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On the Performance of Cognitive Full-Duplex Relaying Systems under Spectrum Sharing Constraints

Samuel Baraldi Mafra, Hirley Alves, Daniel Benevides da Costa, Richard Demo Souza,
Evelio M. G. Fernandez, and Matti Latva-aho

***Abstract*— In this paper, assuming a spectrum sharing environment, we investigate the performance of a full-duplex dual-hop cooperative cognitive network composed by one secondary source, one secondary relay, and one secondary destination, where this latter applies joint decoding with the signals received from the source and relay such that the direct link can be seen as useful information rather than interference. The effects of self-interference at the relay are taken into account in our analysis due to the full-duplex relaying nature. Closed-form expressions for the outage probability and throughput are derived and insightful discussions are provided. Our results show that the proposed joint decoding full-duplex dual-hop secondary network outperforms its dual-hop full-duplex and joint-decoding half-duplex counterparts, even in the presence of strong self-interference.**

***Keywords*— Cooperative cognitive networks, full-duplex relaying, joint decoding, self-interference, spectrum sharing.**

I. INTRODUCTION

In a cognitive radio context under spectrum sharing constraints, a secondary network may transmit concurrently with the primary one as long as the communication of this latter is not compromised. For such an operation, a maximum allowable interference level at the primary receiver is defined, and secondary users (SUs) should take into account this threshold during the transmission in order to adjust their transmit powers to not damage the reception of the primary receiver [1], [2]. This will allow a more efficient use of the frequency spectrum. On the other hand, cooperative communications [3], [4] have emerged as an alternative technique to boost the performance of communication systems. The idea behind this strategy is to make use of one or more nodes (called relays) in order to emulate a physical antenna array. Thus, the same benefits obtained in multiple-input multiple-output systems can also be achieved with the use of single-antenna nodes through the distributed transmission and processing of the information. In cooperative systems, the relay behavior is governed by the so-called cooperative protocols and it can operate on either half-duplex or full-duplex modes [3], [5]. Specifically, in half-duplex mode, the relay transmits and receives in orthogonal channels, whereas in full-duplex mode the transmission and reception are performed at the same time and at the same frequency band. Owing to this fact, half-duplex relays require the use of additional system resources, while full-duplex relays arise as a viable option to alleviate this problem. However, although ideal full-duplex relaying can achieve higher capacity than half-duplex relaying [5], its use introduces self-interference that is inherent to the full-duplex approach (please, see [6]–[8] and references therein). Nevertheless, the works in [6]–[8] showed that full-duplex relays can still achieve high performance, even in the presence of strong interference levels.

Motivated by the important benefits acquired with cognitive radio and cooperative diversity techniques, several recent works have analyzed the performance of cooperative cognitive networks under spectrum sharing constraints [9]–[15]. Common to these works is that they assumed that all nodes operate on a half-duplex mode. However, in [16] the authors considered a scenario with a full-duplex relay subject to self-interference. In that work, through the use of a whitening filter, the interference from the primary network was assumed to be approximately Gaussian. With this assumption in mind, [16] performed a closed-form outage analysis for a full-duplex dual-hop (DH) relaying scheme, in which the self-interference at the relay was taken into account and the direct link was seen as interference at the secondary destination.

Differently from all previous works, in this paper we consider a cooperative cognitive network operating on a spectrum sharing scenario with a full-duplex relay subject to self-interference. In particular, this paper differs from [16] because the secondary destination applies joint decoding with the signals received from the relay and from the secondary source such that the direct link can be seen as useful information rather than interference. Closed-form expressions for the outage probability and throughput are derived and insightful discussions are provided. The proposed scheme, termed as full-duplex joint-decoding (JD) relaying, is compared with the full-duplex DH scheme presented in [16] as well as with the standard half-duplex joint-decoding (HD) relaying scheme. Our results demonstrate that the proposed cognitive cooperative full-duplex relaying scheme can considerably outperform the full-duplex relaying method proposed in [16] for the whole signal-to-noise ratio (SNR) range. Moreover, our results show

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S. B. Mafra, H. Alves and R. D. Souza are with the Federal University of Technology - Paraná (UTFPR), Paraná, Brazil (emails: mafrasamuel@gmail.com, richard@utfpr.edu.br).

H. Alves and M. Latva-aho are with Centre for Wireless Communications (CWC), University of Oulu, Finland (email:{halves,matti.latva-aho}@ee.oulu.fi).

D. B. da Costa is with the Federal University of Ceará (UFC), Ceará, Brazil (email: danielbcosta@ieee.org).

E. M. G. Fernandez is with the Federal University of Paraná (UFPR), Curitiba, Brazil (email: evelio@ufpr.br).

that the proposed JD method performs better than the half-duplex HD scheme in terms of throughput even in the presence of self-interference.

The rest of this paper is organized as follows. In Section II, the system model is introduced. In Section III, an analytical performance analysis of the proposed scheme is carried out in terms of outage probability and throughput. In Section IV, representative numerical plots are shown and insightful discussions are provided. Monte Carlo simulations are also presented in order to corroborate the proposed analysis. Finally, Section V concludes the paper.

II. SYSTEM MODEL

Consider a cooperative cognitive network (CCN) composed by one secondary source s, one full-duplex secondary relay r, one secondary destination d, and one primary receiver p, as depicted[1] in Fig. 1. The CCN operates on a spectrum sharing environment and the transmit power constraints will be detailed later. The quasi-static fading channel between transmitter i and receiver j is denoted by h_{ij}, $i \in \{s, r\}$ and $j \in \{r, d, p\}$. All channels undergo independent identically distributed (i.i.d.) Rayleigh fading, thus $|h_{ij}|^2$ follows an exponential distribution with mean power λ_{ij}.

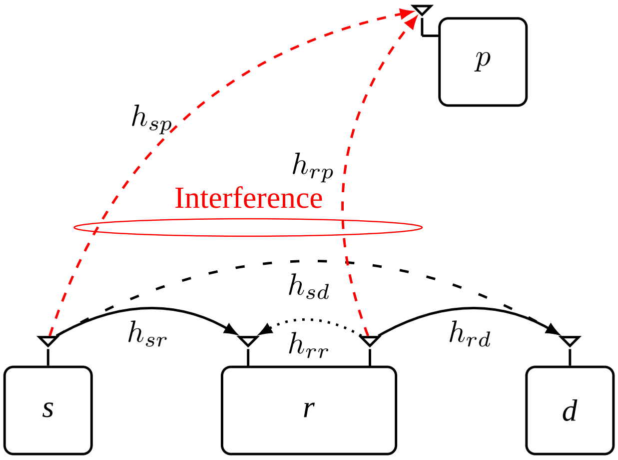

Fig. 1. System model: an underlay cooperative cognitive network with a full-duplex relay.

The received signals at the secondary relay and at the secondary destination can be expressed, respectively, as

$$y_r = \sqrt{P_s}\, h_{sr}\, x_s + \sqrt{P_r} h_{rr}\, x_r + n_r, \quad (1)$$

$$y_d = \sqrt{P_r}\, h_{rd}\, x_r + \sqrt{P_s}\, h_{sd}\, x_s + n_d, \quad (2)$$

where P_i is the transmit power of the node i, x_i is the message sent by the node i, h_{rr} denotes the fading coefficient of the self-interference at the full-duplex relay, $n_j \sim \mathcal{CN}(0, \sigma_n^2)$ stands for the additive white Gaussian noise at node j with variance $\sigma_n^2 = N_0$, where N_0 is the one-sided noise power spectral density. Moreover, $\lambda_{ij} = \frac{1}{(d_{ij})^\alpha}$, with d_{ij} being the distance between nodes i and j, and α represents the path loss exponent. Note that the self-interference may represent the residual interference after the application of some interference cancelation technique at the relay [8], [18]. We recall that the self-interference is dominated by the scattering component once the line-of-sight component is considerably reduced by antenna isolation [8], which leads to in general very small values of λ_{rr} [6].

Due to the spectrum sharing environment, the primary receiver tolerates a maximum interference level given by I. In a spectrum sharing scenario with a full duplex relay, the secondary transmitter and the secondary relay transmit their messages at the same time. Thus, the primary destination receives interference from both transmitters simultaneously. For this case, the transmission powers of the secondary transmitter and secondary relay must be constrained as [16]

$$|h_{sp}|^2 P_s + |h_{rp}|^2 P_r \leq I. \quad (3)$$

As in [16], we consider an equal power allocation scheme such that the secondary transmitter and the secondary relay have their respective transmit powers limited by

$$P_s = \frac{I}{2\,|h_{sp}|^2}, \qquad P_r = \frac{I}{2\,|h_{rp}|^2}. \quad (4)$$

Finally, in what follows, we denote the attempted information rate at the secondary network as $\mathcal{R}$.

III. OUTAGE AND THROUGHPUT ANALYSIS

In this section, we present the outage probability and throughput analysis for the proposed full-duplex JD relaying scheme. Additionally, we also include the outage and throughput formulations for the cases of full-duplex DH and HD joint decoding schemes, which are already known in the literature and which are used as benchmarks for the proposed scheme. The derivations are included for the sake of completeness.

Let us first define outage probability as the probability of a failure in the communication between nodes i and j [19]. Therefore, an outage can be defined as the event that the mutual information, $\mathcal{I}_{ij}$, is lower than the attempted transmission rate $\mathcal{R}$. Thus, assuming a unitary bandwidth and Gaussian inputs, the outage probability is given by [3]

$$\mathcal{O}_{ij} = \Pr\left[\mathcal{I}_{ij} < \mathcal{R}\right] = \Pr\left[\log_2\left(1 + \frac{|h_{ij}|^2 P_i}{N_0}\right) < \mathcal{R}\right], \quad (5)$$

where $\Pr[\theta]$ is the probability of event θ.

A. Full-Duplex Joint Decoding (JD)

In the case of the proposed cooperative communication scheme with the help of a full-duplex relay and with joint decoding at the secondary destination, the mutual information for the link between the secondary transmitter and the relay can be written as

$$\mathcal{I}_{sr}^{JD} = \log_2\left(1 + \frac{|h_{sr}|^2 P_s}{|h_{rr}|^2 P_r + N_0}\right), \quad (6)$$

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[1] Since our analysis focused on the secondary communication, we assume that the primary transmitter is far from the secondary network such that the interference can be seen as noise [17].

while the mutual information for the link between the relay and the secondary destination is given by

$$\mathcal{I}_{rd}^{JD} = \log_2\left(1 + \frac{P_s\,|h_{sd}|^2 + P_r\,|h_{rd}|^2}{N_0}\right). \tag{7}$$

Note that in (7) the signals coming from the secondary transmitter and the relay are seen as useful information at the secondary destination. Moreover, also note that the self-interference at the relay is taken into account in (6).

The overall outage probability of the proposed JD scheme becomes then

$$\begin{aligned}\mathcal{O}_{JD} &= \Pr\left[\min\left(\mathcal{I}_{sr}^{JD}, \mathcal{I}_{rd}^{JD}\right) < \mathcal{R}\right]\\ &= 1 - \left(1 - \Pr\left[\mathcal{I}_{sr}^{JD} < \mathcal{R}\right]\right)\left(1 - \Pr\left[\mathcal{I}_{rd}^{JD} < \mathcal{R}\right]\right)\\ &= \mathcal{O}_{sr}^{JD} + \mathcal{O}_{rd}^{JD} - \mathcal{O}_{sr}^{JD}\mathcal{O}_{rd}^{JD}.\end{aligned} \tag{8}$$

The exact solution of (8) is very intricate. Thus, let us first rewrite $\mathcal{O}_{sr}^{JD}$ as

$$\mathcal{O}_{sr}^{JD} = \Pr\left[\mathcal{I}_{sr}^{JD} < \mathcal{R}\right] = \Pr\left[\frac{Z_s}{Z_r + \frac{N_0}{\mu_r}} < \epsilon\right], \tag{9}$$

where the random variables Z_i are defined as $Z_i = \frac{|h_{ij}|^2}{|h_{ip}|^2}$, with $i = \{s, r\}$ and $j = \{r\}$, whose probability density function (PDF) is given by $f_{Z_i}(z_i) = \frac{\lambda_{ij}\lambda_{ip}}{(\lambda_{ij} + \lambda_{ip} z_i)^2}$ [16]. Note that $\epsilon = 2^{\mathcal{R}} - 1$ and $\mu_r = I/(2N_0)$. Keeping this in mind, we can write the outage probability of the *s-r* link as in (10). On the other hand, $\mathcal{O}_{rd}^{JD}$ can be determined as

$$\mathcal{O}_{rd}^{JD} = \Pr\left[Z_s + Z_r < \frac{\epsilon}{\mu_d}\right], \tag{11}$$

where $\mu_d = \mu_r = I/(2N_0)$. Notice that the random variables are redefined as $Z_i = \frac{|h_{ij}|^2}{|h_{ip}|^2}$, with $i = \{s, r\}$ and $j = \{d\}$. Let us also define $W = Z_s + Z_r$, in which the PDF $f_W(w)$ and the cumulative distribution function (CDF) $F_W(w)$ have been derived in Appendix such that the outage probability of the *r-d* link is given as in (12).

Finally, the overall outage probability can be attained by plugging (10) and (12) into (8). At this point, we define the throughput as the rate of error-free information transfer, which is a function of the overall outage probability and can be mathematically written as

$$\mathcal{T}_{JD} = \mathcal{R}(1 - \mathcal{O}_{JD}). \tag{13}$$

B. Full-Duplex Dual Hop (DH)

In the full-duplex DH scheme introduced in [16], differently from the proposed full-duplex JD scheme, the direct link *s-d* is seen as interference at the secondary destination. Thus, the mutual information of the *s-r* link is written as in (6), while the mutual information of the *s-d* link is now defined as

$$\mathcal{I}_{rd}^{DH} = \log_2\left(1 + \frac{|h_{rd}|^2 P_r}{|h_{sd}|^2 P_s + N_0}\right). \tag{14}$$

Note that, as previously stated, the source transmission is seen as interference in (14). Then, similarly to the JD case, the overall outage probability can be written as

$$\mathcal{O}_{DH} = \mathcal{O}_{sr}^{DH} + \mathcal{O}_{rd}^{DH} - \mathcal{O}_{sr}^{DH}\mathcal{O}_{rd}^{DH}. \tag{15}$$

Also, it can be seen that $\mathcal{O}_{sr}^{DH} = \Pr\left[\mathcal{I}_{sr}^{DH} < \mathcal{R}\right]$ is written as in (10), while $\mathcal{O}_{rd}^{DH} = \Pr\left[\mathcal{I}_{rd}^{DH} < \mathcal{R}\right]$ is also given as in (10) but performing the following substitutions: λ_{rr} by λ_{sd}, λ_{sr} by λ_{rd}, λ_{sp} by λ_{rp}, and λ_{rp} by λ_{sp}.

Finally, the throughput of the full-duplex DH scheme is written as

$$\mathcal{T}_{DH} = \mathcal{R}(1 - \mathcal{O}_{DH}). \tag{16}$$

C. Half-Duplex Joint Decoding (HD)

In the half-duplex HD scheme, the secondary transmission occurs in two time slots. In the first time slot, the source broadcasts its message to the relay and to the secondary destination, while in the second time slot the relay retransmits the source message if correctly decoded and if requested by the secondary destination[2]. Thus, at the secondary destination both messages are combined and jointly decoded.

Based on the above discussion, and making the appropriate substitutions, the mutual information of the *s-r* and *s-d* links can be both written as

$$\mathcal{I}_{ij}^{HD} = \log_2\left(1 + \frac{P_i\,|h_{ij}|^2}{N_0}\right). \tag{17}$$

As the messages from the source and the relay are jointly decoded at the destination, the mutual information of the *r-d* link is

$$\mathcal{I}_{rd}^{HD} = \log_2\left(1 + \frac{P_s\,|h_{sd}|^2 + P_r\,|h_{rd}|^2}{N_0}\right). \tag{18}$$

The outage probabilities of the *s-r* and *s-d* links can be expressed as

$$\mathcal{O}_{ij}^{HD} = \Pr\left[\mathcal{I}_{ij}^{HD} < \mathcal{R}\right] = \frac{\lambda_{ip}\epsilon}{\lambda_{ip}\epsilon + \lambda_{ij}\mu_j}, \tag{19}$$

while $\mathcal{O}_{rd}^{HD}$ can be written as in (12).

The overall outage probability of the HD scheme can be finally defined as

$$\mathcal{O}_{FDHD} = \mathcal{O}_{sd}^{HD}\mathcal{O}_{sr}^{HD} + \left(1 - \mathcal{O}_{sr}^{HD}\right)\mathcal{O}_{rd}^{HD}. \tag{20}$$

Moreover, the throughput of the HD scheme is

$$\mathcal{T}_{HD} = \mathcal{R}\left(1 - \mathcal{O}_{sd}^{HD}\right) + \frac{\mathcal{R}}{2}\mathcal{O}_{sd}^{HD}\left(1 - \mathcal{O}_{sr}^{HD}\right)\left(1 - \frac{\mathcal{O}_{rd}^{HD}}{\mathcal{O}_{sd}^{HD}}\right). \tag{21}$$

Notice that the first term in (21) represents the direct transmission, while the second term corresponds to the cases where the relay cooperates. We recall that, making of the the Bayes rule and because $\mathcal{I}_{rd}^{HD} \geq \mathcal{I}_{sd}^{HD}$, we can define $\Pr\left[\mathcal{I}_{rd}^{HD} < \mathcal{R} | \mathcal{I}_{sd}^{HD} < \mathcal{R}\right] = \frac{\mathcal{O}_{rd}^{HD}}{\mathcal{O}_{sd}^{HD}}$. Note also that the coefficient $\frac{\mathcal{R}}{2}$ appears because of the multiplexing loss inherent to half-duplex cooperative protocols [3]. However, as we consider IDF protocol in the half-duplex relaying scheme, it is still possible to achieve the same maximum throughput $\mathcal{R}$ as in full-duplex schemes.

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[2] It is noteworthy that we assume the incremental decode-and-forward (IDF) protocol [3], in which the relay only acts if requested by the destination and if the source message was decoded free of error. Note that the IDF protocol was chosen as it performs better than the fixed and selective decode-and-forward protocols.

$$\begin{aligned}\mathcal{O}_{sr}^{JD} &= \int_0^{\infty}\int_0^{\epsilon\left(Z_r+\frac{1}{\mu_r}\right)} f_{Z_s}(z_s)f_{Z_r}(z_r)\mathrm{d}z_s\mathrm{d}z_r \\ &= \frac{\lambda_{sp}\epsilon\left(\left(\lambda_{rp}-\lambda_{rr}\mu_r\right)\left(\lambda_{rp}\lambda_{sp}\epsilon+\lambda_{rp}\lambda_{sr}\mu_r-\lambda_{rr}\lambda_{sp}\epsilon\mu_r\right)+\lambda_{rp}\lambda_{rr}\lambda_{sr}\mu_r^2\ln\left(\frac{\lambda_{rp}(\lambda_{sp}\epsilon+\lambda_{sr}\mu_r)}{\lambda_{rr}\lambda_{sp}\epsilon\mu_r}\right)\right)}{\left(\lambda_{rp}\lambda_{sp}\epsilon+\lambda_{rp}\lambda_{sr}\mu_r-\lambda_{rr}\lambda_{sp}\epsilon\mu_r\right)^2}. \end{aligned} \tag{10}$$

$$\begin{aligned}\mathcal{O}_{rd}^{JD} &= \Pr\left[W<\frac{\epsilon}{\mu_d}\right]=\int_0^{\frac{\epsilon}{\mu_d}} f_W(w)\mathrm{d}w \\ &= \lambda_{rp}\lambda_{sp}\frac{\epsilon\left(\epsilon\lambda_{rp}\lambda_{sp}+\lambda_{rp}\lambda_{sd}\mu_d+\lambda_{rd}\lambda_{sp}\mu_d\right)-\lambda_{rd}\lambda_{sd}\mu_d^2\ln\left(\frac{(\epsilon\lambda_{rp}+\lambda_{rd}\mu_d)(\epsilon\lambda_{sp}+\lambda_{sd}\mu_d)}{\lambda_{rd}\lambda_{sd}\mu_d^2}\right)}{\left(\epsilon\lambda_{rp}\lambda_{sp}+\lambda_{rp}\lambda_{sd}\mu_d+\lambda_{rd}\lambda_{sp}\mu_d\right)^2}. \end{aligned} \tag{12}$$

IV. NUMERICAL RESULTS AND DISCUSSIONS

This section presents some numerical results in order to investigate the performance of the proposed full-duplex cooperative cognitive network using joint decoding at the destination. Moreover, the performance of the proposed JD scheme is compared to the full-duplex DH and half-duplex HD schemes. Monte Carlo simulations have been carried out to verify the accuracy of the analytical derivations. In the plots, we assume the path loss model $d_{ij}^{-\alpha}$ with exponent $\alpha = 4$, where $d_{sr} = \frac{1}{4}, d_{sp} = 1, d_{sd} = \frac{1}{2}, d_{rd} = \frac{1}{4}, d_{rp} = 1$. We also consider that the relay *r* is centered in a straight line between *s* and *d*, while the attempted secondary transmission rate is $\mathcal{R} = 4$ bits/s/Hz, and $N_0 = 1$.

Fig. 2 shows the outage probability for the proposed JD scheme as a function of the primary interference threshold I. The performance of the HD and DH methods is also shown. It can be seen that, in terms of outage probability, the HD scheme outperforms the DH and JD schemes. Moreover, with the increment of the primary interference threshold, the outage of the full-duplex JD and DH methods saturates because of the effect of the self-interference. Therefore, for sufficiently large I, the outage probability of the JD and DH schemes becomes independent of I due to a performance floor caused by the self-interference at the full-duplex relay.

In Fig. 3, we analyze the performance of the proposed JD scheme for different values of λ_{rr} and with $\mathcal{R} = 6$ bits/s/Hz. Note that the performance of the JD method increases with the quality of the interference cancelation at the relay, which is reflected in low values for λ_{rr}. We recall that the self-interference cannot be completely removed [18], always resulting at least in a small amount of residual self-interference.

In Fig. 4, the throughput for the three schemes is shown. As discussed above, the HD scheme presents better performance than the full-duplex schemes (JD and DH) in terms of outage probability. On the other hand, when we account for the throughput, the JD scheme considerably outperforms the HD and the DH schemes in the whole SNR range. Moreover, note that the self-interference considerably reduces the performance of the full-duplex DH scheme, so that it even looses in throughput to the half-duplex HD scheme. This shows the importance of applying joint decoding at the secondary destination in the case of a full-duplex relaying scheme, otherwise the multiplexing gain expected from full-duplex schemes may not be realized.

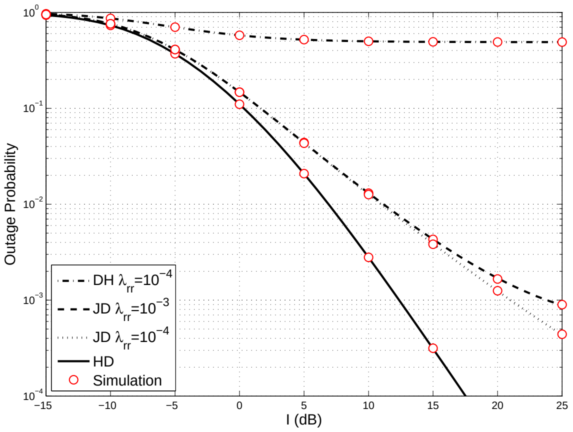

Fig. 2. Outage probability for the proposed JD scheme, and the DH and HD schemes, as a function of the primary interference threshold I.

V. CONCLUSIONS

In this paper, we investigate the performance of a full-duplex cooperative cognitive network with self-interference and subject to spectrum sharing constraints. Assuming that the secondary network is composed by one source, one relay, and one destination, closed-form expressions were derived for the outage probability and throughput. Our results showed that, even though the half-duplex cooperative cognitive network presents the best performance in terms of outage probability, the proposed full-duplex cooperative secondary network is superior in terms of throughput. Moreover, it was shown that the proposed full-duplex cooperative secondary network performs better in terms of outage and throughput than another known full-duplex scheme that considers the source transmission as interference at the secondary destination. As a future work we intend to investigate the impact of optimal power allocation between the secondary source and the relay.

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$$
\begin{aligned}
f_W(w) &= \int_0^w f_{Z_s}(z_s) f_{Z_r}(w - z_s)\mathrm{d}z_s \\
&= \lambda_{rd}\lambda_{sr}\mu_d \frac{w(\lambda_{rd}\lambda_{sp}\mu_d + \lambda_{rp}\lambda_{sr}\mu_d + \lambda_{rd}\lambda_{sr}w)\left(\mu_d\left(\lambda_{rd}^2\lambda_{sp}^2 + \lambda_{rp}^2\lambda_{sr}^2\right) + \lambda_{rd}\lambda_{sr}w(\lambda_{rd}\lambda_{sp} + \lambda_{rp}\lambda_{sr})\right)}{(\lambda_{rp}\mu_d + \lambda_{rd}w)(\lambda_{sp}\mu_d + \lambda_{sr}w)(\lambda_{rd}\lambda_{sp}\mu_d + \lambda_{rp}\lambda_{sr}\mu_d + \lambda_{rd}\lambda_{sr}w)^3} \\
&\quad + \frac{2\lambda_{rp}\lambda_{sp}(\lambda_{rd}\lambda_{sr}\mu_d)^2}{(\lambda_{rd}\lambda_{sp}\mu_d + \lambda_{rp}\lambda_{sr}\mu_d + \lambda_{rd}\lambda_{sr}w)^3} \log\left(\frac{(\lambda_{rp}\mu_d + \lambda_{rd}w)(\lambda_{sp}\mu_d + \lambda_{sr}w)}{\lambda_{rp}\lambda_{sp}\mu_d^2}\right)
\end{aligned}
\tag{22}
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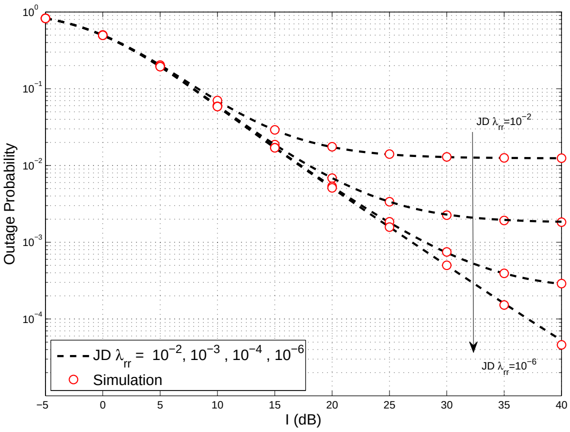

Fig. 3. Outage probability for the proposed JD scheme as a function of the primary interference threshold I, for different values of λ_{rr}.

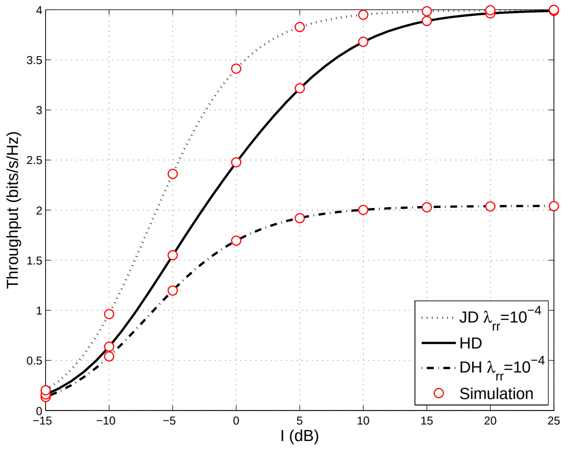

Fig. 4. Throughput of the proposed JD scheme, and the DH and HD methods, as a function of I.

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APPENDIX
PDF AND CDF OF W

We recall that $W = Z_s + Z_r$ and $f_{Z_i}(z_i) = \frac{\lambda_{ij}\lambda_{ip}}{(\lambda_{ij}+\lambda_{ip}z_i)^2}$ [16]. Thus, the PDF $f_W(w)$ is attained as in (22) and the CDF $F_W(w)$ is obtained by integrating (22) from 0 to $\frac{\epsilon}{\mu_d}$, which results in (12).

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