Proactive Relay Selection with Joint Impact of Hardware Impairment and Co-channel Interference

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***Abstract*—In this paper, we investigate the end-to-end performance of dual-hop proactive decode-and-forward relaying networks with Nth best relay selection in the presence of two practical deleterious effects: i) hardware impairment and ii) co-channel interference. In particular, we derive new exact and asymptotic closed-form expressions for the outage probability and average channel capacity of Nth best partial and opportunistic relay selection schemes over Rayleigh fading channels. Insightful discussions are provided. It is shown that, when the system cannot select the best relay for cooperation, the partial relay selection scheme outperforms the opportunistic method under the impact of the same co-channel interference (CCI). In addition, without CCI but under the effect of hardware impairment, it is shown that both selection strategies have the same asymptotic channel capacity. Monte Carlo simulations are presented to corroborate our analysis.**

***Index Terms*—Hardware impairment, decode-and-forward relaying, partial relay selection, opportunistic relay selection, outage probability, channel capacity.**

I. INTRODUCTION

Along the last decade, the concept of cooperative diversity [1] has been well exploited as an efficient means to enhance the performance of wireless communications. The basic idea is to allow single-antenna terminals to share their antennas in order to mimic a physical multiple-antenna array so that spatial diversity can be explored. However, the use of multiple relays may invoke a spectral efficiency loss and relay selection schemes arise as a promising solution for alleviating this problem. Two proactive relay selection strategies[1] that have been widely investigated in the literature are opportunistic relay selection (ORS) [2]–[11] and partial relay selection (PRS) [12]–[19]. In ORS the best relay is chosen relying on the channel state information (CSI) of both source-relay and relay-destination links. The pioneering idea of ORS was proposed in [2], while [3] presented an asymptotic analysis of the symbol error rate (SER) of a selection amplify-and-forward (AF) network. In [4], it was shown that optimal transmission of a single relay among a set of multiple AF relays minimize the outage probability (OP) and outperform any other strategies that involve simultaneous transmissions from more than one AF relay under an aggregate power constraint. In [5], the OP of a cooperative network with multiple potential decode-and-forward (DF) relays and multiple simultaneous transmissions was investigated, in which a selection cooperation scheme was proposed. In [6], closed-form expressions for the OP and the bit error rate (BER) of uncoded threshold-based ORS were derived assuming arbitrary signal-to-noise ratio (SNR) levels, arbitrary number of available DF relays, and arbitrary source-destination channel conditions. In [7], with independent non-identically distributed (i.n.i.d.) Rician fading channels, approximate formulas for the SER of ORS were derived. Considering i.n.i.d. Nakagami-m fading and a selection combining (SC) receiver at the destination, the outage performance of ORS was examined in [8], while [9] derived closed-form expressions for the SER. In [10], exact closed-form expressions for the OP and ergodic capacity (EC) of selection cooperative relaying were derived assuming a maximal-ratio combiner (MRC) at the destination. In [11], an incremental DF ORS scheme was proposed in which the selected relay chooses to cooperate only if the source-destination channel is of an unacceptable quality. A closed-form expression for the OP was derived.

A common feature of all the aforementioned papers is that full diversity gain can be attained. On the other hand, in these works there is the need for continuous channel feedback from all the links, which results in a high power consumption and large overhead, a non-desirable feature for ad-hoc and sensor networks. To alleviate this problem, PRS was proposed in [12], where only CSI of the source-relay link is used to select the best relay. Thus, by monitoring the connectivity of only one-hop rather than two-hop, the lifetime of the network can be prolonged. In [13], tight closed-form approximations for the EC of dual-hop AF relaying networks with PRS were derived. Relying on the channel quality of the second-hop for selecting the best relay, the work in [14] examined the outage performance of DF relaying networks subject to Nakagami-m and employing a MRC receiver at the destination. In [15], a comprehensive performance analysis of dual-hop relaying networks with fixed-gain semi-blind relays was carried out. In particular, closed-form expressions for the OP, probability density function (PDF), moment generating functions (MGFs), and generalized moments of the end-to-end SNR were derived. In addition, the second-order statistics of the end-to-end envelope was studied and the corresponding level crossing rate

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[1]In proactive relay selection, the relay is chosen before the source transmission.

and average fade duration were obtained in an exact manner. In [16], assuming the presence of the direct link between source and destination, an exact performance analysis of DF dual-hop networks with relay selection and subject to i.n.i.d Nakagami-m fading was presented. The diversity and coding gains of PRS schemes subject to Nakagami-m fading were attained in [17], while the impact of feedback delay was analyzed in [18]. Finally, in [19], three novel PRS schemes were proposed.

Common to all these works dealing with ORS and PRS is the assumption of perfect transceiver hardware (i.e., ideal hardware) of the terminals. However, in practice, the transceiver hardware is imperfect due to phase noise, I/Q imbalance and amplifier nonlinearities [20]–[22]. Very few works have investigated the effect of hardware impairments in dual-hop cooperative networks and they are briefly discussed next. In [23], the authors quantified the impact of hardware impairments on dual-hop AF and DF relaying networks subject to Nakagami-m fading. Expressing the OP as a function of the effective end-to-end signal-to-noise-and-distortion ratio (SNDR), exact closed-form and asymptotic formulas for the OP were derived considering hardware impairments at the source, relay, and destination. Upper bounds for the EC were derived as well. In that work, fundamental design guidelines for selecting hardware that satisfies the requirements of a practical relaying system were pointed out. In [24], the authors analyzed the impact of hardware impairments at the relay on the OP and the SER in two-way AF relaying.

Another channel impairment that may be taken into account in practical systems is co-channel interference (CCI). Differently from hardware impairments, the study of CCI in cooperative networks has already been extensively investigated along the last years. In the sequel, three representative works will be discussed. In [25], the outage behavior of dual-hop DF ORS schemes was investigated with CCI at both the relays and the destination. It was shown that the co-channel interferers do not affect the diversity gain. However, such interferers degrade the outage performance by affecting the coding gain of the system. In [26], assuming a multiuser relay network composed by a single source, a single AF relay, and multiple destinations, the outage performance of opportunistic scheduling was examined in which the relay and the multiple destinations undergo CCI. Exact expressions and closed-form lower bounds for the OP were derived. In addition, the impact of CSI feedback delay when CCI is considered only at the relay was studied. Finally, in [27], the impact of CCI in two-way AF relaying systems was analyzed.

In this paper, we investigate the end-to-end performance of dual-hop DF relaying networks in the presence of two practical deleterious effects: i) hardware impairment and ii) CCI. Both ORS and PRS schemes are considered. To the best of the authors' knowledge, this is the first attempt to analyze the joint impact of hardware impairment and CCI in a dual-hop relaying network. Assuming Rayleigh fading, new exact and asymptotic closed-form expressions for the OP and the average channel capacity are derived. Insightful discussions are provided. It is shown that, when the system cannot select the best relay for cooperation, PRS scheme outperforms the opportunistic method under the impact of the same CCI. In addition, without

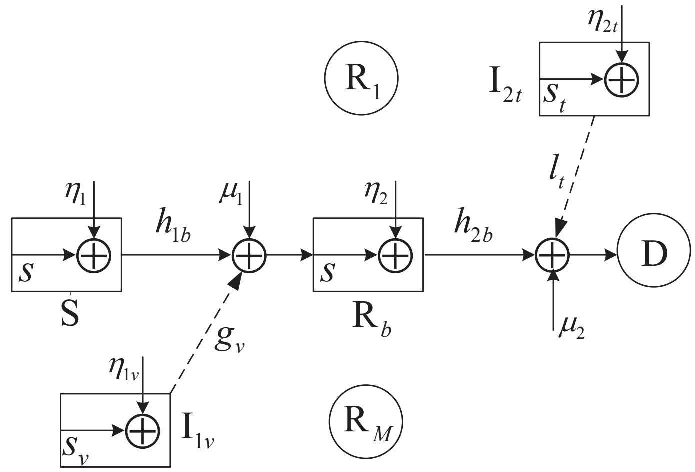

Fig. 1. Dual-hop relay networks in presence of hardware impairments and co-channel interference.

CCI but under the effect of hardware impairment, it is shown that both selection strategies have the same asymptotic channel capacity. Monte Carlo simulations are presented to corroborate our analysis.

The rest of this paper is organized as follows. The system model is described in Section II. In Section III, closed-form expressions for the OP and average channel capacity are derived. Simulation results are presented in Section IV along with representative numerical results. Finally, this paper is concluded in Section V. Appendices A-F present the proofs of the Lemmas and the Theorems.

II. System/Channel Models and Preliminary Results

A. System and Channel Models

Consider a dual-hop proactive relay network in which a source S attempts to transmit its data to the destination D through the help of M available relays R_m, $m = 1, 2, \cdots, M$, as shown in Fig. 1. Each terminal is equipped with a single antenna and operates in a half-duplex mode. Assuming that the direct link between S and D experiences deep shadowing, the communication is realized into two time-slots. In our analysis, depending on the available CSI, we consider two well-known proactive relay selection methods: partial relay selection [12] and opportunistic relay selection [28]. In this case, only one relay R_b satisfying a predefined criterion is selected for helping to forward the source message.

In the first time slot, the source transmits its signal s to the chosen relay R_b. Assume that there are K_1 interference sources I_{1v}, $v = 1, 2, \ldots, K_1$, which are currently using the same channel, and hence creating interferences to the relay R_b. In the second time slot, the relay R_b forwards the source signal to the destination by using a DF protocol. Also, we assume that there are K_2 interference sources I_{2t}, $t = 1, 2, \ldots, K_2$. In the presence of the hardware impairments and co-channel interference, the received signal at R_b and D can be expressed, respectively, as

$$y_{\mathsf{R}_b} = h_{1b}\left(s+\eta_1\right) + \sum_{v=1}^{K_1} g_v\left(s_v+\eta_{1v}\right) + \mu_1 + n_{\mathsf{R}_b}, \quad (1)$$

$$y_{\mathsf{D}} = h_{2b}\left(s+\eta_2\right) + \sum_{t=1}^{K_2} l_t\left(s_t+\eta_{2t}\right) + \mu_2 + n_{\mathsf{D}}, \quad (2)$$

where n_{R_b} and n_{D} are, respectively, the additive white Gaussian noise (AWGN) terms at R and D, with zero mean and variance N_0, s_v and s_t are the signals transmitted by the interference sources I_{1v} and I_{2t}, respectively, h_{1b}, h_{2b}, g_v, and l_t are the channel coefficients of the links $\mathsf{S} \to \mathsf{R}_b$, $\mathsf{R}_b \to \mathsf{D}$, $\mathsf{I}_{1v} \to \mathsf{R}_b$, and $\mathsf{R}_b \to \mathsf{D}$, respectively. In addition, η_1, η_{1v}, η_2 and η_{2t} denote the noises caused by the hardware impairments at the transmitters S, $\mathsf{I}_{1\mathsf{v}}$, R_b, and $\mathsf{I}_{2\mathsf{t}}$, respectively, while μ_1 and μ_2 are the noises generated by the hardware impairments at the receivers R_b and D, respectively.

Assume that all the channels follow a Rayleigh distribution. Thus, the corresponding channel gains $\varphi_{\mathrm{SR_m}} = |h_{1m}|^2$, $\varphi_{\mathrm{R_mD}} = |h_{2m}|^2$ for $m = 1, 2, \ldots, M$, $|g_v|^2$, and $|l_t|^2$ are exponential random variables (RVs) with parameters λ_{SR_m}, $\lambda_{\mathrm{R}_m\mathrm{D}}$, $\lambda_{\mathrm{RI}_{1v}}$, and $\lambda_{\mathrm{DI}_{2t}}$, respectively.

Remark 1: Similar to [23], [24], we can model the distortion noises η_1, η_{1v}, η_2, η_{2t}, μ_1 and μ_2 as circularly-symmetric complex Gaussian distribution with zero-mean and variance $\sigma_1^2\mathcal{P}_{\mathsf{S}}$, $\sigma_{3v}^2\mathcal{P}_{\mathsf{I}}$, $\sigma_2^2\mathcal{P}_{\mathsf{S}}$, $\sigma_{4t}^2\mathcal{P}_{\mathsf{I}}$, $\sigma_3^2\left(|h_{1b}|^2\mathcal{P}_{\mathsf{S}} + |g_v|^2\mathcal{P}_{\mathsf{I}}\right)$, and $\sigma_4^2\left(|h_{2b}|^2\mathcal{P}_{\mathsf{S}} + |l_t|^2\mathcal{P}_{\mathsf{I}}\right)$, respectively. In this case, $\mathcal{P}_{\mathsf{S}}$ and $\mathcal{P}_{\mathsf{I}}$ denote the transmit powers of the source (and relays) and the interference sources, respectively, while σ_1, σ_{3v}, σ_2, σ_{4t}, σ_3 and σ_4 present the level of the hardware impairments at the corresponding transmitters and receivers. Without loss of generality, it is also assumed that all of the nodes have the same structure so that the impairment levels are the same, i.e., $\sigma_1 = \sigma_{3v} = \sigma_{4t} = \sigma_a$, and $\sigma_3 = \sigma_4 = \sigma_b$ [23], [24]. [2]

From (1) and (2), the received signal-to-interference-plus-noise ratio (SINR) at R_b and D can be written, respectively, as

$$\psi_{\mathrm{SR_b}} = \frac{\mathcal{P}_{\mathsf{S}}\varphi_{\mathrm{SR_b}}}{\left(\sigma_1^2+\sigma_3^2\right)\mathcal{P}_{\mathsf{S}}\varphi_{\mathrm{SR_b}} + \sum\limits_{v=1}^{K_1}\left(1+\sigma_{1v}^2+\sigma_3^2\right)\mathcal{P}_{\mathsf{I}}|g_v|^2 + N_0} = \frac{\gamma_{\mathrm{SR_b}}}{\kappa\gamma_{\mathrm{SR_b}} + Z_1 + 1}, \quad (3)$$

$$\psi_{\mathrm{R_bD}} = \frac{\mathcal{P}_{\mathsf{S}}\varphi_{\mathrm{R_bD}}}{\left(\sigma_2^2+\sigma_4^2\right)\mathcal{P}_{\mathsf{S}}\varphi_{\mathrm{R_bD}} + \sum\limits_{t=1}^{K_2}\left(1+\sigma_{2t}^2+\sigma_4^2\right)\mathcal{P}_{\mathsf{I}}|l_t|^2 + N_0} = \frac{\gamma_{\mathrm{R_bD}}}{\kappa\gamma_{\mathrm{R_bD}} + Z_2 + 1}, \quad (4)$$

[2]In case of different levels of hardware impairment, our results can be applied to derive the upper-bound and/or lower-bound of the outage probability and average channel capacity. Moreover, in practice, with knowledge of impairment transceiver levels, we should select the transceivers with similar impairment levels, in order to optimize the system performance (see [23, Corollary 3].

where

$$\gamma_{\mathrm{SR_b}} = \frac{\mathcal{P}_{\mathsf{S}}\varphi_{\mathrm{SR_b}}}{N_0}, \gamma_{\mathrm{R_bD}} = \frac{\mathcal{P}_{\mathsf{S}}\varphi_{\mathrm{R_bD}}}{N_0}, Z_1 = \sum_{v=1}^{K_1}(1+\kappa)\frac{\mathcal{P}_{\mathsf{I}}|g_v|^2}{N_0},$$

$$Z_2 = \sum_{t=1}^{K_2}(1+\kappa)\frac{\mathcal{P}_{\mathsf{I}}|l_t|^2}{N_0}, \kappa = \sigma_a^2 + \sigma_b^2.$$

B. Preliminary Results

In partial relay selection method, the Nth best relay R_b is selected by the following strategy:

$$\mathsf{R}_b = N\mathsf{th} \underset{m=1,2,\ldots,M}{\operatorname{argmax}}\left(\varphi_{\mathrm{SR_m}}\right). \quad (5)$$

On the other hand, in the opportunistic relay selection strategy, the Nth best relay R_b is chosen according to

$$\mathsf{R}_b = N\mathsf{th} \underset{m=1,2,\ldots M}{\operatorname{argmax}} \min\left(\varphi_{\mathrm{SR_m}}, \varphi_{\mathrm{R_mD}}\right). \quad (6)$$

We can observe from (5) and (6) that the relay selection process in the ORS protocol requires each relay to obtain the channel state information (CSI) of the $\mathrm{S} \to \mathrm{R}$ and $\mathrm{R} \to \mathrm{D}$ links, while that in the PRS only needs the CSI of the first link. Hence, the implementation of the ORS protocol is more complex than that of the PRS protocol. Moreover, we note that the relay selection operation in the ORS protocol can be realized by a distributed manner as presented in [2].

Remark 2: Throughout this paper, we assume clustering relay networks where data links are independent and identically distributed (i.i.d.), i.e., $\lambda_{\mathrm{SR}_m} = \lambda_{\mathrm{SR}}$ and $\lambda_{\mathrm{R}_m\mathrm{D}} = \lambda_{\mathrm{RD}}$ for all m. In addition, since the interferers can originate from different cells, the interference links are presumed to be independent non-identically distributed (i.n.i.d.), i.e., $\lambda_{\mathrm{RI}_{1m}} \neq \lambda_{\mathrm{RI}_{1n}}$ if $m \neq n$, and $\lambda_{\mathrm{DI}_{2m}} \neq \lambda_{\mathrm{DI}_{2n}}$ if $m \neq n$.[3]

The PDF of Z_{a}, $\mathsf{a} \in \{1, 2\}$, can be expressed as

$$f_{Z_a}(z_a) = \sum_{u=1}^{K_a} \alpha_{\mathrm{XI}_{au}} \exp\left(-\Omega_{\mathrm{XI}_{au}}\right), \quad (7)$$

where $\mathrm{X} \equiv \mathrm{R}$ if $a = 1$, $\mathrm{X} \equiv \mathrm{D}$ if $a = 2$,

$$\Omega_{\mathrm{XI_{au}}} = \frac{\tilde{\Omega}_{\mathrm{XI_{au}}}}{\bar{\gamma}}, \tilde{\Omega}_{\mathrm{XI_{au}}} = \frac{\lambda_{\mathrm{XI_{au}}}}{(1+\kappa)\, r_P},$$

$$\bar{\gamma} = \frac{\mathcal{P}_{\mathsf{I}}}{N_0} = \frac{\mathcal{P}_{\mathsf{S}}}{N_0} = \frac{\mathcal{P}}{N_0}, \quad \alpha_{\mathrm{XI_{au}}} = \frac{\tilde{\alpha}_{\mathrm{XI_{au}}}}{\bar{\gamma}\, r_P},$$

$$\tilde{\alpha}_{\mathrm{XI_{au}}} = \tilde{\Omega}_{\mathrm{XI_{au}}} \prod_{w=1, w\neq u}^{K_{\mathsf{a}}} \frac{\tilde{\Omega}_{\mathrm{XI_{aw}}}}{\tilde{\Omega}_{\mathrm{XI_{aw}}} - \tilde{\Omega}_{\mathrm{XI_{au}}}}.$$

Since the DF relaying protocol is employed, the end-to-end SINR is given by

$$\psi_{e2e}^{\mathrm{Y}} = \min\left(\psi_{\mathrm{SR}_b}, \psi_{\mathrm{R_bD}}\right), \quad (8)$$

where $\mathrm{Y} \in (\mathrm{ORS}, \mathrm{PRS})$.

[3]Our derivation can be easily extended to i.n.i.d. data links and/or i.i.d. interference links.

III. Performance Analysis

A. Outage Probability

In this subsection, exact closed-form expressions for the OP of both PRS and ORS schemes will be derived. By definition, the OP is the probability that the end-to-end received SINR is lower than a pre-determined threshold γ_{th}.

1) Partial Relay Selection (PRS): The outage probability of the PRS protocol can be formulated as

$$P_{\text{PRS}}^{out} = \Pr\left(\psi_{e2e}^{\text{PRS}} < \gamma_{th}\right) = F_{\psi_{e2e}^{\text{PRS}}}(\gamma_{th}), \tag{9}$$

where $F_{\psi_{e2e}^{\text{PRS}}}(.)$ denotes the CDF of ψ_{e2e}^{PRS}.

Theorem 1: If $x \geq \kappa^{-1}$, then $F_{\psi_{e2e}^{\text{PRS}}}(x) = 1$, and if $x < \kappa^{-1}$, it follows that

$$F_{\psi_{e2e}^{\text{PRS}}}(x) = 1 - \sum_{m=1}^{N} \sum_{n=0, m+n>1}^{M-m+1} \sum_{v=1}^{K_1} \sum_{t=1}^{K_2} (-1)^{n+1} \Delta_1 \Delta_2 \times \frac{(1-\kappa x)^2}{(\Phi_1 + x)(\Phi_2 + x)} \exp\left(-\frac{(\Theta_1 + \Omega_2) x}{1 - \kappa x}\right), \tag{10}$$

where $\Omega_1 = N_0 \lambda_{\text{SR}} / \mathcal{P}$, $C_b^a = \frac{b!}{a!(b-a)!}$, $\Theta_1 = (n+m-1)\Omega_1$, $\Delta_1 = C_M^{m-1} C_{M-m+1}^{n} \alpha_{\text{RI}_{1\text{v}}} / (\Theta_1 - \kappa \Omega_{\text{RI}_{1\text{v}}})$, $\Phi_1 = \Omega_{\text{RI}_{1\text{v}}} / (\Theta_1 - \kappa \Omega_{\text{RI}_{1\text{v}}})$, $\Omega_2 = \lambda_{\text{RD}} N_0 / \mathcal{P}$, $\Delta_2 = \alpha_{\text{DI}_{2\text{t}}} / (\Omega_2 - \Omega_{\text{DI}_{2\text{t}}} \kappa)$ and $\Phi_2 = \Omega_{\text{DI}_{2\text{t}}} / (\Omega_2 - \kappa \Omega_{\text{DI}_{2\text{t}}})$.

Proof 1: The proof is presented in Appendix A.

Lemma 1: Without interference sources, i.e., by setting $\mathcal{P}_I \to 0$ or $r_P \to 0$, and $x < \kappa^{-1}$, the CDF $F_{\psi_{e2e}^{\text{PRS}}}(\cdot)$ can be expressed as

$$F_{\psi_{e2e}^{\text{PRS}}}(x) = 1 - \sum_{m=1}^{N} \sum_{n=0, m+n\neq 1}^{M-m+1} (-1)^{n+1} C_M^{m-1} C_{M-m+1}^{n} \times \exp\left(-\frac{(\Theta_1 + \Omega_2) x}{1 - \kappa x}\right). \tag{11}$$

Proof 2: The proof is given in Appendix B.

Theorem 2: At high transmit SNR and assuming $x < \kappa^{-1}$, the CDF $F_{\psi_{e2e}^{\text{PRS}}}(\cdot)$ can be approximated by

$$F_{\psi_{e2e}^{\text{PRS}}}(x) \overset{\overline{\gamma} \to +\infty}{\approx} 1 - \sum_{m=1}^{N} \sum_{n=0, m+n>1}^{M-m+1} \sum_{v=1}^{K_1} \sum_{t=1}^{K_2} (-1)^{n+1} \times \Delta_1 \Delta_2 \frac{(1-\kappa x)^2}{(\Phi_1 + x)(\Phi_2 + x)}. \tag{12}$$

Proof 3: For high values of $\overline{\gamma}$, (3) and (4) can be approximated by

$$\psi_{\text{SR}_\text{b}} \overset{\overline{\gamma} \to +\infty}{\approx} \frac{\gamma_{\text{SR}_\text{b}}}{\kappa \gamma_{\text{SR}_\text{b}} + Z_1}, \quad \psi_{\text{R}_\text{b}\text{D}} \overset{\overline{\gamma} \to +\infty}{\approx} \frac{\gamma_{\text{R}_\text{b}\text{D}}}{\kappa \gamma_{\text{R}_\text{b}\text{D}} + Z_2}. \tag{13}$$

From (13), with the same manner with Appendix A, we can obtain

$$F_{\psi_{\text{SR}_\text{b}}}(x) \overset{\overline{\gamma} \to +\infty}{\approx} 1 - \sum_{m=1}^{N} \sum_{n=0, m+n>1}^{M-m+1} \sum_{v=1}^{K_1} (-1)^{n+1} \Delta_1 \frac{1 - \kappa x}{\Phi_1 + x},$$

$$F_{\psi_{\text{R}_\text{b}\text{D}}}(x) \overset{\overline{\gamma} \to +\infty}{\approx} 1 - \sum_{t=1}^{K_2} \Delta_2 \frac{1 - \kappa x}{\Phi_2 + x}.$$

By substituting the results above into (A.1), (12) can be attained.

Then, similar to Appendix A, (12) can be attained.

Lemma 2: Without interference sources, i.e., by setting $\mathcal{P}_I \to 0$ or $r_P \to 0$, and $x < \kappa^{-1}$, the CDF $F_{\psi_{e2e}^{\text{PRS}}}(\cdot)$ at high transmit SNR can be expressed as

$$F_{\psi_{e2e}^{\text{PRS}}}(x) \overset{\overline{\gamma} \to +\infty}{\approx} \begin{cases} \Omega_2 x / (1 - \kappa x); & \text{if } N < M \\ (M\Omega_1 + \Omega_2) x / (1 - \kappa x); & \text{if } N = M \end{cases}. \tag{14}$$

Proof 4: The proof is given in Appendix C.

From Lemma 2, one can observe that when $x < \kappa^{-1}$, the diversity order equals 1.

2) Opportunistic Relay Selection (ORS): The OP of the ORS scheme can be formulated as

$$P_{\text{ORS}}^{out} = \Pr\left(\psi_{e2e}^{\text{ORS}} < \gamma_{th}\right) = F_{\psi_{e2e}^{\text{ORS}}}(\gamma_{th}), \tag{15}$$

Theorem 3: If $x \geq \kappa^{-1}$, then $F_{\psi_{e2e}^{\text{ORS}}}(x) = 1$, and if $x < \kappa^{-1}$, it follows that

$$F_{\psi_{e2e}^{\text{ORS}}}(x) = 1 - \sum_{m=1}^{N} \sum_{n=0, m+n>1}^{M-m+1} \sum_{v=1}^{K_1} \sum_{t=1}^{K_2} (-1)^{n+1} \times \left[\frac{\Delta_3}{\Phi_3 + x} + \frac{\Delta_4}{\Phi_4 + x} + \frac{\Delta_5}{\Phi_6 + x} + \frac{\Delta_6}{\Phi_7 + x}\right] \times \frac{(1-\kappa x)^2}{(\Phi_5 + x)} \exp\left(-\frac{\Theta_2 x}{1 - \kappa x}\right), \tag{16}$$

where $\Omega = \Omega_1 + \Omega_2$, $\Theta_2 = (n+m-1)\Omega$, $\Phi_3 = \Omega_{\text{RI}_{1\text{v}}} / (\Omega_1 - \kappa \Omega_{\text{RI}_{1\text{v}}})$, $\Phi_4 = \Omega_{\text{RI}_{1\text{v}}} / (\Theta_2 - \kappa \Omega_{\text{RI}_{1\text{v}}})$, $\Phi_5 = (\Omega_{\text{RI}_{1\text{v}}} + \Omega_{\text{DI}_{2\text{t}}}) / (\Theta_2 - \kappa (\Omega_{\text{RI}_{1\text{v}}} + \Omega_{\text{DI}_{2\text{t}}}))$, $\Phi_6 = \Omega_{\text{DI}_{2\text{t}}} / (\Omega_2 - \kappa \Omega_{\text{DI}_{2\text{t}}})$, $\Phi_7 = \Omega_{\text{DI}_{2\text{t}}} / (\Theta_2 - \kappa \Omega_{\text{DI}_{2\text{t}}})$,

$$\Delta_3 = (n+m-1) C_M^{m-1} C_{M-m+1}^{n} \frac{\Omega_2 \alpha_{\text{RI}_{1\text{v}}} \alpha_{\text{DI}_{2\text{t}}}}{\Omega_2 + (n+m-2)\Omega} \times \frac{1}{(\Theta_2 - \kappa(\Omega_{\text{RI}_{1\text{v}}} + \Omega_{\text{DI}_{2\text{t}}}))(\Omega_1 - \kappa \Omega_{\text{RI}_{1\text{v}}})},$$

$$\Delta_4 = (n+m-2) C_M^{m-1} C_{M-m+1}^{n} \frac{\Omega_1 \alpha_{\text{RI}_{1\text{v}}} \alpha_{\text{DI}_{2\text{t}}}}{\Omega_2 + (n+m-2)\Omega} \times \frac{1}{(\Theta_2 - \kappa \Omega_{\text{RI}_{1\text{v}}})(\Theta_2 - \kappa(\Omega_{\text{RI}_{1\text{v}}} + \Omega_{\text{DI}_{2\text{t}}}))},$$

$$\Delta_5 = (n+m-1) C_M^{m-1} C_{M-m+1}^{n} \frac{\Omega_1 \alpha_{\text{RI}_{1\text{v}}} \alpha_{\text{DI}_{2\text{t}}}}{\Omega_1 + (n+m-2)\Omega} \times \frac{1}{(\Theta_2 - \kappa(\Omega_{\text{RI}_{1\text{v}}} + \Omega_{\text{DI}_{2\text{t}}}))(\Omega_2 - \kappa \Omega_{\text{DI}_{2\text{t}}})},$$

$$\Delta_6 = (n+m-2) C_M^{m-1} C_{M-m+1}^{n} \frac{\Omega_2 \alpha_{\text{RI}_{1\text{v}}} \alpha_{\text{DI}_{2\text{t}}}}{\Omega_1 + (n+m-2)\Omega} \times \frac{1}{(\Theta_2 - \kappa \Omega_{\text{DI}_{2\text{t}}})(\Theta_2 - \kappa(\Omega_{\text{RI}_{1\text{v}}} + \Omega_{\text{DI}_{2\text{t}}}))}.$$

Proof 5: The proof is presented in Appendix D.

Lemma 3: Without interference sources, i.e., by setting $\mathcal{P}_I \to 0$ or $r_P \to 0$, and $x < \kappa^{-1}$, the CDF $F_{\psi_{e2e}^{\text{ORS}}}(\cdot)$ can be expressed as

$$F_{\psi_{e2e}^{\text{ORS}}}(x) = 1 - \sum_{m=1}^{N} \sum_{n=0, n+m>1}^{M-m+1} (-1)^{n+1} C_M^{m-1} C_{M-m+1}^{n} \times \exp\left(-(n+m-1)\frac{\Omega x}{1 - \kappa x}\right). \tag{17}$$

Proof 6: From (D.3), (17) can be obtained.

Theorem 4: At high transmit SNR and assuming $x < \kappa^{-1}$, the CDF $F_{\psi_{e2e}^{\rm PRS}}(\cdot)$ can be approximated by

$$F_{\psi_{e2e}^{\rm ORS}}(x) \overset{\overline{\gamma}\to+\infty}{\approx} 1 - \sum_{m=1}^{N} \sum_{n=0,\, m+n>1}^{M-m+1} \sum_{v=1}^{K_1}\sum_{t=1}^{K_2} (-1)^{n+1} \times \left[\frac{\Delta_3}{\Phi_3+x} + \frac{\Delta_4}{\Phi_4+x} + \frac{\Delta_5}{\Phi_6+x} + \frac{\Delta_6}{\Phi_7+x}\right] \times \frac{(1-\kappa x)^2}{\Phi_5+x}. \quad (18)$$

Proof 7: Note that, for high $\overline{\gamma}$ values, (3) and (4) can be approximated by (13). Hence, similar as obtained (13) from (12), (18) can be attained by omitting the term $\exp\left(-\frac{\Theta_2 x}{1-\kappa x}\right)$ from (16).

Lemma 4: Without interference sources and considering $x < \kappa^{-1}$, the CDF $F_{\psi_{e2e}^{\rm ORS}}(\cdot)$ at high transmit SNR can be written as

$$F_{\gamma_{1b}}(x) \overset{\overline{\gamma}\to+\infty}{\approx} C_M^{N-1} \left(\frac{\Omega x}{1-\kappa x}\right)^{M-N+1}. \quad (19)$$

Proof 8: The proof is similar to that of Lemma 2.
From (19), one can attest that the diversity order of the ORS strategy equals to $M-N+1$.

B. Average Channel Capacity

The average channel capacity can be mathematically defined as

$$C_{avg}^{\rm Y} = \frac{1}{2}\mathcal{E}\left\{\log_2\left(1+\psi_{e2e}^{\rm Y}\right)\right\} = \frac{1}{2\ln 2}\int_0^{\kappa^{-1}} \ln(1+x) f_{\psi_{e2e}^{\rm Y}}(x)\, dx, \quad (20)$$

where $\rm Y \in \{PRS, ORS\}$, $\mathcal{E}\{.\}$ symbolizes expectation, and $f_{\psi_{e2e}^{\rm Y}}(\cdot)$ denotes the PDF of $\psi_{e2e}^{\rm Y}$.

From (10) and (16), (20) can be rewritten as

$$C_{avg}^{\rm Y} = \frac{1}{2\ln 2}\int_0^{\kappa^{-1}} \frac{1-F_{\psi_{e2e}^{\rm Y}}(x)}{1+x} dx. \quad (21)$$

Proposition 1: In the presence of hardware impairments, i.e., $\kappa > 0$, the average channel capacity of both PRS and ORS methods is bounded by

$$C_{avg}^{\rm A} \leq \frac{1}{2\ln 2}\ln\left(1+\frac{1}{\kappa}\right). \quad (22)$$

Proof 9: From (3) and (4), it is easy to see that $\psi_{1b} \leq \kappa^{-1}$ and $\psi_{2b} \leq \kappa^{-1}$, which implies in $\psi_{e2e}^{\rm Y} \leq \kappa^{-1}$. Thus, combining with (20), (22) can be readily obtained.
Before calculating the average capacity of the PRS and ORS strategies, the following integral will be introduced.

$$\mathcal{J}(\kappa,\Omega,\Phi) = \int_0^{\kappa^{-1}} \frac{1}{\Phi+x}\exp\left(-\frac{\Omega x}{1-\kappa x}\right) dx = \exp\left(\frac{\Omega\Phi}{\Phi\kappa+1}\right) E_1\left(\frac{\Omega\Phi}{\Phi\kappa+1}\right) - \exp\left(\frac{\Omega}{\kappa}\right) E_1\left(\frac{\Omega}{\kappa}\right), \quad (23)$$

where $E_1(.)$ denotes the exponential integral function [29].

Proof 10: By interchanging the variable $t = 1/(1-\kappa x)$, $\mathcal{J}(\kappa,\Omega,\Phi)$ can be rewritten as

$$\mathcal{J}(\kappa,\Omega,\Phi) = \frac{\exp(\Omega/\kappa)}{\kappa\Phi+1}\int_1^{+\infty} \frac{\exp(-t\Omega/\kappa)}{t\left(t-1/(\kappa\Phi+1)\right)} dt = \exp\left(\frac{\Omega\Phi}{\kappa\Phi+1}\right)\int_{\frac{\kappa\Phi}{\kappa\Phi+1}}^{+\infty} \frac{\exp(-t\Omega/\kappa)}{t} dt - \exp\left(\frac{\Omega}{\kappa}\right)\int_1^{+\infty} \frac{\exp(-t\Omega/\kappa)}{t} dt.$$

Then, by using the definition of the exponential integral function $E_1(x) = \int_x^{+\infty} \frac{\exp(-t)}{t} dt$, we can easily obtain (23).

1) Partial Relay Selection (PRS):

Theorem 5: The average channel capacity of the PRS method can be expressed as (24), shown at the top of next page, with $\delta_1 = (1+\kappa\Phi_1)^2/(\Phi_2-\Phi_1)$ and $\delta_2 = (1+\kappa\Phi_2)^2/(\Phi_1-\Phi_2)$.

Proof 11: The proof is presented in Appendix E.

Lemma 5: Without interference sources, the average channel capacity of the PRS method is given by

$$C_{avg}^{\rm PRS} = \frac{1}{2\ln 2}\sum_{m=1}^{N}\sum_{n=0,\, m+n>1}^{M-m+1}\sum_{v=1}^{K_1}\sum_{t=1}^{K_2}(-1)^{n+1} \times \Delta_1\Delta_2\mathcal{J}(\kappa,\Theta_1+\Omega_2,1). \quad (25)$$

Proof 12: Relying on (1), (21), and (23), Lemma 5 can be easily proved.

Theorem 6: At high transmit SNR $\overline{\gamma}$, the asymptotic average channel capacity of the PRS method can be derived as (26), shown at the top of next page.

Proof 13: (26) can be attained from (24) by performing the appropriate substitutions, i.e., replacing $\mathcal{J}(\kappa,\Theta_1+\Omega_2,1)$, $\mathcal{J}(\kappa,\Theta_1+\Omega_2,\Phi_1)$, and $\mathcal{J}(\kappa,\Theta_1+\Omega_2,\Phi_2)$ by $\mathcal{J}(\kappa,0,1)$, $\mathcal{J}(\kappa,0,\Phi_1)$ and $\mathcal{J}(\kappa,0,\Phi_1)$, respectively. In addition, note that $\mathcal{J}(\kappa,0,\Omega) = \ln((1+\kappa\Phi)/\kappa\Phi)$.
Finally, one can see that without interference sources, the asymptotic average capacity of the PRS method is given as in (22), i.e.,

$$C_{avg}^{\rm PRS} \overset{\overline{\gamma}\to+\infty}{\approx} \frac{1}{2\ln 2}\ln\left(1+\frac{1}{\kappa}\right). \quad (27)$$

2) Opportunistic Relay Selection (ORS):

Theorem 7: The average channel capacity of the ORS method can be given as (28), shown at the top of next page, with $\delta_3 = (1+\kappa\Phi_3)^2/(\Phi_5-\Phi_3)$, $\delta_4 = (1+\kappa\Phi_5)^2/(\Phi_3-\Phi_5)$, $\delta_5 = (1+\kappa\Phi_4)^2/(\Phi_5-\Phi_4)$, $\delta_6 = (1+\kappa\Phi_5)^2/(\Phi_4-\Phi_5)$, $\delta_7 = (1+\kappa\Phi_6)^2/(\Phi_5-\Phi_6)$, $\delta_8 = (1+\kappa\Phi_5)^2/(\Phi_6-\Phi_5)$, $\delta_9 = (1+\kappa\Phi_7)^2/(\Phi_5-\Phi_7)$, and $\delta_{10} = (1+\kappa\Phi_5)^2/(\Phi_7-\Phi_5)$.

Proof 14: The proof is presented in Appendix F .

Lemma 6: Without interference sources, the average channel capacity can be rewritten as

$$C_{avg}^{\rm ORS} = \sum_{m=1}^{N}\sum_{n=0,\, n+m>1}^{M-m+1}(-1)^n C_M^{m-1} C_{M-m+1}^n \times \mathcal{J}(\kappa,(n+m-1)\Omega x,1). \quad (29)$$

$$C_{avg}^{\mathrm{PRS}} = \frac{1}{2\ln 2}\sum_{m=1}^{N}\sum_{n=0,\, m+n>1}^{M-m+1}\sum_{v=1}^{K_1}\sum_{t=1}^{K_2}(-1)^{n+1}\Delta_1\Delta_2 \times\left[\left(\frac{\delta_1}{\Phi_1-1}+\frac{\delta_2}{\Phi_2-1}+\kappa^2\right)\mathcal{J}\left(\kappa,\Theta_1+\Omega_2,1\right)-\frac{\delta_1}{\Phi_1-1}\mathcal{J}\left(\kappa,\Theta_1+\Omega_2,\Phi_1\right)-\frac{\delta_2}{\Phi_2-1}\mathcal{J}\left(\kappa,\Theta_1+\Omega_2,\Phi_2\right)\right]. \quad (24)$$

$$C_{avg}^{\mathrm{PRS}} \overset{\overline{\gamma}\to+\infty}{\approx} \frac{1}{2\ln 2}\sum_{m=1}^{N}\sum_{n=0,\, m+n>1}^{M-m+1}\sum_{v=1}^{K_1}\sum_{t=1}^{K_2}(-1)^{n+1}\Delta_1\Delta_2 \times\left[\left(\frac{\delta_1}{\Phi_1-1}+\frac{\delta_2}{\Phi_2-1}+\kappa^2\right)\ln\left(\frac{1+\kappa}{\kappa}\right)-\frac{\delta_1}{\Phi_1-1}\ln\left(\frac{1+\kappa\Phi_1}{\kappa\Phi_1}\right)-\frac{\delta_2}{\Phi_2-1}\ln\left(\frac{1+\kappa\Phi_2}{\kappa\Phi_2}\right)\right]. \quad (26)$$

$$\begin{aligned}C_{avg}^{\mathrm{ORS}} = &\frac{1}{2\ln 2}\sum_{m=1}^{N}\sum_{n=0,\, m+n>1}^{M-m+1}\sum_{v=1}^{K_1}\sum_{t=1}^{K_2}(-1)^{n+1}\\ &\times\left(\frac{\Delta_3\delta_3}{\Phi_3-1}+\frac{\Delta_4\delta_5}{\Phi_4-1}+\frac{\Delta_5\delta_7}{\Phi_6-1}+\frac{\Delta_6\delta_9}{\Phi_7-1}+\frac{\Delta_3\delta_4+\Delta_4\delta_6+\Delta_5\delta_8+\Delta_6\delta_{10}}{\Phi_5-1}+\left(\Delta_3+\Delta_4\right)\kappa^2\right)\mathcal{J}\left(\kappa,\Theta_2,1\right)\\ &-\frac{\Delta_3\delta_3}{\Phi_3-1}\mathcal{J}\left(\kappa,\Theta_2,\Phi_3\right)-\frac{\Delta_4\delta_5}{\Phi_4-1}\mathcal{J}\left(\kappa,\Theta_2,\Phi_4\right)-\frac{\Delta_5\delta_7}{\Phi_6-1}\mathcal{J}\left(\kappa,\Theta_2,\Phi_6\right)-\frac{\Delta_6\delta_9}{\Phi_7-1}\mathcal{J}\left(\kappa,\Theta_2,\Phi_7\right)\\ &-\left(\frac{\Delta_3\delta_4+\Delta_4\delta_6+\Delta_5\delta_8+\Delta_6\delta_{10}}{\Phi_5-1}\right)\mathcal{J}\left(\kappa,\Theta_2,\Phi_5\right). \end{aligned} \quad (28)$$

$$\begin{aligned}C_{avg}^{\mathrm{ORS}} \overset{\overline{\gamma}\to+\infty}{\approx} &\frac{1}{2\ln 2}\sum_{m=1}^{N}\sum_{n=0,\, m+n>1}^{M-m+1}\sum_{v=1}^{K_1}\sum_{t=1}^{K_2}(-1)^{n+1}\\ &\times\left(\frac{\Delta_3\delta_3}{\Phi_3-1}+\frac{\Delta_4\delta_5}{\Phi_4-1}+\frac{\Delta_5\delta_7}{\Phi_6-1}+\frac{\Delta_6\delta_9}{\Phi_7-1}+\frac{\Delta_3\delta_4+\Delta_4\delta_6+\Delta_5\delta_8+\Delta_6\delta_{10}}{\Phi_5-1}+\left(\Delta_3+\Delta_4\right)\kappa^2\right)\ln\left(\frac{1+\kappa}{\kappa}\right)\\ &-\frac{\Delta_3\delta_3}{\Phi_3-1}\ln\left(\frac{1+\kappa\Phi_3}{\kappa\Phi_3}\right)-\frac{\Delta_4\delta_5}{\Phi_4-1}\ln\left(\frac{1+\kappa\Phi_4}{\kappa\Phi_4}\right)-\frac{\Delta_5\delta_7}{\Phi_6-1}\ln\left(\frac{1+\kappa\Phi_6}{\kappa\Phi_6}\right)-\frac{\Delta_6\delta_9}{\Phi_7-1}\ln\left(\frac{1+\kappa\Phi_7}{\kappa\Phi_7}\right)\\ &-\left(\frac{\Delta_3\delta_4+\Delta_4\delta_6+\Delta_5\delta_8+\Delta_6\delta_{10}}{\Phi_5-1}\right)\ln\left(\frac{1+\kappa\Phi_5}{\kappa\Phi_5}\right). \end{aligned} \quad (30)$$

Proof 15: Based on (17), (21), and (23), Lemma 6 can be readily proved.

Theorem 8: At high transmit SNR $\overline{\gamma}$, the asymptotic average channel capacity of the PRS method can be derived as (30), shown at the top of next page.

Proof 16: The proof of Theorem 8 is similar to that of Theorem 6.

One can easily prove that the asymptotic average capacity of the PRS method at high $\overline{\gamma}$ is given as in (27), i.e.,

$$C_{avg}^{\mathrm{ORS}} \overset{\overline{\gamma}\to+\infty}{\approx} \frac{1}{2\ln 2}\ln\left(1+\frac{1}{\kappa}\right). \quad (31)$$

From (27) and (31), note that under the impact of hardware impairment and without co-channel interference, the PRS and ORS schemes have the same average channel capacity at high transmit SNR.

IV. Numerical Results and Simulations

In this Section, representative numerical results are presented to illustrate the performance of the two proposed relay selection schemes in the presence of hardware impairment and CCI. Monte Carlo simulation results are also shown to corroborate the proposed analysis. Without any loss of generality, we set $\gamma_{th} < \kappa^{-1}$.

In Fig. 2, the outage probability is plotted as a function of transmit SNR $\overline{\gamma}$. The following parameters are employed: $M = 4$, $K_1 = K_2 = 2$, $r_P = 1$, $\gamma_{th} = 1$, $\kappa = 0.075$, $\lambda_{\mathrm{SR}} = 0.3$, $\lambda_{\mathrm{RD}} = 0.5$, $\lambda_{\mathrm{RI}_{1v}} \in \{1,2\}$, and $\lambda_{\mathrm{DI}_{2t}} \in \{1.5, 2.5\}$. It can be observed that the outage performance of the ORS and PRS schemes is better if the system can select the best relay for the cooperation ($N = 1$). In addition, when $N = 1$, the outage probability of the ORS scheme is lower than that of the PRS one. However, such a metric of the PRS is higher than that of the ORS when $N = 2$. It is because that when the best relay cannot be selected, the end-to-end SINR of the

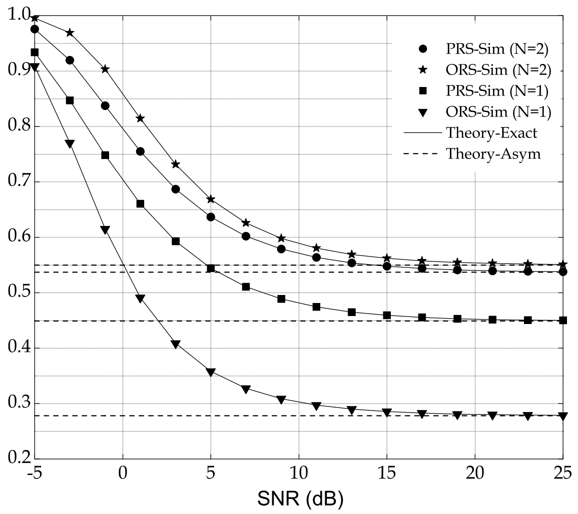

Fig. 2. Outage probability as a function of the transmit SNR $\overline{\gamma}$ when $M = 4$, $K_1 = K_2 = 2$, $r_P = 1$, $\gamma_{th} = 1$, $\kappa = 0.075$, $\lambda_{\rm SR} = 0.3$, $\lambda_{\rm RD} = 0.5$, $\lambda_{{\rm RI}_{1v}} \in \{1, 2\}$, and $\lambda_{{\rm DI}_{2t}} \in \{1.5, 2.5\}$.

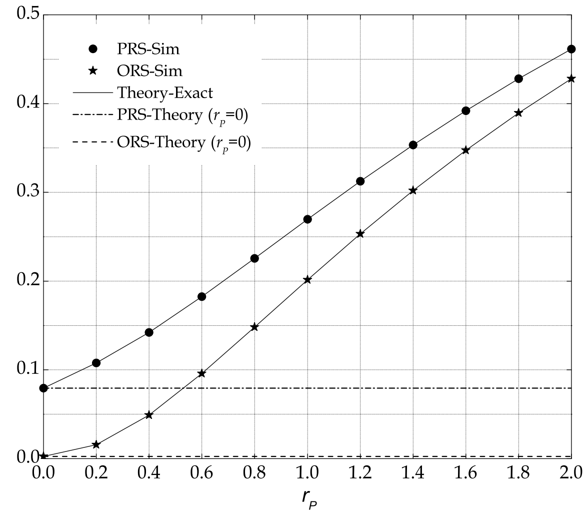

Fig. 4. Outage probability as a function of the ratio r_P when $\overline{\gamma} = 10dB$, $M = 6$, $N = 2$, $K_1 = K_2 = 1$, $\gamma_{th} = 0.5$, $\kappa = 0.08$, $\lambda_{\rm SR} = 1$, $\lambda_{\rm RD} = 0.5$, $\lambda_{{\rm RI}_{11}} = 1.5$, and $\lambda_{{\rm DI}_{21}} = 2$.

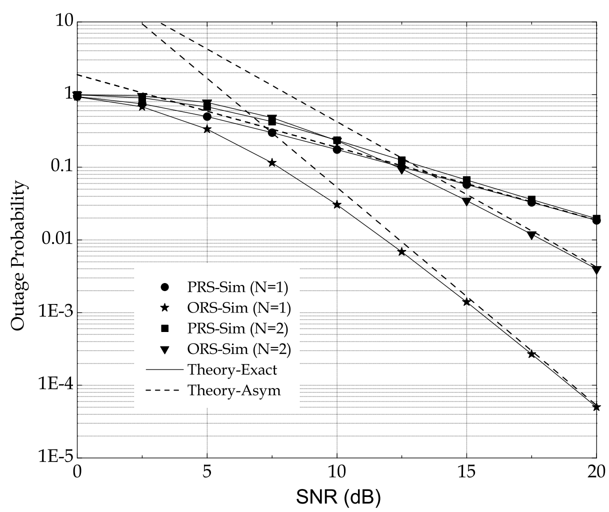

Fig. 3. Outage probability as a function of the transmit SNR $\overline{\gamma}$ when $M = 3$, $r_P = 0$, $\gamma_{th} = 1.5$, $\kappa = 0.08$, $\lambda_{\rm SR} = 1.1$, and $\lambda_{\rm RD} = 1.1$.

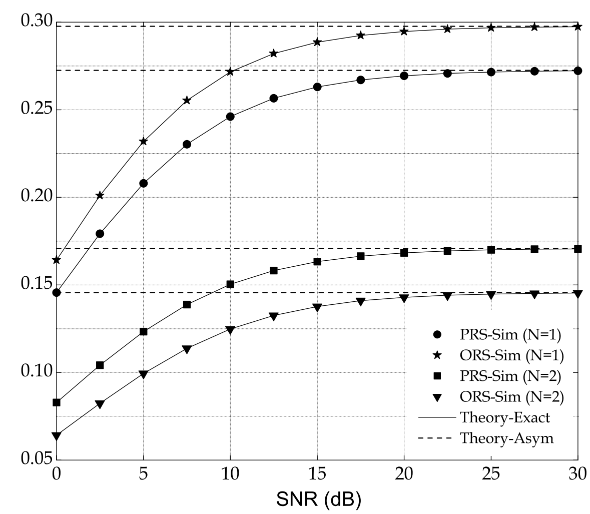

Fig. 5. Average channel capacity as a function of the transmit SNR $\overline{\gamma}$ when $M = 2$, $K_1 = K_2 = 1$, $r_P = 1$, $\kappa = 0.075$, $\lambda_{\rm SR} = 1.1$, $\lambda_{\rm RD} = 1.3$, and $\lambda_{{\rm RI}_{11}} = \lambda_{{\rm DI}_{21}} = 0.7$.

ORS protocol is no longer maximum. Hence, PRS can provide a higher end-to-end SINR than ORS. Finally, it can be seen that the outage probability decreases when the transmit SNR increases. However, the outage performance of both protocols converges to positive constant at high SNR regime. Therefore, we can conclude that the system obtains the zero-diversity order when there are the interference sources in the network.

In Fig. 3, the outage performance is depicted as a function of transmit SNR $\overline{\gamma}$ when there is no interference source and by setting $M = 3$, $r_P = 0$, $\gamma_{th} = 1.5$, $\kappa = 0.08$ and $\lambda_{\rm SR} = \lambda_{\rm RD} = 1.1$. Note that the ORS scheme outperforms the PRS one for both $N = 1, 2$, with the performance gap being higher for the case $N = 1$. The reason is that the diversity order[4] of the ORS scheme equals to 3 for $N = 1$, while it is 2 for $N = 2$. Indeed, for $N = 2$, the performance of both schemes is almost the same at low and medium SNRs, and only at high SNR region a practical difference in performance can be detected.

In Fig. 4, we investigate the impact of the ratio r_P $(\mathcal{P}_I/\mathcal{P}_S)$ on the outage performance of the proposed protocols. For the illustrative purpose, we fix the parameters $\overline{\gamma}$, M, N, K_1, K_2, γ_{th}, κ, $\lambda_{\rm SR}$, $\lambda_{\rm RD}$, $\lambda_{{\rm RI}_{11}}$ and $\lambda_{{\rm DI}_{21}}$ by 10 dB, 6, 2, 1,

[4]The diversity order of the PRS scheme is always 1, regardless of the value of N.

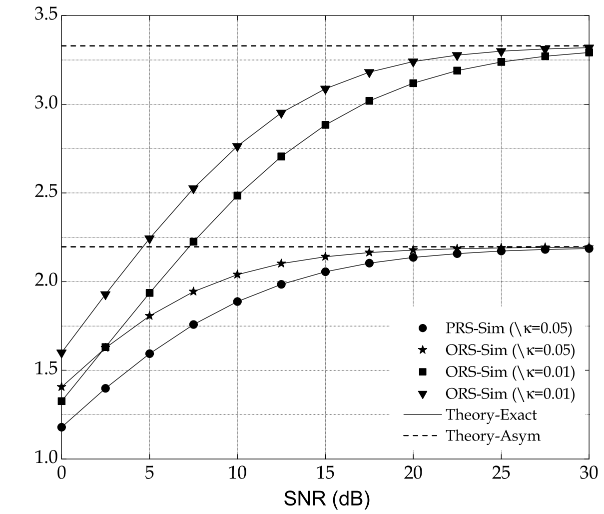

Fig. 6. Average channel capacity as a function of the transmit SNR $\overline{\gamma}$ when $M = 4$, $N = 1$, $r_P = 0$, and $\lambda_{\rm SR} = \lambda_{\rm RD} = 0.1$.

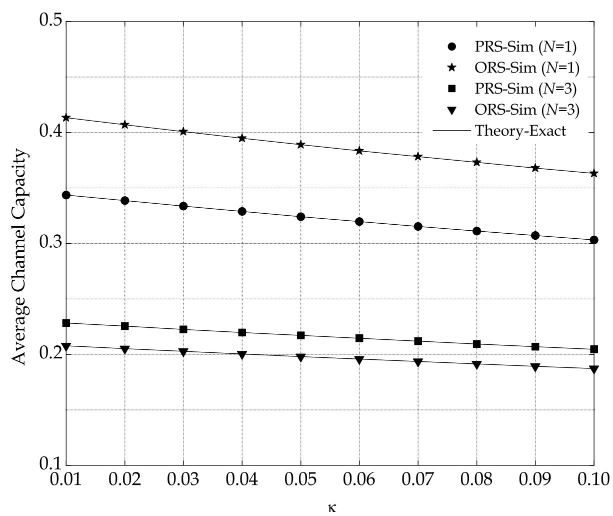

Fig. 7. Average channel capacity as a function of κ when $\overline{\gamma} = 10dB$, $M = 5$, $K_1 = K_2 = 1$, $r_P = 1$, $\lambda_{\rm SR} = \lambda_{\rm RD} = 1$, $\lambda_{{\rm RI}_{11}} = 0.5$, and $lambda_{{\rm RI}_{11}} = 0.75$.

1, 0.5, 0.08, 1, 0.5, 1.5 and 2, respectively. It can be seen from this figure that the outage performance of both protocols decreases when the ratio r_P increases. Different with the results presented in Fig. 2, although the system can only select the second-best relay for the cooperation, the ORS protocol obtains better performance as compared with the PRS protocol.

Fig. 5 presents the average channel capacity of the PRS and ORS protocols as a function of the transmit SNR $\overline{\gamma}$. In this figure, we fix the parameters as follows: $M = 2$, $K_1 = K_2 = 1$, $r_P = 1$, $\kappa = 0.075$ and $\lambda_{\rm SR} = 1.1$, $\lambda_{\rm RD} = 1.3$, and $\lambda_{{\rm RI}_{11}} = \lambda_{{\rm DI}_{21}} = 0.7$. Similar to Fig. 2, the ORS scheme achieves higher channel capacity than PRS one when the system can select the best relay (i.e., $N = 1$) for cooperation. Otherwise, for $N = 2$, i.e., the system selects one the second best relay for cooperation, the PRS strategy attains better performance. Finally, note that the channel capacity of both schemes converges to the asymptotic values at high SNR region.

In Fig. 6, the effect of the hardware impairment level κ on the average channel capacity is investigated. It is assumed that there is no CCI, i.e., $r_P = 0$. The remaining parameters are designed as follows: $M = 4$, $N = 1$, and $\lambda_{\rm SR} = \lambda_{\rm RD} = 0.1$. One can notice that the PRS and ORS schemes have the same asymptotic channel capacity. In addition, it is shown that both strategies obtain better performance as the value of κ decreases, with ORS presenting better performance than PRS.

Fig. 7 presents the average channel capacity as a function of κ when $\overline{\gamma} = 10dB$, $M = 5$, $K_1 = K_2 = 1$, $r_P = 1$, $\lambda_{\rm SR} = \lambda_{\rm RD} = 1$, $\lambda_{{\rm RI}_{11}} = 0.5$, and $\lambda_{{\rm RI}_{11}} = 0.75$. It can be observed from this figure that the channel capacity of the PRS and ORS protocols decreases with the increasing of κ. Again, we can obverse that the performance of the ORS scheme is better than that of the PRS scheme when the best relay can be selected for the cooperation.

V. Conclusions

In this paper, analyzing the impact of hardware impairment and CCI, the end-to-end performance of dual-hop proactive DF relaying networks with Nth PRS and Nth ORS is investigated. Exact and asymptotic closed-form expressions for the outage probability and average channel capacity of both relay selection schemes were derived. Insightful discussions were provided. For instance, it was shown that, when the system cannot select the best relay for cooperation, the partial relay selection scheme outperforms the opportunistic method under the impact of the same co-channel interference.

Acknowledgments

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Appendix A: Proof of Theorem 1

Firstly, we rewrite $F_{\psi_{e2e}^{\rm PRS}}(x)$ as follows

$$F_{\psi_{e2e}^{\rm PRS}}(x) = 1 - \left(1 - F_{\psi_{{\rm SR}_{\rm b}}}(x)\right)\left(1 - F_{\psi_{{\rm R}_{\rm b}{\rm D}}}(x)\right). \quad \text{(A.1)}$$

Thus, in order to attain (A.1), the CDFs $F_{\psi_{{\rm SR}_{\rm b}}}(\cdot)$ and $F_{\psi_{{\rm R}_{\rm b}{\rm D}}}(\cdot)$ are required. Considering first the CDF of $\psi_{{\rm SR}_{\rm b}}$, we have that

$$\begin{aligned} F_{\psi_{{\rm SR}_{\rm b}}}(x) &= \Pr\left(\psi_{{\rm SR}_{\rm b}} < x\right) \\ &= \begin{cases} 1; & \text{if x} \geq \kappa^{-1} \\ \gamma_{{\rm SR}_{\rm b}} < \frac{x + xZ_1}{1-\kappa x}; & \text{if x} < \kappa^{-1} \end{cases} \end{aligned} \quad \text{(A.2)}$$

For $x < \kappa^{-1}$, (A.2) can be formulated as

$$F_{\psi_{{\rm SR}_{\rm b}}}(x) = \int_0^{+\infty} F_{\gamma_{{\rm SR}_{\rm b}}}\left(\frac{x + xz_1}{1-\kappa x}\right) f_{Z_1}(z_1)\, dz_1. \quad \text{(A.3)}$$

Now, using the N-best order statistics [30], the CDF of $\gamma_{\mathrm{SR_b}}$ can be written as

$$\begin{aligned} F_{\gamma_{\mathrm{SR_b}}}(y) &= \sum_{m=1}^{N} C_M^{m-1}(1-\exp(-\Omega_1 y))^{M-m+1} \\ &\times \exp(-(m-1)\Omega_1 y) \\ &= 1 - \sum_{m=1}^{N}\sum_{n=0,n+m>1}^{M-m+1}(-1)^{n+1}C_M^{m-1}C_{M-m+1}^{n} \\ &\times \exp(-(n+m-1)\Omega_1 y), \end{aligned} \tag{A.4}$$

where $\Omega_1 = N_0\lambda_{\mathrm{SR}}/P$ and $C_b^a = \frac{b!}{a!(b-a)!}$, with a and b being integers and $b > a$.

Combining (7), (A.3) and (A.4), and after some algebraic manipulation, it follows that

$$\begin{aligned} F_{\psi_{\mathrm{SR_b}}}(x) &= 1 - \sum_{m=1}^{N}\sum_{n=0,\,m+n>1}^{M-m+1}\sum_{v=1}^{K_1}(-1)^{n+1}\Delta_1 \\ &\times \frac{1-\kappa x}{\Phi_1 + x}\exp\left(-\frac{\Theta_1 x}{1-\kappa x}\right), \end{aligned} \tag{A.5}$$

where $\Theta_1 = (n+m-1)\Omega_1$, $\Delta_1 = C_M^{m-1}C_{M-m+1}^{n}\alpha_{\mathrm{RI_{1v}}}/(\Theta_1 - \kappa\Omega_{\mathrm{RI_{1v}}})$, and $\Phi_1 = \Omega_{\mathrm{RI_{1v}}}/(\Theta_1 - \kappa\Omega_{\mathrm{RI_{1v}}})$. For simplicity, we assume that $\Theta_1 - \kappa\Omega_{\mathrm{RI_{1v}}} \neq 0$.

Similarly, one can see that, if $x \geq \kappa^{-1}$, $F_{\psi_{\mathrm{R_bD}}}(x) = 1$, while if $x < \kappa^{-1}$, then

$$F_{\psi_{\mathrm{R_bD}}}(x) = 1 - \sum_{t=1}^{K_2}\Delta_2\frac{1-\kappa x}{\Phi_2 + x}\exp\left(-\frac{\Omega_2 x}{1-\kappa x}\right), \tag{A.6}$$

where $\Omega_2 = \lambda_{\mathrm{RD}}N_0/P$, $\Delta_2 = \alpha_{\mathrm{DI_{2t}}}/(\Omega_2 - \Omega_{\mathrm{DI_{2t}}}\kappa)$, $\Phi_2 = \Omega_{\mathrm{DI_{2t}}}/(\Omega_2 - \kappa\Omega_{\mathrm{DI_{2t}}})$, and $\Omega_2 - \kappa\Omega_{\mathrm{DI_{2t}}} \neq 0$.

Finally, by substituting (A.5) and (A.6) into (A.1), (10) is attained, which completes the proof.

Appendix B: Proof of Lemma 1

Without interference sources, (3) and (4) can be rewritten as

$$\begin{aligned} \psi_{\mathrm{SR_b}} &= \frac{\gamma_{\mathrm{SR_b}}}{\kappa\gamma_{\mathrm{SR_b}} + 1}, \\ \psi_{\mathrm{R_bD}} &= \frac{\gamma_{\mathrm{R_bD}}}{\kappa\gamma_{\mathrm{R_bD}} + 1}. \end{aligned} \tag{B.1}$$

Similar to (A.2)-(A.5), the CDFs $F_{\psi_{\mathrm{SR_b}}}(\cdot)$ and $F_{\psi_{\mathrm{R_bD}}}(\cdot)$ can be obtained as

$$\begin{aligned} F_{\psi_{\mathrm{SR_b}}}(x) &= 1 - \sum_{m=1}^{N}\sum_{n=0,m+n\neq 1}^{M-m+1}(-1)^{n+1} \\ &\times C_M^{m-1}C_{M-m+1}^{n}\exp\left(-\frac{\Theta_1 x}{1-\kappa x}\right), \\ F_{\psi_{\mathrm{R_bD}}}(x) &= 1 - \exp\left(-\frac{\Omega_2 x}{1-\kappa x}\right). \end{aligned} \tag{B.2}$$

Then, combining the above results with (A.1), the proof of Lemma 1 is concluded.

Appendix C: Proof of Lemma 2

From (A.1) in Appendix A, we can approximate $F_{\psi_{\mathrm{e2e}}^{\mathrm{PRS}}}(x)$ at high SNR region by

$$F_{\psi_{\mathrm{e2e}}^{\mathrm{PRS}}}(x) \overset{\overline{\gamma}\to+\infty}{\approx} F_{\psi_{\mathrm{SR_b}}}(x) + F_{\psi_{\mathrm{R_bD}}}(x), \tag{C.1}$$

where $\psi_{\mathrm{SR_b}}$ and $\psi_{\mathrm{R_bD}}$ are given as (B.1) in Appendix B.

In addition, since $1-\exp(-t) \overset{t\to 0}{\approx} t$ and $\exp(-t) \overset{t\to 0}{\approx} 1$, asymptotic expressions for (B.2) can be written as

$$\begin{aligned} F_{\gamma_{1b}}(x) &\overset{\overline{\gamma}\to+\infty}{\approx} \sum_{m=1}^{N} C_M^{m-1}\left(\frac{\Omega_1 x}{1-\kappa x}\right)^{M-m+1} \\ &\overset{\overline{\gamma}\to+\infty}{\approx} C_M^{N-1}\left(\frac{\Omega_1 x}{1-\kappa x}\right)^{M-N+1}, \\ F_{\gamma_{2b}}(x) &\overset{\overline{\gamma}\to+\infty}{\approx} \frac{\Omega_2 x}{1-\kappa x}. \end{aligned} \tag{C.2}$$

Combining (C.1) and (C.2), (14) is attained, which completes the proof.

Appendix D: Proof of Theorem 3

Firstly, it is easy to see that $F_{\psi_{e2e}^{\mathrm{ORS}}(x)} = 1$ when $x \geq \kappa^{-1}$. Thus, considering the case when $x < \kappa^{-1}$, (16) can be rewritten as

$$\begin{aligned} F_{\psi_{e2e}^{\mathrm{ORS}}}(x) &= 1 - \Pr(\psi_{\mathrm{SR_b}} \geq x, \psi_{\mathrm{R_bD}} \geq x) \\ &= 1 - \Pr\left(\gamma_{\mathrm{SR_b}} \geq \frac{x + xZ_1}{1-\kappa x}, \gamma_{\mathrm{R_bD}} \geq \frac{x + xZ_2}{1-\kappa x}\right). \end{aligned} \tag{D.1}$$

Since $\gamma_{\mathrm{SR_b}}$ and $\gamma_{\mathrm{R_bD}}$ are not independent, the method proposed in [11] will be employed to calculate (D.1). Initially, we will derive the probability $\Pr(\gamma_{\mathrm{SR_b}} \geq u_1,\, \gamma_{\mathrm{R_bD}} \geq u_2)$. To this end, similar to [11], this probability can be formulated as

$$\Pr(\gamma_{\mathrm{SR_b}} \geq u_1,\, \gamma_{\mathrm{R_bD}} \geq u_2) = \int_0^{+\infty}\frac{\partial G(z)}{\partial z}\frac{f_{T_{\max}}(z)}{f_{T_i}(z)}dz. \tag{D.2}$$

In (D.2), $T_{\max} = N\mathrm{th}\max_{m=1,2,\ldots,M}\min(\gamma_{\mathrm{SR_m}}, \gamma_{\mathrm{R_mD}})$, in which its CDF can be expressed similarly to (A.4) as

$$\begin{aligned} F_{T_{\max}}(z) &= 1 - \sum_{m=1}^{N}\sum_{n=0,n+m>1}^{M-m+1}(-1)^{n+1}C_M^{m-1}C_{M-m+1}^{n} \\ &\times \exp(-(n+m-1)\Omega z), \end{aligned} \tag{D.3}$$

where $\Omega = \Omega_1 + \Omega_2$. Thus, the PDF of $T_{\max}$ can be derived as

$$\begin{aligned} f_{T_{\max}}(z) &= \sum_{m=1}^{N}\sum_{n=0,\,m+n>1}^{M-m+1}(-1)^{n}C_M^{m-1}C_{M-m+1}^{n} \\ &\times (m+n-1)\Omega\exp(-(n+m-1)\Omega z). \end{aligned} \tag{D.4}$$

By its turn, in (D.2), $T_i = \min(\gamma_{\mathrm{SR_i}}, \gamma_{\mathrm{R_iD}})$, $i = 1, 2, \ldots, M$, such that its PDF can be expressed as

$$f_{T_i}(z) = \Omega\exp(-\Omega z). \tag{D.5}$$

Finally, the term $G(z)$ in (D.2) can be formulated as

$$G(z) = \Pr(\gamma_{\mathrm{SR_i}} \geq u_1,\, \gamma_{\mathrm{R_iD}} \geq u_2, \min(\gamma_{\mathrm{SR_i}}, \gamma_{\mathrm{R_iD}}) < z). \tag{D.6}$$

In order to calculate $G(z)$, two cases will be considered:

- Case 1: $u_1 \geq u_2$

In this case, $G(z)$ can be obtained as

$$G(z) = \begin{cases} 0; & \text{if } z \leq u_2 \\ \exp(-\Omega_1 u_1 - \Omega_2 u_2) \\ -\exp(-\Omega_1 u_1 - \Omega_2 z); & \text{if } u_2 \leq z < u_1 \\ \exp(-\Omega_1 u_1 - \Omega_2 u_2) \\ -\exp(-\Omega z); & \text{if } z \geq u_1 \end{cases} \quad \text{(D.7)}$$

- Case 2: $u_1 < u_2$

In this case, it follows that

$$G(z) = \begin{cases} 0; & \text{if } z \leq u_1 \\ \exp(-\Omega_1 u_1 - \Omega_2 u_2) \\ -\exp(-\Omega_2 u_2 - \Omega_1 z); & \text{if } u_2 \leq z < u_1 \\ \exp(-\Omega_1 u_1 - \Omega_2 u_2) \\ -\exp(-\Omega z); & \text{if } z \geq u_1 \end{cases} \quad \text{(D.8)}$$

Combining (D.4), (D.5), (D.7) and (D.8), and after some algebraic manipulations, $\Pr(\gamma_{\mathrm{SR_b}} \geq u_1, \gamma_{\mathrm{R_bD}} \geq u_2)$ is derived for Case 1 and Case 2 in (D.9) and (D.10), respectively, shown at the top of next page.

Now, replacing $u_1 = (x + xZ_1)/(1-\kappa x)$ and $u_2 = (x + xZ_2)/(1-\kappa x)$ in (D.9) and (D.10), the outage probability $F_{\psi_{e2e}^{\mathrm{ORS}}}(x)$ can be calculated as[5]

$$F_{\psi_{e2e}^{\mathrm{ORS}}}(x) = 1 - S_1 - S_2, \quad \text{(D.11)}$$

where

$$S_1 = \int_0^{+\infty}\int_0^{z_1} \Pr\left(\gamma_{\mathrm{SR_b}} \geq \frac{x + xz_1}{1-\kappa x}, \gamma_{\mathrm{R_bD}} \geq \frac{x + xz_2}{1-\kappa x}\right) f_{Z_1}(z_1) f_{Z_2}(z_2)\, dz_2 dz_1, \quad \text{(D.12)}$$

$$S_2 = \int_0^{+\infty}\int_0^{z_2} \Pr\left(\gamma_{\mathrm{SR_b}} \geq \frac{x + xz_1}{1-\kappa x}, \gamma_{\mathrm{R_bD}} \geq \frac{x + xz_2}{1-\kappa x}\right) f_{Z_1}(z_1) f_{Z_2}(z_2)\, dz_1 dz_2. \quad \text{(D.13)}$$

By substituting (7) and (D.9) into (D.12), and after some algebraic manipulations, it follows that

$$S_1 = \sum_{m=1}^{N} \sum_{n=0,\, m+n>1}^{M-m+1} \sum_{v=1}^{K_1}\sum_{t=1}^{K_2} (-1)^{n+1} \times \left[\frac{\Delta_3 (1-\kappa x)^2}{(\Phi_3 + x)(\Phi_5 + x)} + \frac{\Delta_4 (1-\kappa x)^2}{(\Phi_4 + x)(\Phi_5 + x)}\right] \times \exp\left(-\frac{\Theta_2 x}{1-\kappa x}\right), \quad \text{(D.14)}$$

where $\Theta_2 = (n+m-1)\Omega$, $\Phi_3 = \Omega_{\mathrm{RI_{1v}}}/(\Omega_1 - \kappa\Omega_{\mathrm{RI_{1v}}})$, $\Phi_4 = \Omega_{\mathrm{RI_{1v}}}/(\Theta_2 - \kappa\Omega_{\mathrm{RI_{1v}}})$, $\Phi_5 = (\Omega_{\mathrm{RI_{1v}}} + \Omega_{\mathrm{DI_{2t}}})/(\Theta_2 - \kappa(\Omega_{\mathrm{RI_{1v}}} + \Omega_{\mathrm{DI_{2t}}}))$, and

$$\Delta_3 = (n+m-1) C_M^{m-1} C_{M-m+1}^{n} \frac{\Omega_2 \alpha_{\mathrm{RI_{1v}}} \alpha_{\mathrm{DI_{2t}}}}{\Omega_2 + (n+m-2)\Omega} \times \frac{1}{(\Theta_2 - \kappa(\Omega_{\mathrm{RI_{1v}}} + \Omega_{\mathrm{DI_{2t}}}))(\Omega_1 - \kappa\Omega_{\mathrm{RI_{1v}}})},$$

$$\Delta_4 = (n+m-2) C_M^{m-1} C_{M-m+1}^{n} \frac{\Omega_1 \alpha_{\mathrm{RI_{1v}}} \alpha_{\mathrm{DI_{2t}}}}{\Omega_2 + (n+m-2)\Omega} \times \frac{1}{(\Theta_2 - \kappa\Omega_{\mathrm{RI_{1v}}})(\Theta_2 - \kappa(\Omega_{\mathrm{RI_{1v}}} + \Omega_{\mathrm{DI_{2t}}}))}.$$

[5] $u_1 \geq u_2$ is equivalent to $Z_1 \geq Z_2$, and vice versa.

Similarly, from (7), (D.10) and (D.13), S_2 can be obtained as

$$S_2 = \sum_{m=1}^{N} \sum_{n=0,\, m+n>1}^{M-m+1} \sum_{v=1}^{K_1}\sum_{t=1}^{K_2} (-1)^{n+1} \times \left[\frac{\Delta_5 (1-\kappa x)^2}{(\Phi_6 + x)(\Phi_5 + x)} + \frac{\Delta_6 (1-\kappa x)^2}{(\Phi_7 + x)(\Phi_5 + x)}\right] \times \exp\left(-\frac{\Theta_2 x}{1-\kappa x}\right), \quad \text{(D.15)}$$

where $\Phi_6 = \Omega_{\mathrm{DI_{2t}}}/(\Omega_2 - \kappa\Omega_{\mathrm{DI_{2t}}})$, $\Phi_7 = \Omega_{\mathrm{DI_{2t}}}/(\Theta_2 - \kappa\Omega_{\mathrm{DI_{2t}}})$, and

$$\Delta_5 = (n+m-1) C_M^{m-1} C_{M-m+1}^{n} \frac{\Omega_1 \alpha_{\mathrm{RI_{1v}}} \alpha_{\mathrm{DI_{2t}}}}{\Omega_1 + (n+m-2)\Omega} \times \frac{1}{(\Theta_2 - \kappa(\Omega_{\mathrm{RI_{1v}}} + \Omega_{\mathrm{DI_{2t}}}))(\Omega_2 - \kappa\Omega_{\mathrm{DI_{2t}}})},$$

$$\Delta_6 = (n+m-2) C_M^{m-1} C_{M-m+1}^{n} \frac{\Omega_2 \alpha_{\mathrm{RI_{1v}}} \alpha_{\mathrm{DI_{2t}}}}{\Omega_1 + (n+m-2)\Omega} \times \frac{1}{(\Theta_2 - \kappa\Omega_{\mathrm{DI_{2t}}})(\Theta_2 - \kappa(\Omega_{\mathrm{RI_{1v}}} + \Omega_{\mathrm{DI_{2t}}}))}.$$

Finally, combining (D.11), (D.14) and (D.15), the proof is concluded.

Appendix E: Proof of Theorem 5

Firstly, we rewrite (10) as

$$F_{\psi_{e2e}^{\mathrm{PRS}}}(x) = 1 - \sum_{m=1}^{N} \sum_{n=0,\, m+n>1}^{M-m+1} \sum_{v=1}^{K_1}\sum_{t=1}^{K_2} (-1)^{n+1} \Delta_1 \Delta_2 \times \left(\frac{\delta_1}{\Phi_1 + x} + \frac{\delta_2}{\Phi_2 + x} + \kappa^2\right) \times \exp\left(-\frac{(\Theta_1 + \Omega_2) x}{1-\kappa x}\right), \quad \text{(E.1)}$$

where $\delta_1 = (1+\kappa\Phi_1)^2/(\Phi_2 - \Phi_1)$ and $\delta_2 = (1+\kappa\Phi_2)^2/(\Phi_1 - \Phi_2)$. Now, by substituting (E.1) into (21), we have

$$C_{avg}^{\mathrm{PRS}} = \frac{1}{2\ln 2} \sum_{m=1}^{N} \sum_{n=0,\, m+n>1}^{M-m+1} \sum_{v=1}^{K_1}\sum_{t=1}^{K_2} (-1)^{n+1} \Delta_1 \Delta_2 \times \int_0^{\kappa^{-1}} \left(\frac{\delta_1}{(1+x)(\Phi_1 + x)} + \frac{\delta_2}{(1+x)(\Phi_2 + x)} + \frac{\kappa^2}{1+x}\right) \times \exp\left(-\frac{(\Theta_1 + \Omega_2) x}{1-\kappa x}\right) dx. \quad \text{(E.2)}$$

Next, rewriting (E.2) as

$$C_{\mathrm{avg}}^{\mathrm{PRS}} = \frac{1}{2\ln 2} \sum_{m=1}^{N} \sum_{n=0,\, m+n>1}^{M-m+1} \sum_{v=1}^{K_1}\sum_{t=1}^{K_2} (-1)^{n+1} \Delta_1 \Delta_2 \times \int_0^{\kappa^{-1}} L_1(x) \exp\left(-\frac{(\Theta_1 + \Omega_2) x}{1-\kappa x}\right) dx, \quad \text{(E.3)}$$

in which

$$L_1(x) = \frac{\delta_1}{\Phi_1 - 1}\left(\frac{1}{1+x} - \frac{1}{\Phi_1 + x}\right) + \frac{\delta_2}{\Phi_2 - 1}\left(\frac{1}{1+x} - \frac{1}{\Phi_2 + x}\right) + \frac{\kappa^2}{1+x}.$$

$$\Pr\left(\gamma_{\mathrm{SR_b}} \geq u_1,\, \gamma_{\mathrm{R_bD}} \geq u_2\right) = \sum_{m=1}^{N} \sum_{n=0,\, m+n>1}^{M-m+1} (-1)^n C_M^{m-1} C_{M-m+1}^{n}$$
$$\times\left[\frac{(n+m-1)\,\Omega_2}{\Omega_2+(n+m-2)\,\Omega}\exp\left(-\Omega_1 u_1-\left(\Omega_2+(n+m-2)\,\Omega\right)u_2\right)+\frac{(n+m-2)\,\Omega_1}{\Omega_2+(n+m-2)\,\Omega}\exp\left(-(n+m-1)\,\Omega u_1\right)\right] \quad \text{(D.9)}$$

$$\Pr\left(\gamma_{\mathrm{SR_b}} \geq u_1,\, \gamma_{\mathrm{R_bD}} \geq u_2\right) = \sum_{m=1}^{N} \sum_{n=0,\, m+n>1}^{M-m+1} (-1)^n C_M^{m-1} C_{M-m+1}^{n}$$
$$\times\left[\frac{(n+m-1)\,\Omega_1}{\Omega_1+(n+m-2)\,\Omega}\exp\left(-\Omega_2 u_2-\left(\Omega_1+(n+m-2)\,\Omega\right)u_1\right)+\frac{(n+m-2)\,\Omega_2}{\Omega_1+(n+m-2)\,\Omega}\exp\left(-(n+m-1)\,\Omega u_2\right)\right] \quad \text{(D.10)}$$

Finally, applying (23) for the corresponding integral in (E.3), we finish the proof of Theorem 5.

APPENDIX F: PROOF OF THEOREM 7

Firstly, we rewrite (16) as (F.1), shown at the top of this page, where $\delta_3 = (1+\kappa\Phi_3)^2/(\Phi_5-\Phi_3)$, $\delta_4 = (1+\kappa\Phi_5)^2/(\Phi_3-\Phi_5)$, $\delta_5 = (1+\kappa\Phi_4)^2/(\Phi_5-\Phi_4)$, $\delta_6 = (1+\kappa\Phi_5)^2/(\Phi_4-\Phi_5)$, $\delta_7 = (1+\kappa\Phi_6)^2/(\Phi_5-\Phi_6)$, $\delta_8 = (1+\kappa\Phi_5)^2/(\Phi_6-\Phi_5)$, $\delta_9 = (1+\kappa\Phi_7)^2/(\Phi_5-\Phi_7)$, and $\delta_{10} = (1+\kappa\Phi_5)^2/(\Phi_7-\Phi_5)$. Now, by substituting (F.1) into (21), and after some algebraic manipulations, it follows that

$$C_{avg}^{\mathrm{ORS}} = \frac{1}{2\ln 2}\sum_{m=1}^{N}\sum_{n=0,\, m+n>1}^{M-m+1}\sum_{v=1}^{K_1}\sum_{t=1}^{K_2}(-1)^{n+1} \times \int_0^{\kappa^{-1}} L_2(x)\exp\left(-\frac{\Theta_2 x}{1-\kappa x}\right)dx, \quad \text{(F.2)}$$

where $L_2(x)$ is a function of x, which is given in (F.3), shown at the top of next page. Next, applying (23) for the corresponding integral in (F.2), the proof is concluded.

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$$F_{\psi_{e2e}^{\mathrm{ORS}}} = 1 - \sum_{m=1}^{N} \sum_{n=0,\, m+n>1}^{M-m+1} \sum_{v=1}^{K_1} \sum_{t=1}^{K_2} (-1)^{n+1} \exp\left(-\frac{\Theta_2 x}{1-\kappa x}\right) \times \Delta_3 \left(\frac{\delta_3}{\Phi_3 + x} + \frac{\delta_4}{\Phi_5 + x} + \kappa^2\right) + \Delta_4 \left(\frac{\delta_5}{\Phi_4 + x} + \frac{\delta_6}{\Phi_5 + x} + \kappa^2\right) + \Delta_5 \left(\frac{\delta_7}{\Phi_6 + x} + \frac{\delta_8}{\Phi_5 + x} + \kappa^2\right) + \Delta_6 \left(\frac{\delta_9}{\Phi_7 + x} + \frac{\delta_{10}}{\Phi_5 + x} + \kappa^2\right). \tag{F.1}$$

$$L_2(x) = \Delta_3 \left(\frac{\delta_3}{\Phi_3 - 1}\left(\frac{1}{1+x} - \frac{1}{\Phi_3 + x}\right) + \frac{\delta_4}{\Phi_5 - 1}\left(\frac{1}{1+x} - \frac{1}{\Phi_5 + x}\right) + \frac{\kappa^2}{1+x}\right) + \Delta_4 \left(\frac{\delta_5}{\Phi_4 - 1}\left(\frac{1}{1+x} - \frac{1}{\Phi_4 + x}\right) + \frac{\delta_6}{\Phi_5 - 1}\left(\frac{1}{1+x} - \frac{1}{\Phi_5 + x}\right) + \frac{\kappa^2}{1+x}\right) + \Delta_5 \left(\frac{\delta_7}{\Phi_6 - 1}\left(\frac{1}{1+x} - \frac{1}{\Phi_6 + x}\right) + \frac{\delta_8}{\Phi_5 - 1}\left(\frac{1}{1+x} - \frac{1}{\Phi_5 + x}\right) + \frac{\kappa^2}{1+x}\right) + \Delta_6 \left(\frac{\delta_9}{\Phi_7 - 1}\left(\frac{1}{1+x} - \frac{1}{\Phi_7 + x}\right) + \frac{\delta_{10}}{\Phi_5 - 1}\left(\frac{1}{1+x} - \frac{1}{\Phi_5 + x}\right) + \frac{\kappa^2}{1+x}\right). \tag{F.3}$$

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