Performance Analysis of Decode and Forward Incremental Relaying in the Presence of Multiple Sources of Interference

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***Abstract*—This article studies the performance of Decode and Forward Incremental Relaying (DF-IR) in the presence of multiple dissimilar sources of Co-Channel Interference (CCI) at both, the relay and the destination. In particular, we consider the case where all links experience flat Rayleigh fading with K_r and K_d sources of CCI affecting the relay and the destination, respectively. The performance is studied in terms of three performance metrics, the normalized average spectral efficiency, the outage probability, and the error probability. The derived results unveil the incurred losses due to CCI. The accuracy of these results were verified using intensive Monte Carlo simulations.**

I. Introduction

Adaptive cooperative diversity techniques have been widely studied as powerful means to enhance the communication reliability and extend the transmission range while preserving the valuable spectral efficiency. A subset of these protocols, including incremental relaying and opportunistic-incremental relaying, exploit relaying only when the direct path between the source and the destination fails to meet a certain quality measure [1]–[3]. By doing so, these techniques preserve the spectral efficiency, and use relaying only when needed. Other protocols exploit the abundance of potential relays to select the best one (or more) to assist the destination. These include selection relaying [1] and opportunistic relaying [4]. Other variations of cooperative diversity protocols have also been considered. For instance, a two-bit-feedback incremental relaying protocol was proposed in [5] while an extension of the incremental and opportunistic relaying protocols where the source is allowed to retransmit the message in certain situations was recently proposed in [6].

The performance of these techniques over the various fading channels has been well reported in the literature. However, as the promises of cooperative diversity techniques made it an inevitable option for CCI-prone networks, like Wireless Sensor Networks (WSNs), Mobile Ad Hoc Networks (MANETs), and the more recent Cognitive Radio Networks (CRNs), its promised performance gains need to be reexamined in an interference-full environment. Unlike cellular networks, where interference is either totally eliminated or is at least controlled by the operator, the aforementioned types of networks are inherently spectrum sharing networks. Hence, CCI is an unavoidable channel impairment. For example, in CRNs, there are two sources of CCI, a licensed-user CCI, and an unlicensed-user CCI. Nonetheless, despite that the reactions of the CRN to these two types are different, their effect on its performance remain the same.

Recently, the performance of a number of cooperative diversity techniques in a CCI-rich environment has been studied. For instance, [7] studied the effect of CCI on opportunistic relaying when all relays are subject to CCI. Similarly, [8] analyzed the performance of a dual hop AF relaying protocol when the relay is subject to CCI. This has been extended in [9] to the case where interference affects both, the relay and the destination. More recently, [10] studied the performance of DF selection relaying when the relays and the destination are affected by CCI.

This article studies the performance of DF-IR protocol in the presence of multiple dissimilar sources of CCI at both, the source and the destination. The studied protocol is amongst the best performing protocols as it preserves the spectral efficiency while maintaining reliable communication. The performance of this protocol is studied using three performance metrics, the normalized average spectral efficiency, the outage probability, and the error probability. Closed form expressions are derived for the first two metrics while the third one is calculated using the Cumulative Distribution Function (CDF) approach as well as the Moment Generating Function (MGF) approach.

The remainder of this article is organized as follows. Section II describes the system model and the communication pattern. Next, the normalized average spectral efficiency, the outage probability, and the error probability are derived in section III. Numerical and simulations results are reported and discussed in section IV while conclusions are drawn in section V.

II. System Model

Consider the 3-terminal relay network shown in Fig.1 consisting of a source S, a Relay R, and a destination D. By default, S communicates with D through a direct link. If this link fails to meet a certain quality measure, R is requested to forward a regenerated replica in the following time slot, otherwise, S sends new data in this slot. However, this whole process takes place while a number of neighboring terminals are using the same channel, hence inducing a certain level of CCI to R and to D. At the end of the n^{th} time slot, the received

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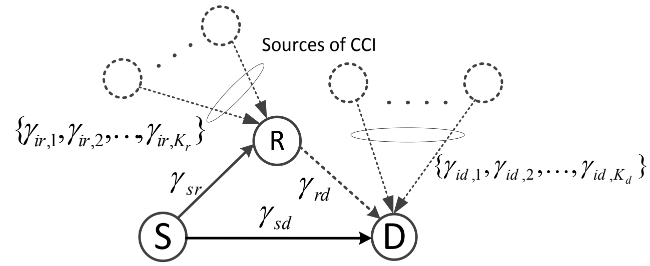

Fig. 1. 3-Terminal relay network with K_r and K_d sources of CCI affecting R and D, respectively.

signals at R and at D can be written as

$$y_r(n) = h_{sr}(n)x_s(n) + \sum_{k=1}^{K_r} h_{ir,k}(n)s_k(n) + w_r(n), \quad (1a)$$

$$y_d(n) = h_{sd}(n)x_s(n) + \sum_{k=1}^{K_d} h_{id,k}(n)s_k(n) + w_d(n), \quad (1b)$$

where $h_{sr}(n)$, $h_{sd}(n)$, $\{h_{ir,k}(n)\}_{k=1}^{K_r}$, and $\{h_{id,k}(n)\}_{k=1}^{K_d}$, are the channel coefficients of the S-R, S-D, $\{\mathrm{I}_k\}_{k=1}^{K_r}$-R, and $\{\mathrm{I}_k\}_{k=1}^{K_d}$-D links, respectively, $x_s(n)$ and $\{s_k(n)\}_{k=1}^{K_r}$ and $\{s_k(n)\}_{k=1}^{K_d}$ are the source and interference signals, respectively, while $w_r(n)$ and $w_d(n)$ are the Additive White Gaussian Noise (AWGN) terms with variances of σ_r^2 and σ_d^2, respectively. All channels are assumed to experience flat Rayleigh fading, and are assumed to vary between time slots, i.e., $h_{ij}(n) \neq h_{ij}(n+1)$ for all i and j.

The relaying decision depends on the quality of the S-D link. If the instantaneous Signal to Interference plus Noise Ratio (SINR) of $y_d(n)$, denoted ψ_{sd}, exceeds a certain threshold, denoted λ, D sends a positive Acknowledgment (ACK) informing S and R that it needs no assistance, and asking S to send a new message in the following time slot. Otherwise, a Negative ACK (NACK) is sent asking R for assistance. The decision threshold λ is chosen in the range $\lambda \in [\psi_{\text{th}}, \infty)$, where $\psi_{\text{th}} \triangleq 2^{\mathcal{Q}} - 1$ is the outage threshold and $\mathcal{Q}$ is the spectral efficiency.

When D sends a NACK, R sends a regenerated replica in the following time slot. In this case, D receives

$$\begin{aligned} y_d(n+1) &= h_{rd}(n+1)\hat{x}_s(n) + w_d(n+1) \\ &+ \sum_{k=1}^{K_d} h_{id,k}(n+1)s_k(n+1), \end{aligned} \quad (2)$$

where $\hat{x}_s(n)$ is the regenerated replica of $x_s(n)$. Finally, D combines the two signals, $y_d(n)$ and $y_d(n+1)$ using Maximal Ratio Combining (MRC)[1] prior to decoding.

[1]Though MRC is the optimum combining method in the absence of CCI, it suffers a performance loss when applied to CCI-rich environments. It was shown in [11] that exploiting the instantaneous knowledge of the interference channels allows the the Optimal Combiner (OC) to surpass the performance of MRC. However, in this article, the interference channels are assumed unknown to R and to D.

The Signal-to-Noise Ratios (SNRs) and the Interference-to-Noise Ratios (INRs) of the different links in the first time slot are defined as $\gamma_{sr} \triangleq E_s|h_{sr}(n)|^2/\sigma_r^2$, $\gamma_{sd} \triangleq E_s|h_{sd}(n)|^2/\sigma_d^2$, $\gamma_{ir,k} \triangleq E_{i,k}|h_{ir,k}(n)|^2/\sigma_r^2$, and $\gamma_{id,k,1} \triangleq E_{i,k}|h_{id,k}(n)|^2/\sigma_d^2$, respectively. Moreover, when relaying occurs, the SNRs and the INRs of the remaining links are defined as $\gamma_{rd} \triangleq E_r|h_{rd}(n+1)|^2/\sigma_d^2$ and $\gamma_{id,k,2} \triangleq E_{i,k}|h_{id,k}(n+1)|^2/\sigma_d^2$, where we have used the 1 and 2 subscripts to differentiate the INRs affecting D in the first and second time slots, respectively. Since all links are modeled as Rayleigh fading channels, these SNRs and INRs are exponentially distributed with mean values of $\bar{\gamma}_{sr}$, $\bar{\gamma}_{sd}$, $\{\bar{\gamma}_{ir,k}\}_{k=1}^{K_r}$, $\bar{\gamma}_{rd}$, and $\{\bar{\gamma}_{id,k}\}_{k=1}^{K_d}$, respectively. It should be remarked that since $\gamma_{id,k,1}$ and $\gamma_{id,k,2}$ are two random variables drawn from a Wide-Sense-Stationary (WSS) stochastic process, they follow the same exponential distribution, but their instantaneous values are generally different.

At the end of the n^{th} time slot, D receives $y_d(n)$ whose SINR can be written as

$$\psi_{sd} \triangleq \frac{\gamma_{sd}}{\sum_{k=1}^{K_d} \gamma_{id,k,1} + 1}, \quad (3)$$

where the Probability Density Function (PDF) of $\gamma_{id,\text{net},1} \triangleq \sum_{k=1}^{K_d} \gamma_{id,k,1}$ can be easily found to be [12, Eqn.14-5-26,27]

$$f_{\gamma_{id,\text{net},1}}(x) = \sum_{k=1}^{K_d} \frac{\pi_{sd,k}}{\bar{\gamma}_{id,k}} e^{-x/\bar{\gamma}_{id,k}}, \quad (4)$$

where

$$\pi_{sd,k} \triangleq \prod_{\substack{j=1 \\ j\neq k}}^{K_d} \frac{\bar{\gamma}_{id,k}}{\bar{\gamma}_{id,k} - \bar{\gamma}_{id,j}}. \quad (5)$$

With the aid of this PDF, the Cumulative Distribution Function (CDF) of ψ_{sd} can be written as

$$F_{\psi_{sd}}(\psi) = 1 - \sum_{k=1}^{K_d} \pi_{sd,k} \frac{\mu_{sd,k}}{\psi + \mu_{sd,k}} e^{-\psi/\bar{\gamma}_{sd}}, \quad (6)$$

where $\mu_{sd,k} \triangleq \bar{\gamma}_{sd}/\bar{\gamma}_{id,k}$ is the average Signal to Interference Ratio (SIR) of the I_k-D link. Moreover, since ψ_{sr} and ψ_{rd} are given by

$$\psi_{sr} = \frac{\gamma_{sr}}{\sum_{k=1}^{K_r} \gamma_{ir,k} + 1}, \quad (7a)$$

$$\psi_{rd} = \frac{\gamma_{rd}}{\sum_{k=1}^{K_d} \gamma_{id,k,2} + 1}, \quad (7b)$$

their CDFs can be written similar to (6) except that K_r and $\mu_{sr,k} \triangleq \bar{\gamma}_{sr}/\bar{\gamma}_{ir,k}$ are used for ψ_{sr} while K_d and $\mu_{rd,k} \triangleq \bar{\gamma}_{rd}/\bar{\gamma}_{id,k}$ are used for ψ_{rd}.

III. Performance Analysis

In this section, we analyze the performance of the described system using three performance metrics. These are the normalized average spectral efficiency, the outage probability, and the error probability.

A. Normalized Average Spectral Efficiency

Observing that the system operates in one of two modes, denoted $\mathbb{M}_1$ where relaying is not needed and $\mathbb{M}_2$ where relaying is needed, the normalized average spectral efficiency, $\bar{\mathcal{Q}}$, can be written as

$$\begin{aligned}\bar{\mathcal{Q}} &= \Pr[\mathbb{M}_1] + \frac{1}{2}\Pr[\mathbb{M}_2] = \Pr[\psi_{sd} \geq \lambda] + \frac{1}{2}\Pr[\psi_{sd} \leq \lambda] \\ &= 1 - \frac{1}{2}F_{\psi_{sd}}(\lambda) = \frac{1}{2}\Big(1 + \sum_{k=1}^{K_d} \frac{\pi_{sd,k}\mu_{sd,k}}{\lambda + \mu_{sd,k}} e^{-\lambda/\bar{\gamma}_{sd}}\Big).\end{aligned} \tag{8}$$

It can be readily observed that this is a monotonically decreasing function of the decision threshold, λ. Hence, as $\lambda \to \infty$ D will ask for assistance more often, and thus $\bar{\mathcal{Q}} \to 0.5$. On the other hand, when $\lambda \to 0$, D will seldom ask for assistance and hence $\bar{\mathcal{Q}} \to 1$.

B. Outage Probability Analysis

For DF-IR, an event of outage happens when either R undergos an outage while D needs assistance, or when R does not experience an outage and assist D, but D still undergo an outage [2]. Mathematically speaking, the outage probability can be written as

$$\begin{aligned}P_{\text{out}} &= \Pr[\psi_{sr} < \psi_{\text{th}}] \cdot \Pr[\psi_{sd} < \lambda] \\ &+ \frac{\Pr[\psi_{sd} < \lambda]}{\Pr[\psi_{sd} < \psi_{\text{th}}]} \cdot \Pr[\psi_{sr} \geq \psi_{\text{th}}] \cdot \Pr[\psi_{\text{tot}} < \psi_{\text{th}}].\end{aligned} \tag{9}$$

where $\psi_{\text{tot}} = \psi_{sd} + \psi_{rd}$. Substituting the corresponding CDFs yields the desired outage probability as

$$\begin{aligned}P_{\text{out}} &= F_{\psi_{sr}}(\psi_{\text{th}}) \cdot F_{\psi_{sd}}(\lambda) \\ &+ \frac{F_{\psi_{sd}}(\lambda)}{F_{\psi_{sd}}(\psi_{\text{th}})}[1 - F_{\psi_{sr}}(\psi_{\text{th}})] \cdot \Pr[\psi_{\text{tot}} < \psi_{\text{th}}].\end{aligned} \tag{10}$$

while the probability $\Pr[\psi_{\text{tot}} < \psi_{\text{th}}]$ can be written as in (13) at the top of the following page. In this expression, $\mathsf{E}_1(z)$ is the exponential integral function defined as $\mathsf{E}_1(z) = \int_z^\infty e^{-x}x^{-1}dx$, while the two functions, $\Omega_1(\eta)$ and $\Omega_2(\eta)$ are defined as

$$\begin{aligned}\Omega_1(\eta) &\triangleq \frac{1}{\mu_{rd,k_1} + \mu_{sd,k_2} + \psi_{\text{th}}} \\ &\times \Big\{e^{-(\mu_{rd,k_1}+\psi_{\text{th}})/\bar{\chi}} \cdot \mathsf{E}_1\Big[\frac{\eta - \mu_{rd,k_1} - \psi_{\text{th}}}{\bar{\chi}}\Big] \\ &- e^{\mu_{sd,k_2}/\bar{\chi}} \cdot \mathsf{E}_1\Big[\frac{\eta + \mu_{sd,k_2}}{\bar{\chi}}\Big]\Big\},\end{aligned} \tag{11}$$

where $1/\bar{\chi} \triangleq 1/\bar{\gamma}_{sd} - 1/\bar{\gamma}_{rd}$, and

$$\begin{aligned}\Omega_2(\eta) &\triangleq \frac{\Omega_1(\eta)}{(\mu_{rd,k_1} + \mu_{sd,k_2} + \psi_{\text{th}})} + \frac{1}{\mu_{sd,k_2} + \mu_{rd,k_1} + \psi_{\text{th}}} \\ &\times \Big\{\frac{1}{\bar{\chi}} e^{\mu_{sd,k_2}/\bar{\chi}} \cdot \mathsf{E}_1\Big[\frac{\eta + \mu_{sd,k_2}}{\bar{\chi}}\Big] - \frac{e^{-\eta/\bar{\chi}}}{\eta + \mu_{sd,k_2}}\Big\},\end{aligned} \tag{12}$$

C. Error Probability Analysis

Error probability analysis is more involved than its outage probability counterpart. In particular, since errors can occur in the two modes of operation, the error probability should be written using the Total Probability Theorem as

$$P_e = P_{e,sd} \cdot [1 - F_{\psi_{sd}}(\lambda)] + P_{e,srd} \cdot F_{\psi_{sd}}(\lambda), \tag{14}$$

where $P_{e,sd}$ is the probability of error of the direct link (S-D), i.e., without relaying, while $P_{e,srd}$ is the probability of error when relaying takes place (S-R-D). In either case, the error probability of a particular link can be evaluated using either, the PDF approach, the CDF approach, or the MGF approach. However, since obtaining a closed form expression for most of the links in our case is an involved process, we resort to use numerical integration to evaluate the error probability using either, the CDF approach or the MGF approach. Using either technique, the error probability of a BPSK over a particular link can be written as

$$\begin{aligned}P_e &= \frac{1}{2\pi}\int_{\theta=0}^{\pi/2} \mathcal{M}_\psi\Big(\frac{-1}{2\sin^2\theta}\Big)d\theta \\ &= \frac{1}{4\sqrt{2\pi}}\int_{\psi=0}^{\infty} \frac{e^{-\psi/2}}{\sqrt{\psi}} F_\psi(\psi)d\psi,\end{aligned} \tag{15}$$

where the conditional error probability is given by $\frac{1}{2}Q(\sqrt{\psi})$, where $Q(x)$ is the Gaussian Q-function defined as $Q(x) \triangleq \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-u^2/2}du$. Moreover, $\mathcal{M}_\psi(s)$ and $F_\psi(\psi)$ are the MGF and the CDF of an arbitrary SINR, ψ. Henceforth, we shall obtain the CDF and the MGF of the SINRs involved in (14)[2].

To evaluate $P_{e,sd}$, we need to find the CDF $F_{\hat{\psi}_{sd}}(\psi) \triangleq \Pr[\psi_{sd} < \psi | \psi_{sd} \geq \lambda]$ and the corresponding MGF. After some manipulations, these two can be written as

$$F_{\hat{\psi}_{sd}}(\psi) = 1 - \frac{1}{1 - F_\psi(\lambda)}\sum_{k=1}^{K_d} \pi_{sd,k}\frac{\mu_{sd,k}}{\mu_{sd,k} + \psi}e^{-\psi/\bar{\gamma}_{sd}}, \tag{16a}$$

$$\begin{aligned}\mathcal{M}_{\hat{\psi}_{sd}}(-s) &= e^{-s\lambda} - \frac{1}{1 - F_\psi(\lambda)}\sum_{k=1}^{K_d} s(\mu_{sd,k} + \lambda) \\ &\times \exp\Big(s\mu_{sd,k} + \frac{\lambda + \mu_{sd,k}}{\bar{\gamma}_{sd}}\Big) \times \mathsf{E}_1\Big[(\mu_{sd,k} + \lambda)\Big(s + \frac{1}{\bar{\gamma}_{sd}}\Big)\Big].\end{aligned} \tag{16b}$$

respectively.

Next, $P_{e,srd}$ can be written as

$$P_{e,srd} = P_{e,sr}P_{\text{prop}} + (1 - P_{e,sr})P_{e,\text{MRC}}, \tag{17}$$

where $P_{e,sr}$ is the error probability of the S-R link, P_{prop} is the error propagation probability, and $P_{e,\text{MRC}}$ is the error probability after the MRC.

[2]Unfortunately, due to space limitations, the MGF of $\psi_{sd} + \psi_{rd}$ given that $\psi_{sd} < \lambda$ will be excluded. However, it will be included in the Journal version of this work.

$$\Pr[\psi_{\text{tot}} < \psi_{\text{th}}] = F_{\psi_{sd}}(\psi_{\text{th}}) - \sum_{k_1=1}^{K_d}\sum_{k_2=1}^{K_d} \pi_{rd,k_1}\pi_{rd,k_2}\mu_{sd,k_2}\cdot\mu_{rd,k_1}e^{-\psi_{\text{th}}/\bar{\gamma}_{rd}}\left\{\frac{\Omega_1(\psi_{\text{th}})-\Omega_1(0)}{\bar{\gamma}_{sd}} + \Omega_2(\psi_{\text{th}}) - \Omega_2(0)\right\}, \quad (13)$$

As for $P_{e,sr}$, the CDF and the MGF of ψ_{sr} can be written as

$$F_{\psi_{sr}}(\psi) = 1 - \sum_{k=1}^{K_r} \pi_{sr,k}\frac{\mu_{sr,k}}{\psi+\mu_{sr,k}}e^{-\psi/\bar{\gamma}_{sr}}, \quad (18a)$$

$$\mathcal{M}_{\psi_{sr}}(-s) = 1 - \sum_{k=1}^{K_d} s\pi_{sr,k}\mu_{sr,k}e^{\mu_{sr,k}(s+1/\bar{\gamma}_{sr})} \times \mathsf{E}_1\left[\mu_{sr,k}\left(s+\frac{1}{\bar{\gamma}_{sr}}\right)\right]. \quad (18b)$$

This error propagates to D with a probability P_{prop}. It was shown in [3, Eqn.12] that P_{prop} for the BPSK modulation can be approximated by

$$P_{\text{prop}} \approx \frac{\bar{\psi}_{rd}}{\bar{\psi}_{rd}+\bar{\psi}_{sd},} \quad (19)$$

where $\bar{\psi}_{rd}$ and $\bar{\psi}_{sd}$ are the average values of ψ_{rd} and ψ_{sd}, which are given by

$$\bar{\psi}_{rd} = \sum_{k=1}^{K_d} \mu_{rd,k}\cdot e^{\mu_{rd,k}/\bar{\gamma}_{rd}}\cdot \mathsf{E}_1[\mu_{rd,k}/\bar{\gamma}_{rd}], \quad (20a)$$

$$\bar{\psi}_{sd} = \sum_{k=1}^{K_d} \mu_{sd,k}\cdot e^{\mu_{sd,k}/\bar{\gamma}_{sd}}\cdot \mathsf{E}_1[\mu_{sd,k}/\bar{\gamma}_{sd}], \quad (20b)$$

Finally, when R sends a correctly decoded and regenerated replica of $x_s(n)$ to D, errors can still happen after the MRC. This error probability, denoted $P_{e,\text{MRC}}$ can be written using the CDF or the MGF of the SINR ψ_{tot} given that $\psi_{sd} < \lambda$. After some manipulations, the CDF can be written as

$$F_{(\psi_{\text{tot}}|\psi_{sd}<\lambda)}(\psi) = \frac{1}{F_{\psi_{sd}}(\lambda)}\sum_{k_1=1}^{K_d}\sum_{k_2=1}^{K_d}\pi_{rd,k_1}\pi_{sd,k_2} \times \begin{cases}\Phi_1(\psi), & \psi \le \lambda,\\ \Phi_2(\psi), & \psi > \lambda\end{cases} \quad (21)$$

where $\Phi_1(\psi)$ and $\Phi_2(\psi)$ are given by (22) at the top of the following page while $\Omega_1(\eta)$ and $\Omega_2(\eta)$ are as given in (11) and (12), respectively, except that ψ_{th} is replaced by ψ in the two equations.

IV. Numerical and Simulation Results

In this section, we verify the accuracy of the derived results using intensive Monte Carlo simulations. We also compare the performance of the studied protocol in CCI-full and CCI-free environments to quantify the incurred losses. To achieve this, we study the performance of the various metrics as functions of the transmit SNR of S and R defined as $\texttt{SNR} \triangleq E/\sigma^2$, where $E_s = E_r = E$, and $\sigma_r^2 = \sigma_d^2 = \sigma^2$. Furthermore, the path loss is accounted for through defining the average channels gains as $\bar{\gamma}_{sd} = (d_{sd}/d_{sd})^n = 1$, $\bar{\gamma}_{sr} = (d_{sd}/d_{sr})^n$, $\bar{\gamma}_{rd} = (d_{sd}/d_{rd})^n$, $\bar{\gamma}_{id,k} = (d_{sd}/d_{id,k})^n$, and $\bar{\gamma}_{ir,k} = (d_{sd}/d_{ir,k})^n$, where n, the path loss exponent, is set to 4 in this article. In addition, d_{sd}, d_{rd}, d_{sr}, $d_{id,k}$ and $d_{ir,k}$ are the distances between the corresponding terminals. Let us first consider the normalized average spectral efficiency. Figure 2 shows the normalized average spectral efficiency as a function of SNR for $\lambda = -5, 5$, and 15 dB. Observe that despite the low average interference power, the system still incurs losses of about $2-4$ dBs when compared to the performance in a CCI-free environment.

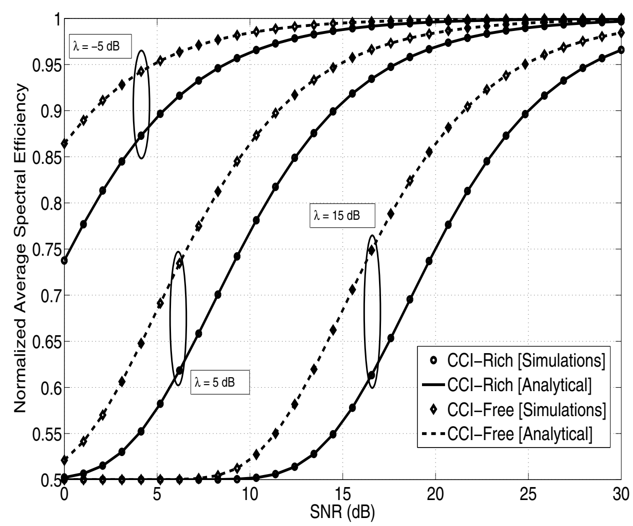

Fig. 2. Normalized average spectral efficiency, $\bar{\mathcal{Q}}$, as a function of SNR for $\lambda = -5, 5$ and 15 dBs. The following parameters were used: $K_d = 4$, and $\{d_{id,k}\}_{k=1}^{K_d}$ are uniformly chosen from the range $[d_{sd}, 2d_{sd}]$.

Figure 3 shows P_{out} for $\lambda = 5$dB. This figure illustrates the losses incurred when the CCI sources become closer to R and D. The figure clearly shows that the impact of CCI on D is more significant to that on R. It also shows that when the CCI sources are as close as $0.5d_{sd}$ to R and to D, a loss of more than 5dBs is incurred. Similar conclusions can be drawn from the error probability performance. Figure 4 compares the error probability for a BPSK system under different interference conditions. It illustrates that the degradation resulting from increasing the number of distant CCI sources is less harmful than the degradation resulting from a fewer nearby sources.

V. Conclusions

This article investigated the impact of CCI on the performance of DF-IR. Closed form expressions have been derived for the normalized average spectral efficiency and the outage

$$\Phi_1(\psi) \triangleq 1 - \frac{\mu_{sd,k_2}}{\psi + \mu_{sd,k_2}} e^{-\psi/\bar{\gamma}_{sd}} - \mu_{sd,k_2} \cdot \mu_{rd,k_1} e^{-\psi/\bar{\gamma}_{rd}} \Big(\frac{\Omega_1(\psi) - \Omega_1(0)}{\bar{\gamma}_{sd}} + \Omega_2(\psi) - \Omega_2(0) \Big), \tag{22a}$$

$$\Phi_2(\psi) \triangleq 1 - \frac{\mu_{sd,k_2}}{\lambda + \mu_{sd,k_2}} e^{-\lambda/\bar{\gamma}_{sd}} - \mu_{sd,k_2} \cdot \mu_{rd,k_1} e^{-\psi/\bar{\gamma}_{rd}} \Big(\frac{\Omega_1(\lambda) - \Omega_1(0)}{\bar{\gamma}_{sd}} + \Omega_2(\lambda) - \Omega_2(0) \Big), \tag{22b}$$

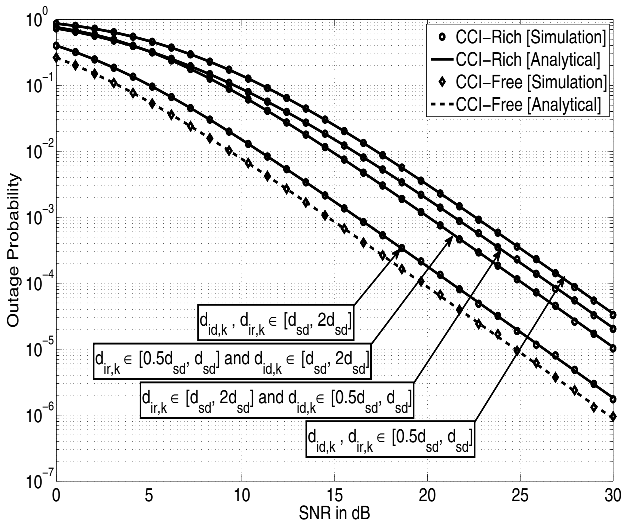

Fig. 3. Outage probability as a function of SNR. The following parameters were used: $\lambda = 5$ dBs, $d_{sr} = d_{rd} = 0.5$, $K_r = K_d = 2$, and $\psi_{\text{th}} = 4.77$dB.

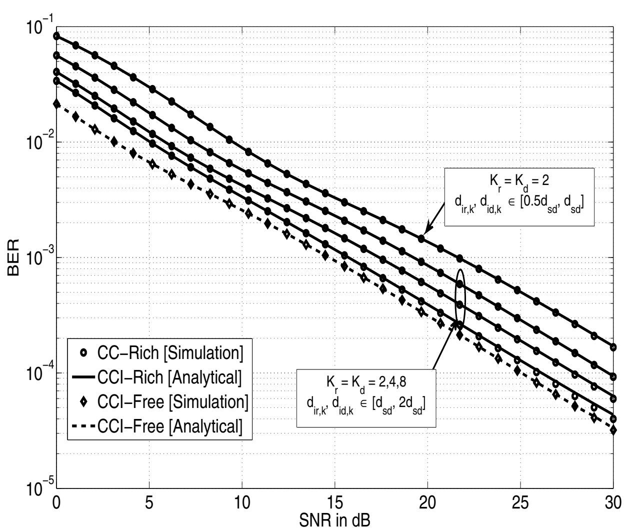

Fig. 4. Error probability as a function of SNR for different interference situations. The following parameters were used: $\lambda = 5$ dBs, $d_{sr} = d_{rd} = 0.5$, $K_r = K_d = 2, 4$, and 8 when $\{d_{ir,k}, d_{id,k}\} \in [d_{sd}, 2d_{sd}]$, and $K_r = K_d = 2$ when $\{d_{ir,k}, d_{id,k}\} \in [0.5d_{sd}, d_{sd}]$, and $\psi_{\text{th}} = 4.77$dB.

probability while exact, non-closed form expressions have been derived for the error probability. The derived results unveiled the losses incurred due to CCI. It helped quantifying the impact of these losses on the various performance metrics. The obtained results are especially important for the emerging CRNs where spectrum sharing, with non-negligible levels of CCI, is an inherent property. In particular, these results suggest that CCI, whether induced by secondary or primary users, has significant effects on the performance of the secondary network. Hence, proper protocols for channel management are indispensable. In addition, these results can be used to build an early spectrum sensing stage that is triggered when the level of interference exceeds a predefined threshold. In this case, the periodic quite periods scheme adopted in the CR standards can be replaced by a sensing on-demand stage. Further investigations on these topics are the subject of our future research.

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