Cognitive Cooperative Networks in Dual-Hop Asymmetric Fading Channels

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Abstract—**Previous works on cognitive relay networks (CRNs) considered only symmetric fading channels. However, in practical wireless propagation scenarios, it is likely that the channels of the secondary user (SU) and primary user (PU) may undergo different fading characteristics. In this paper, we assume that the channels of the secondary network (SU-source→SU-relay→SU-destination) are subject to Rician fading, whereas the channels of the link from the SU to the PU experience Rayleigh fading. Based on this framework, the end-to-end outage probability (OP) of CRNs is investigated for two different relaying schemes: i) in the absence of the direct link with decode-and-forward (DF) protocol and ii) in the presence of the direct link with incremental DF protocol. In particular, we derive both exact and asymptotic OP expressions for the considered CRNs. Our analysis reveals important insights into the impact of fading parameters on the CRN performance under distinct fading distributions.**

I. Introduction

By allowing the secondary user (SU) to concurrently occupy the radio frequency spectrum, which is licensed to the primary user (PU), cognitive radio networks with spectrum-sharing is an emerging technology to overcome the inefficient utilization of scarce radio frequency spectrum [1]–[7]. Recently, the use of amplify-and-forward (AF) and decode-and-forward (DF) relaying protocols has been incorporated into the cognitive radio paradigm to improve the secondary system performance. Several works have investigated the performance of cognitive cooperative networks (CCNs) over various fading channels [8]–[10]. Specifically, in [8] the outage performance of CCNs with AF relaying has been studied for Rayleigh fading channels. More recently, the works in [9] and [10] have analyzed the CCN performance in Nakagami-m fading channels with DF and AF relaying, respectively. Although these previously published works offered important understandings of CCNs, all of them assumed symmetric fading conditions for the secondary and primary links.

In addition to the non line-of-sight (non-LoS) fading model, i.e., Rayleigh and Nakagami-m, the Rician distribution is widely employed to characterize the wireless channels with line-of-sight (LoS) or specular component [11]. On top of this, in practical wireless propagation scenarios, the links of relaying networks may experience different fading characteristics [12]. Motivated by this fact, the performance of non-cognitive relay networks under asymmetric fading channels has been considered in [13], [14]. In particular, the performance of asymmetric fading channels with Rayleigh and Rician fading has been analyzed for semi-blind and channel state information (CSI)-assisted AF relaying in [13] and [14], respectively.

For CCNs, the links of the SU and PU are highly likely to experience different fading characteristics. As such, in this paper, we assume that the secondary relay terminal can be strategically located by the operator [12], which makes the links from the secondary source to secondary relay and to secondary destination experience LoS propagation. As a result, the channels for these links SU-source→SU-relay and SU-relay→SU-destination can be modeled via the Rician distribution, while the links between SU and PU experience Rayleigh fading. We point out that the channel for the link SU-source→SU-destination is also modeled via the Rayleigh distribution. This assumption is sufficiently realistic in urban environments, where the source and destination are normally in non-LoS, such that multiple wavefronts impinge on the latter. For the sake of generality and to pursue a comparative study, we consider two different CCN configurations, with and without direct communication pertaining to the link from the secondary source to the secondary destination. Specifically, for the case without SU's direct link, namely PR1, conventional relaying with DF operation is assumed, whereas for the case with direct link, namely PR2, the incremental DF relaying is utilized to enhance the secondary system performance. In the following, we derive new, analytical expressions for the exact and asymptotic outage probability (OP) of both considered schemes. One of the paper's significant contributions is the asymptotic analysis which reveals the diversity and coding gains of the two considered systems.

The rest of the paper is organized as follows. In Section II, we first present the system and channel model for the two considered protocols in a spectrum-sharing environment. The OP performance is obtained in Section III. Numerical and simulation results are provided in Section IV. Conclusions are drawn in Section V.

II. System and Channel Models

The considered cognitive network consists of a secondary source (S), a secondary destination (D), a secondary relay (R) and a primary receiver (PU), as shown in Fig. 1. Let d_0, d_1, d_2, d_3, and d_4 be the distances S $\rightarrow$ D, S $\rightarrow$ R, R $\rightarrow$ D, S $\rightarrow$ PU, and R $\rightarrow$ PU, respectively. We also denote
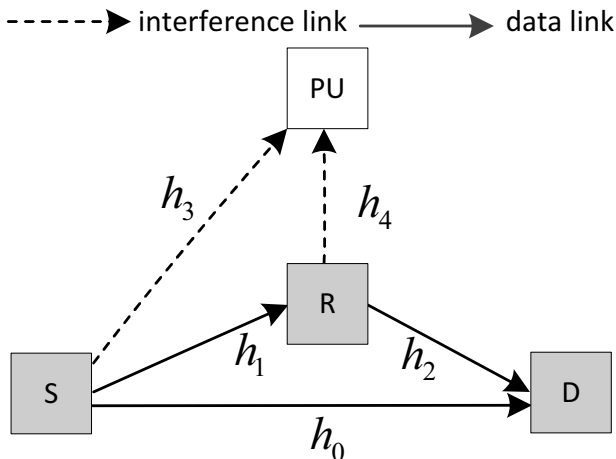
Fig. 1. System model for a cognitive DF relaying network.

$h_0, h_1, h_2, h_3,$ and h_4 the corresponding channel coefficients for the links $S \to D$, $S \to R$, $R \to D$, $S \to PU$, and $R \to PU$, respectively. Here, it is assumed that the channels h_1 and h_2 follow the Rician distribution while $h_0, h_3,$ and h_4 are subject to Rayleigh fading. Hence, $\gamma_j = |h_j|^2$, $j \in \{0, 3, 4\}$ is an exponential random variable (RV) with parameter λ_j. On the other hand, $\gamma_i = |h_i|^2$, $i \in \{1, 2\}$, is a non-central chi-square distributed RV, whose cumulative distribution function (CDF) and probability density function (PDF) are respectively given by

$$F_{\gamma_i}(x) = 1 - Q_1\left(\sqrt{2K_i}, \sqrt{2\psi_i x}\right) \quad (1)$$

$$f_{\gamma_i}(x) = (1 + K_i)\lambda_i e^{-K_i - \psi_i x} I_0\left(2\sqrt{K_i \psi_i x}\right) \quad (2)$$

where $\psi_i \triangleq (1 + K_i)\lambda_i$, $Q_1(\cdot)$, and $I_0(\cdot)$ are the Marcum-Q function [15, Eq. (4.10)] and modified Bessel function of the first kind [16, Eq. (8.445)], respectively. In addition, K_i is the Rician K-factor and $\lambda_i = 1/\bar{\gamma}_i$, where $\bar{\gamma}_i$ is the expected value of γ_i. To take path-loss into account, we model λ_k, $k \in \{1, 2, 3, 4, 5\}$ as $\lambda_k = d_k^\beta$, where β is the path-loss exponent.

A. CCN without Direct Link

In a cognitive network, S and R must adapt their transmit power, P_S and P_R, respectively, so that the interference caused at PU is lower than a predefined interference level I_{th}. Specifically, their transmit powers must be lower than a maximum threshold P_{th} [10]

$$P_S^{\max} = \min\left(P_{th}, \frac{I_{th}}{\gamma_3}\right), \quad P_R^{\max} = \min\left(P_{th}, \frac{I_{th}}{\gamma_4}\right). \quad (3)$$

For the PR1 protocol, the data transmission is divided into two time slots. In the first time slot, S broadcasts its data x to R as

$$y_{SR} = \sqrt{P_S^{\max}} h_1 x + n_{SR}, \quad (4)$$

where n_{SR} is the zero-mean Gaussian noise at R. From (4), the instantaneous signal-to-noise ratio (SNR) received at R is given as

$$\Psi_{SR} = P_S^{\max} |h_1|^2 / N_0 = \min\left(\gamma_P, \frac{\gamma_I}{\gamma_3}\right)\gamma_1, \quad (5)$$

where N_0 is the variance of the Gaussian noise, which is assumed to be the same at all receivers, i.e., R and D, while $\gamma_P = P_{th}/N_0$, and $\gamma_I = I_{th}/N_0$. Without loss of generality, we assume that $\gamma_I = \mu\gamma_P$, where μ is a positive constant.

If R can successfully decode the signal, it will forward the decoded signal to D at the second time slot. As such, the signal received at D, due to the transmission of R, is expressed as

$$y_{RD} = \sqrt{P_R^{\max}} h_2 x + n_{RD}, \quad (6)$$

where n_{RD} is the Gaussian noise at D. Therefore, the SNR for the second-hop is given by

$$\Psi_{RD} = P_R^{\max} |h_2|^2 / N_0 = \min\left(\gamma_P, \frac{\gamma_I}{\gamma_4}\right)\gamma_2. \quad (7)$$

The end-to-end SNR at D is therefore written as [9]

$$\Psi_{e2e}^{PR1} = \min\left(\Psi_{SR}, \Psi_{RD}\right). \quad (8)$$

B. CCN with Direct Link: Incremental Relaying

For the cognitive relaying protocol with incremental relaying, named PR2, if D can successfully decode the S's signal, it feeds back an ACK to S and R to inform the decoding status. In this case, if the transmission is successful, R does nothing. Otherwise, D sends a NACK message to request a retransmission from R. If R can successfully decode the signal, it will forward the decoded signal to D at the second time slot. In the case that R cannot receive the signal correctly, it will keep silent and the signal will be dropped. Therefore, the end-to-end SNR at D can be written as [17]

$$\Psi_{e2e}^{PR2} = \begin{cases} \Psi_{SD} & \text{if } \Psi_{SD} \geq \varphi_{th} \\ \min\left(\Psi_{SR}, \Psi_{RD}\right) & \text{if } \Psi_{SD} < \varphi_{th}, \end{cases} \quad (9)$$

where φ_{th} is a predefined threshold at the relay and Ψ_{SD} is the instantaneous SNR for the direct link $S \to D$, given as

$$\Psi_{SD} = \min\left(\gamma_P, \frac{\gamma_I}{\gamma_3}\right)\gamma_0. \quad (10)$$

III. OUTAGE PROBABILITY: EXACT AND ASYMPTOTIC ANALYSIS

In this paper, we assume that the data transmission is in outage if the instantaneous end-to-end SNRs are lower than a predefined threshold level φ_{th}.

A. CCN without Direct Link

The OP of the PR1 protocol can be expressed as follows:

$$P_{out}^{PR1} = 1 - \left[1 - \Pr\left(\Psi_{SR} < \varphi_{th}\right)\right]\left[1 - \Pr\left(\Psi_{RD} < \varphi_{th}\right)\right]. \quad (11)$$

Considering the probability $\Pr[\Psi_{\mathrm{RD}} < \varphi_{th}]$ in (11), it can be formulated as

$$
\begin{aligned}
\Pr\left(\Psi_{\mathrm{RD}} < \varphi_{th}\right) &= \Pr\left(\min\left(1, \mu/\gamma_4\right)\gamma_P\gamma_2 < \varphi_{th}\right) \\
&= \underbrace{\Pr\left(\gamma_4 < \mu, \gamma_2 < \frac{\varphi_{th}}{\gamma_P}\right)}_{P_1^{out}} + \underbrace{\Pr\left(\gamma_4 \geq \mu, \gamma_2 < \frac{\varphi_{th}}{\mu\gamma_P}\gamma_4\right)}_{P_2^{out}}.
\end{aligned}
\tag{12}
$$

Due to the independence of γ_2 and γ_4, by using the CDF of γ_2 in (1), we can calculate the probability P_1^{out} in (12) as

$$
P_1^{out} = \left(1 - e^{-\lambda_4\mu}\right)\left[1 - Q_1\left(\sqrt{2K_2}, \sqrt{\frac{2\psi_2\varphi_{th}}{\gamma_P}}\right)\right].
\tag{13}
$$

Now, considering P_2^{out} in (12), we have

$$
\begin{aligned}
P_2^{out} &= \int_{\mu}^{\infty} f_{\gamma_4}(x) F_{\gamma_2}\left(\frac{\varphi_{th}}{\mu\gamma_P}x\right)dx = e^{-\lambda_4\mu} \\
&\quad - \int_{\mu}^{\infty} \lambda_4 e^{-\lambda_4 x} Q_1\left(\sqrt{2K_2}, \sqrt{\frac{2\psi_2\varphi_{th}}{\mu\gamma_P}x}\right)dx.
\end{aligned}
\tag{14}
$$

Next, the Marcum-Q function of the first order can be expressed by an infinite series with the help of [15, Eq. (4.35)] and [16, Eq. (8.445)]; applying this expression in (14), we obtain

$$
\begin{aligned}
P_2^{out} &= e^{-\lambda_4\mu} - \lambda_4\mu e^{-K_2 - \lambda_4\mu} \sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\sum_{t=0}^{n}\left[\frac{\psi_2^n}{(m+n)!t!}\right. \\
&\quad \left. \times \frac{\varphi_{th}^n}{\gamma_P^{t-1}} \frac{K_2^{m+n} e^{-\frac{\psi_2\varphi_{th}}{\gamma_P}}}{\left(\lambda_4\mu\gamma_P + \psi_2\varphi_{th}\right)^{n+1-t}}\right].
\end{aligned}
\tag{15}
$$

From (12), (13) and (15), we obtain an exact expression for $\Pr\left(\Psi_{\mathrm{RD}} < \varphi_{th}\right)$ which is shown in (16) at the top of next page.[1] Note that by replacing λ_2, λ_4 and K_2 in (16) with λ_1, λ_3 and K_1, respectively, we can obtain an exact expression for $\Pr\left(\Psi_{\mathrm{SR}} < \varphi_{th}\right)$; then, substituting the obtained results into (11), we have an exact expression for $\mathrm{P_{out}^{PR1}}$.

Proposition 1: Without maximum transmit power constraint γ_P, the outage probability of the PR1 protocol can be expressed by an exact closed-form expression as follows:

$$
\begin{aligned}
\mathrm{P_{out}^{PR1}} &\overset{\gamma_P \to \infty}{=} 1 - \left[1 - \frac{\psi_1\varphi_{th} e^{-\frac{K_1\lambda_3\gamma_I}{\psi_1\varphi_{th} + \lambda_3\gamma_I}}}{\psi_1\varphi_{th} + \lambda_3\gamma_I}\right] \\
&\quad \times \left[1 - \frac{\psi_2\varphi_{th} e^{-\frac{K_2\lambda_4\gamma_I}{\psi_2\varphi_{th} + \lambda_4\gamma_I}}}{\psi_2\varphi_{th} + \lambda_4\gamma_I}\right].
\end{aligned}
\tag{17}
$$

Proof: Without maximum transmit power constraint, P_{th}, the OP $\Pr\left(\Psi_{\mathrm{RD}} < \varphi_{th}\right)$ in this case is obtained by taking the limit of (16) as γ_P goes to infinity. Indeed, after taking the

[1]Although the final expression is given in infinite series, our numerical results show that its convergence is very fast, requiring only few terms to approach the exact results.

limit and some manipulations, we can rewrite (16) as follows:

$$
\begin{aligned}
\lim_{\gamma_P \to \infty} \Pr\left(\Psi_{\mathrm{RD}} < \varphi_{th}\right) &= 1 - \frac{\lambda_4\gamma_I e^{-K_2}}{\psi_2\varphi_{th} + \lambda_4\gamma_I} \\
&\quad \times \sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\frac{K_2^{m+n}}{(m+n)!}\frac{(\psi_2\varphi_{th})^n}{(\psi_2\varphi_{th} + \lambda_4\gamma_I)^n}.
\end{aligned}
\tag{18}
$$

Considering the infinite series sum in (18), we get

$$
\begin{aligned}
\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\frac{K_2^{m+n}}{(m+n)!}\frac{(\psi_2\varphi_{th})^n}{(\psi_2\varphi_{th} + \lambda_4\gamma_I)^n} &= \sum_{n=0}^{\infty}\frac{(\psi_2\varphi_{th})^n}{(\psi_2\varphi_{th} + \lambda_4\gamma_I)^n} \\
&\quad \times \sum_{m=0}^{\infty}\frac{K_2^m}{m!} - \sum_{n=1}^{\infty}\frac{(\psi_2\varphi_{th})^n}{(\psi_2\varphi_{th} + \lambda_4\gamma_I)^n}\sum_{m=0}^{n-1}\frac{K_2^m}{m!}.
\end{aligned}
\tag{19}
$$

In addition, we have

$$
\sum_{n=0}^{\infty}\frac{(\psi_2\varphi_{th})^n}{(\psi_2\varphi_{th} + \lambda_4\gamma_I)^n}\sum_{m=0}^{\infty}\frac{K_2^m}{m!} = \frac{(\psi_2\varphi_{th} + \lambda_4\gamma_I)e^{K_2}}{\lambda_4\gamma_I}
\tag{20}
$$

$$
\sum_{n=1}^{\infty}\frac{(\psi_2\varphi_{th})^n}{(\psi_2\varphi_{th} + \lambda_4\gamma_I)^n}\sum_{m=0}^{n-1}\frac{K_2^m}{m!} = \frac{\psi_2\varphi_{th}}{\lambda_4\gamma_I}e^{\frac{K_2\psi_2\varphi_{th}}{\psi_2\varphi_{th} + \lambda_4\gamma_I}}.
\tag{21}
$$

Substituting (19), (20), and (21) into (18), we obtain

$$
\lim_{\gamma_P \to \infty}\Pr\left(\Psi_{\mathrm{RD}} < \varphi_{th}\right) = \frac{\psi_2\varphi_{th}e^{-\frac{K_2\lambda_4\gamma_I}{\psi_2\varphi_{th} + \lambda_4\gamma_I}}}{\psi_2\varphi_{th} + \lambda_4\gamma_I}.
\tag{22}
$$

Now, let us replace λ_2, λ_4 and K_2 in (22) by λ_1, λ_3 and K_1, respectively, to obtain an expression for $\Pr\left(\Psi_{\mathrm{SR}} < \varphi_{th}\right)$. Finally, substituting the obtained results for $\Pr\left(\Psi_{\mathrm{SR}} < \varphi_{th}\right)$ and $\Pr\left(\Psi_{\mathrm{RD}} < \varphi_{th}\right)$ into (11), we get (17). ∎

Proposition 2: At very large γ_P and γ_I values, i.e., $\gamma_P, \gamma_I \to \infty$, we can express $\mathrm{P_{out}^{PR1}}$ as

$$
\begin{aligned}
\mathrm{P_{out}^{PR1}} &\overset{\gamma_P \to \infty}{\underset{\gamma_I \to \infty}{=}} \left[\psi_1 e^{-K_1}\left(1 + \frac{e^{-\lambda_3\mu}}{\lambda_3\mu}\right)\right. \\
&\quad \left. + \psi_2 e^{-K_2}\left(1 + \frac{e^{-\lambda_4\mu}}{\lambda_4\mu}\right)\right]\frac{\varphi_{th}}{\gamma_P} + O\left(\frac{1}{\gamma_P^2}\right).
\end{aligned}
\tag{23}
$$

Proof: From (16), by using a Taylor expansion, we can obtain an approximating expression for $\Pr\left(\Psi_{\mathrm{RD}} < \varphi_{th}\right)$ at very large γ_P and γ_I value (or $1/\gamma_P \to 0$, $1/\gamma_I \to 0$) as

$$
\Pr\left(\Psi_{\mathrm{RD}} < \varphi_{th}\right) = s_0 + \frac{s_1}{\gamma_P} + O\left(\frac{1}{\gamma_P^2}\right).
\tag{24}
$$

In (24), s_0 is calculated by

$$
s_0 = \lim_{1/\gamma_P \to 0}\Pr\left(\Psi_{\mathrm{RD}} < \varphi_{th}\right) = 0.
\tag{25}
$$

In addition, s_1 in (24) can be formulated as

$$
\begin{aligned}
s_1 &= \lim_{\frac{1}{\gamma_P} \to 0}\frac{\partial \Pr\left(\Psi_{\mathrm{RD}} < \varphi_{th}\right)}{\partial\left(\frac{1}{\gamma_P}\right)} \\
&= \left(1 - e^{-\lambda_4\mu}\right)\psi_2 e^{-K_2}\varphi_{th} + \lambda_4\mu e^{-K_2 - \lambda_4\mu}\left[\sum_{m=0}^{\infty}\frac{K_2^m\psi_2}{m!}\right. \\
&\quad \left. \times \frac{(1 + \lambda_4\mu)}{\lambda_4^2\mu^2} - \sum_{m=0}^{\infty}\frac{K_2^{m+1}\psi_2}{(m+1)!}\left(\frac{1}{\lambda_4^2\mu^2} + \frac{1}{\lambda_4\mu}\right)\right]\varphi_{th}.
\end{aligned}
\tag{26}
$$

$$\Pr\left(\Psi_{\text{RD}} < \varphi_{th}\right) = \left(1 - e^{-\lambda_4\mu}\right)\left[1 - Q_1\left(\sqrt{2K_2}, \sqrt{\frac{2\psi_2\varphi_{th}}{\gamma_P}}\right)\right] + e^{-\lambda_4\mu}$$

$$- \lambda_4\mu e^{-K_2-\lambda_4\mu}\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\sum_{t=0}^{n}\frac{K_2^{m+n}\psi_2^{\ n}}{(m+n)!t!}\frac{\varphi_{th}^n}{\gamma_P^{t-1}}\frac{e^{-\psi_2\varphi_{th}/\gamma_P}}{\left(\lambda_4\mu\gamma_P + \psi_2\varphi_{th}\right)^{n+1-t}}. \tag{16}$$

Using the fact that

$$\sum_{m=0}^{\infty}\frac{K_2^m}{m!} = e^{K_2}, \quad \sum_{m=0}^{\infty}\frac{K_2^{m+1}}{(m+1)!} = e^{K_2} - 1, \tag{27}$$

we obtain

$$s_1 = \psi_2 e^{-K_2}\left(1 + \frac{e^{-\lambda_4\mu}}{\lambda_4\mu}\right)\varphi_{th}. \tag{28}$$

Combining (24), (25) with (28), we get

$$\Pr\left(\Psi_{\text{RD}} < \varphi_{th}\right) = \psi_2 e^{-K_2}\left(1 + \frac{e^{-\lambda_4\mu}}{\lambda_4\mu}\right)\frac{\varphi_{th}}{\gamma_P} + O\left(\frac{1}{\gamma_P^2}\right),$$

$$\Pr\left(\Psi_{\text{SR}} < \varphi_{th}\right) = \psi_1 e^{-K_1}\left(1 + \frac{e^{-\lambda_3\mu}}{\lambda_3\mu}\right)\frac{\varphi_{th}}{\gamma_P} + O\left(\frac{1}{\gamma_P^2}\right). \tag{29}$$

Finally, substituting (29) into (11), we get (23), which completes the proof. ∎

Corollary 1: Without transmit power constraint, the asymptotic OP of the PR1 protocol can be given as

$$\text{P}_{\text{out}}^{\text{PR1}} \overset{\gamma_P \to \infty}{=} \left[\frac{\psi_1 e^{-K_1}}{\lambda_3} + \frac{\psi_2 e^{-K_2}}{\lambda_4}\right]\frac{\varphi_{th}}{\gamma_I} + O\left(\frac{1}{\gamma_I^2}\right). \tag{30}$$

B. CCN with Direct Link: Incremental Relaying

In the second cognitive relaying protocol, named PR2, we assume that the incremental relaying scheme is used to relay the source's data to D [17]. With this transmission scheme, the OP of the PR2 protocol is calculated as follows:

$$\text{P}_{\text{out}}^{\text{PR2}} = \Pr\left(\Psi_{\text{e2e}}^{\text{PR2}} < \varphi_{th}\right) = \Pr\left(\Psi_{\text{SD}} < \varphi_{th}, \Psi_{\text{SR}} < \varphi_{th}\right)$$
$$+ \Pr\left(\Psi_{\text{SD}} < \varphi_{th}, \Psi_{\text{RD}} < \varphi_{th}, \Psi_{\text{SR}} \geq \varphi_{th}\right). \tag{31}$$

Considering the first term $\Pr\left[\Psi_{\text{SD}} < \varphi_{th}, \Psi_{\text{SR}} < \varphi_{th}\right]$ in (31), it can be formulated as

$$\Pr\left(\Psi_{\text{SD}} < \varphi_{th}, \Psi_{\text{SR}} < \varphi_{th}\right)$$
$$= \underbrace{\Pr\left(\gamma_3 < \mu, \gamma_0 < \frac{\varphi_{th}}{\gamma_P}, \gamma_1 < \frac{\varphi_{th}}{\gamma_P}\right)}_{P_3^{out}}$$
$$+ \underbrace{\Pr\left(\gamma_3 \geq \mu, \gamma_0 < \frac{\varphi_{th}}{\mu\gamma_P}\gamma_3, \gamma_1 < \frac{\varphi_{th}}{\mu\gamma_P}\gamma_3\right)}_{P_4^{out}}. \tag{32}$$

By using the CDF of γ_0, γ_1 and γ_3, P_3^{out} in (32) is calculated as

$$P_3^{out} = \left(1 - e^{-\lambda_3\mu}\right)\left(1 - e^{-\lambda_0\frac{\varphi_{th}}{\gamma_P}}\right)$$
$$\times \left[1 - Q_1\left(\sqrt{2K_1}, \sqrt{2\psi_1\frac{\varphi_{th}}{\gamma_P}}\right)\right]. \tag{33}$$

For P_4^{out} in (32), it is easy to see that

$$P_4^{out} = \int_\mu^\infty f_{\gamma_3}(x)F_{\gamma_1}\left(\frac{\varphi_{th}}{\mu\gamma_P}x\right)F_{\gamma_0}\left(\frac{\varphi_{th}}{\mu\gamma_P}x\right)dx. \tag{34}$$

Substituting the CDFs of γ_1 in (1) into (34) together with the fact that the CDF and PDF of exponential RVs X, for $X \in \{\gamma_0, \gamma_3\}$, are given as $F_X(x) = 1 - e^{-\lambda x}$ and $f_X(x) = \lambda e^{-\lambda x}$, respectively, we obtain

$$P_4^{out} = \int_\mu^\infty \lambda_3 e^{-\lambda_3 x}\left(1 - e^{-\frac{\lambda_0\varphi_{th}}{\mu\gamma_P}x}\right)$$
$$\times \left[1 - Q_1\left(\sqrt{2K_1}, \sqrt{2\psi_1\frac{\varphi_{th}}{\mu\gamma_P}x}\right)\right]dx. \tag{35}$$

By using the infinite series expansion of $Q_1(.,.)$ [15, Eq. (4.35)] into (35), we can obtain an expression for P_4^{out} as

$$P_4^{out} = e^{-\lambda_3\mu} - \frac{\lambda_3\mu\gamma_P e^{-(\lambda_0\varphi_{th}/\gamma_P + \lambda_3\mu)}}{\lambda_0\varphi_{th} + \lambda_3\mu\gamma_P} - \lambda_3\mu e^{-K_1-\lambda_3\mu}$$
$$\times \sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\sum_{t=0}^{n}\frac{K_1^{m+n}\psi_1^{\ n}}{(m+n)!t!}\frac{\varphi_{th}^n}{\gamma_P^{t-1}}\left[\frac{e^{-\psi_1\varphi_{th}/\gamma_P}}{\left(\psi_1\varphi_{th} + \lambda_3\mu\gamma_P\right)^{n+1-t}}\right.$$
$$\left. - \frac{e^{-(\lambda_0+\psi_1)\varphi_{th}/\gamma_P}}{\left(\lambda_0\varphi_{th} + \psi_1\varphi_{th} + \lambda_3\mu\gamma_P\right)^{n+1-t}}\right]. \tag{36}$$

From (32), (33) and (36), we have

$$\Pr\left(\Psi_{\text{SD}} < \varphi_{th}, \Psi_{\text{SR}} < \varphi_{th}\right) = \left(1 - e^{-\lambda_3\mu}\right)\left(1 - e^{-\lambda_0\frac{\varphi_{th}}{\gamma_P}}\right)$$
$$\times e^{-\lambda_3\mu}\left[1 - Q_1\left(\sqrt{2K_1}, \sqrt{2\psi_1\frac{\varphi_{th}}{\gamma_P}}\right)\right] - e^{-(\lambda_0\varphi_{th}/\gamma_P + \lambda_3\mu)}$$
$$\times \frac{\lambda_3\mu\gamma_P}{\lambda_0\varphi_{th} + \lambda_3\mu\gamma_P} - \lambda_3\mu e^{-K_1-\lambda_3\mu}\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\sum_{t=0}^{n}\frac{\varphi_{th}^n}{\gamma_P^{t-1}}$$
$$\times \frac{K_1^{m+n}\psi_1^{\ n}}{(m+n)!t!}\left[\frac{e^{-\psi_1\varphi_{th}/\gamma_P}}{\left(\psi_1\varphi_{th} + \lambda_3\mu\gamma_P\right)^{n+1-t}}\right.$$
$$\left. - \frac{e^{-(\lambda_0+\psi_1)\varphi_{th}/\gamma_P}}{\left(\lambda_0\varphi_{th} + \psi_1\varphi_{th} + \lambda_3\mu\gamma_P\right)^{n+1-t}}\right]. \tag{37}$$

Next, the second term in (31) can be written as

$$\Pr\left(\Psi_{\text{SD}} < \varphi_{th}, \Psi_{\text{RD}} < \varphi_{th}, \Psi_{\text{SR}} \geq \varphi_{th}\right)$$
$$= \Pr\left(\Psi_{\text{SD}} < \varphi_{th}, \Psi_{\text{SR}} \geq \varphi_{th}\right)\Pr\left(\Psi_{\text{RD}} < \varphi_{th}\right). \tag{38}$$

Similarly, we can calculate the joint probability $\Pr\left(\Psi_{\text{SD}} < \varphi_{th}, \Psi_{\text{SR}} \geq \varphi_{th}\right)$ in (38) as

$$\Pr\left(\Psi_{\mathrm{SD}} < \varphi_{th}, \Psi_{\mathrm{SR}} \geq \varphi_{th}\right)$$

$$= \Pr\left(\gamma_3 < \mu, \gamma_0 < \frac{\varphi_{th}}{\gamma_P}, \gamma_1 \geq \frac{\varphi_{th}}{\gamma_P}\right)$$

$$+ \Pr\left(\gamma_3 \geq \mu, \gamma_0 < \frac{\varphi_{th}}{\mu\gamma_P}\gamma_3, \gamma_1 \geq \frac{\varphi_{th}}{\mu\gamma_P}\gamma_3\right),$$

$$= \left(1 - e^{-\lambda_3\mu}\right)\left(1 - e^{-\lambda_0\frac{\varphi_{th}}{\gamma_P}}\right) Q_1\left(\sqrt{2K_1}, \sqrt{2\psi_1\frac{\varphi_{th}}{\gamma_P}}\right)$$

$$+ \lambda_3\mu e^{-K_1-\lambda_3\mu} \sum_{m=0}^{+\infty}\sum_{n=0}^{+\infty}\sum_{t=0}^{n} \frac{K_1^{m+n}\psi_1^{\,n}}{(m+n)!\,t!} \frac{\varphi_{th}^n}{\gamma_P^{t-1}}$$

$$\times \left[\frac{e^{-\frac{\psi_1\varphi_{th}}{\gamma_P}}}{\left(\psi_1\varphi_{th} + \lambda_3\mu\gamma_P\right)^{n+1-t}}\right.$$

$$\left. - \frac{e^{-\frac{(\lambda_0+\psi_1)\varphi_{th}}{\gamma_P}}}{\left(\lambda_0\varphi_{th} + \psi_1\varphi_{th} + \lambda_3\mu\gamma_P\right)^{n+1-t}}\right]. \tag{39}$$

Finally, by plugging everything together, i.e., (16), (37), (38), and (39) into (31), the OP of the scheme PR2 over asymmetric fading channels can be obtained in closed-form expression, which is not shown here due to space-limit.

Proposition 3: Without transmit power constraint γ_P, the OP of the PR2 protocol can be expressed by an exact closed-form expression in (40) shown at the top of next page.

Proof: Similar to the proof of Proposition 1, by taking the limit of (37) and (39) as γ_I is fixed and γ_P goes to infinity, we respectively obtain

$$\lim_{\gamma_P\to\infty} \Pr\left(\Psi_{\mathrm{SD}}<\varphi_{th}, \Psi_{\mathrm{SR}}<\varphi_{th}\right) = \frac{\psi_1\varphi_{th} e^{-\frac{K_1\lambda_3\gamma_I}{\psi_1\varphi_{th}+\lambda_3\gamma_I}}}{(1+K_1)\lambda_1\varphi_{th} + \lambda_3\gamma_I}$$

$$- \frac{\lambda_3\gamma_I\psi_1\varphi_{th} e^{-\frac{K_1(\lambda_0\varphi_{th}+\lambda_3\gamma_I)}{\lambda_0\varphi_{th}+\psi_1\varphi_{th}+\lambda_3\gamma_I}}}{\left(\lambda_0\varphi_{th}+\lambda_3\gamma_I\right)\left(\lambda_0\varphi_{th}+\psi_1\varphi_{th}+\lambda_3\gamma_I\right)}. \tag{41}$$

$$\lim_{\gamma_P\to\infty} \Pr\left(\Psi_{\mathrm{SD}} < \varphi_{th}, \Psi_{\mathrm{SR}} \geq \varphi_{th}\right)$$

$$= \frac{\lambda_0\varphi_{th}}{\lambda_0\varphi_{th} + \lambda_3\gamma_I} - \frac{\psi_1\varphi_{th}}{\psi_1\varphi_{th}+\lambda_3\gamma_I} e^{-\frac{K_1\lambda_3\gamma_I}{\psi_1\varphi_{th}+\lambda_3\gamma_I}} \tag{42}$$

$$+ \frac{\lambda_3\gamma_I\psi_1\varphi_{th} e^{-\frac{K_1(\lambda_0\varphi_{th}+\lambda_3\gamma_I)}{\lambda_0\varphi_{th}+\psi_1\varphi_{th}+\lambda_3\gamma_I}}}{\left(\lambda_3\gamma_I + \lambda_0\varphi_{th}\right)\left(\lambda_0\varphi_{th}+\psi_1\varphi_{th}+\lambda_3\gamma_I\right)}. \tag{43}$$

Finally, substituting (22), (41) and (42) into (31), we obtain (40). ∎

Proposition 4: At very large γ_P and γ_I values, i.e., $\gamma_P, \gamma_I \to \infty$, we can express $\mathrm{P}_{\mathrm{out}}^{\mathrm{PR2}}$ as in (44) at the top of next page.

Proof: First, by using the Taylor expansion for (37) for very large γ_P and γ_I values, we can express $\Pr\left(\Psi_{\mathrm{SD}} < \varphi_{th}, \Psi_{\mathrm{SR}} < \varphi_{th}\right)$ as follows:

$$\Pr\left(\Psi_{\mathrm{SD}} < \varphi_{th}, \Psi_{\mathrm{SR}} < \varphi_{th}\right) = t_0 + \frac{t_1}{\gamma_P} + \frac{t_2}{2!}\frac{1}{\gamma_P^2} + O\left(\frac{1}{\gamma_P^3}\right). \tag{45}$$

Similarly, t_0, t_1 and t_2 can be respectively given as

$$t_0 = \lim_{1/\gamma_P\to0} \Pr\left(\Psi_{\mathrm{SD}} < \varphi_{th}, \Psi_{\mathrm{SR}} < \varphi_{th}\right) = 0. \tag{46}$$

$$t_1 = \lim_{1/\gamma_P\to0} \frac{\partial \Pr\left(\Psi_{\mathrm{SD}} < \varphi_{th}, \Psi_{\mathrm{SR}} < \varphi_{th}\right)}{\partial\left(1/\gamma_P\right)} = \frac{\lambda_0\left(1+\lambda_3\mu\right)}{\lambda_3\mu}$$

$$\times e^{-\lambda_3\mu} - e^{-K_1-\lambda_3\mu}\sum_{m=0}^{\infty}\frac{K_1^m}{m!}\frac{\lambda_0\left(1+\lambda_3\mu\right)}{\lambda_3\mu} = 0. \tag{47}$$

$$t_2 = \lim_{1/\gamma_P\to0} \frac{\partial^2 \Pr\left[\Psi_{\mathrm{SD}} < \varphi_{th}, \Psi_{\mathrm{SR}} < \varphi_{th}\right]}{\partial^2\left(1/\gamma_P\right)} = 2\left(1+K_1\right)$$

$$\times \lambda_0\lambda_1 e^{-K_1}\left(1 + \frac{2+2\lambda_3\mu}{\lambda_3^2\mu^2}e^{-\lambda_3\mu}\right)\varphi_{th}^2. \tag{48}$$

From (45) to (48), we have

$$\Pr\left(\Psi_{\mathrm{SD}} < \varphi_{th}, \Psi_{\mathrm{SR}} < \varphi_{th}\right) = \left(1+K_1\right)\lambda_0\lambda_1 e^{-K_1}$$

$$\times \left(1 + \frac{2+2\lambda_3\mu}{\lambda_3^2\mu^2}e^{-\lambda_3\mu}\right)\frac{\varphi_{th}^2}{\gamma_P^2} + O\left(\frac{1}{\gamma_P^3}\right). \tag{49}$$

Similarly, we also obtain

$$\Pr\left[\Psi_{\mathrm{SD}} < \varphi_{th}, \Psi_{\mathrm{SR}} \geq \varphi_{th}\right] = \left(\lambda_0 + \frac{\lambda_0 e^{-\lambda_3\mu}}{\lambda_3\mu}\right)\frac{\varphi_{th}}{\gamma_P}. \tag{50}$$

Now, substituting (29), (49) and (50) into (31), we obtain (44). ∎

Corollary 2: Without transmit power constraint γ_P, the asymptotic outage probability of the PR2 protocol can be given as

$$\mathrm{P}_{\mathrm{out}}^{\mathrm{PR2}} \stackrel{\gamma_P\to\infty}{=} \left(\frac{2\lambda_0\psi_1 e^{-K_1}}{\lambda_3^2} + \frac{\lambda_0\psi_2 e^{-K_2}}{\lambda_3\lambda_4}\right)\frac{\varphi_{th}^2}{\gamma_I^2} + O\left(\frac{1}{\gamma_I^3}\right). \tag{51}$$

Proof: By utilizing the similar approach when γ_I is fixed and γ_P tends to infinity, we can obtain (51), which completes the proof. ∎

From Proposition 2 (Corollary 1) and Proposition 4 (Corollary 2), it is apparent that the diversity order of the PR1 and PR2 protocols equals 1 and 2, respectively.

IV. NUMERICAL RESULTS

In this section, we present various numerical results to verify the theoretical derivation by comparing the analysis with Monte Carlo simulations. Without loss of generality, we assume that the co-ordinates of S, D, R, and PU are $(0,0)$, $(1,0)$, $(x_{\mathrm{R}},0)$, and $(x_{\mathrm{PR}}, y_{\mathrm{PR}})$, respectively. Hence, the corresponding distances are calculated as $d_0 = 1$, $d_1 = x_{\mathrm{R}}$, $d_2 = 1 - x_{\mathrm{R}}$, $d_3 = \sqrt{x_{\mathrm{PR}}^2 + y_{\mathrm{PR}}^2}$, and $d_4 = \sqrt{\left(x_{\mathrm{R}}^2 - x_{\mathrm{PR}}\right)^2 + y_{\mathrm{PR}}^2}$. In all simulations, the path-loss exponent is set as $\beta = 3$ and the threshold level is fixed by $\varphi_{th} = 1$. When infinite series are being used, we truncate them at 50 terms.

In Fig. 2, we plot the OP as a function of γ_P in dB when $\mu = 1$, $x_{\mathrm{R}} = x_{\mathrm{PR}} = y_{\mathrm{PR}} = 0.5$ and $K_1 = K_2 = 1$ dB. It can be seen that the PR2 protocol outperforms the PR1 protocol as it utilizes the direct and relaying links to provide cooperative diversity gain.

In Fig. 3, we investigate the impact of PU's positions on the system performance when the parameters are fixed at $\mu = 1$, $x_{\mathrm{R}} = 0.4$, $K_1 = K_2 = 1.5$ dB. As can clearly seen from this

$$P_{out}^{PR2} \overset{\gamma_P \to \infty}{\equiv} \frac{\psi_1 \varphi_{th}}{\psi_1 \varphi_{th} + \lambda_3 \gamma_I} e^{-\frac{K_1 \lambda_3 \gamma_I}{\psi_1 \varphi_{th} + \lambda_3 \gamma_I}} - \frac{\lambda_3 \gamma_I}{\lambda_0 \varphi_{th} + \lambda_3 \gamma_I} \frac{\psi_1 \varphi_{th} e^{-\frac{K_1(\lambda_0 \varphi_{th} + \lambda_3 \gamma_I)}{\lambda_0 \varphi_{th} + \psi_1 \varphi_{th} + \lambda_3 \gamma_I}}}{\lambda_0 \varphi_{th} + \psi_1 \varphi_{th} + \lambda_3 \gamma_I}$$
$$+ \left[\frac{\lambda_0 \varphi_{th}}{\lambda_0 \varphi_{th} + \lambda_3 \gamma_I} - \frac{\psi_1 \varphi_{th} e^{-\frac{K_1 \lambda_3 \gamma_I}{\psi_1 \varphi_{th} + \lambda_3 \gamma_I}}}{\psi_1 \varphi_{th} + \lambda_3 \gamma_I} + \frac{\lambda_3 \gamma_I}{\lambda_0 \varphi_{th} + \lambda_3 \gamma_I} \frac{\psi_1 \varphi_{th}}{\lambda_0 \varphi_{th} + \psi_1 \varphi_{th} + \lambda_3 \gamma_I} \right.$$
$$\left. \times e^{-\frac{K_1(\lambda_0 \varphi_{th} + \lambda_3 \gamma_I)}{\lambda_0 \varphi_{th} + \psi_1 \varphi_{th} + \lambda_3 \gamma_I}} \right] \frac{\psi_2 \varphi_{th}}{\psi_2 \varphi_{th} + \lambda_4 \gamma_I} e^{-\frac{K_2 \lambda_4 \gamma_I}{\psi_2 \varphi_{th} + \lambda_4 \gamma_I}}. \tag{40}$$

$$P_{out}^{PR2} \overset{\gamma_P \to \infty}{\underset{\gamma_I \to \infty}{\equiv}} \left[\lambda_0 \psi_1 e^{-K_1} \left(1 + \frac{2 + 2\lambda_3 \mu}{\lambda_3^2 \mu^2} e^{-\lambda_3 \mu} \right) + \left(\lambda_0 + \frac{\lambda_0}{\lambda_3 \mu} e^{-\lambda_3 \mu} \right) \psi_2 e^{-K_2} \left(1 + \frac{e^{-\lambda_4 \mu}}{\lambda_4 \mu} \right) \right] \frac{\varphi_{th}^2}{\gamma_P^2} + O\left(\frac{1}{\gamma_P^3} \right). \tag{44}$$
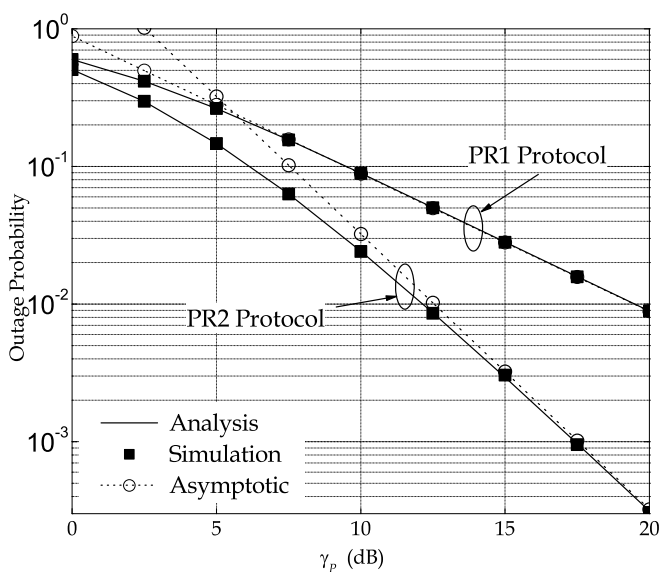

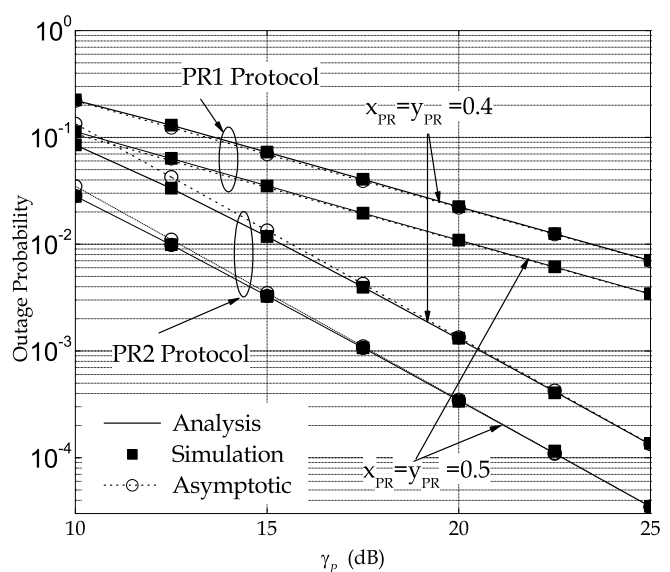Fig. 2. The OP as a function of γ_P in dB when $x_R = x_{PR} = y_{PR} = 0.5$ and $K_1 = K_2 = 1$ dB.

Fig. 3. The OP as a function of γ_P in dB when $\mu = 1$, $x_R = 0.4$, and $K_1 = K_2 = 1.5$ dB.

figure, the outage performance of PR1 and PR2 protocols is enhanced when PU moves further from the secondary source as the power constraint can be more relaxed.

In Fig. 4, we examine the impact of R's positions on the system performance when the parameters are fixed as $x_{PR} = y_{PR} = 0.5$, $K_1 = K_2 = 2$ dB, and $\gamma_P = 10$ dB. It can be seen that for each position of PU, we can find an optimal position of the relay at which the OP yields its lowest value.

In Figs. 5- 6, we use the Golden Section Search method [18] to find the optimal position of R over the interval [0,1] to minimize the outage performance at each fixed position of PU. The purpose of this method is to find an interval $\left[x_R^{Low}, x_R^{Up} \right]$ which includes the optimal point x_R^* and satisfies an uncertainty condition, i.e., $x_R^{Up} - x_R^{Low} \le \varepsilon$. In these simulations, we set ε as $\varepsilon = 10^{-4}$ and the optimal point x_R^* is obtained as $x_R^* = \left(x_R^{Up} + x_R^{Low} \right)/2$. In Figs. 5, we fix $y_{PR} = 0.5$ while changing x_{PR} from 0 to 1. We can see that

at small x_{PR}, i.e., PU is near to S, the optimal value x_R^* is also small. This is due to the fact that R has to be near to S to help it relay the signal to D. In Fig. 6, we place PU at different positions, i.e., $x_{PR} = y_{PR} = 0.05\,i$, $i \in \{1, 2, ..., 19\}$ and use the Golden Section Search method to find x_R^* of both protocols in the case that only interference constraint I_{th} is required.

V. CONCLUSIONS

Two important CCN schemes, with and without direct link, have been investigated when the secondary network experiences Rician fading and the SUs→PU links are subject to Rayleigh fading. Both exact and asymptotic OP expressions have been obtained for the considered CCNs. The CCN with incremental DF relaying has been shown to outperform both conventional dual-hop DF relaying, which reveals the significance of relay deployment in enhancing the performance of secondary networks, operating under strict power conditions.
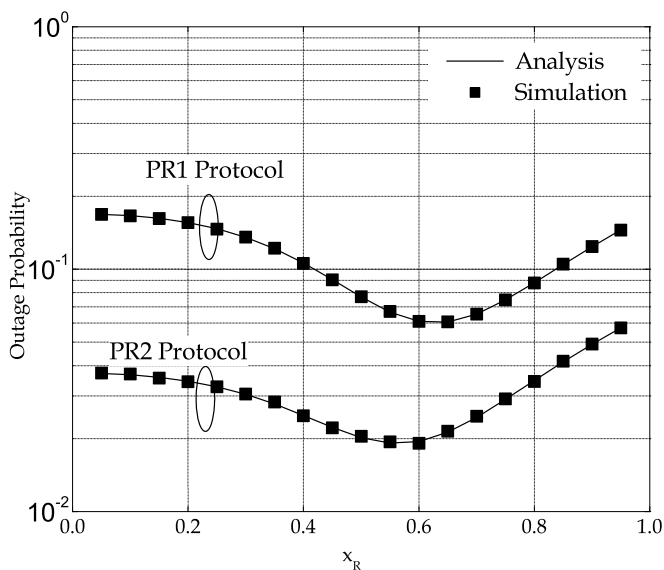
Fig. 4. The OP as a function of x_{R} without P_{th} constraint and $x_{\mathrm{PR}} = y_{\mathrm{PR}} = 0.5$, $K_1 = K_2 = 2$ dB, and $\gamma_P = 10$ dB.
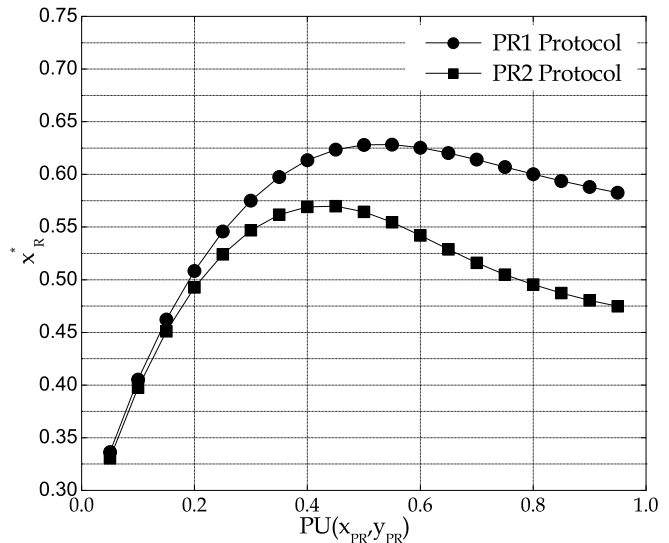

Fig. 6. The optimal value x_{R}^* as a function of PU's positions without P_{th} constraint and $K_1 = K_2 = 2$ dB, and $\gamma_P = 10$ dB.
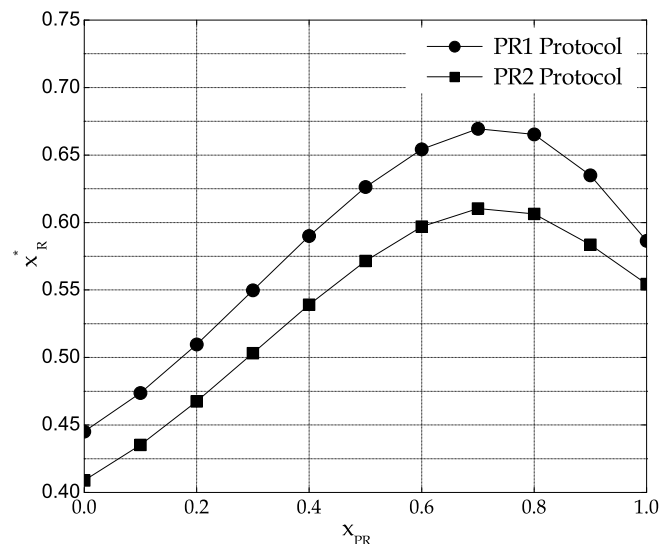

Fig. 5. The optimal value x_{R}^* as a function of x_{PR} when $y_{\mathrm{PR}} = 0.5$, $K_1 = K_2 = 1$ dB, $\mu = 1$, and $\gamma_P = 10$ dB.

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