Outage and Diversity of Cognitive Relaying Systems under Spectrum Sharing Environments in Nakagami-m Fading

Trung Q. Duong, Daniel Benevides da Costa, Theodoros A. Tsiftsis, Caijun Zhong, and A. Nallanathan

***Abstract*—In this letter, the outage performance of dual-hop cooperative spectrum sharing systems with a direct link is investigated. A selection combining receiver is employed at the destination in order to combine the signals received from the decode-and-forward (DF) relay and from the source. Assuming independent non-identically distributed Nakagami-*m* fading channels, exact and asymptotic closed-form expressions are derived for the outage probability. Our results reveal that the diversity order of the considered system is solely determined by the fading severity parameters of the secondary network, being equal to $\min(m_1, m_2) + m_0$, where m_0, m_1, and m_2 represent the fading severity parameters of the secondary nodes i.e., source→destination, source→relay, and relay→destination links, respectively.**

***Index Terms*—Cooperative spectrum sharing systems, decode-and-forward relay, Nakagami-*m* fading.**

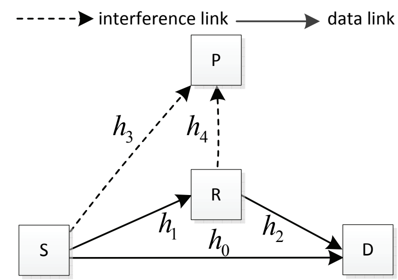

Fig. 1. System model for a cognitive relay network with cooperative diversity under a spectrum sharing environment.

I. Introduction

Cooperative spectrum sharing systems (CSSSs) have recently gained considerable attention in the research community [1], [2] due to the combined use of two promising wireless communication techniques, namely cooperative diversity (CD) [3] and cognitive radio (CR) [4]. On one hand, CD enhances the communication reliability. On the other hand, CR provides an efficient way to improve the spectrum utilization.

The performance of CSSSs over Rayleigh fading channels was evaluated in [1], [2]. These works were extended to Nakagami-*m* fading with decode-and-forward (DF) relaying [5] and amplify-and-forward (AF) relaying [6], [7]. In particular, under the joint constraint of peak interference power and maximal transmit power, the exact and asymptotic outage probability of cognitive DF relay network have been obtained in [5]. However, all of these works have neglected the presence of the direct link between the secondary source and secondary destination. Very recently, the impact of direct communication has been considered for cognitive relay networks over Rayleigh fading channels with single relay [8] and multiple relays [9]. It has been shown in [9] that under the proportional interference power constraint, the full diversity order can be achieved for Rayleigh fading channels. Furthermore, the works in [6]–[9] only focused on Rayleigh fading. As such, this letter aims to generalize the contribution presented in [8], [9] by analyzing the impact of cooperative communications on the outage performance of CR networks over Nakagami-m fading channels. It is noteworthy that such analysis still remains to be addressed even for Rayleigh fading channels. Employing a selection combining (SC) receiver at the secondary user (SU) destination, exact closed-form expressions for the end-to-end outage probability (OP) are derived. Our analytical derivations allow for independent non-identically distributed (i.n.i.d.) Nakagami-*m* fading channels. To gain further insights into how the primary user (PU) network and SU network affect the diversity and coding gains, an asymptotic analysis is carried out. It is shown that the diversity gain equals to $\min(m_1, m_2) + m_0$, where m_0, m_1, and m_2 represent the fading severity parameters pertaining to the secondary source→destination, source→relay, and relay→destination links, respectively. This complies with the result obtained elsewhere in the literature for cooperative DF relay networks.

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II. System and Channel Models

Consider a cognitive radio network where a secondary source S, a secondary relay R, a secondary destination D, and a primary receiver P coexist in the same geographical area, as shown in Fig. 1. For the SUs' communication process, a spectrum sharing strategy is employed, in which S and R must limit their transmit powers so that the interference on the PU does not exceed a threshold I_p, which is the maximum peak interference that the PU receiver P can tolerate.

The communication from S to D takes place in two phases. In phase I (i.e, broadcasting phase), S transmits its signal to both R and D with a transmit power $P_{\mathsf{S}} = \frac{I_p}{|h_3|^2}$ [6], where h_3 denotes the channel coefficient of the link $\mathsf{S} \to \mathsf{P}$. In phase II (i.e, relaying phase), R decodes the signal received from the source and forwards it to D with a transmit power $P_{\mathsf{R}} = \frac{I_p}{|h_4|^2}$ [6], where h_4 stands for the channel coefficient of the link $\mathsf{R} \to \mathsf{P}$. At destination D, the two signals resulting from these two phases are combined by means of a SC receiver. Thus, the instantaneous received signal-to-noise ratios (SNRs) at D

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from the relaying and direct links are written as

$$\gamma_{\rm DF} = \min\left(\frac{\bar{\gamma}|h_1|^2}{|h_3|^2}, \frac{\bar{\gamma}|h_2|^2}{|h_4|^2}\right), \qquad \gamma_{\rm DT} = \frac{\bar{\gamma}|h_0|^2}{|h_3|^2}, \tag{1}$$

where $\bar{\gamma} = \frac{I_p}{N_0}$, with N_0 representing the noise variance, and $\gamma_{\rm DF}$ is the SNR for the relaying link $\mathsf{S} \to \mathsf{R} \to \mathsf{D}$, which is defined as the minimum SNR among the two hops [5]. Additionally, h_0, h_1 and h_2 are the channel coefficients pertaining to the links $\mathsf{S} \to \mathsf{D}$, $\mathsf{S} \to \mathsf{R}$, and $\mathsf{R} \to \mathsf{D}$, respectively. Herein, we assume i.n.i.d. Nakagami-*m* fading channels, in which the channel power gains $|h_0|^2$, $|h_1|^2$, $|h_2|^2$, $|h_3|^2$, $|h_4|^2$ follow a Gamma distribution with fading severity parameters m_0, m_1, m_2, m_3, m_4 and mean powers $\Omega_{\mathsf{S,D}}$, $\Omega_{\mathsf{S,R}}$, $\Omega_{\mathsf{R,D}}$, $\Omega_{\mathsf{S,P}}$, $\Omega_{\mathsf{R,P}}$, respectively. The end-to-end instantaneous SNR at the destination can be written as

$$\gamma_{\rm D} = \max\left\{\gamma_{\rm DF}, \gamma_{\rm DT}\right\}. \tag{2}$$

III. Outage Probability Analysis

A. Exact Closed-Form Analysis

From (1), it can be seen that $\gamma_{\rm DF}$ and $\gamma_{\rm DT}$ are not statistically independent due to the presence of a common random variable (RV) $|h_3|^2$, which renders the analysis too involved. To cope with this difficulty, an analytical approach was proposed in [8] which took into account the non-independence between these RVs. In particular, the cumulative distribution function (CDF) of $\gamma_{\rm D}$ conditioned on h_3 can be written as

$$F_{\gamma_{\rm D}}(\gamma|h_3) = \Pr\left(\gamma_{\rm D} < \gamma|h_3\right) = F_{\gamma_{\rm DF}}(\gamma|h_3)\, F_{\gamma_{\rm DT}}(\gamma|h_3), \tag{3}$$

where (3) arises from the fact that h_3 is statistically independent of the remaining terms h_1, h_2, h_4, h_0[1]. Consequently, the CDF of $\gamma_{\rm DF}$ conditioned on $X = |h_3|^2$ can be given by

$$F_{\gamma_{\rm DF}}(\gamma|X) = 1 - \left[1 - F_Y(\gamma|X)\right]\left[1 - F_Z(\gamma|X)\right], \tag{4}$$

where $Y = \frac{\bar{\gamma}|h_2|^2}{|h_4|^2}$ and $Z = \frac{\bar{\gamma}|h_1|^2}{X}$. Since Y is given by ratio of two independent distributed Gamma RVs and does not depend on X, its CDF can be shown as

$$F_Y(\gamma|X) = \int_0^{\infty} F_{|h_2|^2}\left(\frac{\gamma}{\bar{\gamma}}t\right) f_{|h_4|^2}(t)\, dt = 1 - \Theta(\gamma), \tag{5}$$

where $\Theta(\gamma)$ is the function of γ which does not contain X, being given by

$$\Theta(\gamma) = \sum_{k=0}^{m_2-1} \frac{\beta_4^{m_4}\Gamma(m_4+k)}{k!\Gamma(m_4)\left(\beta_4 + \beta_2\gamma/\bar{\gamma}\right)^{m_4+k}} \left(\frac{\beta_2\gamma}{\bar{\gamma}}\right)^k, \tag{6}$$

with $\Gamma(\cdot)$ denoting the Gamma function [10, Eq. (8.310.1)], $\beta_2 = m_2/\Omega_{\mathsf{R,D}}$, and $\beta_4 = m_4/\Omega_{\mathsf{R,P}}$. By plugging (4), (5) into (3), we obtain

$$F_{\gamma_{\rm D}}(\gamma|X) = \left[1 - \Theta(\gamma)\Gamma\left(m_1, \frac{\beta_1\gamma X}{\bar{\gamma}}\right)/\Gamma(m_1)\right] \times \left[1 - \Gamma\left(m_0, \frac{\beta_0\gamma X}{\bar{\gamma}}\right)/\Gamma(m_0)\right]. \tag{7}$$

[1] It is important to note that for the unconditioned CDFs, the equality does not hold due to the statistical correlation, i.e., $F_{\gamma_{\rm D}}(\gamma) \neq F_{\gamma_{\rm DF}}(\gamma)\, F_{\gamma_{\rm DT}}(\gamma)$ [8].

where $\Gamma(\cdot,\cdot)$ is the upper incomplete Gamma function [10, Eq. (8.350.2)]. The unconditional CDF of $\gamma_{\rm D}$ marginalized out with respect to X is written as

$$F_{\gamma_{\rm D}}(\gamma) = \int_0^{\infty} F_{\gamma_{\rm D}}(\gamma|X)\, f_X(x)\, dx. \tag{8}$$

To this end, substituting (7) into (8) and using [10, Eq. (8.352.2)] to expand the incomplete Gamma function in terms of a finite sum, the CDF of $\gamma_{\rm D}$ can be expressed as

$$F_{\gamma_{\rm D}}(\gamma) = 1 - \Theta(\gamma)\mathcal{I}_1(\gamma) - \mathcal{I}_2(\gamma) + \Theta(\gamma)\mathcal{I}_3(\gamma), \tag{9}$$

where $\mathcal{I}_1(\gamma)$, $\mathcal{I}_2(\gamma)$, and $\mathcal{I}_3(\gamma)$ are, respectively, given by

$$\begin{aligned}
\mathcal{I}_1(\gamma) &= \sum_{k=0}^{m_1-1} \frac{\beta_3^{m_3}}{k!\Gamma(m_3)}\left(\frac{\beta_1\gamma}{\bar{\gamma}}\right)^k \int_0^{\infty} x^{m_3+k-1} e^{-\left(\beta_3 + \frac{\beta_1\gamma}{\bar{\gamma}}\right)x}dx,\\
\mathcal{I}_2(\gamma) &= \sum_{k=0}^{m_0-1} \frac{\beta_3^{m_3}}{k!\Gamma(m_3)}\left(\frac{\beta_0\gamma}{\bar{\gamma}}\right)^k \int_0^{\infty} x^{m_3+k-1} e^{-\left(\beta_3 + \frac{\beta_0\gamma}{\bar{\gamma}}\right)x}dx,\\
\mathcal{I}_3(\gamma) &= \sum_{i=0}^{m_1-1}\sum_{j=0}^{m_0-1} \frac{\beta_3^{m_3}}{i!j!\Gamma(m_3)}\left(\frac{\beta_1\gamma}{\bar{\gamma}}\right)^i \left(\frac{\beta_0\gamma}{\bar{\gamma}}\right)^j\\
&\quad \times \int_0^{\infty} x^{m_3+i+j-1} e^{-\left(\beta_3 + \frac{\beta_0\gamma}{\bar{\gamma}} + \frac{\beta_1\gamma}{\bar{\gamma}}\right)x}dx,
\end{aligned} \tag{10}$$

where $\beta_0 = m_0/\Omega_{\mathsf{S,D}}$, $\beta_1 = m_1/\Omega_{\mathsf{S,R}}$, and $\beta_3 = m_3/\Omega_{\mathsf{S,P}}$. The above integrals are tabulated and can be obtained in closed-form with the help of [10, Eq. (3.381.4)]. Pulling (6), (9), and (10) together, the OP, $P_{\sf out}$, is readily achieved knowing that it equals to the CDF of $\gamma_{\rm D}$ evaluated at $\gamma_{\sf th}$, i.e., $P_{\sf out} = F_{\gamma_{\rm D}}(\gamma_{\sf th})$, with $\gamma_{\sf th}$ being the predefined threshold. The closed-form expression for the OP is finally shown in (11), given at the top of the next page.

B. Asymptotic Analysis

Firstly, let us utilize the infinite series representation of the incomplete Gamma function [10, Eq. (8.354.2)] as

$$\Gamma(\alpha, x) = \Gamma(\alpha) - \sum_{n=0}^{\infty} \frac{(-1)^n x^{\alpha+n}}{n!(\alpha+n)}, \tag{12}$$

which leads to

$$\Gamma(\alpha, x) \overset{x\to 0}{\approx} \Gamma(\alpha) - \frac{x^{\alpha}}{\alpha}. \tag{13}$$

From (13), the conditional CDF $F_Z(\gamma|X)$ is given by

$$F_Z(\gamma|X) \overset{\bar{\gamma}\to\infty}{\approx} \frac{1}{\Gamma(m_1+1)}\left(\frac{\beta_1\gamma X}{\bar{\gamma}}\right)^{m_1}. \tag{14}$$

Similarly, (5) can be rewritten as

$$\begin{aligned}
F_Y(\gamma|X) &\overset{\bar{\gamma}\to\infty}{\approx} \int_0^{\infty} \frac{\beta_4^{m_4} t^{m_2+m_4-1} e^{-\beta_4 t}}{\Gamma(m_2+1)\Gamma(m_4)}\left(\frac{\beta_2\gamma}{\bar{\gamma}}\right)^{m_2} dt\\
&= \frac{\Gamma(m_2+m_4)}{\Gamma(m_2+1)\Gamma(m_4)}\left(\frac{\beta_2\gamma}{\beta_4\bar{\gamma}}\right)^{m_2}.
\end{aligned} \tag{15}$$

Then, substituting (15) and (14) into (4), and after some algebraic manipulations, the conditional CDF of $\gamma_{\rm DF}$ can be

$$P_{\mathsf{out}} = 1 - \left[\sum_{k=0}^{m_2-1} \frac{\beta_4^{m_4}\Gamma(m_4+k)}{k!\Gamma(m_4)} \left(\frac{\beta_2\gamma_{\mathsf{th}}}{\bar{\gamma}}\right)^k \left(\beta_4 + \frac{\beta_2\gamma_{\mathsf{th}}}{\bar{\gamma}}\right)^{-m_4-k}\right] \left[\sum_{k=0}^{m_1-1} \frac{\beta_3^{m_3}\Gamma(m_3+k)}{k!\Gamma(m_3)} \left(\frac{\beta_1\gamma_{\mathsf{th}}}{\bar{\gamma}}\right)^k \left(\beta_3 + \frac{\beta_1\gamma_{\mathsf{th}}}{\bar{\gamma}}\right)^{-m_3-k}\right.$$
$$\left. - \sum_{k=0}^{m_0-1} \frac{\beta_3^{m_3}\Gamma(m_3+k)}{k!\Gamma(m_3)} \left(\frac{\beta_0\gamma_{\mathsf{th}}}{\bar{\gamma}}\right)^k \left(\beta_3 + \frac{\beta_0\gamma_{\mathsf{th}}}{\bar{\gamma}}\right)^{-m_3-k}\right] + \left[\sum_{k=0}^{m_2-1} \frac{\beta_4^{m_4}\Gamma(m_4+k)}{k!\Gamma(m_4)} \left(\frac{\beta_2\gamma_{\mathsf{th}}}{\bar{\gamma}}\right)^k \left(\beta_4 + \frac{\beta_2\gamma_{\mathsf{th}}}{\bar{\gamma}}\right)^{-m_4-k}\right]$$
$$\times \left[\sum_{i=0}^{m_1-1} \sum_{j=0}^{m_0-1} \frac{\beta_3^{m_3}\Gamma(m_3+i+j)}{i!j!\Gamma(m_3)} \left(\frac{\beta_1\gamma_{\mathsf{th}}}{\bar{\gamma}}\right)^i \left(\frac{\beta_0\gamma_{\mathsf{th}}}{\bar{\gamma}}\right)^j \left(\beta_3 + \frac{\beta_0\gamma_{\mathsf{th}}}{\bar{\gamma}} + \frac{\beta_1\gamma_{\mathsf{th}}}{\bar{\gamma}}\right)^{-m_3-i-j}\right]. \tag{11}$$

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represented by

$$F_{\gamma_{\mathrm{DF}}}(\gamma|X) \overset{\bar{\gamma}\to\infty}{\approx} \Xi_1(X)\left(\frac{\gamma}{\bar{\gamma}}\right)^{\min(m_1,m_2)}, \tag{16}$$

$$\Xi_1(X) = \begin{cases} \lambda_1 & \text{if } m_1 > m_2 \\ \lambda_1 + \lambda_2 X^{m_1} & \text{if } m_1 = m_2 \\ \lambda_2 X^{m_1} & \text{if } m_1 < m_2 \end{cases}, \tag{17}$$

in which λ_1 and λ_2 are, respectively, expressed as

$$\lambda_1 = \frac{\Gamma(m_2+m_4)}{\Gamma(m_2+1)\Gamma(m_4)}\left(\frac{\beta_2}{\beta_4}\right)^{m_2}, \quad \lambda_2 = \frac{\beta_1^{m_1}}{\Gamma(m_1+1)} \tag{18}$$

Next, from (13), the conditional CDF of γ_{DT} can be approximated as

$$F_{\gamma_{\mathrm{DT}}}(\gamma|X) \overset{\bar{\gamma}\to\infty}{\approx} \frac{1}{\Gamma(m_0+1)}\left(\frac{\beta_0\gamma X}{\bar{\gamma}}\right)^{m_0}. \tag{19}$$

By substituting (4), (17), (18), (19) into (3), we get

$$F_{\gamma_{\mathrm{D}}}(\gamma|X) \overset{\bar{\gamma}\to\infty}{\approx} \Xi_2(X)\left(\frac{\gamma}{\bar{\gamma}}\right)^{\min(m_1,m_2)+m_0}, \tag{20}$$

where

$$\Xi_2(X) = \begin{cases} \lambda_3 X^{m_0} & \text{if } m_1 > m_2 \\ \lambda_3 X^{m_0} + \lambda_4 X^{m_1+m_0} & \text{if } m_1 = m_2 \\ \lambda_4 X^{m_1+m_0} & \text{if } m_1 < m_2 \end{cases} \tag{21}$$

and, $\lambda_3 = \frac{\beta_0^{m_0}}{\Gamma(m_0+1)}\lambda_1$ and $\lambda_4 = \frac{\beta_0^{m_0}}{\Gamma(m_0+1)}\lambda_2$. Finally, by substituting (20) and (21) into (8) and taking the expectation over the RV $X = |h_3|^2$, the OP can be asymptotically approximated as follows

$$P_{\mathsf{out}} \overset{\bar{\gamma}\to\infty}{\approx} \epsilon\left(\frac{\gamma_{\mathsf{th}}}{\bar{\gamma}}\right)^{\min(m_1,m_2)+m_0}, \tag{22}$$

where ϵ is a constant solely determined by the fading parameters of all links m_{A} and α_{A}, with $\mathsf{A} \in \{0,1,2,3,4\}$, and is shown in (23) at the top of the next page.

As can be observed from (22), the diversity order of the considered network is only determined by the fading severity parameters of the secondary network, i.e., m_{B} with $\mathsf{B} \in \{0,1,2\}$, as the diversity gain $\mathcal{G}_d \triangleq \lim_{\bar{\gamma}\to\infty} \frac{-\log P_{\mathsf{out}}}{\log\bar{\gamma}} = \min(m_1,m_2)+m_0$. It is noteworthy that the primary network only affects the coding gain $\mathcal{G}_c = \frac{\epsilon^{\frac{-1}{m_0+\min(m_1,m_2)}}}{\gamma_{\mathsf{th}}}$.

IV. Numerical Results

In this Section, numerical results are presented in order to validate the proposed analysis. As in [8], we consider a two-dimensional $[x,y]$ plane for the location of all nodes pertaining to the primary and secondary networks. The channel mean power for the link $\mathsf{U}\to\mathsf{V}$ is defined as $\Omega_{\mathsf{U,V}} = d_{\mathsf{U,V}}^{-4}$, where $d_{\mathsf{U,V}}$ is the distance between node U and node V, with $\mathsf{U},\mathsf{V} \in \{\mathsf{P},\mathsf{S},\mathsf{R},\mathsf{D}\}$. Herein, we assume that all secondary nodes are located in a straight line, e.g., S, R, and D are placed on the x-axis with the following coordinates $(0,0)$, $(\frac{1}{2},0)$, and $(1,0)$, respectively. Without any loss of generality, $\Omega_{\mathsf{S,D}} = 1$, $\Omega_{\mathsf{S,R}} = \Omega_{\mathsf{R,D}} = 16$ and the outage threshold γ_{th} is set to

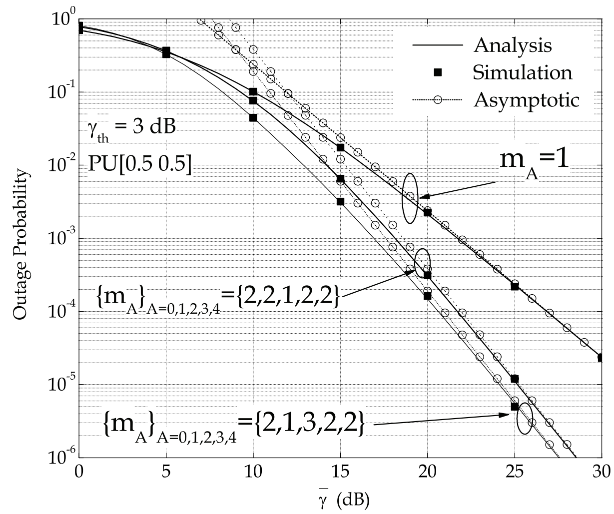

Fig. 2. Outage probability of spectrum sharing DF relay network with selection diversity over Nakagami-m fading channels.

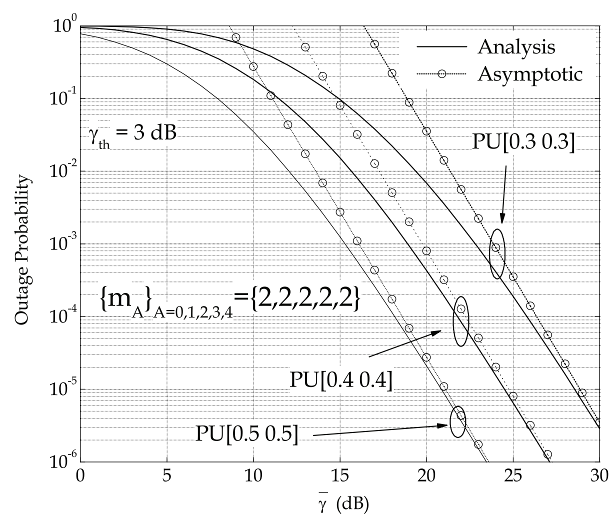

Fig. 3. Effect of primary network on the outage performance: PU's position.

$$\epsilon = \begin{cases} \frac{\beta_0^{m_0}\beta_1^{m_1}\Gamma(m_0+m_1+m_3)}{\beta_3^{m_0+m_1}\Gamma(m_0+1)\Gamma(m_1+1)\Gamma(m_3)} & \text{if } m_1 < m_2 \\ \frac{\beta_0^{m_0}\beta_1^{m_1}\Gamma(m_0+m_1+m_3)}{\beta_3^{m_0+m_1}\Gamma(m_0+1)\Gamma(m_1+1)\Gamma(m_3)} + \left(\frac{\beta_0}{\beta_3}\right)^{m_0}\left(\frac{\beta_2}{\beta_4}\right)^{m_2}\frac{\Gamma(m_0+m_3)\Gamma(m_2+m_4)}{\Gamma(m_0+1)\Gamma(m_2+1)\Gamma(m_3)\Gamma(m_4)} & \text{if } m_1 = m_2 \\ \left(\frac{\beta_0}{\beta_3}\right)^{m_0}\left(\frac{\beta_2}{\beta_4}\right)^{m_2}\frac{\Gamma(m_0+m_3)\Gamma(m_2+m_4)}{\Gamma(m_0+1)\Gamma(m_2+1)\Gamma(m_3)\Gamma(m_4)} & \text{if } m_1 > m_2 \end{cases} \tag{23}$$

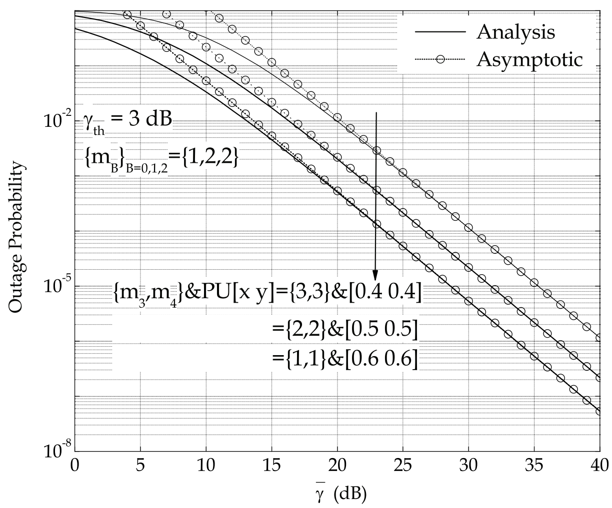

Fig. 4. Effect of primary network on the outage performance: Fading severity level and PU's position.

3 dB. To evaluate the effect of the primary network on the outage performance, the position of P has been varied. The "Analysis" and "Asymptotic" curves are plotted from (11) and (22), respectively.

Fig. 2 plots the OP versus the average SNR $\bar{\gamma}$ of the considered system assuming i.n.i.d. Nakagami-m fading channels. The PU receiver is located at the coordinate $[0.5 \quad 0.5]$. Three sets of severity parameters pertaining to the secondary network are investigated, being given as follows: (i) Case 1: the first hop is more severe than the second hop, e.g., $\{m_\mathsf{A}\}_{\mathsf{A}=0,1,2,3,4} = \{2,1,3,2,2\}$; (ii) Case 2: the fading severities between the two hops are equal, e.g., $\{m_\mathsf{A}\}_{\mathsf{A}=0,1,2,3,4} = \{1,1,1,1,1\}$; and (iii) Case 3: the first hop is less rigorous than the second hop, e.g., $\{m_\mathsf{A}\}_{\mathsf{A}=0,1,2,3,4} = \{2,2,1,2,2\}$. As can clearly be seen from this figure, the analytical and simulation curves are in an excellent agreement and the asymptotic curves match very well with the exact curves in the high SNR regime, which corroborates the accuracy of our derivation. Results indicate that the diversity order, $G_d = \min(m_1, m_2) + m_0$ is proportional to the minimum fading severity between the two hops and that of the direct link. As such, Case 2 results in the poorest performance since $\min(m_1, m_2) + m_0 = 2$ and its slope is less than those of Cases 1 and 3. We also observe the same diversity order for Case 1 and 3 since they have the same value $\min(m_1, m_2) + m_0 = 3$.

Figs. 3 and 4 analyze the effect of the PU's location on the CSSS under study. For Fig. 3, the fading severity parameters are selected to $m_\mathsf{A} = 2$. Note that the PU's position has no impact on the diversity gain. However, the coding gain diminishes when P is located close to the secondary network. In Fig. 4, the fading severity parameters of the secondary network are fixed to $\{m_\mathsf{B}\}_{\mathsf{B}=0,1,2} = \{1,2,2\}$. Three distinct scenarios are considered, e.g., Case 4: $m_2 = m_4 = 3$ and PU$[0.4 \quad 0.4]$; Case 5: $m_2 = m_4 = 2$ and PU$[0.5 \quad 0.5]$, and Case 6: $m_2 = m_4 = 1$ and PU$[0.6 \quad 0.6]$. Again, note that varying the fading severity parameters and the PU's position affects only the coding gain, not the diversity gain.

V. Conclusions

In this letter, incorporating the direct link in a DF cooperative spectrum sharing system subject to i.n.i.d Nakagami-*m* fading, the outage performance was investigated. Closed-form and asymptotic expressions for the outage probability were derived assuming a SC receiver at the SU destination. It was shown that the diversity order of the considered system was solely determined by the fading severity parameters of the secondary network, with the primary network affecting only the coding gain. In addition, the impact of the primary network in the SUs' system performance was examined by varying the PU's position as well as the fading severity parameters of the interference links. In particular, it was shown that the coding gain diminishes when the PU is located close to the secondary network.

References

[1] V. Asghari and S. Aïssa, "Performance of cooperative spectrum-sharing systems with amplify-and-forward relaying," *IEEE Trans. Wireless Commun.*, vol. 11, no. 4, pp. 1295–1300, Apr. 2012.

[2] B. Maham, R. Popovski, X. Zhou, and A. Hjoungnes, "Cognitive multiple access network with outage margin in the primary system," *IEEE Trans. Wireless Commun.*, vol. 10, pp. 3343–3353, Oct. 2011.

[3] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[4] J. Mitola *et al.*, "Cognitive radio: making software radio more personal," *IEEE Pers. Commun.*, pp. 13–18, Aug. 1999.

[5] C. Zhong, T. Ratnarajah, and K.-K. Wong, "Outage analysis of decode-and-forward cognitive dual-hop systems with the interference constraint in Nakagami-m fading channels," *IEEE Trans. Veh. Technol.*, vol. 60, no. 6, pp. 2875–2879, July 2011.

[6] T. Q. Duong, D. B. da Costa, M. Elkashlan, and V. N. Q. Bao, "Cognitive amplify-and-forward relay networks over Nakagami-m fading," *IEEE Trans. Veh. Technol.*, vol. 61, no. 5, pp. 2368–2374, June 2012.

[7] M. Xia and S. Aïssa, "Cooperative AF relaying in spectrum-sharing systems: performance analysis under average interference power constraints and Nakagami-m fading," *IEEE Trans. Commun.*, vol. 60, no. 6, pp. 1523–1533, June 2012.

[8] T. Q. Duong, V. N. Q. Bao, G. C. Alexandropoulos, and H.-J. Zepernick, "Cooperative spectrum sharing networks with AF relay and selection diversity," *Electron. Lett.*, vol. 47, no. 20, pp. 1149–1151, Sep. 2011.

[9] J.-P. Hong, B. Hong, T. W. Ban, and W. Choi, "On the cooperative diversity gain in underlay cognitive radio systems," *IEEE Trans. Commun.*, vol. 60, no. 1, pp. 209–219, Jan. 2012.

[10] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products*, 6th edition. Academic, 2000.