Cognitive Amplify-and-Forward Relaying with Best Relay Selection in Non-Identical Rayleigh Fading

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***Abstract*—This paper investigates several important performance metrics of cognitive amplify-and-forward (AF) relay networks with a best relay selection strategy and subject to non-identical Rayleigh fading. In particular, assuming a spectrum sharing environment consists of one secondary user (SU) source, K SU relays, one SU destination, and one primary user (PU) receiver, closed-form expressions for the outage probability (OP), average symbol error probability (SEP), and ergodic capacity of the SU network are derived. The correctness of the proposed analysis is corroborated via Monte Carlo simulations and readily allows us to evaluate the impact of the key system parameters on the end-to-end performance. An asymptotic analysis is also carried out and reveals that the diversity gain is defined by the number of relays pertaining to the SU network (i.e., K), being therefore not affected by the interference power constraint of the PU network.**

***Index Terms*—Cooperative diversity, performance analysis, relay selection, cognitive radio, Rayleigh fading.**

I. Introduction

ONE of the important technologies for wireless technique that has emerged recently is cooperative diversity (CD), which was proposed for combating the deleterious effects caused by the multipath fading, in addition to be capable of extending coverage. Among the various cooperative strategies, transmission based on relay selection (RS) [1] has been shown to provide substantial cooperative gains while being spectrally and costly more efficient than repetitive transmission techniques. In addition, during the past few years, cognitive radio (CR) technology has been widely employed by the wireless community with the aim to alleviate the spectrum scarcity problem and, at the same time, to support the fast growing demand for wireless applications.

As such, a so-called best relay selection (BRS) [2], [3] has been commonly applied in several CR networks subject to a spectrum sharing condition, either assuming decode-and-forward (DF) relays [4], [5] or amplify-and-forward (AF) relays [6]. It has been shown that exploiting user cooperation significantly enhances the cognitive system performance. In [6], the statistical dependence among the random variables (RVs) associated with the end-to-end signal-to-noise ratio (SNR) was not considered. Indeed, this is the major difference between a cognitive BRS network with and its counterpart, i.e, the conventional BRS network, in terms of the statistical derivation. Therefore, although a more detailed analysis regarding this issue is of paramount importance, it still remains to be carried out for BRS schemes applied in cognitive AF relay networks. To the best authors' knowledge, there is no previous work deriving closed-form and asymptotic expressions for cognitive AF relay networks with BRS by taking into account the statistical dependence among the aforementioned RVs.

In this paper, relying on a spectrum sharing environment consisted of one secondary user (SU) source, K SU relays, one SU destination, and one primary user (PU) receiver, several important performance metrics of a cognitive AF relay network employing a BRS strategy are investigated. Unlike previous works [6], along our analysis we consider the existence of a common RV, given by the channel fading coefficient from the SU transmitter to the PU receiver, in the end-to-end SNR expression. Initially, the first-order statistics of the end-to-end SNR at the secondary network are characterized. Specifically, due to mathematical intricacy in handling the exact end-to-end SNR of the considered system, tight lower bounds are presented so that accurate closed-form approximate expressions are derived for the cumulative distribution function (CDF) and probability density function (PDF) over independent non-necessarily identically distributed (i.n.i.d.) Rayleigh fading channels. From the first-order statistics, closed-form expressions for the outage probability (OP), average symbol error probability (SEP), and ergodic capacity are derived. Our analytical expressions are validated through Monte Carlo simulations and readily allow us to evaluate the impact of some key system parameters on the end-to-end performance, such as the number of SU relays. Finally, with the aim to examine the diversity and coding gains of the considered system, asymptotic expressions for the OP and average SEP are derived and insightful discussions are provided. Throughout the paper, $F_Z(\cdot)$ and $f_Z(\cdot)$ stand for the CDF and PDF of a RV Z, respectively.

II. System and Channel Models

Consider a dual-hop cooperative spectrum sharing system consisted of one SU source S, K AF SU relays R_k ($k = 1, \ldots, K$), one SU destination D, and one PU receiver P, as shown in Fig. 1. All terminals are single-antenna devices and

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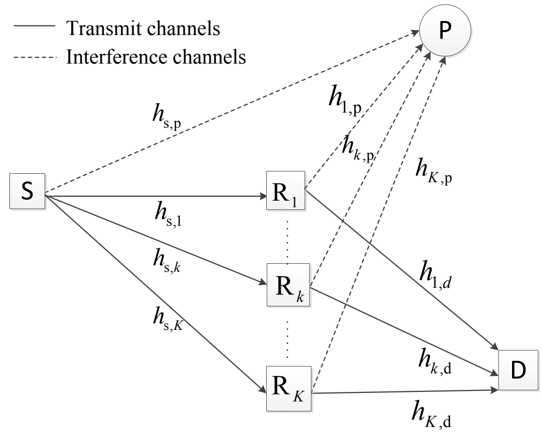

Fig. 1. System model for the cognitive network with BRS.

operate in a half-duplex mode. We assume that there is no direct link between S and D due to the severe shadowing and pathloss. In the first-hop transmission, the SU source transmits its signal x to K relays under a transmit power constraint which guarantees that the interference on the PU receiver P does not exceed a threshold $\mathcal{I}_{\mathsf{p}}$. As a result, the transmit power at S is given by $P_{\mathsf{S}} = \mathcal{I}_{\mathsf{p}}/|h_{\mathsf{S,P}}|^2$, where $h_{\mathsf{S,P}}$ denotes the channel coefficient of the link $\mathsf{S} \rightarrow \mathsf{P}$. In the second-hop transmission, R_k amplifies the received signal from S with a variable gain G_k and forwards the resulting signal to the SU destination. In this case, the transmit power at R_k is defined as $P_{\mathsf{R}_k} = \mathcal{I}_{\mathsf{p}}/|h_{k,\mathsf{P}}|^2$, where $h_{k,\mathsf{P}}$ represents the channel coefficient of the link $\mathsf{R}_k \rightarrow \mathsf{P}$. Hence, the received signal at D through the k-th relay R_k can be given by $y_{\mathsf{D}_k} = \sqrt{P_{\mathsf{S}}} G_k h_{k,\mathsf{D}} h_{\mathsf{S},k} x + G_k h_{k,\mathsf{D}} n_{\mathsf{R}_k} + n_{\mathsf{D}_k}$, where $h_{\mathsf{S},k}$ and $h_{k,\mathsf{D}}$ are the channel coefficients of the links $\mathsf{S} \rightarrow \mathsf{R}_k$ and $\mathsf{R}_k \rightarrow \mathsf{D}$, respectively, n_{R_k} and n_{D_k} designate the additive white Gaussian noise (AWGN) terms at R_k and D, respectively, having the same power N_0. Since we assume that the SU relays operate in a channel state information (CSI)-assisted AF mode, the gain G_k can be expressed as $1/G_k^2 = |h_{k,\mathsf{P}}|^2 \left(\frac{|h_{\mathsf{S},k}|^2}{|h_{\mathsf{S,P}}|^2} + \frac{N_0}{\mathcal{I}_{\mathsf{p}}}\right)$. Thus, the instantaneous end-to-end SNR of the link $\mathsf{S} \rightarrow \mathsf{R}_k \rightarrow \mathsf{D}$ can be written as [6]

$$\gamma_k = \frac{\frac{\bar{\gamma}|h_{\mathsf{S},k}|^2}{|h_{\mathsf{S,P}}|^2} \frac{\bar{\gamma}|h_{k,\mathsf{D}}|^2}{|h_{k,\mathsf{P}}|^2}}{\frac{\bar{\gamma}|h_{\mathsf{S},k}|^2}{|h_{\mathsf{S,P}}|^2} + \frac{\bar{\gamma}|h_{k,\mathsf{D}}|^2}{|h_{k,\mathsf{P}}|^2} + 1} = \frac{\frac{X_{1k}}{Y} X_{2k}}{\frac{X_{1k}}{Y} + X_{2k} + 1}, \tag{1}$$

where $X_{1k} = \bar{\gamma}|h_{\mathsf{S},k}|^2$, $Y = |h_{\mathsf{S,P}}|^2$, $X_{2k} = \frac{\bar{\gamma}|h_{k,\mathsf{D}}|^2}{|h_{k,\mathsf{P}}|^2}$, and $\bar{\gamma} = \mathcal{I}_{\mathsf{p}}/N_0$. Knowing that a BRS strategy is employed for the SU communication, it follows that the relay which has the highest value of γ_k is selected. Hence, the end-to-end received SNR at D can be given by

$$\begin{aligned}\gamma_{\mathsf{D}} &= \max_{k=1,2,\ldots,K} \gamma_k \\ &\overset{(a)}{\simeq} \gamma_{\mathsf{up}} = \max_{k=1,2,\ldots,K} \left\{ \min\Bigg(\underbrace{\frac{X_{1k}}{|h_{\mathsf{S,P}}|^2}}_{\gamma_{1k}}, \underbrace{\frac{\bar{\gamma}|h_{k,\mathsf{D}}|^2}{|h_{k,\mathsf{P}}|^2}}_{\gamma_{2k}} \Bigg) \right\},\end{aligned} \tag{2}$$

where step (a) obtaining γ_{up} arises as a tight approximation, as will be seen in Section IV. Herein, we assume that all channel coefficients undergo i.n.i.d. Rayleigh fading, which implies that the channel gains $|h_{\mathsf{S,P}}|^2$, $|h_{\mathsf{S},k}|^2$, $|h_{k,\mathsf{D}}|^2$, and $|h_{k,\mathsf{P}}|^2$ follow an exponential distribution, with mean powers $\frac{1}{\Omega_{\mathsf{s,p}}}$, $\frac{1}{\Omega_{\mathsf{s},k}}$, $\frac{1}{\Omega_{k,\mathsf{d}}}$, and $\frac{1}{\Omega_{k,\mathsf{p}}}$, respectively.

III. Performance Analysis

A. Closed-Form Analysis

1) Outage Probability: The OP is defined as the probability that the instantaneous SNR at D goes below a predefined threshold γ_{th}, i.e., $P_{\text{out}} = \Pr(\gamma_{\mathsf{D}} \le \gamma_{\text{th}})$. Then, in order to evaluate the OP, the CDF of γ_{D} is required. From (2), note that there exists a common RV $h_{\mathsf{S,P}}$ for all k, $k = 1, 2, \ldots, K$, which leads to a statistical dependence related to the RVs γ_k. This fact was also witnessed in several other works, such as [5, Eq. (3)], [6, Eq. (6)], and [7, Eq. (9)]. However, the statistical dependence among the RVs was not taken into account in those works, where, for $\gamma_{\mathsf{up}} = \max_{k \in K} \gamma_k^{\mathsf{up}}$ with $\gamma_k^{\mathsf{up}} = \min(\gamma_{1k}, \gamma_{2k})$ the CDF of γ_{up} was written as $F_{\gamma_{\mathsf{up}}}(\gamma) = \prod_{k=1}^{K} F_{\gamma_k^{\mathsf{up}}}(\gamma)$, which indeed only holds when independent RVs γ_k^{up} are considered. As a result, the derivations presented in [5]–[7] serve as a loosing bound. In particular, they are lower bounds for the OP [6], [7] and upper bounds for the ergodic capacity [5].

Herein, we first apply the conditional statistics on the fading channel from S to P. With this aim, thanks to the independence among the remaining RVs, i.e., $h_{\mathsf{S},k}$, $h_{k,\mathsf{D}}$, and $h_{k,\mathsf{P}}$, the CDF of γ_{up} conditioned on $h_{\mathsf{S,P}}$ can be expressed as[1]

$$\begin{aligned}F_{\gamma_{\mathsf{up}}}(\gamma | h_{\mathsf{S,P}}) &= \prod\nolimits_{k=1}^{K} F_{\gamma_k^{\mathsf{up}}}(\gamma | h_{\mathsf{S,P}}) \\ &= \prod_{k=1}^{K} \left[1 - \left(1 - F_{\gamma_{1k}}(\gamma | h_{\mathsf{S,P}})\right)\left(1 - F_{\gamma_{2k}}(\gamma | h_{\mathsf{S,P}})\right)\right].\end{aligned} \tag{3}$$

In addition, it is easy to see that

$$F_{\gamma_{1k}}(\gamma | h_{\mathsf{S,P}}) = 1 - e^{-\lambda_{1k}\gamma|h_{\mathsf{S,P}}|^2}, \tag{4}$$

$$\begin{aligned}F_{\gamma_{2k}}(\gamma | h_{\mathsf{S,P}}) &= \int_0^\infty F_{|h_{k,\mathsf{D}}|^2}\left(\frac{\gamma}{\bar{\gamma}} x\right) f_{|h_{k,\mathsf{P}}|^2}(x)\, dx \\ &= 1 - (1 + \lambda_{2k}\gamma)^{-1},\end{aligned} \tag{5}$$

where $\lambda_{1k} = 1/(\Omega_{\mathsf{s},k}\bar{\gamma})$ and $\lambda_{2k} = \Omega_{k,\mathsf{p}}/(\Omega_{k,\mathsf{d}}\bar{\gamma})$. By substituting (4) and (5) into (3), and applying the identity

$$\prod_{k=1}^{K} (1 - x_k) = \sum_{k=0}^{K} \frac{(-1)^k}{k!} \sum_{n_1,\ldots,n_k}^{K} \prod_{t=1}^{k} x_{n_t}, \tag{6}$$

with $\sum\limits_{n_1,\ldots,n_k}^{K}$ being the short-hand notation of $\sum\limits_{\substack{n_1=\cdots=n_k=1 \\ n_1\neq\cdots\neq n_k}}^{K} \cdots \sum^{K}$, (3) can be rewritten as

$$\begin{aligned}F_{\gamma_{\mathsf{up}}}(\gamma | h_{\mathsf{S,P}}) = &\sum_{k=0}^{K} \frac{(-1)^k}{k!} \sum_{n_1,\ldots,n_k}^{K} \\ &\times \prod_{t=1}^{k} \frac{\exp\left(-\lambda_{1n_t}\gamma|h_{\mathsf{S,P}}|^2\right)}{1 + \lambda_{2n_t}\gamma}.\end{aligned} \tag{7}$$

[1] It is important to note that this equation only holds when γ_{up} is conditioned on $h_{\mathsf{S,P}}$. In other words, $F_{\gamma_{\mathsf{up}}}(\gamma) \neq \prod_{k=1}^{K} F_{\gamma_k^{\mathsf{up}}}(\gamma)$.

Finally, the OP can be expressed as

$$P_{\text{out}} \simeq \int_0^\infty F_{\gamma_{\text{up}}}\left(\gamma_{\text{th}}|h_{\text{S,P}}\right) f_{|h_{\text{S,P}}|^2}(y)\,dy = \sum_{k=0}^{K} \frac{(-1)^k}{k!} \times \sum_{n_1,\ldots,n_k}^{K} \left(\prod_{t=1}^{k} \left(1+\lambda_{2n_t}\gamma_{\text{th}}\right)^{-1}\right)\left(\frac{\lambda_{\text{s,p}}}{\lambda_{\text{s,p}}+\gamma_{\text{th}}\sum_{t=1}^{k}\lambda_{1n_t}}\right), \tag{8}$$

where $\lambda_{\text{s,p}} = \frac{1}{\Omega_{\text{s,p}}}$.

2) Symbol Error Probability: Making use of the approach employed in [8], a general expression for SEP is written as

$$P_e \simeq \frac{a\sqrt{b}}{2\sqrt{\pi}} \int_0^\infty \frac{e^{-b\gamma}}{\sqrt{\gamma}} F_{\gamma_{\text{up}}}(\gamma)\,d\gamma, \tag{9}$$

where a and b are two constants determined by the modulation scheme. By replacing γ_{th} with γ in (8) and using partial fraction, we obtain the CDF expression for γ_{up} as follows:

$$F_{\gamma_{\text{up}}}(\gamma) = 1 + \sum_{k=1}^{K}\frac{(-1)^k}{k!}\sum_{n_1,\ldots,n_k}^{K}\left[\frac{\mathcal{B}}{1+\frac{\gamma}{\lambda_{\text{s,p}}}\sum_{t=1}^{k}\lambda_{1n_t}} + \sum_{t=1}^{k}\frac{\mathcal{A}_t}{1+\lambda_{2n_t}\gamma}\right], \tag{10}$$

where $\mathcal{A}_t$ and $\mathcal{B}$ are the expansion coefficients given by

$$\mathcal{A}_t = \lambda_{2n_t}^{k}\left(\lambda_{2n_k} - \frac{1}{\lambda_{\text{s,p}}}\sum_{t=1}^{k}\lambda_{1n_t}\right)^{-1}\prod_{t=1,t\neq k}^{t}\left(\lambda_{2n_k}-\lambda_{2n_t}\right)^{-1},$$

$$\mathcal{B} = \left(\frac{\sum_{t=1}^{k}\lambda_{1n_t}}{\lambda_{\text{s,p}}}\right)^{k}\left[\prod_{t=1}^{k}\left(\frac{\sum_{\ell=1}^{k}\lambda_{1n_\ell}}{\lambda_{\text{s,p}}} - \lambda_{2n_t}\right)\right]^{-1} \tag{11}$$

From (10) and (9), and based on [9, Eq. (3.361.2)], [9, Eq. (3.363.2)], a closed-form expression for SEP over i.n.i.d. Rayleigh fading channels can be derived as

$$P_e \simeq \frac{a}{2} + \frac{a\sqrt{b}}{2}\sum_{k=1}^{K}\frac{(-1)^k}{k!}\sum_{n_1,\ldots,n_k}^{K}\left[\mathcal{B}\sqrt{\frac{\lambda_{\text{s,p}}}{\sum_{t=1}^{k}\lambda_{1n_t}}} \times \exp\left(\frac{b\lambda_{\text{s,p}}}{\sum_{t=1}^{k}\lambda_{1n_t}}\right)\operatorname{erfc}\left(\sqrt{\frac{b\lambda_{\text{s,p}}}{\sum_{t=1}^{k}\lambda_{1n_t}}}\right) + \sum_{t=1}^{k}\frac{\mathcal{A}}{\sqrt{\lambda_{2n_t}}}\exp\left(\frac{b}{\lambda_{2n_t}}\right)\operatorname{erfc}\left(\sqrt{\frac{b}{\lambda_{2n_t}}}\right)\right], \tag{12}$$

where $\operatorname{erfc}(\cdot)$ is the complementary error function [9, Eq. (8.250.4)].

3) Ergodic Capacity: In wireless systems, the ergodic capacity (nat/s/Hz) can be evaluated as $C = \int_0^\infty \ln(1+\gamma)\, f_{\gamma_{\text{up}}}(\gamma)\,d\gamma$, which requires the determination of the PDF of γ_{up}. By taking the derivative of (10) w.r.t. γ, this statistics can be easily achieved as

$$f_{\gamma_{\text{up}}}(\gamma) = \sum_{k=1}^{K}\frac{(-1)^k}{k!}\sum_{n_1,\ldots,n_k}^{K}\left[\frac{-\mathcal{B}\sum_{t=1}^{k}\lambda_{1n_t}/\lambda_{\text{s,p}}}{\left(1+\frac{\gamma}{\lambda_{\text{s,p}}}\sum_{t=1}^{k}\lambda_{1n_t}\right)^2} - \sum_{t=1}^{k}\frac{\mathcal{A}_t\lambda_{2n_t}}{\left(1+\lambda_{2n_t}\gamma\right)^2}\right]. \tag{13}$$

Then, a closed-form expression for the ergodic capacity is derived as

$$C \simeq \sum_{k=1}^{K}\frac{(-1)^k}{k!}\sum_{n_1,\ldots,n_k}^{K}\left(\frac{\mathcal{B}\ln\left(\sum_{t=1}^{k}\lambda_{1n_t}/\lambda_{\text{s,p}}\right)}{1-\sum_{t=1}^{k}\lambda_{1n_t}/\lambda_{\text{s,p}}} + \sum_{t=1}^{k}\frac{\mathcal{A}_t\ln\lambda_{2n_t}}{1-\lambda_{2n_t}}\right). \tag{14}$$

B. Asymptotic Analysis

Now, in order to derive an asymptotic expression for the OP, we apply the following Taylor expansion for $(1+z)^{-m}$

$$(1+z)^{-m} = 1 - mz + \frac{m(m+1)}{2!}z^2 - \frac{m(m+1)(m+2)}{3!}z^3\ldots \tag{15}$$

Then, plugging (15) into (8), an asymptotic expression for the OP can be represented as

$$P_{\text{out}} \overset{\bar{\gamma}\to\infty}{\approx} \sum_{k=0}^{K}\frac{(-1)^k}{k!}\sum_{n_1,\ldots,n_k}^{K}\left[\left(\prod_{t=1}^{k}\frac{\lambda_{\text{s,p}}\alpha_{2n_t}}{\alpha_{1n_t}}\right)\left(\prod_{t=1}^{K}\frac{\alpha_{1t}}{\lambda_{\text{s,p}}}\right)\right] \times \left(\frac{\gamma_{\text{th}}}{\bar{\gamma}}\right)^{K}, \tag{16}$$

where $\alpha_{1k} = \frac{1}{\Omega_{\text{s},k}}$ and $\alpha_{2k} = \frac{\Omega_{k,\text{p}}}{\Omega_{k,\text{d}}}$.

By replacing γ_{th} with γ in (16), we can obtain the asymptotic CDF of γ_{up}. Finally, the respective asymptotic SEP expressions for the i.n.i.d. fading can be easily obtained by substituting this result into (9), which then yields

$$P_e \overset{\bar{\gamma}\to\infty}{\approx} \frac{a\Gamma(K+\frac{1}{2})}{2\sqrt{\pi}}\sum_{k=0}^{K}\frac{(-1)^k}{k!} \times \sum_{n_1,\ldots,n_k}^{K}\left[\left(\prod_{t=1}^{k}\frac{\lambda_{\text{s,p}}\alpha_{2n_t}}{\alpha_{1n_t}}\right)\left(\prod_{t=1}^{K}\frac{\alpha_{1t}}{\lambda_{\text{s,p}}}\right)\right]\left(\frac{1}{b\bar{\gamma}}\right)^{K}. \tag{17}$$

As attested from (16) and (17), the diversity gain of cognitive AF relaying with BRS is the same as that of its non-cognitive counterpart, see, e.g., [8, Eq. (6)] and [8, Eq. (7)]. Specifically, it is equal to the number of relays pertaining to the secondary network and does not depend on the primary network.

IV. Numerical Results and Discussions

In this section, we provide the numerical results to validate our analysis. Specifically, Figs. 2, 3, and 4 depict the OP, SEP, and ergodic capacity, respectively, versus $\mathcal{I}_{\text{p}}/N_0$ for i.n.i.d. Rayleigh fading and assuming the following parameters: $K = \{2,3\}$, $\Omega_{\text{s,p}} = 4$, $\{\Omega_{\text{s},k}\}_{k=1}^{3} = \{1.2, 2.3, 3.1\}$, $\{\Omega_{k,\text{d}}\}_{k=1}^{3} = \{0.5, 0.9, 0.7\}$, $\{\Omega_{k,\text{p}}\}_{k=1}^{3} = \{1.1, 3.2, 2.1\}$, and $\gamma_{\text{th}} = 3$ dB. In Fig. 2, the analytical and asymptotic OP curves are plotted from (8) and (16), respectively, and by setting $\gamma_{\text{th}} = 3$ dB. On the other hand, in Fig. 3, the analytical and asymptotic SEP curves are plotted from (12) and (17), respectively, and assuming a QPSK modulation. Finally, in Fig. 4 the analytical results for the ergodic capacity are plotted from (14).

To illustrate the tightness of the proposed bounds, we also compare the analytical results against the exact results obtained through Monte Carlo simulations. As can be observed

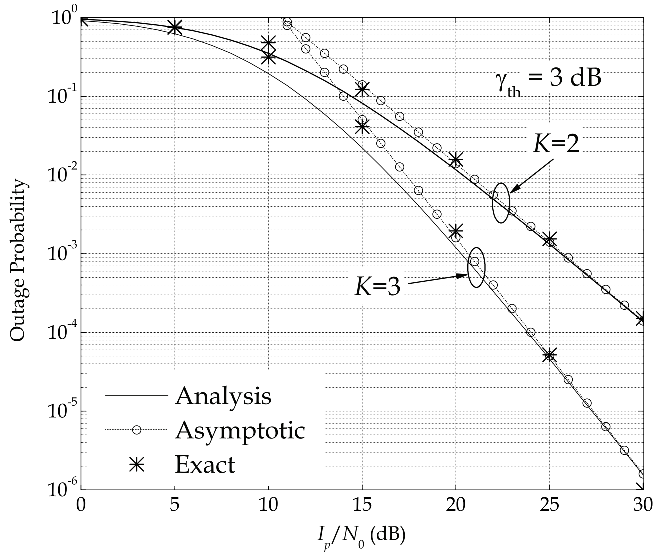

Fig. 2. OP of cognitive AF relaying in spectrum sharing condition.

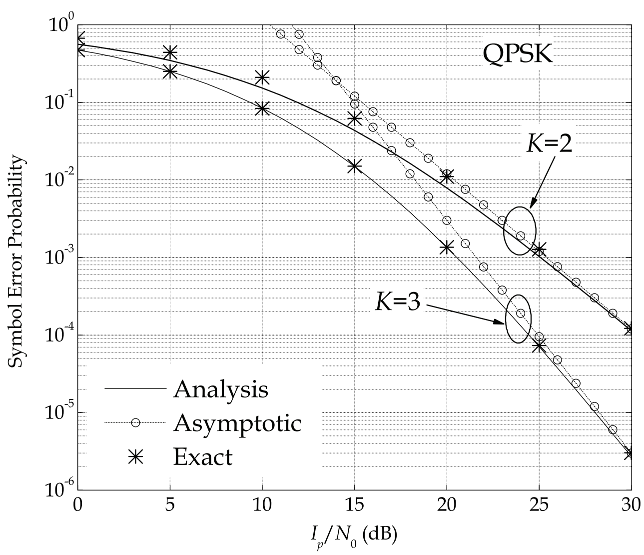

Fig. 3. SEP of cognitive AF relaying in spectrum sharing condition.

from Figs. 2 and 3, the asymptotic curves tightly converge to the exact ones and the analytical bounds are indeed very tight, validating the accuracy of our methodology. There is only a slightly difference in the low to medium SNR regime. However, in the high SNR regime, the lower bounds almost overlap with the exact values. Observe also that the diversity order improves when the number of relays increases, which demonstrates the achievable diversity gain obtained in the previous section. Turning our attention to Fig. 4, there exists a small gap between the upper bounds and the exact curves. This difference can be explained by the fact that $\ln(x)$ function in the ergodic capacity expression converges slowly when compared to the polynomial x^n in the OP and SEP expressions.

V. Conclusion

In this paper, we have first derived the exact CDF and PDF of a tight bound for the end-to-end SNR for the cognitive AF

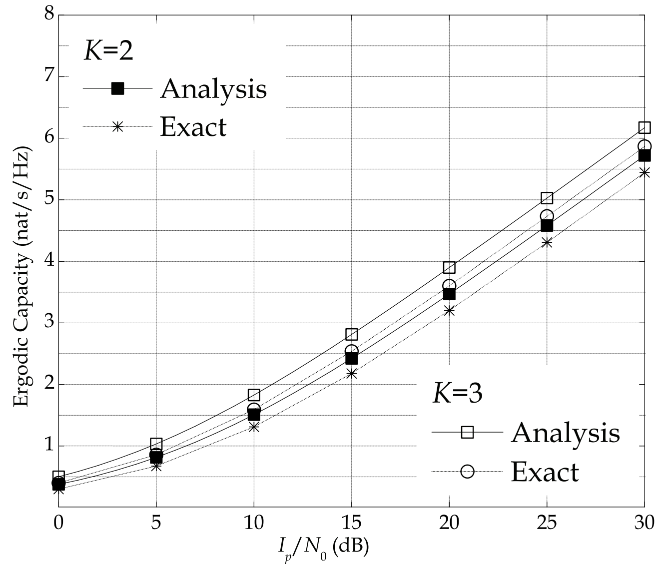

Fig. 4. Capacity of cognitive AF relaying in spectrum sharing condition.

relay network with BRS. Based on these analytical derivations, closed-form expressions for the OP, SEP, and ergodic capacity have been developed for i.n.i.d. Rayleigh fading channels and validated by Monte-Carlo simulations. Moreover, the asymptotic expressions for the OP and SEP have also been obtained to reveal the impact of key parameters on the system performance. Using these asymptotic results, we have shown that the cognitive AF relay network under spectrum sharing condition and BRS obtains the same diversity gain as the conventional AF relay network.

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