Cooperative Relaying in Spectrum-Sharing Systems with Beamforming and Interference Constraints*

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***Abstract*—In this paper, we use a distributed Zero Forcing Beamforming (ZFB) method in cognitive radio relay networks in an effort to enhance the spectrum efficiency and improve the performance of the cognitive (secondary) system. In particular, we consider a spectrum sharing system where a set of decode-and-forward (DF) relays are employed to help a pair of secondary users in the presence of a licensed (primary) user. In this context, we derive expressions for the probability density functions (PDFs) of the received signal-to-noise ratio (SNR) at the relays as well as at the secondary destination. We also derive closed form expressions for the outage and bit error rate (BER) probabilities over independent and identically distributed (i.i.d.) Rayleigh fading channels. Numerical results demonstrate the efficacy of beamforming in improving the outage and BER performance.**

I. Introduction

Cognitive Radio (CR) is a promising solution to enhance the wireless spectrum utilization efficiency [1]. In cognitive radio networks (CRNs), one of the spectrum sharing paradigms is the underlay model [2]. In this model, the cognitive users are permitted to simultaneously transmit with the licensed users over the same frequency band provided that their interference power levels at the primary receivers are kept below a tolerable threshold known as the interference-temperature constraint [1]. Beamforming is an effective technology that enables simultaneous transmissions of primary users (PUs) and secondary users (SUs) in a CRN [3]. However, beamforming needs multi-antennas to be deployed in the unit to be realized which is prohibited in the first CR based IEEE standard (IEEE 802.22) where a single antenna communication is used at each secondary node [4]. Specifically, the underutilized television bands between 54 and 862 MHz prohibit the use of multiple transmit antennas at the user side, hence creating a virtual antenna array via cooperative relaying becomes a necessity.

Cooperative relaying emerged as a powerful solution for improving the performance of single-antenna communication nodes. This is gained by making use of intermediate relay nodes, which are used to assist transmission from the source to destination. One of the most common cooperation protocols is the adaptive DF scheme [5]. In this scheme, only a subset of the potential relays, which have good channels to the source, decode and retransmit the source's signal to the destination. The performance of this scheme has been investigated intensively in conventional systems [6] and we adopt it in this paper as well. Recently, there have been a few articles on relaying schemes in CRNs [7]- [8]. The End-to-End performance of cooperative relaying in spectrum-sharing systems with quality of service requirements is studied in [7] where the authors investigate the bit error rate (BER) and outage probability for a DF relaying system. All these works considered only a single relay. The authors in [8] investigate the outage probability for a multi-relay system with best relay selection based on spectrum sharing constraints. All the previous works considered either the received peak or average power interference constraints or both to limit the interference to PUs. Other works exploited beamforming to mitigate the interference to PUs. The authors in [9] use a Zero Forcing Beamforming (ZFB) method at the relays to suppress the interference to the PU in order to enhance the opportunistic spectrum access and they use some sort of a scheduling methods for transmission.

In this paper, we consider an adaptive DF relaying in an underly CRN where the secondary source communicates with its destination in the presence of the PU in a spectrum sharing environment. We limit the inflicted interference at the PU from both the secondary source and relays. A peak power interference constraint is imposed on the source's transmission in the broadcasting phase while a distributed ZFB is applied to null the interference to the PU in the the relaying phase. To analyze the performance, we derive the cumulative distribution functions (CDFs) and probability density functions (PDFs) of the broadcasting and relaying phases. Making use of these statistics, we derive closed form expressions for the outage and bit error probabilities.

The rest of this paper is organized as follows. Section II describes the system model. The outage probability is analyzed in Section III while Section IV analyzes the BER. Numerical results are given in Section V. Finally, Section VI concludes the paper. Throughout this paper, the Frobenius norm of the vectors are denoted by $||.||$, The Transpose and the Conjugate Transpose operations are denoted by $(.)^T$ and $(.)^\dagger$, respectively. $|x|$ means the magnitude of a complex number x. $\mathcal{CN} \sim (0,1)$ refers to a complex Gaussian normal random variable with zero-mean and unit variance.

* This paper was made possible by NPRP grant # 09-126-2-054 from the Qatar National Research Fund (a member of Qatar Foundation). The statements made herein are solely the responsibility of the authors.

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978-1-4673-0971-4/12/$31.00 © 2012 IEEE

II. System and Channel Models

Consider a relay-assisted CRN shown in Fig.1 where each SU and PU is equipped with a single antenna. Specifically, our system model consists of a secondary source (SS), a secondary destination (SD) and a set of M DF secondary Relays R_i, $i = 1,..,M$. There is no direct link between the source and destination, and they only communicate via potential relays $L_s \le M$ that correctly decode the source's message. A primary user coexists in the same area with SUs. The SUs are allowed to share the same frequency spectrum with the PU as long as the interference to the PU is limited to a predefined threshold. They are transmitting simultaneously in underly manner. The transmission protocol consists of two orthogonal time slots and is divided into two phases as shown in Fig. 1.

In the first phase, based on the interference channel state between the SS and PU_1, SS adjusts its transmit power under a predefined threshold and broadcasts its message to the set of relays. Any data transmitted from SS resulting in a higher interference level than the interference temperature at the PU_1 is not allowed. The interference temperature Q is the maximum tolerable interference power level at the PU_1. So a constraint on the peak power received at PU_1 is imposed.

In the second phase, the potential relays, which can correctly decode the message, become members of the decoding relays set $\mathcal{C}$ where ZFB is applied to null the interference from $\mathcal{C}$ to PU_2. By applying ZFB, the set of potential relays are allowed to always transmit without interfering with PU_2. It is assumed that SS and $\mathcal{C}$ have perfect knowledge of their interference channel power gains which can be acquired through a spectrum-band manager that mediates between the primary and secondary users [7]. It is also assumed that full channel state information (CSI) is available at nodes SS, $\mathcal{C}$ and SD. The interference from the primary transmitter is neglected and can be represented in terms of noise when its message is generated by random Gaussian codebooks [7].

A. CR Channel Model

All channel coefficients are assumed to be independent Rayleigh flat fading. Let $h_{a,b}$ denote the channel coefficient between nodes a and b, which is modeled as a zero mean, circularly symmetric complex Gaussian (CSCG) random variable with variance $\lambda_{a,b}$. n_a denotes additive white Gaussian noise which is also modeled as a zero mean, CSCG random variable with variance σ^2. Let h_{s,r_i} denote the channel coefficient between the source's transmit antenna and the receive antenna of the i^{th} relay and its channel power gain is $|h_{s,r_i}|^2$ which is exponentially distributed with parameter λ_{s,r_i}. Denote $h_{s,p}$ as the interference channel coefficient between SS and PU_1 and its channel power gain $|h_{s,p}|^2$, which is also exponentially distributed with parameter $\lambda_{s,p}$. Let $h_{r_i,p}$ and $h_{r_i,d}$ represent the interference channel coefficients between the i^{th} relay and PU_2 and between the i^{th} relay and SD, respectively. In the following section, we derive the CDFs and PDFs of the SNRs at relays and SD and use them in our outage and error probabilities analysis.

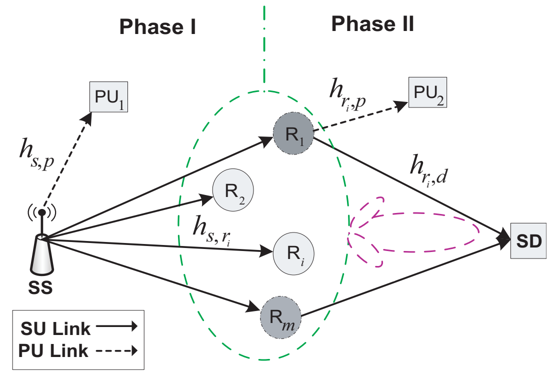

Fig. 1: System model for dual-hop system in CRN.

B. Mathematical Model

In the underlay approach of this model, the SU can utilize the PU's spectrum as long as the interference it generates at the PU remains below the interference threshold Q, which is the maximum tolerable interference level at which the PU can still maintain reliable communication [2]. For that reason, the SS's power P is constrained as $P \le \min\left\{\frac{Q}{|h_{s,p}|^2}, P_s\right\}$ where P_s is the maximum transmission power of SS [8].
So the received SNR γ_{s,r_i} at the i^{th} relay is given as

$$\gamma_{s,r_i} = \begin{cases} \frac{P_s|h_{s,r_i}|^2}{\sigma^2}, & P_s < \frac{Q}{|h_{s,p}|^2} \\ \frac{Q|h_{s,r_i}|^2}{\sigma^2|h_{s,p}|^2}, & P_s \ge \frac{Q}{|h_{s,p}|^2} \end{cases} \tag{1}$$

where σ^2 is the noise variance at each relay. Firstly, we find the CDF of γ_{s,r_i} as

$$\begin{aligned} Pr(\gamma_{s,r_i} < \gamma) &= Pr(P_s|h_{s,r_i}|^2 < \sigma^2\gamma, P_s < \frac{Q}{|h_{s,p}|^2}) \\ &+ Pr(\frac{Q|h_{s,r_i}|^2}{|h_{s,p}|^2} < \sigma^2\gamma, P_s \ge \frac{Q}{|h_{s,p}|^2}) \\ &= \int_{z=0}^{\sigma^2\gamma/P_s}\int_{y=0}^{Q/P_s} f_{z,y}(z,y)dydz \\ &+ \int_{y=Q/P_s}^{\infty}\int_{z=0}^{\sigma^2\gamma y/Q} f_{z,y}(z,y)dzdy \end{aligned}$$

where

$$f_{z,y}(z,y) = f_{|h_{s,r_i}|^2,|h_{s,p}|^2}(z,y) = \lambda_{s,r_i}\lambda_{s,p}e^{-(\lambda_{s,r_i}z+\lambda_{s,p}y)},$$

and $|h_{s,r_i}|^2, |h_{s,p}|^2$ are two independent exponential random variables. After doing the integration, the CDF of γ_{s,r_i} is given as

$$F_{\gamma_{s,r_i}}(\gamma) = 1 - e^{\frac{-\lambda_{s,p}\gamma}{\gamma_s}} + \frac{\gamma e^{-\frac{\frac{\lambda_{s,r_i}Q}{\sigma^2}+\lambda_{s,p}\gamma}{\gamma_s}}}{\frac{\lambda_{s,r_i}Q}{\lambda_{s,p}}+\gamma}, \tag{2}$$

where $\gamma_s = \frac{P_s}{\sigma^2}$. By differentiating $F_{\gamma_{s,r_i}}(\gamma)$ with respect to γ, we get the PDF, i.e.,

$$f_{\gamma_{s,r_i}}(\gamma) = \frac{\lambda_{s,p}}{\gamma_s} e^{\frac{-\lambda_{s,p}\gamma}{\gamma_s}} + \frac{e^{-\frac{\frac{\lambda_{s,r_i}Q}{\sigma^2}+\lambda_{s,p}\gamma}{\gamma_s}}}{\frac{\lambda_{s,r_i}Q}{\lambda_{s,p}}+\gamma} \times \left(1-\frac{\lambda_{s,p}}{\gamma_s}\gamma - \frac{\gamma}{\frac{\lambda_{s,r_i}Q}{\lambda_{s,p}}+\gamma}\right). \quad (3)$$

We define $\mathcal{C}$ to be the set of relays which perfectly decode the signal received in the first time slot, which implies that there is no outage at these relays. This translates to the fact that the mutual information between SS and each relay is above a specified target value. For simplicity, we neglect the bit errors at the relays and assume that decoding is performed accurately. In this case, the potential i^{th} relay is only required to meet the decoding constraint given as [5]

$$\Pr\left[R_i \in \mathcal{C}\right] = \Pr\left[\frac{1}{2}\log_2(1+\gamma_{s,r_i}) \geq R_{min}\right], \quad i=1,...,M \quad (4)$$

where $(1/2)$ is from the dual-hop transmission in two time slots and R_{min} denotes the minimum target rate below which outage occurs. According to (2), we can get

$$\begin{aligned}\Pr\left[R_i \in \mathcal{C}\right] &= 1 - F_{\gamma_{s,r_i}}(\gamma_{min}) \\ &= e^{\frac{-\lambda_{s,p}\gamma_{min}}{\gamma_s}} - \frac{\gamma_{min} e^{-\frac{\frac{\lambda_{s,r_i}Q}{\sigma^2}+\lambda_{s,p}\gamma_{min}}{\gamma_s}}}{\frac{\lambda_{s,r_i}Q}{\lambda_{s,p}}+\gamma_{min}}, \quad (5)\end{aligned}$$

where $\gamma_{min} = 2^{2R_{min}} - 1$ is the SNR threshold.

Without loss of generality, for all sub-channels are symmetrical, i.e., $\lambda_{s,r_i} = \lambda_{s,r}\,\forall i$, then $\Pr\left[R_i \in \mathcal{C}\right]$ is exactly the same for all i. Let $\Pr\left[R_i \in \mathcal{C}\right] = q$, and denote the cardinality of the set $\mathcal{C}$ as $|\mathcal{C}|$, then according to the Bionomial Law, $\Pr\left[|\mathcal{C}| = L_s\right]$ becomes

$$\Pr\left[|\mathcal{C}| = L_s\right] = \binom{M}{L_s} q^{L_s}(1-q)^{M-L_s}. \quad (6)$$

Now, for the second phase, when the potential relays forward the SS's signal after applying ZFB , the received signal at the SD is given as

$$y_d = P_r \mathbf{h}_{\mathbf{rd}}^{\dagger} \mathbf{w}_{\mathbf{zf}} x_s + n_d, \quad (7)$$

where P_r is the total power at the relays, x_s is the decoded symbol and it is assumed that $E\left[|x_s|^2\right] = 1$, $\mathbf{h}_{\mathbf{rd}}$ is the channel vector between the relays and SD, $\mathbf{w}_{\mathbf{zf}}$ is the ZFB weighting vector, and n_d denotes the noise at SD with variance σ^2.

C. ZFB Weights Design

In CRN, we cannot apply the typical approach of ZFB by only setting the weight vector values to be the pseudo inverse of the channel vector. This will cause interference to the PU. Our aim is to maximize the received power at the destination in order to maximize the mutual information of the secondary system. ZFB scheme is used as an alternative for the optimal scheme because of its simplicity and low complexity. To be able to apply ZFB, we consider the general assumption that the number of relays must be greater than or equal to the number of PRs plus SD, hence $L_s \geq 2$.

Let the ZFB vector be $\mathbf{w}_{\mathbf{zf}}^T = [w_1, w_2, ..., w_{L_s}]$. Also let $\mathbf{h}_{\mathbf{rd}}^T = [h_{r_1,d}, ..., h_{r_{L_s},d}]$, and $\mathbf{h}_{\mathbf{rp}}^T = [h_{r_1,p}, ..., h_{r_{L_s},p}]$ be the channel vectors between the relays and both SD and PU_2, respectively. According to the ZFB principles, the transmit weight vector $\mathbf{w}_{\mathbf{zf}}$ is chosen to lie in the orthogonal space of $\mathbf{h}_{\mathbf{rp}}^{\dagger}$ such that $|\mathbf{h}_{\mathbf{rp}}^{\dagger}\mathbf{w}_{\mathbf{zf}}| = 0$ and $|\mathbf{h}_{\mathbf{rd}}^{\dagger}\mathbf{w}_{\mathbf{zf}}|$ is maximized. So the problem formulation for finding the optimal weight vector is as follows.

$$\begin{aligned} \max_{\mathbf{w}_{\mathbf{zf}}} \quad & |\mathbf{h}_{\mathbf{rd}}^{\dagger}\mathbf{w}_{\mathbf{zf}}| \\ \text{s.t.:} \quad & |\mathbf{h}_{\mathbf{rp}}^{\dagger}\mathbf{w}_{\mathbf{zf}}| = 0 \\ & \|\mathbf{w}_{\mathbf{zf}}\| = 1. \end{aligned} \quad (8)$$

To find the optimal vector, we consider the following lemma from projection matrix theory [10].

Lemma 1: Let $\mathbf{T}$ be an $n \times k$ matrix with full column rank k, $k < n$, then the nonzero matrix $\mathbf{T}(\mathbf{T^H T})^{-1}\mathbf{T^H}$ is an idempotent symmetric matrix and its orthogonal projection matrix is $\mathbf{I} - \mathbf{T}(\mathbf{T^H T})^{-1}\mathbf{T^H}$ with rank $(n-k)$ [10, Theorems 4.21, 4.22].

By using Lemma 1 and applying a standard Lagrangian multiplier method, the weight vector that satisfies the above optimization method is given as

$$\mathbf{w}_{\mathbf{zf}} = \frac{\mathbf{T}^{\perp}\mathbf{h}_{\mathbf{rd}}}{\|\mathbf{T}^{\perp}\mathbf{h}_{\mathbf{rd}}\|}, \quad (9)$$

where $\mathbf{T}^{\perp} = \left(\mathbf{I} - \mathbf{h}_{\mathbf{rp}}(\mathbf{h}_{\mathbf{rp}}^{\dagger}\mathbf{h}_{\mathbf{rp}})^{-1}\mathbf{h}_{\mathbf{rp}}^{\dagger}\right)$ is the projection idempotent matrix with rank $(L_s - 1)$. Then, after substituting the ZFB weights, the total received SNR at the SD γ_{rd} is expressed in a vector form as

$$\gamma_{rd} = \frac{P_r|\mathbf{h}_{\mathbf{rd}}^{\dagger}\mathbf{w}_{\mathbf{zf}}|^{\mathbf{2}}}{\sigma^2} = \frac{P_r||\mathbf{T}^{\perp}\mathbf{h}_{\mathbf{rd}}||^{\mathbf{2}}}{\sigma^2}, \quad (10)$$

where we exploit the idempotent matrix property $(\mathbf{T}^{\perp})^2 = \mathbf{T}^{\perp}$. To proceed, we need the following Lemma to find the CDF of γ_{rd}.

Lemma 2: Let each entry of $\mathbf{h}_{\mathbf{rd}}$ be i.i.d. $\mathcal{CN} \sim (0,1)$, then $\left\|\mathbf{T}^{\perp}\mathbf{h}_{\mathbf{rd}}\right\|^2$ is a chi squared random variable with $2(L_s-1)$ degrees of freedom [11, theorem 2 Ch.1].

According to Lemma 2, the CDF of γ_{rd} results in a chi-square random variable with $2(L_s-1)$ degrees of freedom and is given as

$$F_{\gamma_{rd}}(\gamma) = 1 - e^{-\frac{\gamma}{\gamma_r}} \sum_{l=0}^{L_s-2} \frac{(\frac{\gamma}{\gamma_r})^l}{l!}, \; \gamma \geq 0, \quad (11)$$

where $\gamma_r = \frac{P_r}{\sigma^2}$. Accordingly, the PDF of $f_{\gamma_{rd}}(\gamma)$ is given as

$$f_{\gamma_{rd}}(\gamma) = \frac{(\gamma)^{L_s-2} e^{-\frac{\gamma}{\gamma_r}}}{(L_s-2)!(\gamma_r)^{L_s-1}}, \; \gamma \geq 0, \; L_s \geq 2. \quad (12)$$

and is plotted in Fig. 2 for various values of L_s.

III. Outage Probability Analysis

The mutual information at SD, I_{DF}, can be written as [5]

$$I_{DF} = \frac{1}{2}\log_2(1 + \sum_{i \in \mathcal{C}} \gamma_i), \quad (13)$$

where γ_i represents the received SNR for each relay-destination link. An outage event occurs when I_{DF} falls below a certain target rate. For a given rate R_{min}, the outage probability, P_{out}, can be rewritten using the total probability theorem as

$$P_{out} = \sum_{L_s=0}^{M} \Pr(|\mathcal{C}| = L_s)\Pr(I_{DF} < R_{min}|\,|\mathcal{C}| = L_s). \quad (14)$$

While the conditional probability $\Pr(I_{DF} < R_{min}|\,|\mathcal{C}| = L_s)$ depends on the SNRs $\gamma_{r_i,d}$ $\forall i = 1,..,L_s$, the probability term $\Pr(|\mathcal{C}| = L_s)$ depends on the SNRs γ_{s,r_i} $\forall i = 1,..,M$. There exist two exclusive outage events for the secondary system with distributed ZFB. Event A: failing to apply ZFB when $L_s < 2$, and Event B: failing to achieve the target rate when $L_s \geq 2$. The probability of event A is $\Pr(A) = \sum_{L_s=0}^{1}\binom{M}{L_s} q^{L_s}(1-q)^{M-L_s}$, and the probability of event B is

$$\begin{aligned}\Pr(B) &= \Pr(I_{DF} < R_{min}|\,|\mathcal{C}| = L_s)\\ &= \Pr\left[\frac{1}{2}\log_2(1+\gamma_{rd}) < R_{min}\right] = F_{\gamma_{rd}}(\gamma_{min}),\end{aligned}$$

where γ_{rd} is the total received SNR at SD using ZFB and $\gamma_{min} = 2^{2R_{min}} - 1$.
Substituting (6), Pr(A) and Pr(B) into (14), the total outage probability is expressed as

$$\begin{aligned}P_{out} &= \sum_{L_s=0}^{1}\binom{M}{L_s} q^{L_s}(1-q)^{M-L_s} + \sum_{L_s=2}^{M}\binom{M}{L_s} q^{L_s}\\ &\times (1-q)^{M-L_s}\left(1 - e^{-\frac{\gamma_{min}}{\gamma_r}}\sum_{l=0}^{L_s-2}\frac{(\frac{\gamma_{min}}{\gamma_r})^l}{l!}\right)\\ &= \sum_{L_s=0}^{M}\binom{M}{L_s} q^{L_s}(1-q)^{M-L_s}\\ &\times \left(1 - e^{-\frac{\gamma_{min}}{\gamma_r}}\sum_{l=0}^{L_s-2}\frac{(\frac{\gamma_{min}}{\gamma_r})^l}{l!}\right) \quad (15)\end{aligned}$$

P_{out} can also be rewritten in terms of $1 - \Pr(\text{no outage})$ as

$$\begin{aligned}P_{out} = 1 - &\sum_{L_s=2}^{M}\binom{M}{L_s} q^{L_s}(1-q)^{M-L_s}\\ &\times \left(e^{-\frac{\gamma_{min}}{\gamma_r}}\sum_{l=0}^{L_s-2}\frac{(\frac{\gamma_{min}}{\gamma_r})^l}{l!}\right). \quad (16)\end{aligned}$$

IV. Bit Error Rate Analysis

We analyze the BER performance due to errors occurring at SD assuming that all participating relays have accurately decoded and regenerated the message. As such, the BER analysis follows similar lines like those of the outage probability.

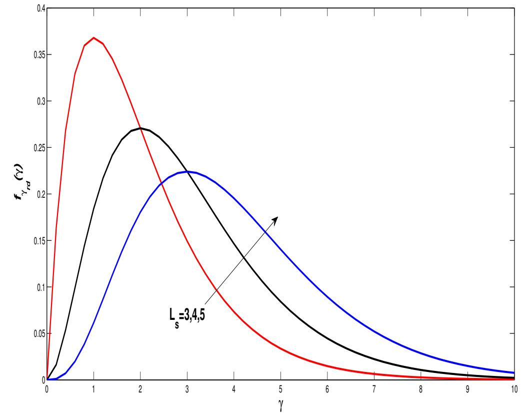

Fig. 2: PDF of the received SNR at SD, $f_{\gamma_{rd}}(\gamma)$.

In particular, the error probability at SD can be written as

$$P_{e,SD} = \sum_{L_s=0}^{M} \Pr(|\mathcal{C}| = L_s)\Pr(P_e||\mathcal{C}| = L_s), \quad (17)$$

where $\Pr(P_e||\mathcal{C}| = L_s)$ is the error probability conditioned on $|\mathcal{C}| = L_s$. This probability could be evaluated by averaging the error probability P_e over the the PDF in (12). Since P_e depends on the modulation scheme, many expressions can be used. In this paper, we consider Binary Phase Shift Keying (BPSK) for which $P_e = Q(\sqrt{2\gamma_{rd}})$ where $Q(.)$ is the Q-function given by $\frac{1}{2\pi}\int_x^{\infty} e^{-x^2/2}dx$. After averaging this expression over the PDF in (12), $\Pr(P_e||\mathcal{C}| = L_s)$ becomes [12, Eqn.14-4-15]

$$P_e(|\mathcal{C}| = L_s) = [\frac{1}{2}(1-\mu)]^{L_s-1}\sum_{k=0}^{L_s-2}\binom{L_s-2+k}{k}[\frac{1}{2}(1+\mu)]^k \quad (18)$$

where $\mu = \sqrt{\frac{\gamma_r}{1+\gamma_r}}$.
With the aid of this expression along with the expression for $\Pr[|\mathcal{C}| = L_s]$ in (6), $P_{e,SD}$ can be obtained as

$$\begin{aligned}P_{e,SD} &= \sum_{L_s=0}^{M}\binom{M}{L_s} q^{L_s}(1-q)^{M-L_s}[\frac{1}{2}(1-\mu)]^{L_s-1}\\ &\times \sum_{k=0}^{L_s-2}\binom{L_s-2+k}{k}[\frac{1}{2}(1+\mu)]^k. \quad (19)\end{aligned}$$

V. Numerical Results

In this section, we study the performance of some of the derived results through numerical evaluation. Let us start with the outage probability for the identical case where $\lambda_{s,p} = \lambda_{s,r} = 1$. We also fix the SNRs as $\gamma_r = \gamma_s = 10$dB. Fig. 3 shows the outage performance of the system versus the peak interference level Q at PU_1 for different numbers of potential relays, $M = 5, 6$ at different minimum rates $R_{min} = 0.2, 0.5, 1$ bits/s/Hz. It can be readily seen that increasing the number of potential relays improves the outage performance for less strict constraint values of Q. Clearly, the higher the tolerable interference level, the better the outage

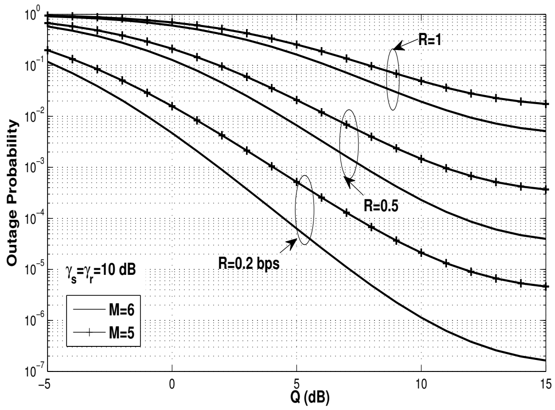

Fig. 3: Outage Probability vs. Q(dB) for different number of relays M=5,6 for R_{min}=0.2, 0.5 and 1 bits/s/Hz.

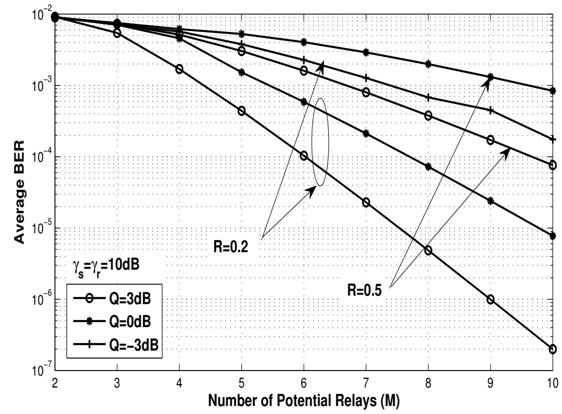

Fig. 5: Average BER vs. number of potential relays for $Q = -3, 0, 3$ dB for both $R_{min} = 0.2, 0.5$ bits/s/Hz.

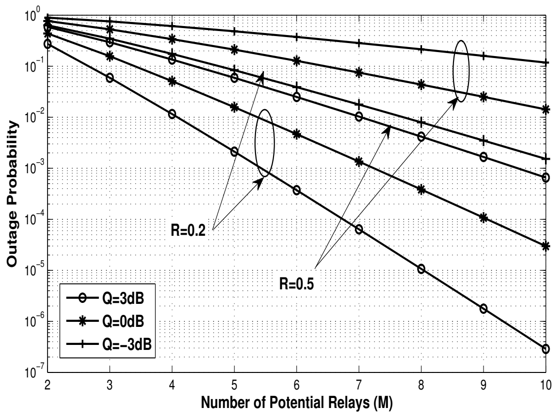

Fig. 4: Outage Probability vs. number of potential relays for $Q = -3, 0, 3$dB for both $R_{min} = 0.2, 0.5$ bits/s/Hz.

performance. Here the effect of the distributed ZFB method by increasing number of relays is obvious, that is, it maximizes the received SNR and hence less outage. In Fig. 4, we simulate the outage probability versus the number of potential relays at different values of interference levels $Q = -3, 0, 3$ dBs for both $R_{min} = 0.2, 0.5$. It is clear that by increasing the number of relays that participate in the second phase, the outage performance improves, which is not the case of non-beamforming adaptive DF [6]. This is attributed to the fact that applying ZFB acts as opportunistic relaying in the second phase and only needs one time slot to transmit in contrast to TDMA schemes that need M time slots. So ZFB is a solution to the drawback of using TDMA DF scheme beside nulling interference in CRN. In Fig. 5, we simulate the average BER versus the number of potential relays at different values of $Q = -3, 0, 3$ dB for both $R_{min} = 0.2, 0.5$. Again, by increasing the number of relays that participate in the second phase, the BER performance improves significantly. We also observe from figures as expected, the BER performance improves as R_{min} decreases.

VI. Conclusion

We proposed an adaptive DF relaying system model in CRNs that limits the interference to primary system by imposing a peak interference power constraint in the first phase and applying a distributed ZFB method in the second phase. We analyzed the performance of the secondary system by deriving the outage and BER probabilities. Our numerical results showed the benefits of our proposed system. Results showed that the distributed ZFB method improves the outage and BER performances by increasing number of participating relays in addition to limiting interference to PU. As an extension to this work, we can consider the amplify and forward scenario and compare the performance with the DF scheme.

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