}\overline{\gamma}_{\ell_t,2}}$. The proof for (27) is given in Appendix D.

2) Threshold Based Relay Selection: The CDF of the output SIR given $\mathcal{C}$, $\gamma_{\text{out}|\mathcal{C}}$, can be expressed as[2]

$$\begin{aligned}F_{\gamma_{\text{out}|\mathcal{C}}}(\gamma) = & \pi^2\Gamma(2m_{r,1})\sum_{h,q=0}^{\infty}\sum_{g_1,g_2=0}^{\left|h-\frac{1}{2}-q\right|-\frac{1}{2}}\mathcal{A}_2 \\ & \times\left[\prod_{j=1}^{2}\frac{(1-\rho_j)^{m_{r,j}}2^{1-p_{4,j}-m_{I_d,1}+g_j}}{\Gamma(m_{I_d,j})\overline{\gamma}_{I_d,j}^{m_{I_d,1}}}\right] \\ & \times\frac{\rho_1^h\rho_2^q 2\Gamma\left(2m_{I_d,1}+p_{4,1}\right)}{\Gamma(h+m_{r,1})\Gamma(q+m_{r,2})h!q!p_{4,1}}\mathcal{B}_2\left(\frac{\gamma}{\overline{\gamma}_{r,1}\overline{\gamma}_{r,3}\hat{\rho}}\right)^{\frac{p_{4,1}}{2}} \\ & \times\frac{{}_2F_1\left(1,2m_{I_d,1}+p_{4,1};1+p_{4,1},\frac{\frac{\sqrt{\gamma}}{\sqrt{\overline{\gamma}_{r,1}\overline{\gamma}_{r,3}\hat{\rho}}}}{\frac{\sqrt{\gamma}}{\sqrt{\overline{\gamma}_{r,1}\overline{\gamma}_{r,3}\hat{\rho}}}+\sqrt{\frac{1}{\overline{\gamma}_{I_d,1}\overline{\gamma}_{I_d,2}}}}\right)}{\left(\frac{\sqrt{\gamma}}{\sqrt{\overline{\gamma}_{r,1}\overline{\gamma}_{r,3}\hat{\rho}}}+\sqrt{\frac{1}{\overline{\gamma}_{I_d,1}\overline{\gamma}_{I_d,2}}}\right)^{2m_{I_d,1}+p_{4,1}}},\end{aligned} \tag{28}$$

where

$$\mathcal{A}_2 = \prod_{j=1}^{2}\frac{(g_j+|h-\frac{1}{2}-q|-\frac{1}{2})!}{g_j!\left(-g_j+|h-\frac{1}{2}-q|-\frac{1}{2}\right)!\Gamma(m_{r,j})^2},$$

and $\mathcal{B}_2$ is given in (29) (shown at the top of the next page). Moreover, in (29), $p_{6,\ell,i}=\frac{\ell}{\sqrt{\overline{\gamma}_{r,2}\overline{\gamma}_{r,4}\hat{\rho}}}+\ell i\sqrt{\frac{1}{\overline{\gamma}_{r,1}\overline{\gamma}_{r,3}}}$, $\overline{\gamma}_{I_d,j}=P_I\Omega_{I_d,j}$, $\gamma(.,.)$ and $\Gamma(.,.)$ denote the lower and the upper incomplete gamma functions [23, eqs. (8.350/1-2)], respectively. The proof for (28) is given in Appendix E.

3) Asymptotic Analysis: Assuming $\rho=\rho_1=\rho_2$, higher values of $\overline{\gamma}_{r,i}$, the modified Bessel function appearing in (4) can be approximated as $I_v(z)\simeq\frac{1}{\Gamma(v+1)}\left(\frac{z}{2}\right)^v$ [23, eq. (03.02.06.0004.01)]. Based on this approximation and using the approaches presented in Appendices A and E, a closed-form asymptotic expression for the CDF of $\gamma_{\text{out}|\mathcal{C}}$, for the t-RS scheme, is obtained in (30) (shown at the top of the next page), where $p_7=\overline{\gamma}_{r,1}\overline{\gamma}_{r,3}\hat{\rho}$. Moreover, since for higher values of $\overline{\gamma}_{r,i}$ the second (summation) term in (30) has a negligible effect on the performance, while for $\gamma_{\text{th}}\simeq\overline{\gamma}_{r,i}\Rightarrow\Gamma(n,z)\simeq\Gamma(n)$ (since $z\to 0$) [28, eq. (06.06.06.0006.01)], (30) can be further simplified to

$$\begin{aligned}F_{\gamma_{\text{out}|\mathcal{C}}}(\gamma) \simeq & \left[\prod_{j=1}^{2}\frac{\overline{\gamma}_{I_d,j}^{m_{r,1}}}{\Gamma(m_{I_d,j})}\frac{\Gamma\left(m_{r,1}+m_{I_d,j}\right)}{\Gamma(m_{r,j})^2}\right] \\ & \times\frac{\pi 2^{1-2m_{r,1}}\Gamma\left(2m_{r,1}\right)\gamma^{m_{r,1}}(1-\rho)^{1/2}}{m_{r,1}}\overline{\gamma}^{-m_{r,1}},\end{aligned} \tag{31}$$

with $\overline{\gamma}=\overline{\gamma}_{r,1}\overline{\gamma}_{r,3}$.

V. V2V Cooperative Relaying Communications: Performance Evaluation

In this section using the previously derived results, analytical expressions for important performance metrics are obtained, such as the OP and the SEP.

[2]Since the analytical results presented for the t-RS hold only for identically distributed statistics, the relay index n will be omitted.

$$\begin{aligned}\mathcal{B}_2 = {} & \frac{\Gamma(m_{r,1})\Gamma(m_{r,2})}{\sqrt{\pi}\Gamma(2m_{r,1})}\Gamma\left(p_{4,2}, \frac{2\sqrt{\gamma_{\text{th}}}}{\sqrt{\overline{\gamma}_{r,2}\overline{\gamma}_{r,4}\hat{\rho}}}\right) + \sum_{t=1}^{2} \frac{2^{1-2m_{r,1}}(|\mathcal{C}|-t+1)}{\left(\overline{\gamma}_{r,2}\overline{\gamma}_{r,4}\hat{\rho}\right)^{\frac{p_{4,2}}{2}}} \sum_{i=0}^{|\mathcal{C}|-t} \binom{|\mathcal{C}|-t}{i} \sum_{\substack{n_1,\ldots,n_{2m_{r,1}}=0 \\ n_1+\cdots+n_{2m_{r,1}}=i}}^{i} \frac{\prod_{\ell=1}^{2m_{r,1}-1} \frac{1}{\left(\left(\overline{\gamma}_{r,1}\overline{\gamma}_{r,3}\right)^{\ell/2}\ell!\right)^{n_{\ell+1}}}}{p_{6,1,i}^{p_{4,2}+\sum_{\ell=1}^{2m_{r,1}-1}\ell n_{\ell+1}}} \\ & \times \frac{i!(-1)^i}{n_1!\cdots n_{2m_{r,1}}!}\left[(2-t)\gamma\left(p_{4,2}+\sum_{\ell=1}^{2m_{r,1}-1}\ell n_{\ell+1}, p_{6,2,i}\sqrt{\gamma_{\text{th}}}\right) + (t-1)F_{\gamma_x}(\gamma_{\text{th}})\Gamma\left(p_{4,2}+\sum_{\ell=1}^{2m_{r,1}-1}\ell n_{\ell+1}, p_{6,2,i}\sqrt{\gamma_{\text{th}}}\right)\right].\end{aligned} \tag{29}$$

$$\begin{aligned}F_{\gamma_{\text{out}|\mathcal{C}}}(\gamma) \simeq {} & \left\{\Gamma\left(2m_{r,1}, \frac{2\sqrt{\gamma_{\text{th}}}}{\sqrt{p_7}}\right) + \sum_{i=1}^{2}(|\mathcal{C}|+1-i)\left(\frac{\sqrt{\pi}/m_{r,1}}{\Gamma(m_{r,1})\Gamma(m_{r,2})}\right)^{|\mathcal{C}|-i}\left[(2-i)\left(\frac{2}{p_7}\right)^{2(|\mathcal{C}|-1)m_{r,1}}\gamma\left(2|\mathcal{C}|m_{r,1}, \frac{2\sqrt{\gamma_{\text{th}}}}{\sqrt{p_7}}\right)\right.\right. \\ & \left.\left. +(i-1)F_{\gamma_x}(\gamma_{\text{th}})\left(\frac{2}{1-\rho}\right)^{2(2-|\mathcal{C}|)m_{r,1}}\Gamma\left(2m_{r,1}(|\mathcal{C}|-1), \frac{2\sqrt{\gamma_{\text{th}}}}{\sqrt{p_7}}\right)\right]\right\}\left[\prod_{j=1}^{2}\frac{\overline{\gamma}_{I_d,j}^{m_{r,1}}}{\Gamma(m_{I_d,j})}\frac{\Gamma\left(m_{r,1}+m_{I_d,j}\right)}{\Gamma(m_{r,j})^2\overline{\gamma}_{r,3-j}^{m_{r,1}}}\right]\frac{\pi(1-\rho)^{1/2}\gamma^{m_{r,1}}}{m_{r,1}2^{2m_{r,1}-1}}.\end{aligned} \tag{30}$$

A. *Outage Probability*

The OP is defined as the probability that the instantaneous received SIR falls below a predetermined threshold γ_{T}.

1) Best Relay Selection: According to the theorem of total probability, the OP, which is related with the unconditional CDF of the output SIR, can be evaluated as

$$\begin{aligned}P_{\text{out}} = {} & \prod_{n=1}^{N} P_{\text{off}_n} + \sum_{b=1}^{N}\sum_{n_{1:b}}^{N}\prod_{i=1}^{b}(1-P_{\text{off}_i}) \\ & \times \prod_{\substack{\ell=1 \\ \ell\neq n_1,\ldots,n_b}}^{N} P_{\text{off}_\ell}F_{\gamma_{\text{out}|\mathcal{C}}}(\gamma_{\text{T}}),\end{aligned} \tag{32}$$

where $\sum_{n_{1:b}}^{N} = \sum_{n_1=1}^{N}\sum_{n_2=n_1+1}^{N}\cdots\sum_{n_b=n_{b-1}+1}^{N}$ and $R_{n_1}, R_{n_2}, \cdots, R_{n_b} \subseteq \mathcal{C}$. In (32), the first summation term refers to the probability that all relays decoded incorrectly, while with the multiple sums, which follow the first term, the probability of outage of all possible combinations of relays is evaluated.

2) Threshold-Based Relay Selection: As far as t-RS scheme is concerned, under the assumption of identical distributed fading, the OP can be evaluated as

$$P_{\text{out}} = P_{\text{off}}^{N} + \sum_{k=1}^{N}\binom{N}{k}P_{\text{off}}^{N-k}\left(1-P_{\text{off}}\right)^{k}F_{\gamma_{\text{out}|\mathcal{C}}}(\gamma_{\text{T}}). \tag{33}$$

3) Asymptotic Analysis: In the high SNR regime, the OP in (33) is reduced to $P_{\text{out}} \simeq \sum_{k=1}^{N}\binom{N}{k}F_{\gamma_{\text{out}|\mathcal{C}}}(\gamma_{\text{T}})$. Substituting (31) in (33), an asymptotic expression for the OP can be obtained. Based on this expression, and under the assumption $\overline{\gamma}_{s_n,j} = \overline{\gamma}_{r_n,j} = \overline{\gamma}$, $m_{s_n,j} = m_{r_n,j} = m$, useful outcomes can be extracted. More specifically, assuming that the average INR remains constant, as the average SNR increases, the total diversity order is equal to m. Moreover, assuming that the average INR increases in the same level as the average SNR does, then the diversity order is zero, resulting to error floor. In any case, when outdated CSI is present, the diversity order does not depend on the number of relays, which agrees with previous outcomes derived in the past, e.g., [36], [38]. On the other hand, assuming $\rho = 1$, i.e., no feedback delay exists, and an interference free scenario, employing (18) in (33), using the approach presented in [35], it can be concluded that the system's diversity order is equal to mL. Thus, the full diversity order can be only realized when perfect CSI is available.

B. *Symbol Error Probability*

The SEP is one of the most important performance measures, the minimization of which is the main objective in designing wireless communication systems.

1) Best Relay Selection: The SEP can be evaluated as

$$P_{\text{se}} = \prod_{n=1}^{N} P_{\text{off}_n} + \sum_{b=1}^{N}\sum_{n_{1:b}}^{N}\prod_{i=1}^{b}(1-P_{\text{off}_i}) \prod_{\substack{\ell=1 \\ \ell\neq n_1,\ldots,n_b}}^{N} P_{\text{off}_\ell}P_{\text{se}|\mathcal{C}}, \tag{34}$$

where

$$\begin{aligned}P_{\text{se}|\mathcal{C}} = {} & \sum_{n=1}^{|\mathcal{C}|}\left[\prod_{\substack{\ell=1 \\ \ell\neq n}}^{|\mathcal{C}|}\frac{\sqrt{\pi}\Gamma\left(2m_{r_\ell,1}\right)2^{1-2m_{r_\ell,1}}}{\Gamma\left(m_{r_\ell,1}\right)\Gamma\left(m_{r_\ell,2}\right)}\right]\sum_{h,q=0}^{\infty}\sum_{g_1,g_2=0}^{\left|h-\frac{1}{2}-q\right|-\frac{1}{2}} \\ & \times\mathcal{A}_1\frac{\rho_1^h\rho_2^q(1-\rho_2)^{1/2}\left(p_{4,2}+2m_{r_n,1}-1\right)}{h!q!2^{3/2}\Gamma(m_{r_n,1}+h)\Gamma(m_{r_n,2}+q)p_{4,2}}\sum_{k=0}^{2m_{r_n,1}-1}(-1)^k \\ & \times\frac{\left(1-2m_{r_n,1}\right)_k a\sqrt{b}\left(\hat{\rho}\overline{\gamma}_{r_n,2}\overline{\gamma}_{r_n,4}\right)^{\frac{p_{4,2}+1}{2}}}{\Gamma\left(m_{I_d,1}\right)\Gamma\left(m_{I_d,2}\right)\left(p_{4,2}+1\right)_k}\frac{\mathcal{D}_1+\mathcal{B}_1\mathcal{D}_2}{\left(\overline{\gamma}_{I_d,1}\overline{\gamma}_{I_d,2}\right)^{\frac{1}{2}}} \\ & \times G_{2,3}^{3,2}\left(\frac{b\overline{\gamma}_{r_n,2}\overline{\gamma}_{r_n,4}\hat{\rho}}{2\overline{\gamma}_{I_d,1}\overline{\gamma}_{I_d,2}}\middle|_{0,\frac{2m_{r_n,1}-k-2}{2},\frac{2m_{r_n,1}-k-1}{2}}^{\frac{-p_{4,2}-k}{2},\frac{1-p_{4,2}-k}{2}}\right).\end{aligned} \tag{35}$$

For deriving (35), the following procedure was followed. First, (28) is substituted in $P_{\text{se}|k} = \int_0^\infty \frac{a\sqrt{b}}{2\sqrt{2\pi}\sqrt{\gamma}}\exp\left(-\frac{b\gamma}{2}\right)F_{\gamma_{\text{out}|\mathcal{C}}}(\gamma)d\gamma$. Then, a simplified expression for ${}_2F_1(\cdot)$ [28, eq. (07.23.03.0142.01)] is used, followed by [27, eqs. (10 and 11)]. Finally, using [27, eq. (21)] and after some mathematical manipulations yields (35).

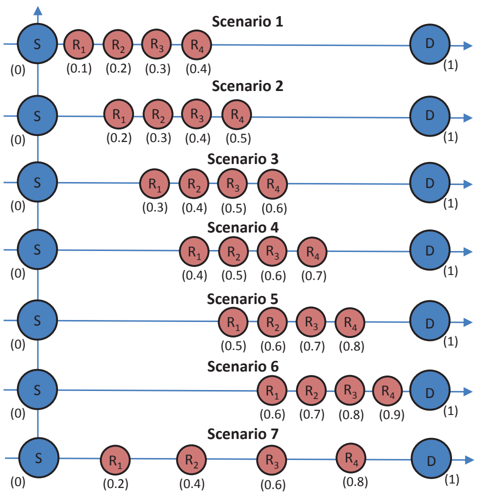

Fig. 3. Communication scenarios that have been used in Figs. 4-5.

2) Threshold-Based Relay Selection: For t-RS, the SEP can be evaluated as

$$P_{\rm se}=P_{\rm off}^{N}+\sum_{k=1}^{N}\binom{N}{k}P_{\rm off}^{N-k}\left(1-P_{\rm off}\right)^{k}P_{{\rm se}|\mathcal{C}},\tag{36}$$

where

$$P_{{\rm se}|\mathcal{C}}=\Gamma(2m_{r,1})\sum_{h,q=0}^{\infty}\sum_{g_1,g_2=0}^{\left|h-\frac{1}{2}-q\right|-\frac{1}{2}}\frac{\rho_1^h\rho_2^q}{h!q!}\left[\prod_{j=1}^{2}\frac{(1-\rho_j)^{m_{r,j}}}{\Gamma(m_{I_d,j})\overline{\gamma}_{I_d,j}^{1/2}}\right]$$
$$\times\frac{\Gamma\left(2m_{I_d,1}+p_{4,1}\right)a\sqrt{b}\mathcal{B}_2}{\Gamma(h+m_{r,1})\Gamma(q+m_{r,2})p_{4,1}}\sum_{k=0}^{2m_{r_n,1}-1}\frac{\mathcal{A}_2\sqrt{2\pi\overline{\gamma}_{r,1}\overline{\gamma}_{r,3}\hat{\rho}}/k!}{2^{p_{4,1}+3g_1+g_2+2m_{I_d,1}-k}}$$
$$\times\frac{(1-2m_{I_d,1})_k(p_{4,1})_k}{(p_{4,1}+1)_k\Gamma(p_{4,1}+k)}G_{2,3}^{3,2}\left(\frac{b\overline{\gamma}_{r,1}\overline{\gamma}_{r,3}\hat{\rho}}{2\overline{\gamma}_{I_d,1}\overline{\gamma}_{I_d,2}}\middle|^{\frac{-p_{4,1}-k}{2},\frac{1-p_{4,1}-k}{2}}_{-\frac{1}{2},0,0}\right).\tag{37}$$

For deriving (37), a similar procedure as the one used for deriving (35) has been followed.

VI. Numerical Results

In this section, we present numerical and simulation results to verify the preceding analysis. In the following, we assume an 1D dimensional network topology, where the location of all nodes is determined by their coordinates in an one-dimensional space (x) [39]. In particular, Figs. 4-5 consider different scenarios regarding the locations of the relay nodes, as depicted in Fig. 3. Moreover, the average link SNRs are determined based on the $P_t d^{-\alpha}$ rule, where d represents the distance between two arbitrary nodes and α corresponds to the path loss exponent, which is assumed equal to 3. Such a topology, which results to different distances between the various nodes, can only be explored by a non-identically distributed-based analysis, as it is done in this paper.

In Fig. 4, based on the scenarios depicted in Fig. 3, the OP of BRS is plotted as a function of the outage threshold γ_T. To obtain this figure the following assumptions have been made: $P_t=0$dB, for the first link, $m_{s_n,1}=1$, $m_{I_n,1}=1.5$, $P_I\mathbb{E}\left\langle Z_{I_n}^2\right\rangle=P_I\mathbb{E}\left\langle Z_{I_d}^2\right\rangle=4$dB, $\rho_1=\rho_2=0.85$, $m_{r_n,1}=1$, $m_{I_d,1}=1$. In this figure, it is shown that as the set of relays approaches the final destination, the performance improves with an increased rate. Moreover, it is interesting to note that for lower values of γ_T, a performance floor appears due to the effect of interference. In Fig. 5, for the same parameters, the OP of BRS is also plotted as a function of γ_T for different scenarios and values of the correlation coefficients. It is shown that the performance improves as ρ_j increases, i.e., the estimated SNR at the selection instance approaches the exact one at the reception instance. Moreover, as it is also shown in this figure, the performance gap between the two correlation coefficients decreases as the set of relays approaches the destination. This means that the performance gain obtained by the relay selection mechanism is higher when all relays are closer to the source. Moreover, the performance floor is more clearly observed.

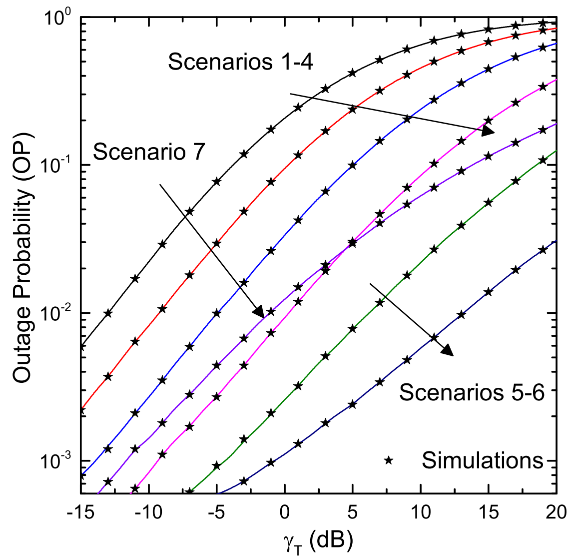

Fig. 4. OP vs γ_T of BRS for different communication scenarios.

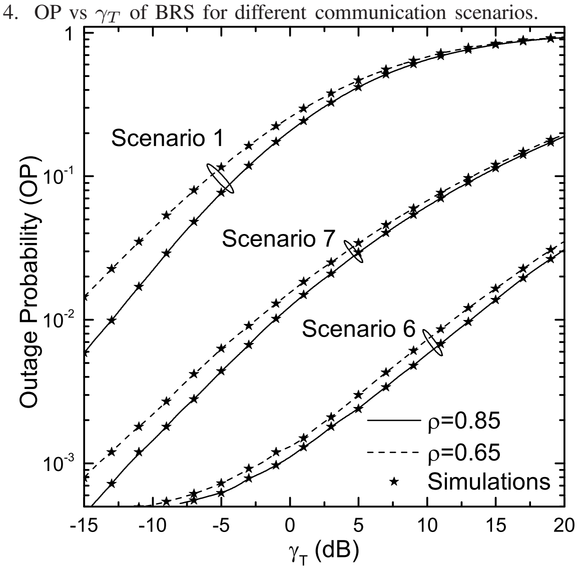

Fig. 5. OP vs γ_T of BRS for different communication scenarios and correlation coefficients.

In Fig. 6, the SEP of BRS is plotted as a function of transmitted SNR P_t for different scenarios regarding the number and the location of the relay nodes as well as the values of the correlation coefficients. More specifically, the following scenarios have been assumed, i) $N = 2$, with $R_1(0.333)$ and $R_2(0.666)$, ii) $N = 3$, with $R_1(0.25)$, $R_2(0.5)$, and $R_3(0.75)$, and iii) $N = 4$, with $R_1(0.2)$, $R_2(0.4)$, $R_3(0.6)$, and $R_4(0.8)$. To obtain this figure, the following assumptions have been made: $m_{s_n,1} = 1$, $m_{I_n,1} = 1.5$, $P_I \mathbb{E}\left\langle Z_{I_n}^2 \right\rangle = P_I \mathbb{E}\left\langle Z_{I_d}^2 \right\rangle = 5$dB, $m_{r_n,1} = 1$, $m_{I_d,1} = 1.5$. It is shown that the performance improves with an increase on the number of relays, with, however, a decreased rate. It is also shown that the performance gap for the different values of ρ_j increases as N decreases, i.e., the influence of the outdated CSI is higher for higher values of N. Moreover, in the same figure, the corresponding performance when the relay selection is random is depicted. From these results, it can be easily verified the performance improvement induced when BRS is used, even in cases where ρ_{DN} is low.

For obtaining Figs. 7 and 8, identical fading conditions have been assumed and thus the network topology approach presented previously will be omitted. In Fig. 7 and based on the BRS scheme, the OP is plotted as a function of γ_T. To obtain this figure the following assumptions have been made; $P_t = 0$dB, $m_{s_n,1} = 1.5$, $\mathbb{E}\left\langle X_j^2 \right\rangle = 8$dB, $m_{I_n,1} = 1.5$, $P_I \mathbb{E}\left\langle Z_{I_n}^2 \right\rangle = P_I \mathbb{E}\left\langle Z_{I_d}^2 \right\rangle = 5$dB, $m_{r_n,1} = 1.5$, $m_{I_d,1} = 3.5$. The scope of this figure is to compare the negative consequences of i) outdated CSI, with ii) increased number of interfering signals at the destination. It is noted that the corresponding analysis for the CDF of the output SIR for the latter case, i.e., the scenario in which the final destination operates in the presence of L interfering signals (and under ideal CSI), is given in Appendix F. In particular, in this Appendix an approximated expression for $F_{\gamma_{\text{out}}|\mathcal{C}}$ is derived, i.e., (F-4), which can be included in (33) in order to directly evaluate the OP. In Fig. 7, it is shown that the performance worsens as L increases with a decreased rate. Moreover, it is shown the close agreement between the approximated expression derived in (F-4) with the exact one obtained with simulations. Another interesting observation is that the impact of outdated CSI is much more severe, as compared to the increase on the number of interfering signals L, especially for lower values of γ_T and even for large values of ρ, i.e., $\rho = 0.9$. Therefore, the system designer, in addition to the interference countermeasures that should adopt, he/she should also investigate techniques that take into account the impact of outdated CSI, since in many cases outdated CSI may have more negative consequences to the system's performance.

In Fig. 8 and based on the t-RS scheme, the OP is plotted as a function of $\overline{\gamma}_{r,j}$. The number of relays is $N = 4$, shaping parameter of the desired link $m_{s,1} = 1.5$, mean values $\overline{\gamma}_{s,j} = 10^{\frac{10}{10}}/m_{s,j}$, $m_{I,1} = 1.5$, average INR $P_I \mathbb{E}\left\langle Z_{I_d}^2 \right\rangle = 4$dB, while $m_{r,1} = 1.5$, $m_{I_d,1} = 1$, average INR $P_I \mathbb{E}\left\langle Z_{I_d}^2 \right\rangle = 4$dB. Moreover, the processing complexity of the proposed scheme is also evaluated based on the approach provided in [35]. More specifically, as a performance indicator for the complexity, the average number of active relays (NAR) (N_{out}) is adopted. It is obvious that as the NAR

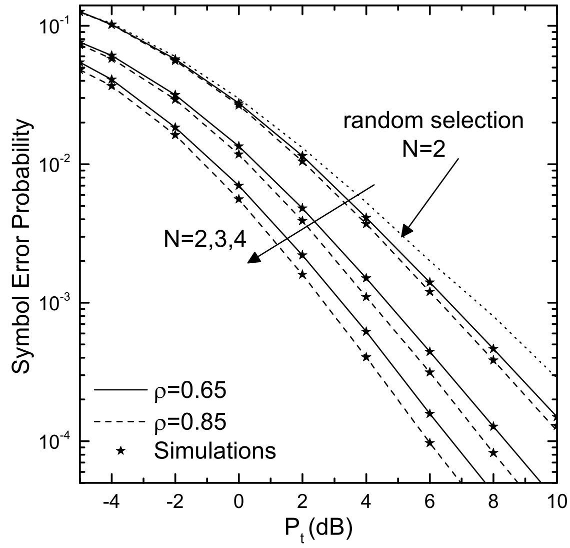

Fig. 6. SEP vs P_t of BRS for different communication scenarios and correlation coefficients.

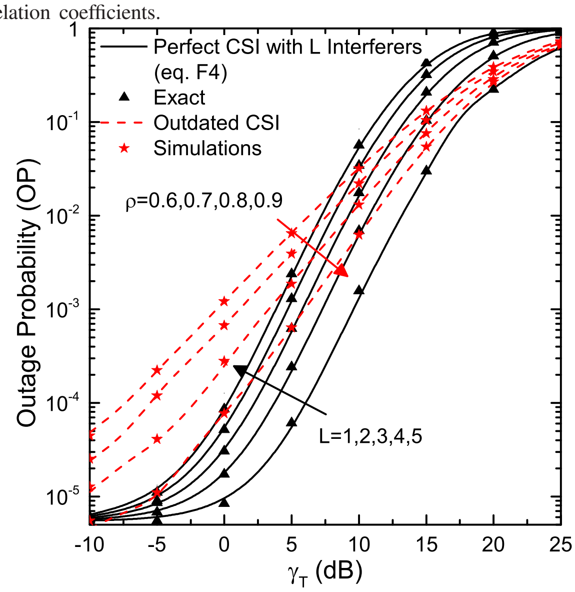

Fig. 7. OP vs γ_T for BRS and different values of ρ and L.

increases, the processing and feedback load will also increase. In the proposed scheme, NAR has been evaluated as $N_{\text{out}} = P_{\text{off}}^N + \sum_{k=1}^{N} \binom{L}{k} P_{\text{off}}^{N-k} (1 - P_{\text{off}})^k \left[1 + (k-1) F_{\gamma_{r_n}}(\gamma_{\text{th}})\right]$. Therefore, in Fig. 8, assuming $\gamma_T = 10$dB, $\gamma_{\text{th}} = 20$dB, the OP of t-RS is plotted as a function of $\overline{\gamma}_{r,j}$, for different values of ρ_j as well as for the scenario of random relay selection. In this figure, it is depicted that a gap among performances exists for $\overline{\gamma}_{r,j} < \gamma_{\text{th}}$, with the random relay selection having always the worst performance. This behavior is due to the mode of operation of the new scheme, since for $\overline{\gamma}_{r,j} > \gamma_{\text{th}}$, it is very likely that all second hop links satisfy the switching threshold and thus the number of switching operations is expected to decrease, resulting to a reduced diversity gain. Moreover, the asymptotic curves, which are also included in the same figure, approximate quite well the exact ones for higher values of the average SNR, i.e., $\overline{\gamma}_{r,j} > 25$dB, while the approximation improves for lower values of ρ_j. In addition, the average NAR

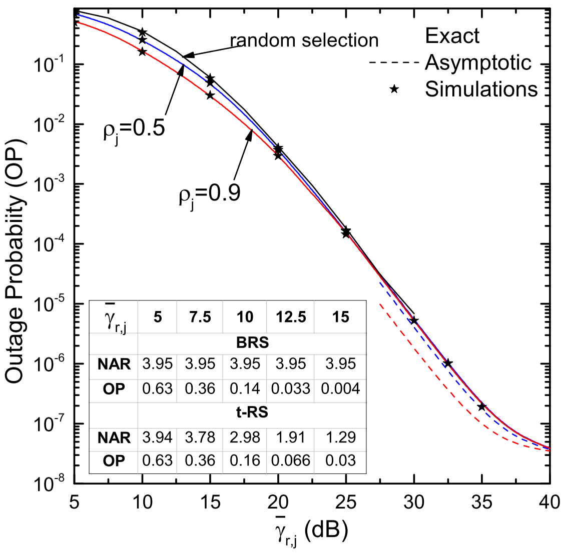

Fig. 8. OP vs the average SNR of the 2nd hop, assuming t-RS and different values of ρ_j.

is also evaluated for both t-RS and BRS and presented in the Table included in Fig. 8. In the same Table, the OP of BRS is also presented. It is shown that for lower values of $\overline{\gamma}_{r,j}$, the proposed scheme offers an excellent compromise between performance and complexity as compared to BRS. Finally, simulation performance results are also included in all figures, verifying the validity of the proposed theoretical approach.

VII. Conclusions

In this paper, we investigated the impact of interference and outdated CSI on the performance of a V2V cooperative relaying system. To this aim, 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. The analysis considered the DF protocol and two relay selection schemes, namely, the BRS and a new threshold-based relay selection, which reduces the overhead processing of the conventional BRS approach. The performance of these systems has been evaluated using well known performance metrics, namely the OP and the SEP. The analytical exact and asymptotic expressions quantified the degradation on the system performance due to outdated CSI and interference. It was shown that the system performance improves as the relays get closer to the destination for both relay selection schemes. In many cases, the new scheme outperforms BRS in terms of the performance versus complexity trade-off. Finally, based on an approximated expression for the PDF of the sum of DN RVs that has been also derived, it is shown that the impact of outdated CSI to the system's performance is more severe as compared to the accumulated interference.

Appendix A
Proof for Equation (4)

Based on (3), the joint PDF of Z_1 and Z_2 is given by

$$f_{Z_1,Z_2}(x,y) = \int_0^\infty\int_0^\infty \frac{f_{X_1,X_3}(z,q)}{zq} f_{X_2,X_4}\left(\frac{x}{z},\frac{y}{q}\right) dzdq. \tag{A-1}$$

Substituting (1) in (A-1), results to an integral representation for the bivariate DN distribution. In addition, employing the infinite series representation of the Bessel functions [23, eq. (8.445)], i.e., $I_v(z) = \sum_{h=0}^{\infty} = \frac{1}{h!\Gamma(v+h+1)}\left(\frac{z}{2}\right)^{v+2h}$, making a change of variables of the form $z^2 = y$ and using [23, eq. (3.471/9)], yields the final expression for the joint PDF of Z_1 and Z_2 given in (4) and also completes the proof.

Appendix B
Error in Truncating the Infinite Series in (4)

The error in truncating the infinite series in (4) is given by

$$\begin{aligned} E_P = {} & \sum_{h=P}^{\infty}\sum_{q=P}^{\infty} \frac{16/[\Gamma(m_1)\Gamma(m_2)]}{\Gamma(m_1+h)h!\Gamma(m_2+q)q!} \\ & \times \frac{\rho_1^h\rho_2^q(xy)^{p_1-1}}{(\Omega_1\Omega_2\Omega_3\Omega_4)^{\frac{p_1}{2}}(1-\rho_1)^{h+q+m_2}(1-\rho_2)^{h+q+m_1}} \\ & \times K_{p_2}\left(\frac{2x}{\sqrt{\Omega_1\Omega_3\hat{\rho}}}\right)K_{p_2}\left(\frac{2y}{\sqrt{\Omega_2\Omega_4\hat{\rho}}}\right). \end{aligned} \tag{B-1}$$

Assuming $h+m_1 > q+m_2$, (B-1) is bounded by

$$\begin{aligned} E_P \leq {} & \sum_{h=P}^{\infty}\sum_{q=P}^{\infty} \frac{16/[\Gamma(m_1)\Gamma(m_2)]}{\Gamma(m_1+h)h!\Gamma(m_2+q)q!} \\ & \times \frac{\rho_1^h\rho_2^q(xy)^{p_1-1}}{(\Omega_1\Omega_2\Omega_3\Omega_4)^{\frac{p_1}{2}}(1-\rho_1)^{h+q+m_2}(1-\rho_2)^{h+q+m_1}} \\ & \times K_{h+m_1}\left(\frac{2x}{\sqrt{\Omega_1\Omega_3\hat{\rho}}}\right)K_{h+m_1}\left(\frac{2y}{\sqrt{\Omega_2\Omega_4\hat{\rho}}}\right), \end{aligned} \tag{B-2}$$

which holds due to the fact that $K_v(x)$ is an even function, with respect to its order, while $K_v(x) < K_{v+1}(x)$ for real positive x, [40]. Moreover, making some mathematical manipulations and using the bound $x^v K_v(x) < 2^{v-1}\Gamma(v)$, derived in [41], (B-2) can be bounded as

$$\begin{aligned} E_P \leq {} & \frac{4(xy)^{m_2-1}(1-\rho_1)^{m_1-m_2}}{\Gamma(m_1)\Gamma(m_2)(\Omega_1\Omega_2\Omega_3\Omega_4)^{\frac{m_2}{2}}}\sum_{h=P}^{\infty}\sum_{q=P}^{\infty}\frac{\rho_1^h}{h!} \\ & \times \left(\frac{\rho_2 xy}{\sqrt{\Omega_1\Omega_2\Omega_3\Omega_4\hat{\rho}}}\right)^q \frac{\Gamma(h+m_1)}{\Gamma(m_2+q)q!}. \end{aligned} \tag{B-3}$$

Finally, based on the definition of the generalized hypergeometric function ${}_pF_q(\cdot)$ [23, eq. (9.14)], (B-3) is bounded by

$$\begin{aligned} E_P \leq {} & \frac{4(xy)^{m_2-1}(1-\rho_1)^{m_1-m_2}}{\Gamma(m_1)\Gamma(m_2)(\Omega_1\Omega_2\Omega_3\Omega_4)^{\frac{m_2}{2}}}\,{}_pF_q(m_1;;\rho_1) \\ & \times {}_pF_q\left(;m_2;\frac{\rho_2 xy}{\sqrt{\Omega_1\Omega_2\Omega_3\Omega_4\hat{\rho}}}\right), \end{aligned} \tag{B-4}$$

which in our case converges for all values. Since $K_v(x)$ is an even function, with respect to its order, the same approach can be followed for the case when $h+m_1<q+m_2$, while for $h+m_1=q+m_2$, using also [23, eq. (9.14)], a similar to (B-4) bound for the error can be extracted.

Appendix C
Validity of (4)

Since $K_v(x)>0$ for all real v, it can be easily verified that $f_{Z_1,Z_2}(x,y)$, in (4), is a non-negative function. Moreover, substituting (4) in $\mathcal{I}_0=\int_0^\infty\int_0^\infty f_{Z_1,Z_2}(x,y)\,\mathrm{d}x\mathrm{d}y$, using [23, eq. (6.561/16)] and after some mathematical manipulation yields

$$\mathcal{I}_0=(1-\rho_1)^{m_1}(1-\rho_2)^{m_2}\sum_{h=0}^{\infty}\sum_{q=0}^{\infty}\frac{\rho_1^h\rho_2^q(m_1)_h(m_2)_q}{h!q!}, \tag{C-1}$$

in which $(a)_n$ denotes the Pochhammer symbol [23, p. xliii]. Moreover, based on the definition of the generalized hypergeometric function, i.e., [23, eq. (9.114)], (C-1) can be re-expressed to the following closed-form expression

$$\mathcal{I}_0=(1-\rho_1)^{m_1}(1-\rho_2)^{m_2}\,{}_PF_Q\left(m_1;;\rho_1\right)\,{}_PF_Q\left(m_2;;\rho_2\right). \tag{C-2}$$

Finally, using [28, eq. (07.19.02.0002.01)] in (C-2), it is straight-forward to show that $\mathcal{I}=1$. Therefore, $f_{Z_1,Z_2}(x,y)$ in (4) represents a valid PDF [42].

Appendix D
Proof for Equation (27)

Firstly, a convenient expression for $\prod_{\ell=1}^{|\mathcal{C}|}F_{\gamma_{r_\ell}}(x)$ is provided. In this context and based on (14), by employing [28, eq. (07.34.03.0732.01)] as well as [23, eq. (8.352/1)], the following mathematically tractable expression is derived

$$\begin{aligned}\prod_{\ell=1}^{|C|}\left(F_{\gamma_{r,\ell}}(x)\right)&=\prod_{\ell=1}^{|C|}\frac{\sqrt{\pi}2^{1-2m_{r_\ell,1}}\Gamma(2m_{r_\ell,1})}{\Gamma\left(m_{r_\ell,1}\right)\Gamma\left(m_{r_\ell,2}\right)}\Bigg[1\\&-\exp\left(-\sqrt{\frac{4x}{\overline{\gamma}_{r_\ell,1}\overline{\gamma}_{r_\ell,2}}}\right)\sum_{j=1}^{2m_{r_\ell,1}-1}\frac{x^{\frac{j}{2}}2^j/j!}{\left(\overline{\gamma}_{r_\ell,1}\overline{\gamma}_{r_\ell,3}\right)^{\frac{j}{2}}}\Bigg]\\&\overset{(1)}{=}\left[\prod_{\ell=1}^{|C|}\frac{\sqrt{\pi}\Gamma\left(2m_{r_\ell,1}\right)2^{1-2m_{r_\ell,1}}}{\Gamma\left(m_{r_\ell,1}\right)\Gamma\left(m_{r_\ell,2}\right)}\right]\\&\times\left[1+\mathcal{B}_1x^{\sum_{t=1}^{k}\frac{d_{k,t}}{2}}\exp\left(-2\sum_{t=1}^{k}\sqrt{p_{5,t}}x^{1/2}\right)\right],\end{aligned} \tag{D-1}$$

where (1) holds due to the following useful identity

$$\begin{aligned}\prod_{k=a}^{L}(1-t_k)&=1+\sum_{k=a}^{L}(-1)^{k-a+1}\\&\sum_{\lambda_a=a}^{L-k+a}\;\sum_{\lambda_{a+1}=\lambda_a+1}^{L-k+a+1}\cdots\sum_{\lambda_k=\lambda_{k-1}+1}^{L}\prod_{n=a}^{k}t_{\lambda_n}.\end{aligned} \tag{D-2}$$

Moreover, assuming $|m_{r_n,2}-m_{r_n,1}|=1/2$, using [23, eq. (8.468)], and after some mathematical manipulation, an alternative expression for the bivariate PDF of the DN distribution, given in (22), is obtained as

$$\begin{aligned}f_{\gamma_{r_n},\tilde{\gamma}_{r_n}}(x,y)=&\sum_{h,q=0}^{\infty}\sum_{g_1,g_2=0}^{\left|h-\frac{1}{2}-q\right|-\frac{1}{2}}\frac{\pi\mathcal{A}_1\rho_1^h\rho_2^q(1-\rho_2)^{1/2}/(h!q!)}{\Gamma(m_{r_n,1}+h)\Gamma(m_{r_n,2}+q)}\\&\times\frac{(xy)^{\frac{2m_{r_n,1}+h+q}{2}-1}}{x^{g_1/2}y^{g_2/2}}\exp\left(-\frac{2x^{1/2}}{\sqrt{\overline{\gamma}_{r_n,1}\overline{\gamma}_{r_n,3}\hat{\rho}}}-\frac{2y^{1/2}}{\sqrt{\overline{\gamma}_{r_n,2}\overline{\gamma}_{r_n,4}\hat{\rho}}}\right).\end{aligned} \tag{D-3}$$

Substituting (15), (D-3), and (D-1) in (21), integrals of the following form appear

$$\mathcal{I}_1=\int_0^\infty x^{a_1}\exp\left(b_1x^{1/2}\right)dx \tag{D-4}$$

where $a_1,b_1\in\mathbb{R}^+$. These integrals can be solved with the aid of [23, eq. (8.310/1)] and after some mathematical manipulations, the following expression for the PDF of γ_{sel} given $\mathcal{C}$ is obtained

$$\begin{aligned}f_{\gamma_{\text{sel}}|\mathcal{C}}(y)=&\sum_{n=1}^{|\mathcal{C}|}\left[\prod_{\substack{\ell=1\\\ell\neq n}}^{|\mathcal{C}|}\frac{\sqrt{\pi}\Gamma\left(2m_{r_\ell,1}\right)2^{1-2m_{r_\ell,1}}}{\Gamma\left(m_{r_\ell,1}\right)\Gamma\left(m_{r_\ell,2}\right)}\right]\\&\sum_{h,q=0}^{\infty}\sum_{g_1,g_2=0}^{\left|h-\frac{1}{2}-q\right|-\frac{1}{2}}\mathcal{A}_1\frac{\pi\rho_1^h\rho_2^q(1-\rho_2)^{1/2}/(h!q!)}{\Gamma(m_{r_n,1}+h)\Gamma(m_{r_n,2}+q)}y^{\frac{p_{4,2}}{2}}\\&\times\exp\left(-\frac{2y^{1/2}}{\sqrt{\overline{\gamma}_{r_n,2}\overline{\gamma}_{r_n,4}\hat{\rho}}}\right)\left(\mathcal{D}_1+\mathcal{B}_1\mathcal{D}_2\right).\end{aligned} \tag{D-5}$$

The corresponding CDF expression can be derived as

$$\begin{aligned}F_{\gamma_{\text{sel}}|\mathcal{C}}(y)=&\sum_{n=1}^{|\mathcal{C}|}\left[\prod_{\substack{\ell=1\\\ell\neq n}}^{|\mathcal{C}|}\frac{\sqrt{\pi}\Gamma\left(2m_{r_\ell,1}\right)2^{1-2m_{r_\ell,1}}}{\Gamma\left(m_{r_\ell,1}\right)\Gamma\left(m_{r_\ell,2}\right)}\right]\\&\sum_{h,q=0}^{\infty}\sum_{g_1,g_2}^{\left|h-\frac{1}{2}-q\right|-\frac{1}{2}}\mathcal{A}_1\frac{\pi\rho_1^h\rho_2^q(1-\rho_2)^{1/2}\left(\mathcal{D}_1+\mathcal{B}_1\mathcal{D}_2\right)}{\Gamma(m_{r_n,1}+h)\Gamma(m_{r_n,2}+q)}\\&\times\frac{\left(\overline{\gamma}_{r_n,2}\overline{\gamma}_{r_n,4}\hat{\rho}\right)^{\frac{p_{4,2}}{2}}}{2^{p_{4,2}-1}h!q!}\gamma\left(p_{4,2},2\sqrt{\frac{y}{\overline{\gamma}_{r_n,2}\overline{\gamma}_{r_n,4}\hat{\rho}}}\right).\end{aligned} \tag{D-6}$$

Moreover, based on (20), the CDF of $\gamma_{\text{out}|\mathcal{C}}$ can be evaluated by

$$F_{\gamma_{\text{out}|\mathcal{C}}}(\gamma)=\int_0^\infty F_{\gamma_{\text{sel}}|\mathcal{C}}(y\gamma)f_{I_d}(y)dy. \tag{D-7}$$

Substituting (D-6) and the PDF of I_d, i.e.,

$$\begin{aligned}f_{I_d}(y)=&\frac{2\left(\frac{1}{\overline{\gamma}_{I_d,1}\overline{\gamma}_{I_d,2}}\right)^{\frac{m_{I_d,1}+m_{I_d,2}}{2}}}{\Gamma\left(m_{I_d,1}\right)\Gamma\left(m_{I_d,2}\right)}\\&\times y^{\frac{m_{I_d,1}+m_{I_d,2}}{2}-1}K_{m_{I_d,2}-m_{I_d,1}}\left(2\sqrt{\frac{y}{\overline{\gamma}_{I_d,1}\overline{\gamma}_{I_d,2}}}\right),\end{aligned} \tag{D-8}$$

in (D-7), using first [23, eq. (8.469/3)], then [23, eq. (6.455/2)] and after some mathematical manipulation, yields (27) and also completes this proof.

Appendix E
Proof for Equation (28)

Firstly, a convenient expression for $\left(F_{\gamma_{r_n}}(x)\right)^{|\mathcal{C}|}$ is provided. In this context and based on (14), by employing [28, eq. (07.34.03.0732.01)] as well as [23, eq. (8.352/1)], the following mathematically tractable expression is derived

$$\begin{aligned}\left(F_{\gamma_{r_n}}(x)\right)^{|\mathcal{C}|} &= \Bigg\{ \frac{\sqrt{\pi}2^{\frac{3}{2}-m_{r,1}-m_{r,2}}\Gamma(2m_{r,1})}{\Gamma(m_{r,1})\Gamma(m_{r,2})} \\ &\times \left[1-\exp\left(-2\sqrt{\frac{x}{\overline{\gamma}_{r,1}\overline{\gamma}_{r,2}}}\right)\sum_{\ell=0}^{2m_{r,1}-1}\frac{2^{\ell}}{\ell!}\left(\frac{x}{\overline{\gamma}_{r,1}\overline{\gamma}_{r,2}}\right)^{\frac{\ell}{2}}\right]\Bigg\}^{|\mathcal{C}|} \\ &\overset{(1)}{=} \frac{\sqrt{\pi}2^{\frac{3}{2}-m_{r,1}-m_{r,2}}\Gamma(2m_{r,1})}{\Gamma(m_{r,1})\Gamma(m_{r,2})}\sum_{i=0}^{|\mathcal{C}|}\binom{|\mathcal{C}|}{i}\sum_{\substack{n_1,\ldots,n_{2m_{r,1}}=0\\ n_1+\cdots+n_{2m_{r,1}}=i}}^{i}(-1)^i i! \\ &\times \frac{\prod_{\ell=1}^{2m_{r,1}-1}\left(\frac{2}{\left(\overline{\gamma}_{r,1}\overline{\gamma}_{r,2}\right)^{\ell/2}\ell!}\right)^{n_{\ell+1}}}{n_1!\cdots n_{2m_{r,1}}!}x^{\sum_{\ell=1}^{2m_{r,1}-1}\frac{\ell n_{\ell+1}}{2}}\exp\left(\frac{-2i\sqrt{x}}{\sqrt{\overline{\gamma}_{r,1}\overline{\gamma}_{r,2}}}\right),\end{aligned} \tag{E-1}$$

where (1) holds due to the use of the binomial and the multinomial identities. Moreover, based on (E-1) and by substituting (19), (22) in (21), the following type of integrals appear

$$\begin{aligned}\mathcal{I}_2 &= \int_0^{\gamma_{\rm th}} x^{a_1}\exp\left(b_1 x^{1/2}\right)dx \\ \mathcal{I}_3 &= \int_{\gamma_{\rm th}}^{\infty} x^{a_2}\exp\left(b_2 x^{1/2}\right)dx.\end{aligned} \tag{E-2}$$

These integrals can be solved with the aid of [23, eqs. (8.350/1-2)] and after some mathematics, the following expression for the PDF of $\gamma_{\rm sel}$ given $\mathcal{C}$ is obtained

$$\begin{aligned}f_{\gamma_{\rm sel}|\mathcal{C}}(y) &= \pi^{\frac{3}{2}}\Gamma(2m_{r,1})\sum_{h,q=0}^{\infty}\sum_{g_1,g_2=0}^{\left|h-\frac{1}{2}-q\right|-\frac{1}{2}}\frac{\rho_1^h\rho_2^q}{\left(\overline{\gamma}_{r,1}\overline{\gamma}_{r,3}\right)^{\frac{p_{4,1}}{2}}h!q!} \\ &\times \left[\prod_{j=1}^{2}\frac{\left(g_j+|h-1/2-q|-\frac{1}{2}\right)!(1-\rho_j)^{\frac{g_1-h-q}{2}}}{g_j!\left(-g_j+|h-\frac{1}{2}-q|-\frac{1}{2}\right)!\Gamma(m_{r,j})^2}\right]\mathcal{B}_2 \\ &\times \frac{2^{1-2g_1-2g_2-p_{4,2}}(1-\rho_2)^{\frac{1}{2}}}{\Gamma(h+m_{r,1})\Gamma(q+m_{r,2})}y^{\frac{p_{4,1}}{2}-1}\exp\left(-\frac{2y^{1/2}}{\sqrt{\overline{\gamma}_{r,1}\overline{\gamma}_{r,3}\hat{\rho}}}\right),\end{aligned} \tag{E-3}$$

with the corresponding CDF given by

$$\begin{aligned}F_{\gamma_{\rm sel}|\mathcal{C}}(y) &= \pi^{3/2}\Gamma(2m_{r,1})\sum_{h,q=0}^{\infty}\sum_{g_1,g_2=0}^{\left|h-\frac{1}{2}-q\right|-\frac{1}{2}}\frac{\rho_1^h\rho_2^q}{h!q!} \\ &\times \left[\prod_{j=1}^{2}\frac{\left(g_j+|h-1/2-q|-\frac{1}{2}\right)!(1-\rho_j)^{\frac{g_1-h-q}{2}}}{g_j!\left(-g_j+|h-1/2-q|-\frac{1}{2}\right)!\Gamma(m_{r,j})^2 2^{p_{4,j}}}\right] \\ &\times \frac{(1-\rho_2)^{1/2}\hat{\rho}^{\frac{p_{4,1}}{2}}/2^{2(g_1+g_2-1)}}{\Gamma(h+m_{r,1})\Gamma(q+m_{r,2})}\mathcal{B}_2\gamma\left(p_{4,1},\frac{2\sqrt{\gamma}}{\sqrt{\overline{\gamma}_{r,1}\overline{\gamma}_{r,3}\hat{\rho}}}\right).\end{aligned} \tag{E-4}$$

Moreover, substituting (E-4) and (D-8) in (D-7), using first [23, eq. (8.469/3)], then [23, eq. (6.455/2)], and after some analysis yields (28) and also completes this proof.

TABLE I
Adjustment Factor Values

$\mathbf{m_{I_d,1}}$	$\mathbf{m_{I_d,2}}$	ϵ
1	1.5	0.7
1.5	2	0.32
2	2.5	0.25
2.5	3	0.17
3	3.5	0.11
3.5	4	0.08
4	4.5	0.05

Appendix F
Outage Probability under L Interfering Signals

We consider a communication system with N relays, in which all relays are subjected to one interfering signal. This system employs a BRS mechanism to forward the signal to the final destination, which is subjected to L interfering signals. This OP can be evaluated by substituting (25) and (D-7) in (33). However, for the scenario of L interfering signals, in order to evaluate the integral in (D-7), the PDF of $I_d = \sum_{i=1}^{L}\gamma_{I_i}$ should be evaluated, in which γ_{I_i} follow the DN distribution with PDF given by (D-8). To the best of the authors' knowledge, an exact closed-form expression for the PDF of I_d does not exist. An alternative approach, which is also adopted here, is to use an approximated expression for this PDF, based on the framework proposed in [43]. In particular, assuming that Z is a Gamma distributed RV, the PDF of Z is given be

$$f_Z(\gamma) = \frac{\gamma^{k-1}}{\Gamma(k)\theta^k}\exp\left(-\frac{\gamma}{\theta}\right), \tag{F-1}$$

where k,θ are the shaping and scaling parameters of the distribution, respectively. Based on the moment matching method and more specifically by equating the first two moments of the Gamma and the DN distributions, the following relation among the parameters has been obtained

$$\begin{aligned}k &= \frac{m_{I_d,1}m_{I_d,2}}{m_{I_d,1}+m_{I_d,2}+1-m_{I_d,1}m_{I_d,2}\epsilon} \\ \theta &= \left(m_{I_d,1}+m_{I_d,2}+1-m_{I_d,1}m_{I_d,2}\epsilon\right)\overline{\gamma}_{I_d,1}\overline{\gamma}_{I_d,2}.\end{aligned} \tag{F-2}$$

In (F-2), ϵ denotes an adjustment factor that is added for improving the approximation in the lower and the upper tail regions of the PDF [43]. More specifically, in Table I, assuming different scenarios regarding the DN shaping parameters, the corresponding values of the adjustment factor are provided. Additionally, based on the fact that the sum of L Gamma RVs, with parameters k,θ, is also a Gamma RV with parameters kL,θ, the PDF in (F-1), with $Z \sim \mathcal{G}(kL,\theta)$, can accurately approximate the PDF of I_d. Therefore, substituting (E-1) and (F-1) in (D-7), an integral of the following type appears

$$\mathcal{I}_3 = \int_0^{\infty}\gamma^{a-1}\exp\left(-A\gamma^{1/2}\right)\exp\left(-B\gamma\right)d\gamma, \tag{F-3}$$

where $a,A,B \in \mathbb{R}^+$. This integral can be solved by making a change of variables of the form $x=\sqrt{\gamma}$ and using [23, eqs. (3.462/1) and (9.240)]. Based on this solution and after some mathematical simplifications, the following approximated closed-form expression for the CDF of $\gamma_{\text{out}|\mathcal{C}}$ is derived

$$
\begin{aligned}
F_{\gamma_{\text{out}|\mathcal{C}}}(\gamma) \simeq & \frac{\sqrt{\pi}\Gamma(2m_{r,1})}{\Gamma(m_{r,1})\Gamma(m_{r,2})}\sum_{i=0}^{|\mathcal{C}|}\binom{|\mathcal{C}|}{i}\sum_{\substack{n_1,\ldots,n_{2m_{r,1}}=0\\ n_1+\cdots+n_{2m_{r,1}}=i}}^{i} \\
& \times(-1)^i i! \frac{\prod_{\ell=1}^{2m_{r,1}-1}\left(\frac{2}{\left(\overline{\gamma}_{r,1}\overline{\gamma}_{r,3}\right)^{\ell/2}\ell!}\right)^{n_{\ell+1}}}{n_1!\cdots n_{2m_{r,1}}!2^{m_{r,1}+m_{r,2}-\frac{3}{2}}} \frac{\theta^{\frac{1}{2}}\left(\gamma\theta\right)^{\sum_{\ell=1}^{2m_{r,1}-1}\frac{\ell n_{\ell+1}}{2}}}{\Gamma(k)} \\
& \times\left[\frac{1}{\theta^{1/2}}{}_1F_1\left(\sum_{\ell=1}^{2m_{r,1}-1}\frac{\ell n_{\ell+1}}{2}+k;\frac{1}{2};\frac{i^2\gamma b}{\overline{\gamma}_{r,1}\overline{\gamma}_{r,3}}\right)\right. \\
& \times\Gamma\left(\sum_{\ell=1}^{2m_{r,1}-1}\frac{\ell n_{\ell+1}}{2}+k\right)-\Gamma\left(\sum_{\ell=1}^{2m_{r,1}-1}\frac{\ell n_{\ell+1}}{2}+k+\frac{1}{2}\right) \\
& \left.\times\left(\frac{4i^2\gamma}{\overline{\gamma}_{r,1}\overline{\gamma}_{r,3}}\right)^{\frac{1}{2}}{}_1F_1\left(\sum_{\ell=1}^{2m_{r,1}-1}\frac{\ell n_{\ell+1}}{2}+k+\frac{1}{2};\frac{3}{2};\frac{i^2\gamma b}{\overline{\gamma}_{r,1}\overline{\gamma}_{r,3}}\right)\right\},
\end{aligned}
\tag{F-4}
$$

with ${}_1F_1(\cdot;\cdot;\cdot)$ being the confluent hypergeometric function [23, eq. (9.210/1)]. Nevertheless, substituting (F-4) and (25) in (33), results to the requested OP.

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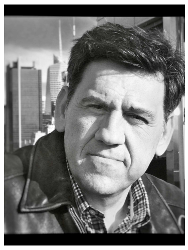

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