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Collaborative Beamforming for Spectrum-Sharing Two-Way Selective Relay Networks under Co-Channel Interferences*

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***Abstract*—In this paper, we consider collaborative beamforming for spectrum-sharing two-way relay networks in an effort to improve the performance of the cognitive system and enhance the spectrum efficiency. In such a joint relaying/spectrum-sharing setting, a pair of secondary transceivers communicates via a set of secondary decode-and-forward (DF) relays in the presence of multiple primary transceivers. Among the available relays, only those that receive the signals reliably participate in the cooperative beamforming process to nullify the interference inflicted on primary receivers. Furthermore, the received signals at relays and at secondary transceivers are unavoidably interfered by the signals from primary transmitters. To study the performance of the cognitive system under the effects of these co-channel interferences (CCIs) from the primary transmitters, we derive closed-form expressions for the outage probability and bit error rate (BER) over independent and identically distributed (i.i.d.) Rayleigh fading channels. Numerical results demonstrate the effectiveness of beamforming in compensating the cognitive system performance loss due to the CCIs in addition to mitigating the interference to the primary users.**

I. Introduction

Spectrum-sharing in cognitive radio networks (CRNs) is a promising solution to overcome the under-utilization of the wireless spectrum efficiency. In this regard, secondary users (SUs) are allowed to get access to the spectrum with the primary users (PUs) while adhering to the interference limitations to the latter [1]. On the other hand, cooperative relaying in spectrum-sharing systems has proven to be effective in guaranteeing reliable transmission for the secondary systems [2]. While the cooperative one-way relaying systems in CRNs are extensively studied, the two-way relaying systems in spectrum-sharing environment are rarely investigated. Recently, in [3], the outage probability expression is derived for a two-way decode-and-forward (DF) relaying system where a SU helps two PUs to communicate in an overly model.

Beamforming is an emerging technique to alleviate the inflicted interference in the spectrum-sharing systems. Recently, the authors in [4] obtain the optimal beamforming coefficients in a cognitive two-way relaying system using iterative semidefinite programming (SDP) and bisection search methods with the objective of minimizing the interference at the PU with SUs' signal-to-interference-plus-noise ratio (SINR) constraints. This scheme considers only one PU. In [5], transceiver design for an overly cognitive two-way relay network is considered where a secondary multi- antenna relay helps two PUs to communicate. Optimal precoders using SDB methods are found with the aim of maximizing the achievable transmission rate of the SU while maintaining the rate requirements of the PUs for different relay strategies. We remark that all previous works suffers from high computational complexity and implementation difficulties. Meanwhile, zero forcing beamforming (ZFB) is an alternative sub-optimal approach that can be practically implemented. In our previous work [6], a distributed ZFB method for two-way amplify-and-forward (AF) relaying in a spectrum-sharing environment is studied where a comparison between two and three time-slot transmission protocols is investigated. Also, in [7], we extend the work for a DF two-way relaying spectrum-sharing system where the weighted signals are combined linearly (symbol-level superposition). However, in the previous works, the co-channel interferences from primary transmitters are represented in terms of Gaussian noise.

Motivated by the tremendous potential of combining two-way relaying and beamforming, we adopt in this paper collaborative distributed ZFB in two-way DF selective relaying CRN. In particular, we consider a spectrum-sharing system comprising two secondary transceivers communicating with each other in three consecutive time-slot, a number of secondary DF relays and a number of PUs. Only the relays that receive the signals (from the transceivers) reliably are used for relaying and beamforming process in the third time-slot. Specifically, the selected relays add the decoded bits exclusively (bit-level XORing) and employ distributed ZFB to nullify the inflicted interference to the primary receivers in addition to improving the performance of the secondary system. To analyze the system performance under the impact of the CCIs, we derive closed-form expressions of the outage probability and bit error error (BER). As a result, the ZFB approach has the potential for improving the secondary performance and limiting the interference in a simple practical manner compared to other complex approaches.

The rest of this paper is organized as follows. Section II describes the system and channel models. Section III presents the ZFB weights design. System performance analysis is introduced in Section IV. Numerical results are given in Section V. Finally, Section VI concludes the paper.

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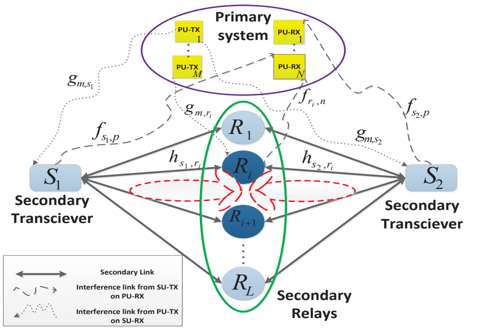

Fig. 1: Spectrum-Sharing System with Two-Way DF Relaying.

II. System and Channel Models

A. System model

We consider a two-way relaying system that is composed of two secondary transceivers S_j, $j = 1, 2$ and a set of L DF secondary relays denoted by R_i for $i = 1, ..., L$ coexisting in the same spectrum band with a primary system which consists of a cluster of M primary transmitters (PU-TXs)-N primary receivers (PU-RXs) pairs as shown in Fig. 1. All nodes are equipped with one antenna. The two sources wish to communicate with each other in a half-duplex way. Due to the severe impairments such as multipath effects, there is no direct link between the sources and thus they can only exchange messages via secondary relay nodes using time division broadcast (TDBC) protocol during three time-slots $(\text{TS}_i), i = 1, 2, 3$ [8]. In TS_1, based on the interference channel state information (CSI) from S_1 to the nth PU-RX, which suffers the most interference caused by S_1 (the strongest interference channel), S_1 adjusts its transmit power under predefined threshold Q_1 and broadcasts its message to all relays. Similarly, in TS_2, based on the interference CSI from S_2 to the $\bar{n}$th PU-RX, which suffers the most interference caused by S_2 (the nth and $\bar{n}$th PU-RXs could be different or the same), S_2 adjusts its transmit power under predefined threshold Q_2 and broadcasts its message to all relays. In TS_3, ZFB is applied to null the interference from the selected potential relays L_s (which decided to participate) to the PU-RXs so that the relays are always able to transmit without interfering with the PU-RXs. The ZFB processing $L_s \times L_s$ matrix, namely $\mathbf{W_{zf}}$, is optimized so as to maximize the received SNRs at both transceivers, while nulling the inflicted interference to the existing PU-RXs.

All channel coefficients are assumed to be independent Rayleigh flat fading such that $|h_{s_j,r_i}|^2, |f_{s_j,p}|^2, |f_{r_i,n}|^2, |g_{m,s_j}|^2$, $|g_{m,r_i}|^2$ and $|g_{\bar{m},r_i}|^2$ are exponential distributed random variables with parameters $\lambda_{s_j,r_i}, \lambda_{s_j,p}, \lambda_{r_i,n}, \lambda_{m,s_j}$, λ_{m,r_i} and $\lambda_{\bar{m},r_i}$ respectively. We also assume that the channels are reciprocal, i.e., $|h_{s_j,r_i}|^2 = |h_{r_i,s_j}|^2$. All the noises are assumed to be additive white complex Gaussian with zero-mean and variance σ^2. Let the ZFB vectors $\mathbf{w}^T_{\mathbf{zf_1}} = [w_{11}, w_{12}, ..., w_{1L_s}]$ used to direct the signal to S_1 and $\mathbf{w}^T_{\mathbf{zf_2}} = [w_{21}, w_{22}, ..., w_{2L_s}]$ used to direct the signal to S_2. Let $\mathbf{h}^T_{r,s_j} = [h_{r_1,s_j}, ..., h_{r_{L_s},s_j}]$ be the channel vectors between the potential relays and S_j, $\forall j = 1, 2$. Let $\mathbf{F}^T_{\mathbf{rp}} = [\mathbf{f_{r,p_1}}, ..., \mathbf{f_{r,p_N}}]$ be the channel matrix between the relays and all N PU-RXs where $\mathbf{f_{r,p_n}} = [f_{r_1,n}, ..., f_{r_{L_s},n}]$. It is assumed that S_1, S_2 and the relays 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]. Perfect CSI is required at every relay. The ith relay obtains the CSI for the links $(R_i - S_1)$, $(R_i - S_2)$ and $(R_i - n\text{th PU-RX})$ through training-based acquisition method [9]. In the training method, all relay nodes transmit their training signals sequentially so that the neighbouring relays can estimate their local CSI accordingly, which are used to determine the beamformer. Finally, the interference power incurred from the PU-TXs on the SU-RXs, i.e. (sources and relays) is considered.

B. Transmission protocol

As mentioned earlier, the communication process occurs over three time-slots. In TS_1, S_1 broadcasts its signal to all L relays, then the received signal at the ith relay is given as

$$y_{r_i,1} = \sqrt{P_1} h_{s_1,r_i} x_{s_1} + \sum_{m=1}^{M} \sqrt{P_{int}}\, g_{m,r_i} \hat{x}_{im,1} + n_1, \quad (1)$$

where P_1 is S_1 transmit power, P_{int} is interference power from PU-TXs, x_{s_1} is the information symbol of S_1, $\hat{x}_{im,1}$ is the mth PU-TX interfering symbol at the ith relay and n_1 denotes the noise at the ith relay in TS_1. In TS_2, similarly, S_2 also broadcasts its signal to all L relays, and the received signal at the ith relay is

$$y_{r_i,2} = \sqrt{P_2} h_{s_2,r_i} x_{s_2} + \sum_{m=1}^{M} \sqrt{P_{int}}\, \bar{g}_{m,r_i} \hat{x}_{im,2} + n_2, \quad (2)$$

where P_2 is the S_2 transmit power, x_{s_2} is the S_2 symbol, $\hat{x}_{im,2}$ is the mth interfering symbol at the ith relay and n_2 denotes the noise at the ith relay in TS_2. We assume that the transmitted symbols are equiprobable with unit energy.

In TS_3, the decoding set $\mathcal{C}$ which consists of the relays that can correctly decode both of x_{s_1} and x_{s_2} by using cyclic redundancy codes transmits to both sources simultaneously by using beamforming. Each relay combines the received signals from TS_1 and TS_2 by adding the decoded bit sequences exclusively. Let $\mathbf{b_{s_j}}$ denote the decoded bit sequence from x_{s_j}, for $j = 1, 2$. By applying XOR operation ($\oplus$), the combined bit sequence results in $\mathbf{b_{s_{1,2}}} = \mathbf{b_{s_1}} \oplus \mathbf{b_{s_2}}$. Then the combined bit sequence is encoded, modulated and weighted as $L_s \times 1$ signal $\mathbf{x}_{s_{1,2}} = \mathbf{W_{zf}} \mathbf{b_{s_{1,2}}}$. Thus the received signal at each S_j is given by

$$y_{s_j,3} = \sqrt{P_r} \mathbf{h}^T_{r,s_j} \mathbf{x}_{s_{1,2}} + \sum_{m=1}^{M} \sqrt{P_{int}}\, g_{m,s_j} \hat{x}_{jm,3} + n_{3j}, \quad (3)$$

where n_{3j} is the noise at each S_j in TS_3. Each S_j can demodulate the received signal and then XOR it with its own transmit bits to obtain the desired data.

Therefore, the corresponding total received SNR at S_j given $\mathcal{C}$, denoted $\gamma_{tot_j|\mathcal{C}}$, is given by

$$\gamma_{tot_j|\mathcal{C}} = \frac{P_r|\mathbf{h}_{r,s_j}^T \mathbf{x}_{s_{1,2}}|^2}{\sum_{m=1}^{M} P_{int}\,|g_{m,s_j}|^2 + \sigma^2}. \quad (4)$$

C. Mathematical Model and Size of $\mathcal{C}$

In the underlay approach of this model, S_j can utilize the PU's spectrum as long as the interference it generates at the most affected PU-RX remains below the interference threshold Q_j. For that reason, P_j is constrained as $P_j = \min\left\{\frac{Q_j}{|f_{s_j,p}|^2}, P_{s_j}\right\}$ where P_{s_j} is the maximum transmission power of S_j, $\forall j = 1,2$ [7]. So the received signal to interference ratio (SIR) γ_{s_j,r_i} at the ith relay is given as $\gamma_{s_j,r_i} = \min\left\{\frac{Q_j}{|f_{s_j,p}|^2}, P_{s_j}\right\}\frac{|h_{s_j,r_i}|^2}{\sum_{m=1}^{M} P_{int}|g_{m,r_i}|^2}$ which can be expressed as[1]

$$\gamma_{s_j,r_i} = \begin{cases} \frac{P_{s_j}|h_{s_j,r_i}|^2}{\sum_{m=1}^{M} P_{int}|g_{m,r_i}|^2}, & P_{s_j} < \frac{Q_j}{|f_{s_j,p}|^2} \\ \frac{Q_j|h_{s_j,r_i}|^2}{\sum_{m=1}^{M} P_{int}|g_{m,r_i}|^2|f_{s_j,p}|^2}, & P_{s_j} \geq \frac{Q_j}{|f_{s_j,p}|^2} \end{cases}, \quad (5)$$

Let $X = |h_{s_j,r_i}|^2, Y = |f_{s_j,p}|^2, Z = \sum_{m=1}^{M} P_{int}|g_{m,r_i}|^2$, then the CDF of γ_{s_j,r_i} conditioned on Z is given as

$$F_{\gamma_{s_j,r_i}|Z}(\gamma) = \underbrace{\Pr\left(\frac{Q_j X}{Y} < Z\gamma, Y \geq \frac{Q_j}{P_{s_j}}\right)}_{I_1(Z)} + \underbrace{\Pr\left(P_{s_j}X < Z\gamma, Y < \frac{Q_j}{P_{s_j}}\right)}_{I_2(Z)}.$$

To continue, we average over $F_{\gamma_{s_j,r_i}|Z}$ with respect to Z. Because Z is the sum of M exponential random variables with parameter $\lambda_z P_{int}$, it presents a chi-square random variable with $2M$ degrees of freedom and its PDF is given by

$$f_Z(z) = \frac{z^{M-1}e^{-\frac{\lambda_z z}{P_{int}}}}{\Gamma(M)P_{int}^M}. \quad (6)$$

Performing the averaging, $F_{\gamma_{s_j,r_i}}(\gamma)$ expression is yielded as

$$\begin{aligned} F_{\gamma_{s_j,r_i}}(\gamma) &= 1 - (1 - e^{-\lambda_{s_j,p}\vartheta})\left(1 + \frac{P_{int}\lambda_{m,r_i}\gamma}{P_{s_j}\lambda_{s_j,r_i}}\right)^{-M} \\ &- \frac{\kappa e^{-\lambda_{s,p}\vartheta}}{\Gamma(M)P_{int}^M}\Big[-1^{M-2}\kappa^{M-1}e^{\kappa\eta}Ei\left[\kappa\eta\right] \\ &+ \sum_{k=1}^{M-1}\Gamma(k)\left(-\kappa\right)^{M-1-k}\left(\eta\right)^{-k}\Big], \end{aligned} \quad (7)$$

where $\vartheta = \frac{Q_j}{P_{s_j}}$, $\kappa = \left(\frac{Q_j\lambda_{s_j,p}}{\lambda_{s_j,r_i}\gamma}\right)$, $\eta = \left(\frac{\lambda_{s_j,r_i}\gamma\vartheta}{Q_j} + \frac{\lambda_{m,s_j}}{P_{int}}\right)$ and $Ei[.]$ is the exponential integral defined in [10].

As mentioned earlier, we define $\mathcal{C}$ to be the set of relays which perfectly decode both signals received in TS_1 and TS_2, which implies that there is no outage at these relays. This translates to the fact that the mutual information between each S_j and each ith relay is above a specified target value. In this case, the potential ith relay is only required to meet the decoding constraint given as [11]

$$\Pr\left[R_i \in \mathcal{C}\right] = \Pr\left[\frac{1}{3}\log_2(1+\gamma_{s_j,r_i}) \geq \frac{R_{min}}{2}\right], i = 1,..,L \quad (8)$$

where $(1/3)$ is from the message transmission in three time-slots and R_{min} denotes the minimum target rate below which outage occurs. By using the the Binomial distribution, the probability $\Pr\left[|\mathcal{C}| = L_s\right]$ becomes

$$\Pr\left[|\mathcal{C}| = L_s\right] = \binom{L}{L_s} P_{\text{off}}^{L-L_s}(1 - P_{\text{off}})^{L_s}, \quad (9)$$

where P_{off} denotes the probability that the relay does not decode correctly both of signals and keeps silent in TS_3. Let P_{o_1} and P_{o_2} be the outage probabilities at any R_i for a signal transmitted from S_1 and S_2, respectively, then P_{off} is computed as

$$P_{\text{off}} = 1 - (1 - P_{o_1})(1 - P_{o_2}), \quad (10)$$

where P_{o_j} for $j = 1,2$ can be computed from (7) as follows

$$P_{o_j} = F_{\gamma_{s_j,r_i}}(\gamma_{th}), \quad (11)$$

where $\gamma_{th} = 2^{\frac{3}{2}R_{min}} - 1$ is the SIR threshold.

III. Sub-optimal ZFB Weights Design

Our objective here is to maximize the received SNRs at the two transceivers in order to enhance the performance of the secondary system while limiting the interference reflected on the PU-RXs. To be able to apply ZFB, the general assumption $L_s > N$ is considered. According to the ZFB principles, the transmit weight vectors $\mathbf{w_{zf_1}}$, $\mathbf{w_{zf_2}}$ are chosen to lie in the orthogonal space of $\mathbf{F_{rp}}^H$ such that $|\mathbf{f}_{\mathbf{r,p_i}}^H\mathbf{w_{zf_1}}| = 0$ and $|\mathbf{f}_{\mathbf{r,p_i}}^H\mathbf{w_{zf_2}}| = 0$, $\forall i = 1,...,N$ and $|\mathbf{h}_{r,s_1}^H\mathbf{w_{zf_1}}|$, $|\mathbf{h}_{r,s_2}^H\mathbf{w_{zf_2}}|$ are maximized. So the problem formulation for finding the optimal weight vectors is divided into two parts as follows.

$$\begin{aligned} \max_{\mathbf{w_{zf_1}}} \quad & |\mathbf{h}_{r,s_1}^H\mathbf{w_{zf_1}}|^2 \\ \text{s.t.:} \quad & |\mathbf{f}_{\mathbf{r,p_i}}^H\mathbf{w_{zf_1}}| = 0, \quad \forall i = 1,...,N \\ & \|\mathbf{w_{zf_1}}\| = 1. \end{aligned} \quad (12)$$

$$\begin{aligned} \max_{\mathbf{w_{zf_2}}} \quad & |\mathbf{h}_{r,s_2}^H\mathbf{w_{zf_2}}|^2 \\ \text{s.t.:} \quad & |\mathbf{f}_{\mathbf{r,p_i}}^H\mathbf{w_{zf_2}}| = 0, \quad \forall i = 1,...,N \\ & \|\mathbf{w_{zf_2}}\| = 1. \end{aligned} \quad (13)$$

By applying a standard Lagrangian multiplier method, the weight vectors that satisfy the above optimization methods are given as

$$\mathbf{w_{zf_1}} = \frac{\mathbf{\Xi}^{\perp}\mathbf{h}_{r,s_1}}{\|\mathbf{\Xi}^{\perp}\mathbf{h}_{r,s_1}\|}, \; \mathbf{w_{zf_2}} = \frac{\mathbf{\Xi}^{\perp}\mathbf{h}_{r,s_2}}{\|\mathbf{\Xi}^{\perp}\mathbf{h}_{r,s_2}\|}, \quad (14)$$

where $\mathbf{\Xi}^{\perp} = \left(\mathbf{I} - \mathbf{F_{rp}}(\mathbf{F_{rp}^H}\mathbf{F_{rp}})^{-1}\mathbf{F_{rp}^H}\right)$ is the projection idempotent matrix with rank $(L_s - N)$ [6]. Since each relay

[1] In this paper, we consider an interference-limited scenario where the impact of the interference power from PU-TXs is dominant compared to the noise, and therefore noise effects can be discarded.

knows the CSI of the channels between itself and both secondary sources and between itself and the primary receivers, the ZFB matrix $\mathbf{W_{zf}}$ is made up by the diagonal of the product of the two ZFB vectors $\mathbf{w_{zf_1}}$ and $\mathbf{w_{zf_2}}$ which is represented as [4], [12] and references therein

$$\mathbf{W_{zf}} = \mathbf{w_{zf_1}} \mathbf{w_{zf_2}}^T. \tag{15}$$

It is worth noting that the relays transmit only their own received signal and there is no data exchange among the relays. Thus, the algorithm works in a distributed manner.

Now, after finding $\mathbf{W_{zf}}$, we substitute (15) into equation (4) to get

$$\gamma_{s_j|\mathcal{C}} = \frac{P_r||\mathbf{\Xi}^{\perp}\mathbf{h_{r,s_j}}||^2}{\sum_{m=1}^{M} P_{int}|g_{m,s_j}|^2}, \tag{16}$$

To analyze the system, we firstly need to obtain the PDF and CDF of $\gamma_{s_j|\mathcal{C}}$. Let $X_1 = P_r||\mathbf{\Xi}^{\perp}\mathbf{h_{r,s_j}}||^2$ and $Y = \sum_{m=1}^{M} P_{int}|g_{m,s_j}|^2$, then we need the PDF of X_1 which is determined as [7]

$$f_{X_1}(x_1) = \frac{x_1^{L_s-N-1} e^{-\frac{x_1}{P_r}}}{\Gamma(L_s-N)(P_r)^{L_s-N}}, \; x_1 \geq 0, \; L_s > N. \tag{17}$$

Incorporating both PDFs of Y and X_1 from (6) and (17) respectively, into [13, Eq. 6.60], and using [10, 3.326.2], the conditional PDF of $\gamma_{s_j|\mathcal{C}}$ is given as

$$f_{\gamma_{s_j|\mathcal{C}}}(\gamma) = \zeta \; \Gamma[\varphi+M] \left[\frac{\gamma^{\varphi-1}}{\left(\frac{\gamma}{P_r} + \frac{\lambda_{m,s_j}}{P_{int}}\right)^{\varphi+M}} \right], \tag{18}$$

where $\zeta = \frac{(\lambda_{m,s_j})^M}{\Gamma(\varphi)\Gamma(M)P_{int}^M(P_r)^{\varphi}}$ and $\varphi = L_s - N$. Finally, the unconditional PDF of the total received SNR, denoted γ_{s_j}, is written as

$$\begin{aligned} f_{\gamma_{s_j}}(\gamma) &= \sum_{L_s=0}^{N} \binom{L}{L_s} P_{\text{off}}^{L-L_s}(1-P_{\text{off}})^{L_s}\delta(\gamma) \\ &+ \sum_{L_s=N+1}^{L} \binom{L}{L_s} P_{\text{off}}^{L-L_s}(1-P_{\text{off}})^{L_s} \\ &\times \zeta \; \Gamma[\varphi+M] \left[\frac{\gamma^{\varphi-1}}{\left(\frac{\gamma}{P_r} + \frac{\lambda_{m,s_j}}{P_{int}}\right)^{\varphi+M}} \right], \end{aligned} \tag{19}$$

where $\delta(\,.)$ is the Dirac function that refers to received SNR when the relays are not active. To compute the CDF of γ_{s_j}, we integrate (19) which by the help of [10, 3.194.1] results in

$$\begin{aligned} F_{\gamma_{s_j}}(\gamma) &= \sum_{L_s=0}^{N} \binom{L}{L_s} P_{\text{off}}^{L-L_s}(1-P_{\text{off}})^{L_s} \\ &+ \sum_{L_s=N+1}^{L} \binom{L}{L_s} P_{\text{off}}^{L-L_s}(1-P_{\text{off}})^{L_s} \\ &\times \xi\gamma^{\varphi} \, {}_2F_1\left(\varphi+M, \varphi; \varphi+1; -\frac{P_{int}\gamma}{\lambda_{m,s_j}P_r}\right) \end{aligned} \tag{20}$$

where $\xi = \frac{(\lambda_{m,s_j})^{M-L_s}\Gamma(\varphi+M)P_{int}^{\varphi}}{\Gamma(\varphi+1)\Gamma(M)(P_r)^{\varphi}}$ and ${}_2F_1(\,.)$ is a Gauss-hypergeometric function defined in [10].

IV. Performance Analysis

A. Outage Probability

An outage event occurs when the total received SNR falls below a certain threshold γ_{th} and is expressed as $P_{out} = \Pr(\gamma_{s_j} < \gamma_{th})$. By using (20) the user outage probability of S_j in a closed-form can be written as

$$P_{out_j} = F_{\gamma_{s_j}}(\gamma_{th}). \tag{21}$$

B. E2E BER performance

We analyze the BER performance due to errors occurring at S_j assuming that all participating relays have accurately decoded and regenerated the message. This probability could be evaluated using the following identity

$$P_e = \frac{a\sqrt{b}}{2\sqrt{\pi}} \int_0^{\infty} \frac{e^{-bu}}{\sqrt{u}} F_{\gamma_{s_j}}(u) du. \tag{22}$$

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 $(a,b) = (1,1)$. First, we represent the Gauss-hypergeometric of $F_{\gamma_{s_j}}(u)$ and also the exponential function of (22) in terms of Meijer's G-functions using [14, Eq. 10, 11], which are given, respectively, as $\frac{\varphi\, P_{int}\, u}{\Gamma(L_s)P_r}\left[G_{2,2}^{1,2}\left(-\frac{P_{int}\,u}{P_r}\Big|_{-1,-(\varphi+1)}^{-L_s,-\varphi}\right)\right]$ and $G_{0,1}^{1,0}\left(bu|_{0}^{-}\right)$. Thus, $P_{e|\mathcal{C}}$ yields as

$$\begin{aligned} P_{e|\mathcal{C}} &= \varpi\,\epsilon \int_0^{\infty} \left(u^{\varphi+\frac{1}{2}} G_{2,2}^{1,2}\left(-\frac{P_{int}u}{P_r}\Big|_{-1,-(\varphi+1)}^{-L_s,-\varphi}\right)\right. \\ &\times \left. G_{0,1}^{1,0}\left(bu|_{0}^{-}\right)\right) du, \end{aligned} \tag{23}$$

where $\varpi = \frac{a\sqrt{b}}{2\sqrt{\pi}} \frac{\Gamma(L_s)P_{int}^{\varphi}}{\Gamma(\varphi+1)\Gamma(M)(P_r)^{\varphi}}$ and $\epsilon = \frac{(\varphi)P_{int}}{\Gamma(L_s)P_r}$. Exploiting that the integral of the product of a power term and two Meijer's G-function [14, Eq. 21], (23) results in

$$P_{e|\mathcal{C}} = \varpi\,\epsilon \left(\frac{P_r}{P_{int}}\right)^{\nu} G_{2,3}^{3,1}\left(-\frac{\nu\, b\, P_r}{P_{int}}\Big|_{0,-M-\frac{1}{2},-\frac{1}{2}}^{\frac{1}{2}-\varphi,\frac{1}{2}}\right) \tag{24}$$

where $\nu = \varphi + \frac{3}{2}$. Therefore, a closed-form expression for the unconditional BER at S_j is given by

$$\begin{aligned} P_e &= 0.5 \sum_{L_s=0}^{N} \binom{L}{L_s} P_{\text{off}}^{L-L_s}(1-P_{\text{off}})^{L_s} \\ &+ \sum_{L_s=N+1}^{L} \binom{L}{L_s} P_{\text{off}}^{L-L_s}(1-P_{\text{off}})^{L_s} \\ &\times \varpi\,\epsilon \left(\frac{P_r}{P_{int}}\right)^{\nu} G_{2,3}^{3,1}\left(-\frac{\nu\, b\, P_r}{P_{int}}\Big|_{0,-M-\frac{1}{2},-\frac{1}{2}}^{\frac{1}{2}-\varphi,\frac{1}{2}}\right). \end{aligned} \tag{25}$$

V. Numerical Results and Discussion

In this section, we investigate the performance of some of the derived results through numerical examples and simulations. Without loss of generality, we assume that the relays are located on a straight line vertical to the distance between the two sources. The distance between the sources equals one.

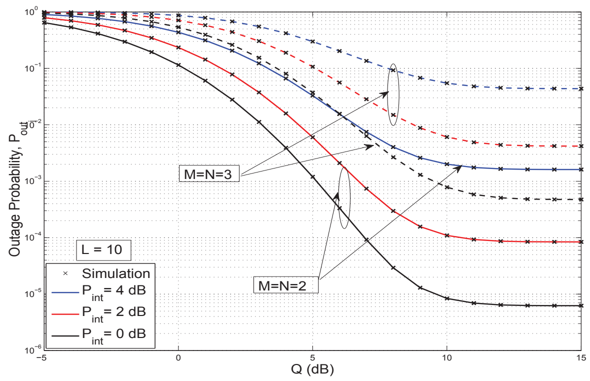

Fig. 2: Outage probability vs. Q (dB) for L=10 and $M = N = 2, 3$.

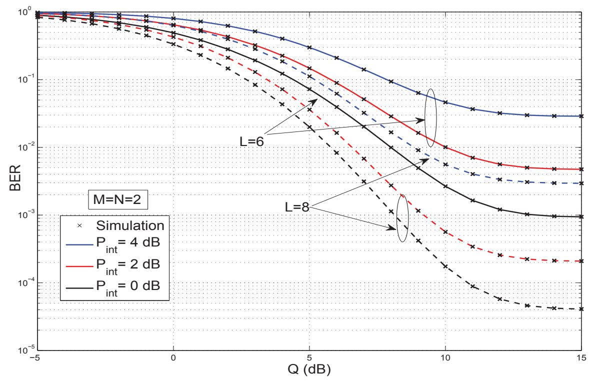

Fig. 3: BER vs. Q (dB) for L=6, 8 and $M = N = 2$.

Furthermore, the path loss exponents is set to four. We further assume that the primary system forms a cluster where PU-TXs are closely located to each others and as all PU-RXs. Unless otherwise stated, we also assume that $\lambda_{s_1,p} = \lambda_{s_2,p} = 1$, $\lambda_{m,s_1} = \lambda_{m,s_2} = 5$ and $\lambda_{m,r_i} = \lambda_m = 1$. we fix the value of $\gamma_{th} = 1$ dB, $P_r = 5$ dB.

Figs. 2 shows the outage performance of S_j versus Q for $L = 10$, $M = N = 2, 3$ and different values of $P_{int} = 0, 2, 4$dB. As observed from the figure, as the value of Q increases, the outage performance improves substantially. Clearly, as the number of existing PU-TX increases from two to three, the outage performance becomes worse as this will increase the sum of the CCIs that severely affects the received signals at transceivers. Also, the figure shows the impact of co-channel interferences on the outage performance. As P_{int} increases, it degrades the system performance significantly. However, a compensation of this loss in performance is gained by the use of beamforming process.

Figs. 3 illustrates the BER performance versus Q for L= 6, 8 and $M = N = 2$. It is obvious that the BER performance improves substantially as the number of relays increases and Q becomes looser. This is attributed to the combined cooperative diversity and beamforming which enhances the total received SNR at the receiver. In addition, it is observed from the BER and outage figures that there is an error floor in high Q region and the curves results in zero-diversity. This error flooring is due to the limitations on the secondary transmit powers and co-channel interferences.

VI. Conclusion

We investigated a cooperative two-way DF selective relaying based distributed ZFB in a spectrum-sharing system in the presence of multiple PU-RXs. The proposed system limits the interference to the PU-RXs using a distributed ZFB approach and peak interference power constraints. The beamforming weights were optimized to maximize the received SNR at both secondary transceivers and to null the interference inflicted on the primary users. We analyzed the performance of the secondary system by deriving the outage probability and BER metrics. Our numerical results showed that the combination of the distributed ZFB and the cooperative diversity enhances the secondary link performance by compensating the performance loss due to the CCIs.

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