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Cooperative Spectrum-Sharing with Two-Way AF Relaying in the Presence of Direct Communications

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Abstract

In this paper, we investigate a three-phase two-way (TW) amplify-and-forward (AF) relaying for cognitive radio networks. By utilizing the direct communications, the end user can employ diversity combining techniques, i.e., maximal ratio combining (MRC) and selection combining (SC), to achieve the full diversity. We derive the closed-form and asymptotic expressions for user and system outage probabilities which allows us to highlight the advantage of cooperative cognitive communications. The numerical results, obtained through compact forms of these outage probabilities, yield that the cognitive TW AF relaying scheme can significantly enhance the reliability of unlicensed networks in which the transmit power at secondary users is strictly governed.

Keywords: Cooperative Spectrum, AF Relaying, Two-way

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1. Introduction

With a tremendous growth of wireless multimedia services and the number of customers, it has been an enormous pressure on available frequency bands and spectrum allocation policies. However, most of frequency bands are under-utilization according to the report of Federal Communication Commission (FCC). To get around this troublesome, cognitive radio (CR) technique has been proposed to allow the unlicensed user can utilize the licensed spectrum band [1]. The principal idea of CR networks is that the secondary users (SUs) is able to use the spectrum bands of primary users (PUs) provided that the quality of service (QoS) of licensed networks is not compromised. Several CR schemes have been introduced in the literature to implement the CR network. In particular, for interweave paradigm, the unlicensed users is not allowed to occupy the spectrum bands if PU activities are detected. As such, the transmission of CR network strictly relies on the primary system. On the other hand, the underlay spectrum-sharing paradigm allows SUs to transmit its information simultaneously with PUs as long as the maximal interference does not exceed the predefined threshold. For this approach, it ensures the stable transmission for SUs at an expense of limited coverage area and low QoS.

One efficient way to alleviate the disadvantages of CR underlay scheme is to combine CR with relay networks [2, 3], where the latter is know as an efficient approach for combating the effect of fading channels and expanding the communication range through the assistance of third party named relay. In particular, relay node helps source node to transmit its signal by adopting one of relaying techniques, i.e., amplify and forward (AF) and decode and forward (DF) [4]. At destination, multiple replicas of source's message via relaying and direct links are combined by applying various diversity combining schemes, such as, maximal ratio combining (MRC) and selection combining (SC) to obtain a full diversity gain in a distributed fashion.

Although the one-way cognitive relay network can overcome both the impact of fading channels and the drawbacks of underlay scheme, the spectral efficiency of this system is still constrained by multiple time-slots owing to half-duplex relaying protocol [5]. More recently, two-way relaying (TWR) technique has drawn a lot of attention due to fully compensating this loss by permitting two users concurrently transmit its signal to each other with the help of half-duplex

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relays [6]. Despite getting higher spectral efficiency than the traditional cognitive one-way relay networks, only few works investigated the performance of two-way counterpart [7–12]. The performance of two-way relaying with single and multiple relays has been reported in [7] and [9], respectively. In [9], the exact outage probability of opportunistic two-way relaying with spectrum-sharing has been presented. Moreover, it has been proved that system performance largely depends on the number of relay nodes and the location of relay nodes together with primary user. In [10], the tight lower bound of user outage performance of in multiple primary users environment has been obtained in two cases, i.e., two users and two group of users. The optimal relay selection for two-way cognitive relay networks has been discussed in [11, 12]. In addition, relay selection combined with power allocation for two-way relaying in the presence of imperfect channel state information (CSI) were studied in [13, 14]. It is important to note that all of these previous works have only considered DF relaying and neglected the impact of direct communication.

Different from the above works, in this paper, we investigate the two-way AF relaying for underlay spectrum-sharing with the existence of the direct link between two users. Generally, there are two distinct two-way relaying schemes depending on the number of required time-slots to complete the communication [15]: i) time division broadcast (TDBC) or three-phase two-way relay (3P-TWR) and ii) multiple access broadcast (MABC) or two-phase TWR (2P-TWR) [16]. For CR networks, the performance of SU is limited due to the fact that its transmit power is governed by the maximal allowable interference power constraint at PU. As such, in this paper, we exploit the direct link in 3P-TWR where the communication reliability is enhanced via diversity combining between the direct and relaying links. Our considered scheme can enhance both spectral efficiency for cognitive relay networks while keeping the desired QoS of secondary networks satisfactorily. Our main contribution in this paper is summarized as follows:

- We consider the cognitive two-way relay networks in the presence of direct communication under the peak interference power constraint impinged on the licensed user.
- We investigate the spatial diversity gain for cognitive two-way relay networks by employing MRC and SC techniques between relaying and direct links.
- We characterize the statistics for the end-to-end SNR of cognitive two-way AF relay networks with MRC and SC by deriving the exact cumulative distribution function (CDF). Utilizing this result, the exact closed-form expressions for both user and system outage probability

2. System Model

We consider a CR network in which two secondary users (S_1 and S_2) exchange information with each other with the help of a non-regenerative relay R as shown in Fig. 1. The secondary network co-exists with the primary network that represents by one PU receiver. All nodes are operated in half-duplex mode and equipped with one antenna. In addition, all channels are assumed to be Rayleigh flat fading, time-invariant and reciprocal while exchanging data. Let us denote h_m and f_n, with $(m \in \{0, 1, 2\}, n \in \{1, 2, r\})$, as fading coefficients of data links and interference links. Particularly, h_0, h_1 and h_2 are data links between $S_1 \leftrightarrow S_2$, $S_1 \leftrightarrow R$ and $S_2 \leftrightarrow R$, respectively. Similarly, f_1, f_2 and f_r are interference links between $S_1 \leftrightarrow PU$, $S_2 \leftrightarrow PU$ and $R \leftrightarrow PU$, successively. As a consequence, the channel gains, i.e., $|h_m|^2$ and $|f_n|^2$, are exponential random variables (RVs) with parameter λ_m and ω_n.

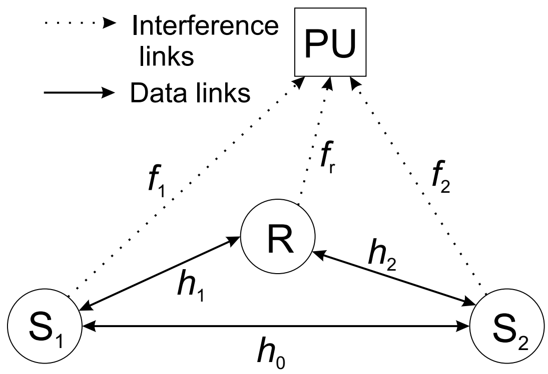

Figure 1. Two-way relaying in cognitive cooperative communications.

On the other hand, owing to adopting underlay approach, the transmit power of secondary users could not exceed the maximal tolerable interference level $\mathcal{I}_p$. Mathematically, we have

$$P_n = \frac{\mathcal{I}_p}{|f_n|^2}. \tag{1}$$

The communication between S_1 and S_2 is taken over three phase. In the first phase, user S_1 transmits its modulated signal x_1 to user S_2 and relay R. Followed by, S_2 send its signal x_2 to user S_1 and relay R in the second phase. The received signal at relay R and user S_j in i-phase $(i, j \in \{1, 2\}, i \neq j)$ is given by

$$\begin{aligned} y_{R,i} &= \sqrt{P_i} h_i x_i + n_{R,i} \\ y_{S_j,i} &= \sqrt{P_i} h_0 x_i + n_{S_j,i}, \end{aligned} \tag{2}$$

where n is a circular symmetric complex Gaussian random variable with zero mean and variance $\mathcal{N}_0$. Finally, in the third phase, relay R broadcasts the scaling version of two previous received signals as

$$x_{\mathrm{R},3} = G\left(y_{\mathrm{R},1} + y_{\mathrm{R},2}\right), \quad (3)$$

where $G = \sqrt{\frac{P_r}{P_1|h_1|^2+P_2|h_2|^2+2\mathcal{N}_0}}$ is the amplifying gain. Signal is received by user S_j in the third phase after canceling self-interference term is given as follows:

$$y_{\mathrm{S}_j,3} = G\sqrt{P_i}h_i h_j x_i + Gh_j\left(n_{\mathrm{R},1} + n_{\mathrm{R},2}\right) + n_{\mathrm{S}_j,3}. \quad (4)$$

3. Performance Analysis

3.1. Maximal Ratio Combining

For MRC technique, two end-users will combine two links, namely, direct and indirect link, linearly. The end to end signal to noise ratios (SNRs) at user S_j denoted as γ_{ij} is obtained as

$$\gamma_{ij} = P_i\left|h_0\right|^2 + \frac{P_r P_i\left|h_i\right|^2\left|h_j\right|^2}{2P_r\left|h_j\right|^2 + P_i\left|h_i\right|^2 + P_j\left|h_j\right|^2 + 2}. \quad (5)$$

The upper bound of equation (5) is given by

$$\gamma_{ij} \le P_i\left|h_0\right|^2 + \min\left(\frac{P_r P_i\left|h_i\right|^2}{2}P_r + P_j, P_r\left|h_j\right|^2\right). \quad (6)$$

User Outage Probability (UOP). In this subsection, we study the outage probability (OP) of each user with MRC is used at the secondary users. OP at user S_j occurs when the information flow from node $i \to j$ is below the target rate $\mathcal{R}$. Mathematically, we have

$$\mathrm{UOP}^j_{\mathrm{MRC}} = \Pr\left[\frac{1}{3}\log_2\left(1+\gamma_{ij}\right) < \mathcal{R}\right] = \Pr\left[\gamma_{ij} < \gamma_{\mathrm{th}}\right], \quad (7)$$

where $\gamma_{\mathrm{th}} = 2^{3\mathcal{R}} - 1$. Due to sharing the same variable, i.e., $|f_i|^2$ the direct and indirect link are not independent. As a result, (7) is rewritten as

$$\mathrm{UOP}^j_{\mathrm{MRC}} = \int_0^\infty\int_0^\gamma F_{\gamma_{\mathrm{R}}\left||f_i|^2\right.}\left(\gamma - y\right) f_{\gamma_0\left||f_i|^2\right.}(y)\, f_{|f_i|^2}(x)\,dy\,dx. \quad (8)$$

As can be observed in (8), we need to find out the cumulative distribution function (CDF) of two links before evaluating the user outage probability. The CDF of indirect link under condition $|f_i|^2$ is given as

$$F_{\gamma_{\mathrm{R}}|x}(\gamma) = \Pr\left[\min\left(\frac{by\overline{\gamma}}{2bx+ax}, \frac{\overline{\gamma}z}{a}\right) < \gamma\right]. \quad (9)$$

After some manipulations with the help of [17, Eq. 354.4], we get (10) as shown in the top of this page. In (10), $\overline{\gamma} = \frac{\mathcal{I}_p}{\mathcal{N}_0}$ denotes as an average SNRs of system and $E_1(x)$ is exponential integral function, defined in [17, Eq. 8.211].

The probability density function (PDF) of $|f_i|^2$ and $\gamma_{0||f_i|^2}$ are given as

$$f_{|f_i|^2}(x) = \frac{1}{\omega_i}\exp\left(-\frac{x}{\omega_i}\right), \quad (11)$$

$$f_{\gamma_0|x}(y) = \frac{x}{\overline{\gamma}\lambda_0}\exp\left(-\frac{yx}{\overline{\gamma}\lambda_0}\right). \quad (12)$$

Finally, the outage probability at user S_j is given in equation (13) at the top of next page.

Here

$$J_1(a,b,c) = \frac{ac}{b+ac}, \quad J_2(a,b,c,d,g) = A_1\log\left(1-\frac{gb}{a}\right) + B_1\log\left(1-\frac{gd}{c}\right) + \frac{gB_2d^2}{c(c-dg)}, \quad (14)$$

where $A_1 = -\frac{1}{bd^2\left(\frac{a}{b}-\frac{c}{d}\right)^2}$, $B_2 = -\frac{1}{bd^2\left(\frac{c}{d}-\frac{a}{b}\right)}$ and $B_1 = \frac{1}{bd^2\left(\frac{c}{d}-\frac{a}{b}\right)^2}$ and

$$J_3(a,b,c,d,g) = -\frac{8\sqrt{2}\pi\mathbf{a}_N\mathbf{a}_I}{b^3}\sum_{n=1}^{N+1}\sum_{i=1}^{I+1}\sum_{o=1}^{3}\sqrt{b_n} \times\left[C_oJ_4\left(\gamma,\frac{E+F}{2},o\right) + D_oJ_4\left(\gamma,\frac{E-F}{2},o\right)\right],$$

$$J_4(a,b,n) = \begin{cases}\log\left(1-\frac{a}{b}\right) & ;n=1\\ \frac{(-b)^{1-n}-(a-b)^{1-n}}{(n-1)} & ;n\neq 1\end{cases} \quad (15)$$

$$E = \frac{a+bd-c\left(1-4b_nb_i\right)}{b}, \quad (16)$$

$$F = \sqrt{E^2 - 4\left(\frac{ad}{b} - \frac{cg}{b}\left(1-4b_nb_i\right)\right)} \quad (17)$$

$$C_o = \frac{1}{(3-o)!}\frac{d^{(3-o)}}{dy}\left[\frac{(g-y)(y-d)}{\left(y-\frac{E+F}{2}\right)^3}\right]\Bigg|_{y=\frac{E-F}{2}}$$

$$D_o = \frac{1}{(3-o)!}\frac{d^{(3-o)}}{dy}\left[\frac{(g-y)(y-d)}{\left(y-\frac{E-F}{2}\right)^3}\right]\Bigg|_{y=\frac{E+F}{2}}. \quad (18)$$

Here $\mathbf{a}_N$, $\mathbf{a}_I$, b_n and b_i are calculated similar in [18].

The remain UOP at S_i gets easily by applying the similar steps.

System Outage Probability (SOP). The system outage probability (SOP) appears when one of two user's data

$$F_{\gamma_R|x}(\gamma) = 1 - \frac{\overline{\gamma}\lambda_j}{\gamma\omega_r + \overline{\gamma}\lambda_j}\exp\left(-2\frac{\gamma x}{\lambda_i\overline{\gamma}}\right) + x\frac{\overline{\gamma}\left(\lambda_j\right)^2\gamma\omega_r}{\lambda_i\omega_j\left(\gamma\omega_r + \overline{\gamma}\lambda_j\right)^2}\exp\left[-x\left(\frac{2\gamma}{\lambda_i\overline{\gamma}} - \frac{\gamma\lambda_j\omega_r}{\lambda_i\omega_j\left(\gamma\omega_r + \overline{\gamma}\lambda_j\right)}\right)\right]E_1\left(x\frac{\gamma\lambda_j\omega_r}{\lambda_i\omega_j\left(\gamma\omega_r + \overline{\gamma}\lambda_j\right)}\right). \tag{10}$$

$$\mathrm{UOP}^j_{\mathrm{MRC}} = J_1\left(\omega_i, \overline{\gamma}\lambda_0, \gamma_{\mathrm{th}}\right) - \frac{\lambda_j}{\lambda_0\omega_i}J_2\left(\gamma_{\mathrm{th}}\omega_r + \overline{\gamma}\lambda_j, \omega_r, \frac{2\gamma_{\mathrm{th}}}{\overline{\gamma}\lambda_i} + \frac{1}{\omega_i}, \frac{2}{\overline{\gamma}\lambda_i} - \frac{1}{\overline{\gamma}\lambda_0}, \gamma_{\mathrm{th}}\right) + \frac{\left(\lambda_j\right)^2}{\lambda_0\lambda_i\omega_i\omega_j\omega_r}J_3\left(\frac{2\gamma}{\overline{\gamma}\lambda_i} + \frac{1}{\omega_i}, \frac{2}{\overline{\gamma}\lambda_i} - \frac{1}{\overline{\gamma}\lambda_0}, \frac{\lambda_j}{\lambda_i\omega_j}, \gamma + \frac{\overline{\gamma}\lambda_j}{\omega_r}, \gamma\right). \tag{13}$$

is under the threshold, γ_{th}. Mathematically, we have

$$\begin{aligned}\mathrm{SOP}_{\mathrm{MRC}} &= \Pr\left[\min\left(\gamma_{ij}, \gamma_{ji}\right) \le \gamma_{\mathrm{th}}\right] \\ &= \Pr\left\{\min\left[P_i|h_0|^2 + \min\left(\frac{P_rP_i|h_i|^2}{2P_r + P_j}, P_r\left|h_j\right|^2\right)\right.\right. \\ &\quad \left.\left. P_j|h_0|^2 + \min\left(\frac{P_rP_j\left|h_j\right|^2}{2P_r + P_i}, P_r|h_i|^2\right)\right] \le \gamma_{\mathrm{th}}\right\}\end{aligned} \tag{19}$$

Equation (19) is bounded by the following expression

$$\begin{aligned}\mathrm{SOP}_{\mathrm{MRC}} &= \Pr\left[\min\left(P_i, P_j\right)|h_0|^2 + \frac{P_r}{2P_r + \max\left(P_i, P_j\right)}\min\left(P_i|h_i|^2, P_j\left|h_j\right|^2\right) \le \gamma_{\mathrm{th}}\right] \\ &= \underbrace{\Pr\left[T_1 \le \gamma_{\mathrm{th}}, P_i \le P_j\right]}_{\Omega_1} + \underbrace{\Pr\left[T_2 \le \gamma_{\mathrm{th}}, P_j \le P_i\right]}_{\Omega_2},\end{aligned}$$

$$T_1 = P_i|h_0|^2 + \frac{P_r\min\left(P_i|h_i|^2, P_j\left|h_j\right|^2\right)}{2P_r + P_j}, \tag{20}$$

$$T_2 = P_j|h_0|^2 + \frac{P_r\min\left(P_i|h_i|^2, P_j\left|h_j\right|^2\right)}{2P_r + P_i}. \tag{21}$$

By using the same approach as UOP, the CDF of indirect links of Ω_i is given in equation (22) at the next page. After that we get Ω_i which is offer in equation (23) at the next page. Here

$$J_5(a, b, c, d, g) = \frac{1}{d^2}\left[G_1J_4(g, a, 1) + H_1J_4(g, b, 1) + K_1J_4\left(g, -\frac{c}{d}, 1\right) + K_2J_4\left(g, -\frac{c}{d}, 2\right)\right], \tag{24}$$

where $G_1 = \frac{1}{(a-b)\left(a+\frac{c}{d}\right)^2}$, $H_1 = \frac{1}{(b-a)\left(b+\frac{c}{d}\right)^2}$, $K_2 = \frac{1}{\left(\frac{c}{d}+a\right)}\frac{1}{\left(\frac{c}{d}+b\right)}$ and $K_1 = \frac{a+b+\frac{2c}{d}}{\left(a+\frac{c}{d}\right)^2\left(b+\frac{c}{d}\right)^2}$, and

$$\begin{aligned}J_6(a, b, c, d, e, f, g, h, i) &= \frac{1}{b^3}\sum_{u=1}^{2}\sum_{k=1}^{4}U_{n_k,u}J_4\left(\gamma_{\mathrm{th}}, n_k, u\right) \\ &+ \frac{2}{b^3}\sum_{u=1}^{3}\sum_{k=3}^{4}\left[\sum_{o=3}^{4}V_{n_k,u}J_7\left(n_o, n_k, \gamma_{\mathrm{th}}, u\right) - \sum_{o=5}^{6}V_{n_k,u}J_7\left(n_o, n_k, \gamma_{\mathrm{th}}, u\right)\right]\end{aligned} \tag{25}$$

where

$$\begin{aligned}U_{n_k,u} &= \frac{1}{(2-u)!}\frac{d^{(2-u)}}{dy} \times \left[\frac{\left(y-n_k\right)^2(i-y)(a-y)(S-3Q)}{\left(y-n_1\right)^2\left(y-n_2\right)^2\left(y-n_3\right)^2\left(y-n_4\right)^2}\right]\Bigg|_{y=n_k}, \\ V_{n_k,u} &= \frac{1}{(3-u)!}\frac{d^{(3-u)}}{dy}\left[\frac{\left(y-n_k\right)^3(i-y)(a-y)}{\left(y-n_3\right)^3\left(y-n_4\right)^3}\right]\Bigg|_{y=n_k}, \\ Q &= S + (a-y)\left(y + \frac{c}{b}\right) - \frac{d}{b}y^2 + \frac{d(i+e)}{b}y - \frac{edi}{b}, \\ S &= \frac{f}{b}y^2 - \frac{f}{b}(g+h)y + \frac{fgh}{b},\end{aligned} \tag{26}$$

n_1, n_2 are roots of $S-Q$, n_3, n_4 are roots of Q, n_5, n_6 are roots of S and

$$J_7(a, b, c, n) = \int_0^c \frac{\log(a-y)}{(y-b)^n}dy = W(a) - W(a-c). \tag{27}$$

Here W is calculated with the support of [17, 2.727.1].

On the other hand, due to the symmetric between Ω_1 and Ω_2, we solely need to obtain Ω_1 then taking similar steps to find out Ω_2.

$$\begin{aligned}F_{\gamma_{\mathrm{R}}^{\mathrm{sys}}|x}(\gamma) =& 1-\exp\left(-\frac{x}{\omega_j}\right)-\frac{\overline{\gamma}\lambda_j}{\overline{\gamma}\lambda_j\omega_j+\gamma\omega_r\omega_j}\exp\left(-x\frac{2\gamma}{\overline{\gamma}\lambda_i}\right)\left\{\frac{\overline{\gamma}\lambda_j\omega_j}{\overline{\gamma}\lambda_j+2\gamma\omega_j}\left[1-\exp\left(-x\frac{\overline{\gamma}\lambda_j+2\gamma\omega_j}{\overline{\gamma}\lambda_j\omega_j}\right)\right]\right.\\&-x\frac{\gamma\omega_r\lambda_j}{\lambda_i}\left(\overline{\gamma}\lambda_j+\gamma\omega_r\right)\exp\left(x\frac{\gamma\omega_r\left(\overline{\gamma}\lambda_j+2\gamma\omega_j\right)}{\overline{\gamma}\omega_j\lambda_i\left(\overline{\gamma}\lambda_j+\gamma\omega_r\right)}\right)\\&\left.\times\left\{E_1\left(x\frac{\gamma\omega_r\left(\overline{\gamma}\lambda_j+2\gamma\omega_j\right)}{\overline{\gamma}\omega_j\lambda_i\left(\overline{\gamma}\lambda_j+\gamma\omega_r\right)}\right)-E_1\left[x\left(\frac{\overline{\gamma}\lambda_j+2\gamma\omega_j}{\overline{\gamma}\lambda_j\omega_j}\right)\left(\frac{\gamma\omega_r\lambda_j+\lambda_i\left(\overline{\gamma}\lambda_j+\gamma\omega_r\right)}{\lambda_i\left(\overline{\gamma}\lambda_j+\gamma\omega_r\right)}\right)\right]\right\}\right\}. \end{aligned} \tag{22}$$

$$\begin{aligned}\Omega_1 =& \int_0^\infty\int_0^\gamma F_{\gamma_R^{\mathrm{sys}}||f_i|^2}(\gamma-y)\,f_{\gamma_0||f_i|^2}(y)\,f_{|f_i|^2}(x)\,dydx\\
=&J_1\left(\omega_i,\overline{\gamma}\lambda_0,\gamma_{\mathrm{th}}\right)-\left(1+\tfrac{\omega_j}{\omega_i}\right)J_1\left(\left(\tfrac{1}{\omega_i}+\tfrac{1}{\omega_j}\right)^{-1},\overline{\gamma}\lambda_0,\gamma_{\mathrm{th}}\right)+\\
&\tfrac{\overline{\gamma}(\lambda_j)^2}{2\lambda_0\omega_i\omega_j\omega_r}\left[J_5\left(\tfrac{\overline{\gamma}\lambda_j\omega_j+\gamma\omega_r\omega_j}{\omega_r\omega_j},\tfrac{\overline{\gamma}\lambda_j+2\gamma\omega_j}{2\omega_j},\tfrac{2\gamma}{\overline{\gamma}\lambda_i}+\tfrac{1}{\omega_i},\tfrac{1}{\overline{\gamma}\lambda_0}-\tfrac{2}{\overline{\gamma}\lambda_i},\gamma_{\mathrm{th}}\right)\right.\\
&\left.-J_5\left(\tfrac{\overline{\gamma}\lambda_j\omega_j+\gamma\omega_r\omega_j}{\omega_r\omega_j},\tfrac{\overline{\gamma}\lambda_j+2\gamma\omega_j}{2\omega_j},\tfrac{2\gamma}{\overline{\gamma}\lambda_i}+\tfrac{1}{\omega_i}+\tfrac{2\gamma}{\overline{\gamma}\lambda_j}+\tfrac{1}{\omega_j},\tfrac{1}{\overline{\gamma}\lambda_0}-\tfrac{2}{\overline{\gamma}\lambda_i}-\tfrac{2}{\overline{\gamma}\lambda_j},\gamma_{\mathrm{th}}\right)\right]\\
&+\tfrac{(\lambda_j)^2}{\lambda_0\lambda_i\omega_i\omega_j\omega_r}\left[J_6\left(\gamma+\tfrac{\overline{\gamma}\lambda_j}{\omega_r},\tfrac{1}{\overline{\gamma}\lambda_0}-\tfrac{2}{\overline{\gamma}\lambda_i},\tfrac{1}{\omega_i}+\tfrac{2\gamma}{\overline{\gamma}\lambda_i},\tfrac{2}{\overline{\gamma}\lambda_i},\gamma+\tfrac{\overline{\gamma}\lambda_j}{2\omega_j},\tfrac{2}{\overline{\gamma}\lambda_i},\gamma,\gamma+\tfrac{\overline{\gamma}\lambda_j}{2\omega_j},\gamma\right)\right.\\
&\left.-J_6\left(\gamma+\tfrac{\overline{\gamma}\lambda_j}{\omega_r},\tfrac{1}{\overline{\gamma}\lambda_0}-\tfrac{2}{\overline{\gamma}\lambda_i},\tfrac{1}{\omega_i}+\tfrac{2\gamma}{\overline{\gamma}\lambda_i},\tfrac{2}{\overline{\gamma}\lambda_i},\gamma+\tfrac{\overline{\gamma}\lambda_j}{2\omega_j},\tfrac{2}{\overline{\gamma}\lambda_j}+\tfrac{2}{\overline{\gamma}\lambda_i},\gamma+\tfrac{\overline{\gamma}\lambda_i\lambda_j}{\omega_r(\lambda_i+\lambda_j)},\gamma+\tfrac{\overline{\gamma}\lambda_j}{2\omega_j},\gamma\right)\right].\end{aligned} \tag{23}$$

Finally, the $\mathrm{SOP}_{\mathrm{MRC}}$ is performed as follows:

$$\mathrm{SOP}_{\mathrm{MRC}} = \Omega_1 + \Omega_2. \tag{28}$$

Asymptotic System Outage Probability (ASOP). In this subsection, we derive the asymptotic system outage probability (ASOP) for discovering the system diversity. As this case, we assume that $\overline{\gamma} \to \infty$ and using the fact that

$$\begin{aligned}\mathrm{ASOP}_{\mathrm{MRC}} &\overset{\overline{\gamma}\to\infty}{=} \mathrm{AUOP}^1_{\mathrm{MRC}} + \mathrm{AUOP}^2_{\mathrm{MRC}}\\ &\quad - \mathrm{AUOP}^1_{\mathrm{MRC}}\mathrm{AUOP}^2_{\mathrm{MRC}}\\ \mathrm{ASOP}_{\mathrm{MRC}} &= \mathrm{AUOP}^1_{\mathrm{MRC}} + \mathrm{AUOP}^2_{\mathrm{MRC}}.\end{aligned} \tag{29}$$

Here $\mathrm{AUOP}^i_{\mathrm{MRC}}$, $i \in \{1, 2\}$, is the asymptotic of i-th user outage probability. By using binomial expansion [17, Eq. 1.110] and vanishing the second term, the asymptotic OP of S_i is given in expression (30) at next page. Here

$$\begin{aligned}
\mathcal{E} &= \sum_{n=1}^{N+1}\sum_{i=1}^{I+1}\frac{8\sqrt{2b_n}\pi a_{\mathbf{N}}a_{\mathbf{I}}\left(\lambda_i\lambda_j\lambda_0\right)^2}{\omega_i\omega_j\omega_r\left(\lambda_i-2\lambda_0\right)^3}, \mathcal{C} = \frac{a_2 D\gamma_{\mathrm{th}}}{a_1 a_2},\\
\mathcal{B} &= \frac{3\left(2a_2\omega_r+\left(\lambda_j-a_1\omega_r\right)\right)\gamma_{\mathrm{th}}}{2a_1\omega_r\left[a_2\left(a_1-4a_2\right)\right]^2}, a_1 = \frac{-\lambda_0\lambda_j\left(4b_n b_i-1\right)}{\omega_j\left(\lambda_i-2\lambda_0\right)},\\
\mathcal{A} &= \frac{\gamma_{\mathrm{th}}\left(\lambda_j-a_1\omega_r\right)}{2\omega_r\left(a_1a_2\right)^2\left(a_1-4a_2\right)}, \mathcal{F} = \frac{-2\left(a_1\left(a_1-4a_2\right)D+1\right)}{\sqrt[3]{a_1\left(a_1-4a_2\right)}},\\
\mathcal{D} &= \frac{3\left(\lambda_j-a_1\omega_r\right)-6a_2\omega_r+\omega_r\left(a_1-4a_2\right)}{\omega_r a_1\left[\left(a_1-4a_2\right)\right]^2},\\
\mathcal{G} &= \mathcal{F}\left[\tanh^{-1}\left(a_6\right)-\tanh^{-1}\left(a_7\right)\right], a_6 = \frac{2\gamma_{\mathrm{th}}-a_1\overline{\gamma}}{\overline{\gamma}\sqrt{a_1\left(a_1-4a_2\right)}},\\
\mathcal{H} &= \frac{2a_2\left(\lambda_j-\omega_r a_1\right)\left(\overline{\gamma}\right)^2+a_5\left(\overline{\gamma}\right)+a_2a_3a_4\left(2\lambda_j-\omega_r a_1\right)}{\left(\overline{\gamma}\right)^2\omega_r\left(a_2+\frac{\gamma_{\mathrm{th}}}{\overline{\gamma}}\right)},\\
a_2 &= \frac{\lambda_i\omega_j}{\omega_i\omega_r\left(4b_nb_i-1\right)}, a_3 = \frac{\gamma_{\mathrm{th}}\left(\lambda_j-a_1\omega_r\right)}{a_2\left(2\lambda_j-a_1\omega_r\right)}\\
a_5 &= 2a_2\left(\lambda_j-\omega_r a_1\right)\left(a_3+a_4\right)+\omega_r\left(a_2a_3+a_1\gamma_{\mathrm{th}}-a_2\gamma_{\mathrm{th}}\right),\\
a_4 &= \frac{\gamma_{\mathrm{th}}}{2a_2}-\frac{\gamma_{\mathrm{th}}}{a_1}, a_7 = \sqrt{\frac{a_1}{a_1-4a_2}},
\end{aligned} \tag{31}$$

$$\mathrm{AUOP}^{\mathrm{i}}_{\mathrm{MRC}} \overset{\overline{\gamma}\to\infty}{=} \mathcal{E}\left\{\mathcal{G} - \frac{1}{(\overline{\gamma})}\left[\mathcal{A}+\mathcal{B}+\mathcal{C} - \frac{\gamma_{\mathrm{th}}}{a_1 (a_2)^2}\mathcal{H}\right] - \frac{1}{(\overline{\gamma})^2}\left[\frac{\gamma_{\mathrm{th}}}{a_2}(\mathcal{A}+\mathcal{C}) + \frac{2\gamma_{\mathrm{th}}}{a_1}(\mathcal{B}-\mathcal{A})\right]\right\} \quad (30)$$

Moreover, the AUOP of S_j is obtained by applying the similar approach. Finally, the ASOP of MRC is obtained by substituting equation (30) into (29).

As can be seen in (30), the diversity gain of consider system with MRC technique is equal to 2.

3.2. Selection Combining

For SC, the upper bound of γ_{ij} is given as

$$\gamma_{ij} \le \max\left[P_i |h_0|^2, \min\left(\frac{P_r P_i |h_i|^2}{2P_r + P_j}, P_r |h_j|^2\right)\right]. \quad (32)$$

User Outage Probability. For this technique, the user outage event occurs when the largest link between direct and indirect links is below the predefined threshold γ_{th} and it is given as follows:

$$\begin{aligned}\mathrm{UOP}^j_{\mathrm{SC}} &= \int_0^\infty F_{\gamma_{R||f_i|^2}}(\gamma) f_{\gamma_{0||f_i|^2}}(y) f_{|f_i|^2}(x)\,dx \\ &= 1 - \frac{\overline{\gamma}\lambda_0}{\overline{\gamma}\lambda_0 + \gamma_{\mathrm{th}}\omega_i} - \frac{\overline{\gamma}\lambda_j}{\gamma_{\mathrm{th}}\omega_r + \overline{\gamma}\lambda_j} \\ &\times\left[\frac{\overline{\gamma}\lambda_i}{\overline{\gamma}\lambda_i + 2\gamma_{\mathrm{th}}\omega_i} - \frac{\overline{\gamma}\lambda_0\lambda_i}{\overline{\gamma}\lambda_0\lambda_i + \gamma_{\mathrm{th}}\lambda_i\omega_i + 2\gamma_{\mathrm{th}}\lambda_0\omega_i}\right] \\ &+\left[J_8(2,\mathcal{H},\chi(-\mathcal{H})) - J_8\left(2,\mathcal{H},\chi(-\mathcal{H}) + \frac{\gamma_{\mathrm{th}}}{\overline{\gamma}\lambda_0}\right)\right] \\ &\times \frac{\gamma_{\mathrm{th}}\overline{\gamma}\lambda_j^2\omega_r}{\omega_i\lambda_i\omega_j\left(\gamma_{\mathrm{th}}\omega_r + \overline{\gamma}\lambda_j\right)^2}. \end{aligned} \quad (33)$$

Here $\mathcal{H} = \frac{\gamma_{\mathrm{th}}\lambda_j\omega_r}{\lambda_i\omega_j(\gamma_{\mathrm{th}}\omega_r + \overline{\gamma}\lambda_j)}$, $\chi(x) = \frac{2\gamma_{\mathrm{th}}}{\overline{\gamma}\lambda_i} + \frac{1}{\omega_i} + x$ and $J_8(a,b,c) = \int_0^\infty x^{a-1}\exp(-cx) E_1(bx)\,dx$ is calculated with the assistance of [17, 6.228.2].

System Outage Probability. The SOP with SC at the terminal can be bounded as follows:

$$\begin{aligned}\mathrm{SOP}_{\mathrm{SC}} &= \Pr\left\{\max\left[\min(P_i,P_j)|h_0|^2, \frac{P_r}{2P_r + \max(P_i,P_j)}\right.\right. \\ &\left.\left.\times\min\left(P_i|h_i|^2, P_j|h_j|^2\right)\right] \le \gamma_{\mathrm{th}}\right\} \\ &= \underbrace{\Pr\left[R_1 \le \gamma_{\mathrm{th}}, P_i \le P_j\right]}_{\pi_1} + \underbrace{\Pr\left[R_2 \le \gamma_{\mathrm{th}}, P_j \le P_i\right]}_{\pi_2}\end{aligned}$$

$$R_1 = \max\left[P_i|h_0|^2, \frac{P_r}{2P_r + P_j}\min\left(P_i|h_i|^2, P_j|h_j|^2\right)\right] \quad (34)$$

$$R_2 = \max\left[P_j|h_0|^2, \frac{P_r}{2P_r + P_i}\min\left(P_i|h_i|^2, P_j|h_j|^2\right)\right] \quad (35)$$

π_1 is obtained by taking the average of direct and indirect links over the interference links and given at the next page.

Here $\mathcal{P} = \frac{\overline{\gamma}\lambda_j\omega_j}{\overline{\gamma}\lambda_j + 2\gamma_{\mathrm{th}}\omega_j}$, $\mathcal{Q} = \mathcal{H}\omega_j$. Like MRC case, π_1 and π_2 are symmetric so π_2 can be performed similar to π_1 by changing $\lambda_i = \lambda_j$, $\omega_i = \omega_j$, respectively.

Finally, the $\mathrm{SOP}_{\mathrm{SC}}$ is given as

$$\mathrm{SOP}_{\mathrm{SC}} = \pi_1 + \pi_2. \quad (37)$$

Asymptotic System Outage Probability (ASOP). For SC, the ASOP is calculated directly from equation (36) and (37) and given as follows:

$$\pi_1 \overset{\overline{\gamma}\to\infty}{=} \frac{1}{(\overline{\gamma})^2}\mathcal{X}\frac{(\gamma_{\mathrm{th}}\omega_i)^2\omega_r}{\lambda_0\lambda_i\omega_j}. \quad (38)$$

Here ${}_2F_1(a,b;c;z)$ is gaussian hypergeometric function which is defined in [17, Eq. 9.100] and $\mathcal{X} = \frac{\omega_i(\omega_j)^2}{(\omega_i+\omega_j)^3}\left[1 - {}_2F_1\left(1,1;2;\frac{\omega_j}{\omega_i+\omega_j}\right)\right] - 2\left[1 - {}_2F_1\left(1,1;2;1 - \frac{\gamma_{\mathrm{th}}\omega_r\omega_i}{\overline{\gamma}\omega_j\lambda_i}\right)\right]$.

From (38), it is clear that the diversity gain of SC combining has the same order with MRC. In addition, although two techniques have the same diversity gain, they are quite different in coding gain as can be observed in equation (30) and (38).

4. Numerical Results

Let us consider our simulation model in two-dimensional plane in which user S_1 and S_2 locate at (0,0) and (1,0), respectively. Whereas, the position of relay and primary user are $(x_{\mathrm{R}}, y_{\mathrm{R}})$ and $(x_{\mathrm{PU}}, y_{\mathrm{PU}})$, successively. Furthermore, only the location of relay and PU is changeable when two users situation is fixed throughout this section. The channel gain λ_m and ω_n are calculated by a simplified path loss model, i.e., $\lambda_1 = d^{\eta}_{\mathrm{S_1R}}$, with d_{ij} is distance from node i to j, η is path loss exponent.

Fig. 2 and Fig. 3 plot UOP and SOP of MRC and SC combining with the location of relay and PU are (0.4,0.2) and (0.8,0.8), respectively. As can be seen in Fig. 2, our analyses absolutely match with simulation results. Moreover, the SOP curve is equal to the curve

$$\begin{aligned}
\pi_1 &= 1 - \frac{\omega_j}{\omega_j + \omega_i} - \frac{\overline{\gamma}\lambda_0}{\overline{\gamma}\lambda_0 + \gamma_{\rm th}\omega_i} + \frac{\overline{\gamma}\lambda_0\omega_j}{\overline{\gamma}\lambda_0\omega_j + \overline{\gamma}\lambda_0\omega_i + \gamma_{\rm th}\omega_i\omega_j} \\
&\quad - \frac{\left(\overline{\gamma}\lambda_j\right)^2}{\omega_i\left(\overline{\gamma}\lambda_j + \gamma_{\rm th}\omega_r\right)\left(\overline{\gamma}\lambda_j + 2\gamma_{\rm th}\omega_j\right)}\left[\frac{1}{\chi(0)} - \frac{1}{\chi\left(\frac{1}{\mathcal{P}}\right)} - \frac{1}{\chi\left(\frac{\gamma_{\rm th}}{\overline{\gamma}\lambda_0}\right)} + \frac{1}{\chi\left(\frac{1}{\mathcal{P}} + \frac{\gamma_{\rm th}}{\overline{\gamma}\lambda_0}\right)}\right] \\
&\quad + \frac{\overline{\gamma}\lambda_j^2\gamma_{\rm th}\omega_r}{\omega_j\lambda_i\left(\overline{\gamma}\lambda_j + \gamma_{\rm th}\omega_r\right)^2} \\
&\quad \times\left[J_8\left(2, \frac{\mathcal{Q}}{\mathcal{P}}, \chi\left(-\frac{\mathcal{Q}}{\mathcal{P}}\right)\right) - J_8\left(2, \frac{\mathcal{Q}+1}{\mathcal{P}}, \chi\left(-\frac{\mathcal{Q}}{\mathcal{P}}\right)\right)\right. \\
&\quad \left. - J_8\left(2, \frac{\mathcal{Q}}{\mathcal{P}}, \chi\left(\frac{\gamma_{\rm th}}{\overline{\gamma}\lambda_0} - \frac{\mathcal{Q}}{\mathcal{P}}\right)\right) + J_8\left(2, \frac{\mathcal{Q}+1}{\mathcal{P}}, \chi\left(\frac{\gamma_{\rm th}}{\overline{\gamma}\lambda_0} - \frac{\mathcal{Q}}{\mathcal{P}}\right)\right)\right].
\end{aligned} \tag{36}$$

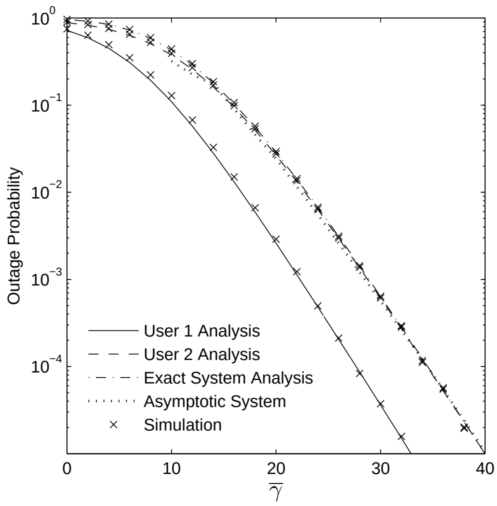

Figure 2. Outage Probability of MRC vs $\overline{\gamma}$ with $\mathcal{R} = 1$ and $\eta = 3$.

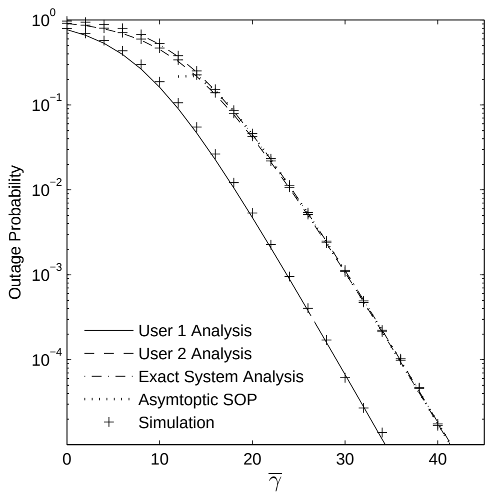

Figure 3. Outage Probability of SC vs $\overline{\gamma}$ with $\mathcal{R} = 1$ and $\eta = 3$.

of UOP at user 2 especially in high SNRs region. It shows that the overall outage probability of consider network is completely depend on the weaker user's rate. In addition, the ASOP also has the same value with exact curve in high SNRs regime.

Fig. 3 presents all of outage probability in case SC combining instead of MRC combining. Similar to MRC circumstances, the SOP of SC combining is constrained by the UOP of the weaker rate.

Fig. 4 illustrates a comparison between two diversity combining. It has proven our above analyses that two schemes have the same diversity gain but different in coding gain. More precisely, the MRC combining is only better than SC about 1 dB in high SNRs regime.

Fig. 5 plots the OP versus x_R where $y_R = 0$, and PU = (0.8,0.8). As we can be seen that when x_R is quite small or it is close to the S_1, the UOP of S_1 is outperform than S_2 and vice versa. In addition, the SOP only leans on the weaker rate while the relative position between relay node and primary user is sufficient large, whereas it has a little gap with the weaker rate. Once again, the MRC technique only get a bit better than SC in all of OP curves.

Fig. 6 illustrates the impact of PU position on the performance of consider system. Particularly, the location of PU is changing from (0,1) to (1,1), it means only the x-axis is vary. In this figure, we see that when the PU is proximity to S_1 or x_{PU} is tiny, the SOP is limited by UOP1 curve and vice versa. It can be explained that the transmit power of a specific user is approach to zero when the PU is quite closely. Thereby, it easily go into outage events.

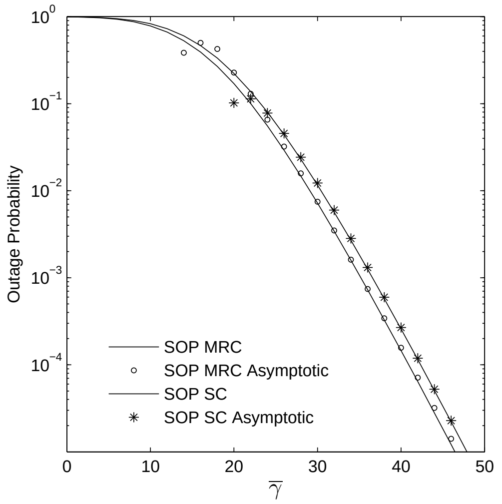

Figure 4. SOP of different diversity combining with $\mathcal{R} = 1$ and $\eta = 3$.

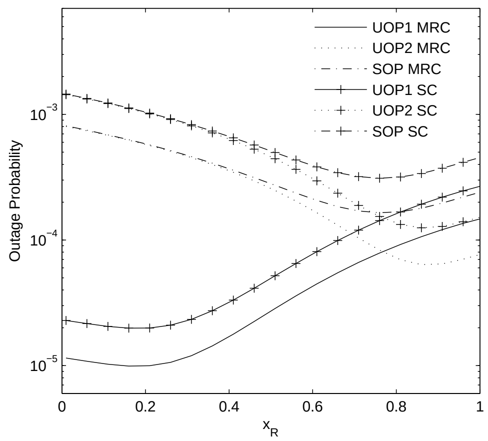

Figure 5. Outage Probability versus the position of relay with $\overline{\gamma} = 30$ dB, $\mathcal{R} = 1$ and $\eta = 3$.

5. Conclusions

In this paper, outage performance has been studied in TW cognitive spectrum sharing in the presence of the direct link. In particular, the closed-form and asymptotic expression for both user and system OP have been addressed in basically tractable functions. Furthermore, it is proven that full diversity is got by adopting diversity combining techniques (MRC and SC) at two end users. The correctness of our analysis is verified by a number of simulations based on Monte Carlo method. It shows that the numerical results exactly agree with our expressions.

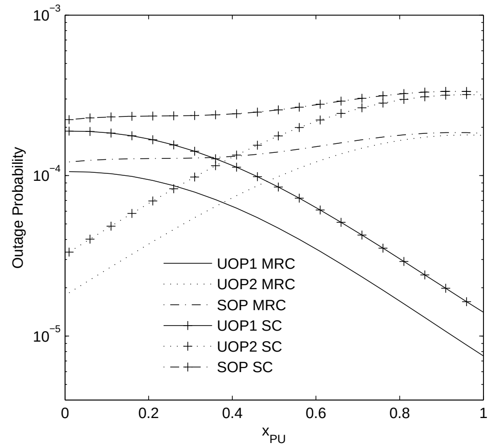

Figure 6. Outage Probability versus the position of primary user with $\overline{\gamma} = 30$, PR = (0.4,0.2), $\mathcal{R} = 1$ dB and $\eta = 3$.

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