Cognitive amplify-and-forward relay networks with beamforming under primary user power constraint over Nakagami-\(m\) fading channels

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ABSTRACT

In this paper, we analyze the performance of cognitive amplify-and-forward (AF) relay networks with beamforming under the peak interference power constraint of the primary user (PU). We focus on the scenario that beamforming is applied at the multi-antenna secondary transmitter and receiver. Also, the secondary relay network operates in channel state information-assisted AF mode, and the signals undergo independent Nakagami-\(m\) fading. In particular, closed-form expressions for the outage probability and symbol error rate (SER) of the considered network over Nakagami-\(m\) fading are presented. More importantly, asymptotic closed-form expressions for the outage probability and SER are derived. These tractable closed-form expressions for the network performance readily enable us to evaluate and examine the impact of network parameters on the system performance. Specifically, the impact of the number of antennas, the fading severity parameters, the channel mean powers, and the peak interference power is addressed. The asymptotic analysis manifests that the peak interference power constraint imposed on the secondary relay network has no effect on the diversity gain. However, the coding gain is affected by the fading parameters of the links from the primary receiver to the secondary relay network. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS

cognitive radio; beamforming; amplify-and-forward relaying; outage probability; symbol error rate; Nakagami-\(m\) fading

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1. INTRODUCTION

In recent years, studies of cognitive radio networks (CRNs), which have been known as an efficient avenue to enhance the utilization of the limited spectrum, have been well established. Among various aspects of CRNs, the combination of spectrum sharing with cooperative communications has gained increased interest in the literature [1–4]. In particular, bounds on the outage probability of a cognitive relay network using opportunistic relaying (OR) under spectrum sharing constraints were presented in [3]. In addition, the outage probability of cognitive decode-and-forward relay networks utilizing the OR strategy under interference constraints was analyzed in [1]. Taking the outage probability constraint of the primary user (PU) into account, the outage performance of cognitive relay networks using the OR scheme with partial channel state information and experiencing Rayleigh fading has been investigated in [2]. In [4], an outage analysis of cognitive decode-and-forward relay networks employing OR and being subject to Nakagami-\(m\) fading wherein the secondary transmission does not cause harmful interference to the PU has been reported. Recently, an exact analysis for the outage performance of cognitive amplify-and-forward (AF) relay networks under the peak interference power constraint of the PU has been presented in [5].

Beamforming transmission in wireless environments provides substantial advantages such as enhancing the signal reliability, spectral efficiency, and extending the radio coverage of the wireless relay networks [6,7]. In light of this, beamforming has recently gained significant interest in the field of CRNs (see, e.g., [8–11]). Specifically, in [8], the secondary users (SUs) share the same spectrum with the PU while keeping the interference power at the PU below a given threshold. Also, power allocation for beamforming transmission has been developed for CRNs.
to guarantee quality of service of the primary network, as the SUs are granted access to the licensed spectrum of the PUs [9–11]. In [9], the issue of joint beamforming and power allocation for CRNs to minimize the total transmit power while guaranteeing quality of service and the signal-to-interference-plus-noise ratio (SINR) requirements of the SUs as well as the tolerant interference of the PU are considered. In addition, the problem of minimizing the total transmit power of the beamforming CRN has been solved, provided that the received interferences at the PUs are kept below a predefined level as well as the SINR at the SU is guaranteed to be greater than a given threshold [10]. Power allocation strategies for cognitive relay networks with multiple sources and a multiple antenna relay are considered in [11], wherein the worst normalized SINR among all destinations is maximized such that total transmit powers do not exceed given thresholds.

Apart from the aforementioned studies on power allocation strategies for cognitive cooperative networks with beamforming transmission, other network performance metrics such as outage probability, symbol error rate (SER), diversity gain, and coding gain are also essential for the system design. Recently, in [12], analytical closed-form expressions for the outage probability and the SER rather than asymptotic evaluations of cognitive AF relay networks with beamforming transmission and feedback delay over Rayleigh fading have been reported. Furthermore, although most of these works consider Rayleigh channels, the more general case of Nakagami fading, covering a broad variety of fading models, has gained less attention. Inspired by the above, in this paper, we analyze the performance of a cognitive AF relay network with beamforming transmission subject to the peak interference power constraint of the PU. Our analysis accounts for beamforming transmission being implemented at both the multiple antenna secondary transmitter and receiver. Also, it is assumed that all channels are subject to Nakagami-\(m\) fading, and the secondary relay operates in AF mode. Our contributions are summarized as follows:

- Closed-form expressions for the outage probability and SER for a cognitive AF channel state information-assisted relay network with beamforming transmission under the peak interference power constraint at the PU are derived.
- An asymptotic performance analysis, which reveals insights into the cooperative diversity behavior of the considered network, is presented. Our results show that, subject to the peak interference power constraint of the PU, the diversity gain of the secondary network is equal to the minimum of the summation of fading severity in the two hops.
- Utilizing these closed-form expressions, we study the effect of several important network parameters on the system performance. For instance, the impact of fading severity parameter \(m\), the number of antennas at the secondary transmitter and secondary receiver, and the distances from the PU to the secondary transmitter and secondary relay, on the system performance is examined.

The remainder of this paper is organized as follows. The system model is introduced in Section 2. In Section 3, a closed-form expression for the outage probability is derived. A tight approximation for the SER is presented in Section 4. Furthermore, asymptotic performance is derived in Section 5. Finally, numerical results are provided in Section 6. Concluding remarks are given in Section 7.

**Notation:** In this paper, lowercase letters stand for vectors. The Frobenius norm of a vector is represented as \(\| \cdot \|_F \). \(\mathbb{E}\{\cdot\}\) denotes the expectation operator. The superscript \((\cdot)^H\) stands for the complex transpose conjugate. \(I_n\) denotes the \(n \times n\) identity matrix. The probability density function (PDF) and the cumulative distribution function (CDF) of a random variable (RV) \(X\) are denoted as \(f_X(\cdot)\) and \(F_X(\cdot)\), respectively. \(C^n_k = [n!/(n-k)!]\) is the binomial coefficient. \(\Gamma(n)\) denotes the gamma function [13, eq. (8.310.1)], and \(\Gamma_n(n, x)\) is the incomplete gamma function [13, eq. (8.350.2)]. \(K_n(\cdot)\) is the \(n\)-th order modified Bessel function of the second kind [13, eq. (8.432.1)]. \(\mathbb{W}_{\lambda, \rho}(x)\) represents the Whittaker function [13, eq. (9.222)]. \(U(a, b; x)\) is the confluent hypergeometric function [13, eq. (9.211.4)]. Finally, \(\mathbb{F}_1(a, b; c; x)\) stands for the Gauss hypergeometric function [13, eq. (9.100)].

## 2. SYSTEM AND CHANNEL MODELS

Consider a dual-hop spectrum-sharing beamforming relay network consisting of a PU and a secondary relay network as shown in Figure 1. Assume that the secondary relay network comprises of an \(N_1\)-antenna secondary transmitter SU\(_{TX}\), a single-antenna AF relay SU\(_{AF}\), and an \(N_2\)-antenna secondary receiver SU\(_{RX}\). The licensed spectrum of PU can be utilized by SU\(_{TX}\) and SU\(_{AF}\) provided that both do not cause harmful interference to PU. In addition, all terminals operate over Nakagami-\(m\) fading channels, and the direct link from SU\(_{TX}\) to SU\(_{RX}\) is not applicable because of severe shadowing. In the first hop, SU\(_{TX}\) transmits the signal \(s(t)\) to SU\(_{AF}\) with transmit power \(P_1\). At SU\(_{AF}\), the received signal is given by

\[
y_1(t) = \mathbf{h}_1(t)^H w_1^H(t) s(t) + n_1(t)
\]

where \(w_1(t) = \mathbf{h}_1(t)/\|\mathbf{h}_1(t)\|_F\) is the beamforming vector at SU\(_{TX}\), \(\mathbf{h}_1(t)\) is the \(1 \times N_1\) channel coefficient vector of the links from SU\(_{TX}\) to SU\(_{AF}\) with identical fading severity parameter \(m_1\) and channel mean power \(\mathbb{E}_1\), and \(n_1(t)\) is the additive white Gaussian noise at SU\(_{AF}\) with zero mean and variance \(N_0\). Assume that the PU is able to tolerate the peak interference power \(Q\). To prevent PU from harmful interference, the maximum transmit power \(P_1\) must satisfy
P_1 = Q / ||h_3(t)||^2, where h_3(t) is the 1 \times N_1 channel coefficient vector of the links from SU_TX to PU with identical fading severity parameter \( m_3 \) and channel mean power \( \Omega_3 \).

In the second hop, SU_AF amplifies its received signal \( y_1(t) \) with amplifying gain \( \beta \) and forwards the result to SU_RX. Again, the transmit power of SU_AF, \( P_2 \), is limited to guarantee the peak interference power constraint for PU as \( P_2 = Q / |h_4(t)|^2 \), where \( h_4(t) \) is the channel coefficient from SU_AF to PU with fading severity parameter \( m_4 \) and channel mean power \( \Omega_4 \). The SU_RX will apply beamforming processing for the received signal to generate the signal

\[
y_2(t) = \beta w_2(t)h_3^H(t)h_1(t)w_1^H(t)s(t) + \beta w_2(t)h_3^H(t)n_1(t) + w_2(t)n_2^H(t)
\]

where \( n_2(t) \) is an \( 1 \times N_2 \) noise vector at SU_RX whose elements are complex Gaussian RVs with zero mean and variance \( N_0 \). \( w_2(t) = h_2(t)/||h_2(t)||_F \) is the beamforming vector at SU_RX, and \( h_2(t) \) is the \( 1 \times N_2 \) channel coefficient vector of the links from SU_AF to SU_RX with identical fading severity parameter \( m_2 \) and channel mean power \( \Omega_2 \). Given the power constraint at SU_AF, that is, \( \beta^2 (P_1 ||h_1(t)||^2 + N_0) = P_2 \), and the assumption that the signal power is much greater than the noise power, the amplifying gain is selected as \( \beta^2 = P_2 (P_1 ||h_1||_F^2)^{-1} \).

From (2), we can write the instantaneous signal-to-noise ratio (SNR) as

\[
\gamma = \frac{\mathbb{E} \left[ |s(t)|^2 |w_2(t)h_3^H(t)h_1(t)w_1^H(t)|^2 \right]}{\mathbb{E} \left[ |n_1(t)|^2 |w_2(t)h_3^H(t)h_1(t)w_1^H(t)|^2 + |w_2(t)n_2^H(t)|^2 \right]} \tag{3}
\]

Because the noise terms \( n_1(t) \) and \( n_2(t) \) are independently distributed RVs, (3) can be rewritten as

\[
\gamma = \frac{\beta^2 \mathbb{E} \left[ |s(t)|^2 \right] |w_2(t)h_3^H(t)h_1(t)w_1^H(t)|^2}{\beta^2 \mathbb{E} \left[ |n_1(t)|^2 \right] |w_2(t)h_3^H(t)h_1(t)w_1^H(t)|^2 + \mathbb{E} \left[ |w_2(t)n_2^H(t)|^2 \right]} \tag{4}
\]

Note that

\[
\mathbb{E} \left[ |w_2(t)h_3^H(t)h_1(t)w_1^H(t)|^2 \right] = w_2(t)\mathbb{E} \left[ n_2^H(t)n_2(t) \right] w_2^H(t) = N_0w_2(t)I_{N_2}w_2^H(t) = N_0 \tag{5}
\]

Substituting (5) into (4) with some simplifications, we get

\[
\gamma = \frac{\beta^2 P_1 |h_1(t)|^2 |h_2(t)|^2}{\beta^2 N_0|h_3(t)|^2 + N_0} \tag{6}
\]

Next, substituting \( \beta^2 = P_2 (P_1 ||h_1||_F^2)^{-1} \), \( P_1 = Q / |h_4(t)|^2 \), and \( P_2 = Q / |h_4(t)|^2 \) into (6), after some manipulations, the instantaneous SNR at SU_RX can be formulated as

\[
\gamma = \rho \frac{X_1X_2}{X_1X_4 + X_2X_3} \tag{7}
\]

where \( \rho = Q / N_0, X_k = |h_k|^2, k = 1, 2, 3, \) and \( X_4 = |h_4|^2 \). Because \( X_1, X_2, \) and \( X_3 \) are the summation of independently and identically gamma distributed RVs, they are also gamma distributed RVs with respective parameters \( (N_1m_1, \alpha_1^{-1}) \), \( (N_2m_2, \alpha_2^{-1}) \), and \( (N_3m_3, \alpha_3^{-1}) \), where \( \alpha_k = m_k / \Omega_k \). In addition, \( X_4 \) is a gamma distributed RV with parameters \( (m_4, \alpha_4^{-1}) \), where \( \alpha_4 = m_4 / \Omega_4 \). In the sequel, analytical and asymptotic closed-form expressions for outage probability and SER are derived.

### 3. OUTAGE PERFORMANCE ANALYSIS

In this section, the CDF of the instantaneous SNR is derived, which enables us to obtain a closed-form expression for the outage probability. For further calculations, we require the PDF and CDF of a gamma distributed RV \( X \) with parameters \( (m, \alpha^{-1}) \), \( m \) is a positive integer number, which are given by

\[
f_X(x) = \frac{\alpha^m}{\Gamma(m)} x^{m-1} \exp(-\alpha x) \tag{8}
\]

\[
F_X(x) = 1 - \exp(-\alpha x) \sum_{q=0}^{m-1} \frac{\alpha^q x^q}{q!} \tag{9}
\]

It is noted that the instantaneous SNR in (7) is represented as a complicated function of multiple RVs, that is, \( \{X_k\}_{k=1}^4 \). Therefore, we utilize the total probability theorem to obtain the statistical distribution of the SNR. For convenience, in (7), we define an intermediate RV \( \gamma_0 \) as

\[
\gamma_0 = X_1X_2 / (X_1X_4 + X_2X_3) = \gamma / \rho \tag{10}
\]

Hence, a closed-form expression for \( F_{\gamma_0}(\gamma) \) can be found via the CDF of \( \gamma_0 \) given in (10) as \( F_{\gamma_0}(\gamma) = F_{\gamma_0}(\gamma / \rho) \). From (7), we can express the CDF of \( \gamma_0 \) as

\[
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\]

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where $D = \{(x_1, x_2, x_3, x_4) | x_1 x_2 / (x_1 x_4 + x_2 x_3) < \gamma\}$ represents the integration domain. Because of the statistical independence of RVs $X_k$, $k \in \{1, \ldots, 4\}$, the joint PDF $f_{X_1 X_2 X_3 X_4}(x_1, x_2, x_3, x_4)$ can be given in terms of the product of the PDF of each RV, $f_{X_k}(x_k)$. Furthermore, using the total probability theorem, we have [12]

$$F_{\gamma_0}(\gamma) = P\{\gamma_0 < \gamma\} = \int_0^\infty \int_0^\infty \int_0^\infty P \left\{ \frac{X_1 x_2}{X_1 x_4 + x_2 x_3} \right\} f_{X_1 X_2 X_3 X_4}(x_1, x_2, x_3, x_4) dx_1 dx_2 dx_3 dx_4$$

(11)

Theorem 1. Assuming that the fading severity parameters $m_k$, $k \in \{1, 2, 3, 4\}$, are integers, the CDF of the instantaneous SNR $\gamma$ in (7) can be formulated in closed-form as

$$F_\gamma(\gamma) = 1 - \sum_{p=0}^{N_1 m_1 - 1} \frac{a_p^p}{p!} \sum_{q=0}^{N_2 m_2 - 1} \frac{a_2^{m_2}}{\Gamma(N_2 m_2)} \frac{a_3^{m_3}}{\Gamma(N_1 m_3)} \frac{a_4^{m_4}}{\Gamma(N_4 m_4)} \sum_{r=0}^{N_2 m_2 - 1} \frac{c_r^{N_2 m_2 - 1}}{\Gamma(N_2 m_2 + m_4)}$$

$$\times \Gamma(N_1 m_3 + p + r - q + 1) \Gamma(N_3 m_3 + p + r - q + 1) \Gamma(N_4 m_4 + p + r - q + 1)$$

$$\times \left( a_1 \frac{\gamma}{\rho} + a_3 \right)^{-N_1 m_3 + p + r - q + 1} \left( a_2 \frac{\gamma}{\rho} + a_4 \right)^{-N_2 m_2 + m_4 + N_1 m_3 + p} \psi(\gamma)$$

(13)

where $\psi(\gamma) = [(a_2 a_3 + a_1 a_4) \gamma / \rho + a_3 a_4] / [(a_1 a_2 / \rho + a_3) (a_1 a_3 / \rho + a_4)]$

Proof. See Appendix A.

Therefore, the outage probability, $P_{\text{out}}$, which is the probability that the instantaneous SNR falls below a predefined threshold $\gamma_{\text{th}}$, can be readily obtained as

$$P_{\text{out}} = F_\gamma(\gamma_{\text{th}})$$

(14)

Note that the closed-form expression for the outage probability in (14) can be particularized into the case of Rayleigh fading ($m = 1$) and (or) the conventional single-antenna cognitive AF relay network ($N_1 = N_2 = 1$).

4. SYMBOL ERROR RATE
performance analysis

In this section, the error performance of the considered network is investigated by deriving a tightly approximated expression for the SER. Specifically, the expression for the SER that is valid for binary phase shift keying or quadrature phase shift keying, binary frequency shift keying, and M-ary phase shift keying is evaluated as [14]

$$\gamma_{\text{th}} = \min(\gamma_1, \gamma_2)$$

(16)

In fact, the moment generating function (MGF) of the reciprocal of the instantaneous SNR can be utilized to evaluate the exact error probability performance in the considered context. This approach has been well studied recently [15–17]. Typically, the error probability can be given in the form of a single-integral expression, for example, [16, eq. (4c); 17, eq. (3)], which can be computed numerically. Similarly, for the considered system, the MGF of the reciprocal of the instantaneous SNR given in (7) can be derived. However, the SER expression may be given in integral form. To overcome this limitation, the CDF of the upper bound on $\gamma_0$, denoted as $\gamma_{\text{U}}$, is therefore utilized for the analysis. In particular, this bound is given by [18, eq. (25)]
The CDF of the RV $\gamma_{01}$ is given by

$$F_{\gamma_{01}}(\gamma) = 1 - \frac{a_3^{m_4}}{\Gamma(m_4)} \sum_{q=0}^{N_2m_2-1} \frac{\Gamma(m_4 + q) a_2^q a_3^{N_1m_3}}{q! \Gamma(N_1m_3)} \prod_{r=0}^{N_1m_1-1} \frac{\gamma^{q+r}}{(\alpha_1^{q+r} + \alpha_3)^{N_1m_3+r+q}(\alpha_2^{q+r} + \alpha_4)^{m_4+q}}$$

(17)

**Proof.** See Appendix B. □

With the CDF of $\gamma_{01}$ at hand, we now obtain a closed-form expression for the SER as in Corollary 1.

**Corollary 1.** A closed-form expression for the SER is derived as

$$P_e = \frac{a_3^{m_4}}{2\sqrt{\pi}} \frac{a_2^q a_4^{N_1m_1}}{\Gamma(m_4)} \sum_{q=0}^{N_2m_2-1} \frac{\Gamma(m_4 + q) a_2^q a_3^{N_1m_3}}{q! \Gamma(N_1m_3)} \prod_{r=0}^{N_1m_1-1} \frac{\gamma^{q+r}}{(\alpha_1^{q+r} + \alpha_3)^{N_1m_3+r+q}(\alpha_2^{q+r} + \alpha_4)^{m_4+q}}$$

$$\times \left[ \sum_{i=1}^{N_1m_3+r} \kappa_i \Gamma(q + r + \frac{1}{2}) \left( \frac{\alpha_3}{\alpha_1} \right)^{q+r-i+\frac{1}{2}} U(q + r + \frac{1}{2}, q + r - i + \frac{3}{2}, b \rho) \frac{a_3^{q+r-i+\frac{1}{2}}}{a_2^{q+r-i+\frac{1}{2}}} \right]$$

$$+ \sum_{i=1}^{m_4+q} \theta_{qi} \Gamma(q + r + \frac{1}{2}) \left( \frac{\alpha_4}{\alpha_2} \right)^{q+r-i+\frac{1}{2}} U(q + r + \frac{1}{2}, q + r - i + \frac{3}{2}, b \rho) \frac{a_4^{q+r-i+\frac{1}{2}}}{a_2^{q+r-i+\frac{1}{2}}} \right]$$

(18)

**Proof.** See Appendix C. □

### 5. ASYMPTOTIC PERFORMANCE ANALYSIS

Although the closed-form expression given in (13) can be used to obtain exact outage performance for the considered network, it is difficult to examine the impact of network parameters on the system performance as well as to identify the diversity and coding gains because of its complicated mathematical representation. To render insights into the spatial diversity, an asymptotic outage probability is provided in this section.

### 5.1. Asymptotic outage probability

By definition, the expression for the outage probability at high SNR is represented as [19]

$$P_{out}^\infty = (G_c \rho)^{-G_d} + o(\rho^{-G_d})$$

(19)

where $G_d$ and $G_c$ correspond to the diversity and coding gains and $o(g(x))$ denotes the higher order terms of $g(x)$, that is, $\lim_{x \to \infty} o(x)/g(x) = 0$. In (19), the diversity gain $G_d$ is the absolute value of the slope of the asymptotic outage probability curve as

$$G_d = \lim_{\rho \to \infty} \left( \frac{-\log(P_{out})}{\log(\rho)} \right)$$

(20)

The coding gain of the network $G_c$ is defined as the SNR advantage of the asymptotic outage probability curve as compared with the reference curve $\rho^{-G_d}$.

**Proof.** The MacLaurin expansion of the CDF of the instantaneous SNR $F_\gamma(\gamma)$ at zero is employed to analyze the asymptotic performance. However, it is not feasible to obtain the asymptotic performance from $F_\gamma(\gamma)$ because of its complex mathematical representation. Thus, we apply [20, Lemma 1], which concludes that the CDF of RV $\gamma_{01}$ owns the same first nonzero coefficient of MacLaurin series as the CDF of $\gamma_0$. The asymptotic outage probability can be obtained as in the following theorem.

**Theorem 3.** Assuming that $\rho \to \infty$, the asymptotic expression for the outage probability of the considered network is given by

$$P_{out}^\infty = \begin{cases} 
\frac{\Gamma(N_1m_1 + N_1m_3)}{\Gamma(N_1m_1 + 1) \Gamma(N_1m_3)} \frac{\alpha_1^{N_1m_1}}{\alpha_3^{N_1m_1}} \left( \frac{\gamma_b}{\rho} \right)^{N_1m_1}, & N_1m_1 < N_2m_2 \\
\frac{\Gamma(N_2m_2 + m_4)}{\Gamma(N_2m_2 + 1) \Gamma(m_4)} \frac{\alpha_2^{N_2m_2}}{\alpha_4^{N_2m_2}} \left( \frac{\gamma_b}{\rho} \right)^{N_2m_2}, & N_1m_1 > N_2m_2 \\
\frac{\Gamma(N_1m_1 + N_1m_3)}{\Gamma(N_1m_1 + 1) \Gamma(N_1m_3)} \frac{\alpha_1^{N_1m_1}}{\alpha_3^{N_1m_1}} \left( \frac{\gamma_b}{\rho} \right)^{N_1m_1} + \frac{\Gamma(N_2m_2 + m_4)}{\Gamma(N_2m_2 + 1) \Gamma(m_4)} \frac{\alpha_2^{N_2m_2}}{\alpha_4^{N_2m_2}} \left( \frac{\gamma_b}{\rho} \right)^{N_2m_2}, & N_1m_1 = N_2m_2
\end{cases}$$

(21)
Proof. See Appendix D. □

Clearly, from the three cases given in (21), we can see that the diversity gain of the considered network is dominated by the more severe hop of the secondary relay network, that is, \( G_i = \min(N_i m_1, N_2 m_2) \). This means that the presence of the peak interference power constraint of the PU imposed on the secondary relay network does not affect its diversity gain.

### 5.2. Asymptotic symbol error rate

**Corollary 2.** Assuming that \( \rho \to \infty \), the asymptotic expression for the SER of the considered network is obtained as

\[
P_E^\infty = \begin{cases} 
\frac{a}{2 \sqrt{\pi} b N_{1m1}^2 \rho^{N_{1m1}}} \Gamma(N_{1m1} + N_{1m3}) \Gamma(N_{1m1} + \frac{1}{2}) a_1^{N_{1m1}}, & N_{1m1} < N_{2m2} \\
\frac{a}{2 \sqrt{\pi} b N_{2m2}^2 \rho^{N_{2m2}}} \Gamma(N_{2m2} + m_4) \Gamma(N_{2m2} + \frac{1}{2}) a_2^{N_{2m2}}, & N_{1m1} > N_{2m2} \\
\frac{a}{2 \sqrt{\pi} b N_{1m1}^2 \rho^{N_{1m1}}} \Gamma(N_{1m1} + N_{1m3}) \Gamma(N_{1m1} + \frac{1}{2}) a_1^{N_{1m1}}, & N_{1m1} = N_{2m2} \\
\frac{a}{2 \sqrt{\pi} b N_{2m2}^2 \rho^{N_{2m2}}} \Gamma(N_{2m2} + m_4) \Gamma(N_{2m2} + \frac{1}{2}) a_2^{N_{2m2}} \end{cases}
\] (22)

**Proof.** Substituting (D.10) of Appendix C in (15) followed by utilizing [13, eq. (3.381.4)], we obtain the above asymptotic expression for the SER as in (22). □

The closed-form expression given in (22) indicates that the behavior of the asymptotic SER is similar to that of the asymptotic outage probability given in (21). Only the number of antennas at \( SUTX N_1 \) and at \( SURX N_2 \) along with the fading severity parameters of the two hops of the secondary relay network, \( m_1 \) and \( m_2 \), determine the diversity gain.

### 6. NUMERICAL RESULTS

In this section, numerical results are provided to validate the developed analysis for example scenarios. For brevity, we denote \( d_1, d_2, d_3, \) and \( d_4 \) as the distances for the links \( SUTX \to SUAF, SUAF \to SURX, SURX \to PU, \) and \( SUAF \to PU, \) respectively. Assume that the channel mean power between two arbitrary terminals \( A \) and \( B \) is attenuated according to the exponential path loss model as \( d_i^{-L}, \ i \in \{1, 2, 3, 4\} \) with \( A \in \{SUTX, SUAF\} \) and \( B \in \{SUAF, SURX, PU\} \). The path loss exponent is selected as \( L = 4, \) which is applicable to a highly shadowed urban area. The outage threshold value is set as \( \gamma_{th} = 10 \) dB. For all the plots, it can be seen that excellent agreement between analytical results and simulations is achieved. Also, it can be observed that the asymptotic results tightly converge to the analytical results.

Figure 2 shows the outage probability for four different cases of fading channels:

- \( \{m_1, m_2\} = \{1, 1\} \): Rayleigh channels.
- \( \{m_1, m_2\} = \{2, 2\} \): Fading of the two relay hops is identically severe.
- \( \{m_1, m_2\} = \{2, 3\} \): Fading of the first relay hop is more severe than the second relay hop.
- \( \{m_1, m_2\} = \{4, 3\} \): Fading of the first relay hop is less severe than the second relay hop.

The number of antennas at \( SUAF \) is set as \( N_1 = 2 \) and \( N_2 = 2 \), respectively. The diversity gains as observed in Figure 2 agree with analytical results for the four different scenarios of fading severity relationship in the two hops. As expected, the outage performance will be...
improved prominently as the minimum value of the fading severities between the two hops, min\(m_1, m_2\), increases. This can be deduced from (21), which shows that the diversity gain proportionally increases with min\(m_1, m_2\) when the number of antennas at the SU\(_{TX}\) and SU\(_{RX}\) is identical, \(N_1 = N_2\).

Figure 3 depicts the outage probability for different number of antennas at SU\(_{TX}\) and SU\(_{RX}\). Pronounced improvement in the outage probability can be achieved as the minimum of the numbers of antennas at SU\(_{TX}\) and SU\(_{RX}\), \(\min(N_1, N_2)\), increases. This benefit can be attributed to the fact that the diversity gain is proportional to \(\min(N_1, N_2)\) for the case of identical fading severity parameters of the two relaying hops, that is, \(m_1 = m_2\), as given in (21). In all cases, the diversity gains in Figure 3 agree with the analytical derivations for different cases of fading severity relationship between the two hops.

Figure 4 shows the outage performance for various distances from PU to SU\(_{TX}\) and from PU to SU\(_{AF}\), that is, \(d_3\) and \(d_4\), respectively. As can be seen from the figure, an increase of the distances \(d_3\) and \(d_4\) leads to an improvement in outage probability. This advantage can be explained by the fact that as the PU moves far away from the secondary relay network, the limit of the transmit power of SU\(_{TX}\) and SU\(_{AF}\) can be increased.

Figure 5 presents the outage probability versus the distance ratio \(d_2/d_1\) for different values of peak interference power \(Q\). For a fixed value of the distance between SU\(_{TX}\) and SU\(_{AF}\), \(d_1\), and \(d_2 \leq d_1\), as the distance between SU\(_{AF}\) and SU\(_{RX}\), \(d_2\), decreases, the outage probability almost remains constant. This indicates that when fading condition of the second relaying hop is better than that of the first relaying hop, improvement in fading power at the second hop slightly improves the system performance. For the case of \(d_2 \geq d_1\), that is, fading condition of the first relaying hop is more favorable than that of the second relaying hop, the outage performance diminishes when fading condition of the second relaying hop becomes worse, that is, \(d_2\) increases. This can be understood from the fact that the worse fading condition of the second relaying hop relative to that of the first hop may lead to this performance degradation.

Figure 6 draws the SER of 8-PSK modulation for different fading channels. It can be seen from Figure 6 that the SER will decrease significantly when the minimum value of the fading severity parameters of the two relaying hops, \(\min(m_1, m_2)\), increases. This improvement in the SER performance can be understood from the fact that the diversity gain is proportional to \(\min(m_1, m_2)\) when the number of antennas at SU\(_{TX}\) and SU\(_{RX}\) is identical, \(N_1 = N_2\), according to (22).

Figure 7 displays the SER of 8-PSK modulation for different number of antennas at SU\(_{TX}\), \(N_1\), and at SU\(_{RX}\), \(N_2\).
The fading severity parameters of the two relaying hops are fixed as $m_1 = m_2 = 2$. As expected, the SER performance of the considered network obtains substantial enhancement when the minimum of the number of antennas at SU$_{TX}$ and SU$_{RX}$, $\min(N_1, N_2)$, increases. Theoretically, in this case, the diversity gain of the considered network is proportional to the value $\min(N_1, N_2)$ as can be seen from (22).

Figure 8 draws the SER for different distances from PU to SU$_{TX}$ and from PU to SU$_{AF}$, that is, $d_3$ and $d_4$, respectively. It can be seen that when PU is placed far away from SU$_{TX}$ and SU$_{AF}$, that is, $d_3$ and $d_4$ increase, the outage probability is enhanced. This benefit results from the fact that the constraint of transmit power of SU$_{TX}$ and SU$_{AF}$ becomes more relaxed.

Figure 9 depicts the SER versus the distance ratio $d_2/d_1$ for different values of peak interference power $Q$. For each curve, the shifted position between the two floors occurs when the distances from SU$_{AF}$ to SU$_{TX}$ and from SU$_{AF}$ to SU$_{RX}$ are almost the same. High difference of the values of $d_1$ and $d_2$ leads to serious unbalance of fading conditions between the two hops of the secondary relay network.

7. CONCLUSIONS

In this paper, we have studied the performance of cognitive beamforming AF relay networks under the peak interference power constraint of the PU. In particular, a closed-form expression for the outage probability and a tight bounded closed-form expression for the SER of the considered network over Nakagami-$m$ fading has been derived. Furthermore, an asymptotic analysis, which provides im-
important insights into the diversity behavior, has been presented. These closed-form expressions can be utilized to evaluate the performance of cognitive beamforming AF relay networks as well as investigate the impact of several important network parameters on the system performance.

In this appendix, we find a closed-form expression for the CDF of $y_0$, $F_{y_0}(\gamma)$, given in (12) in order to identify the CDF of the instantaneous SNR $F_{\gamma_0}(\gamma)$. To derive the CDF $F_{y_0}(\gamma)$ given in (12), we adopt the similar approach as in [12]. Specifically, the integration domain can be separated into two subsets as $X_1 > \frac{\gamma x_2 x_3}{x_2 - \gamma x_4}$ if $x_2 < \gamma x_4$ and $X_1 < \frac{\gamma x_2 x_3}{x_2 - \gamma x_4}$ if $x_2 > \gamma x_4$, which results in

$$F_{y_0}(\gamma) = \int_0^\infty \int_0^\infty \int_0^{\gamma x_4} f_{X_2}(x_2) f_{X_3}(x_3) f_{X_4}(x_4) d\gamma x_2 dx_3 dx_4$$
$$J_1 = 1 - F_{X_2}(y|x_4) - 2 \sum_{p=0}^{N_1m_1-1} \frac{\alpha_1^p}{p!} \sum_{q=0}^{p} \frac{C_p^q \alpha_2^{r-q+1}}{\Gamma(N_2m_2)} \sum_{r=0}^{N_2m_2-1} \frac{C_r}{\Gamma(N_1m_3)} \left( \frac{\alpha_1}{\alpha_2} \right)^{\frac{r-q+1}{2}} \frac{2N_3m_2+p+q-1}{\alpha_3} \times y^{2N_3m_2+p} \frac{x_4^2}{\alpha_3} \right) \exp(-\alpha_2 y x_4)$$

(A.8)

Then, substituting the expression of $J_1$ given in (A.8) and the PDF of $X_3$ into $J_2$ given in (A.5), rearranging terms, and performing some manipulations leads to the expression for $J_2$ as

$$J_2 = 1 - F_{X_2}(y|x_4) - 2 \sum_{p=0}^{N_1m_1-1} \frac{\alpha_1^p}{p!} \sum_{q=0}^{p} \frac{C_p^q \alpha_2^{r-q+1}}{\Gamma(N_2m_2)} \sum_{r=0}^{N_2m_2-1} \frac{C_r}{\Gamma(N_1m_3)} \left( \frac{\alpha_1}{\alpha_2} \right)^{\frac{r-q+1}{2}} \frac{2N_3m_2+p+q-1}{\alpha_3} \times y^{2N_3m_2+p} \frac{x_4^2}{\alpha_3} \right) \exp(-\alpha_2 y x_4)$$

(A.9)

The remaining integral in (A.9) is solved by applying [13, eq. (6.643.3)] together with some simplifications, which results in

$$J_2 = 1 - F_{X_2}(y|x_4) - 2 \sum_{p=0}^{N_1m_1-1} \frac{\alpha_1^p}{p!} \sum_{q=0}^{p} \frac{C_p^q \alpha_2^{r-q+1}}{\Gamma(N_2m_2)} \sum_{r=0}^{N_2m_2-1} \frac{C_r}{\Gamma(N_1m_3)} \left( \frac{\alpha_1}{\alpha_2} \right)^{\frac{r-q+1}{2}} \frac{2N_3m_2+p+q-1}{\alpha_3} \times y^{2N_3m_2+p} \frac{x_4^2}{\alpha_3} \right) \exp(-\alpha_2 y x_4)$$

(A.10)

To obtain a closed-form expression for the integral $J$, the closed-form expression for the integral $J_2$ given in (A.10) is then substituted into (A.6). Rearranging terms as well as performing several algebraic manipulations, the integral $J$ can be rewritten as

$$J = 1 - \int_0^\infty F_{X_2}(y|x_4)/X_4(x_4)dx_4 - 2 \sum_{p=0}^{N_1m_1-1} \frac{\alpha_1^p}{p!} \sum_{q=0}^{p} \frac{C_p^q \alpha_2^{r-q+1}}{\Gamma(N_2m_2)} \sum_{r=0}^{N_2m_2-1} \frac{C_r}{\Gamma(N_1m_3)} \left( \frac{\alpha_1}{\alpha_2} \right)^{\frac{r-q+1}{2}} \frac{2N_3m_2+p+q-1}{\alpha_3} \times y^{2N_3m_2+p} \frac{x_4^2}{\alpha_3} \right) \exp(-\alpha_2 y x_4)$$

(A.11)

Eventually, adding the first integral $I$ in (A.3) and the second integral $J$ after simplifying the remaining integral in (A.11) in view of [13, eq. (7.621.3)] and using the relationship $F_{Y}(y) = F_{Y_0}(y)/\rho$, the closed-form expression for $F_{Y}(y)$ is obtained.

**APPENDIX B: PROOF OF THEOREM 2**

From the order statistics theory, the CDF of $y_{OU}$ can be determined as
Hence, we first derive an expression for the CDF of $\gamma_1$, which can be written as

$$ F_{\gamma_1}(\gamma) = \Pr \left( \frac{X_2}{X_4} < \gamma \right) = \int_0^\infty F_{X_2}(\gamma x_4) f_{X_4}(x_4) \, dx_4 $$

(B.2)

Substituting the CDF of $X_2$ and the PDF of $X_4$ into (D.1), it follows that

$$ F_{\gamma_1}(\gamma) = 1 - \frac{\alpha_4 m_4}{\Gamma(m_4)} \sum_{q=0}^{N_2 m_2-1} \frac{\Gamma(m_4+q)}{q!} \frac{\alpha_q^{m_4+q}}{(\alpha_2 \gamma + \alpha_4)^{m_4+q}} $$

(B.4)

Applying [13, eq. (3.381.4)] to solve the remaining integral in (D.1), it follows that

$$ F_{\gamma_1}(\gamma) = 1 - \frac{\alpha_4 m_4}{\Gamma(m_4)} \sum_{q=0}^{N_2 m_2-1} \frac{\Gamma(m_4+q)}{q!} \frac{\alpha_q^{m_4+q}}{(\alpha_2 \gamma + \alpha_4)^{m_4+q}} $$

(B.5)

In a similar treatment of deriving the CDF of $\gamma_1$, the CDF of $\gamma_2$, $F_{\gamma_2}(\gamma)$, can be written as

$$ F_{\gamma_2}(\gamma) = 1 - \frac{\alpha_3 N_1 m_3}{\Gamma(N_1 m_3)} \sum_{r=0}^{N_1 m_1-1} \frac{\Gamma(N_1 m_3 + r) \alpha_1^{r} \gamma^{r}}{r!(\alpha_1 \gamma + \alpha_3)^{N_1 m_3+r}} $$

(B.6)

Substituting (B.4) and (B.5) in (B.1), the proof is completed.

**APPENDIX C: PROOF OF COROLLARY 1**

To prove Corollary 1, we substitute the closed-form expression for the CDF of $\gamma_{U}$ given in (17) into (15), followed by rearranging terms and performing algebraic manipulations. Then, the SER can be expressed as

$$ P_e = \frac{a \sqrt{b}}{2\sqrt{\pi}} \frac{1}{\rho^2} \int_0^\infty \gamma^{-\frac{1}{2}} \exp(-\rho \gamma) \, d\gamma = \frac{a \sqrt{b}}{2\sqrt{\pi}} \frac{1}{\rho^2} \frac{\alpha_4 m_4}{\Gamma(m_4)} \sum_{q=0}^{N_2 m_2-1} \frac{\Gamma(m_4+q)}{q!} \frac{\alpha_q^{m_4+q}}{(\alpha_2 \gamma + \alpha_4)^{m_4+q}} \int_0^\infty \frac{\gamma^{q+r-\frac{1}{2}}}{(\alpha_1 \gamma + \alpha_3)^{N_1 m_3+r}(\alpha_2 \gamma + \alpha_4)^{m_4+q}} \exp(-\rho \gamma) \, d\gamma $$

(C.1)

Clearly, the second remaining integral in (C.1) is not given in tabulated form. Therefore, to solve this integral, we utilize the partial fraction [13, eq. (3.326.2)] as follows:

$$ \frac{\gamma^{q+r-\frac{1}{2}}}{(\gamma + \alpha_3 \alpha_1^{-1})^{N_1 m_3+r}(\gamma + \alpha_4 \alpha_2^{-1})^{m_4+q}} = \frac{1}{\alpha_1^{N_1 m_3+r} \alpha_2^{m_4+q}} \left( \sum_{i=1}^{N_1 m_3+r} \beta_{qi} \gamma^{q+r-\frac{1}{2}} \left( \frac{\gamma}{\alpha_3 \alpha_1^{-1}} \right)^{i} + \sum_{i=1}^{m_4+q} \theta_{qi} \gamma^{q+r-\frac{1}{2}} \left( \frac{\gamma}{\alpha_4 \alpha_2^{-1}} \right)^{i} \right) $$

(C.2)

where

$$ \beta_{qi} = \left. \frac{d^{N_1 m_3+r-i}}{dy^{N_1 m_3+r-i}} \frac{1}{(y + \alpha_3 \alpha_1^{-1})^{m_4+q}} \right|_{y = -\alpha_3 \alpha_1^{-1}} $$

(C.3)
Because of the fact that \( \phi(x, y) \big|_{y=0} \neq 0 \) if and only if \( v = 0 \) as well as

\[
\frac{\partial^u F_{X_2}(x, y)}{\partial \phi^u} \bigg|_{y=0} = \begin{cases} 
0, & u < N_2 m_2 \\
\alpha_2^{N_2 m_2}, & u = N_2 m_2
\end{cases} \tag{D.4}
\]

we consider only the case of \( n = u = N_2 m_2 \) and \( v = 0 \), leading to

\[
F_{Y_1}(y) \bigg|_{y=0} = \frac{\Gamma(N_2 m_2 + m_4)}{\Gamma(N_2 m_2 + 1) \Gamma(m_4)} \alpha_4^{N_2 m_2} y^{N_2 m_2} + o(y^{N_2 m_2}) \tag{D.8}
\]

Similarly, the MacLaurin expansion of \( F_{Y_2}(y) \) at zero is given by

\[
\theta_{q_i} = \frac{1}{(m_4 + q - i)!} \frac{d^{m_4+q-i} \left[ (y + \alpha_3 \alpha_1^{-1})^{N_1 m_3 + r} \right]}{dy^{m_4+q-i}} \bigg|_{y=\alpha_4^2} \tag{C.4}
\]

Substituting (C.2) into (C.1) and rearranging terms, we get

\[
P_c = \frac{a_1}{2} \frac{a_2 \sqrt{b_1 \rho_2}}{2 \sqrt{\pi}} \frac{\alpha_4^{N_1 m_3 - 1}}{\Gamma(m_4)} \sum_{q=0}^{N_2 m_2 - 1} \frac{\Gamma(m_4 + q) a_2^q}{q!} \frac{\alpha_3^{N_1 m_3}}{\Gamma(N_1 m_3)} \sum_{r=0}^{N_1 m_3 - 1} \Gamma(N_1 m_3 + r) a_2^r \frac{\alpha_4^{N_1 m_3 + r} a_2^{m_4 + q}}{r! a_1^{N_1 m_3 + r} a_2^{m_4 + q}} \times \left( \sum_{i=1}^{N_1 m_3 + r} \kappa_i \int_0^{\infty} \frac{y^{q+r-\frac{1}{2}}}{(y + \alpha_3 \alpha_1^{-1})^{N_1 m_3 + r}} \exp(-b \rho y) dy \right) \tag{C.5}
\]

Using [21, eq. (2.3.6.9)] to solve the remaining integrals in (C.5), (18) is now readily found.

**APPENDIX D: PROOF OF THEOREM 3**

In this appendix, we derive the first nonzero coefficient of the MacLaurin series of \( F_{Y_1}(y) \). Equation (B.1) indicates that the MacLaurin expansion of \( F_{Y_1}(y) \) can be obtained by obtaining the MacLaurin series of \( F_{X_1}(y) \), \( i = 1, 2 \) independently. To this end, we rewrite the CDF \( F_{Y_1}(y) \) as follows:

\[
F_{Y_1}(y) = \int_0^{\infty} F_{X_2}(\phi(x_4, y)) f_{X_4}(x_4) dx_4 \tag{D.1}
\]

where \( \phi(x_4, y) = y x_4 \). Applying the \( n \)-th order derivative at zero to the two sides of (D.1) yields

\[
F_{Y_1}^{(n)}(y) \bigg|_{y=0} = \int_0^{\infty} \left. \frac{\partial^n F_{X_2}(\phi(x_4, y))}{\partial y^n} \right|_{y=0} f_{X_4}(x_4) dx_4 \tag{D.2}
\]

The term \( \left. \frac{\partial^n F_{X_2}(\phi(x_4, y))}{\partial y^n} \right|_{y=0} \) can be rewritten in view of [13, eq. (0.430.1)] as

\[
\left. \frac{\partial^n F_{X_2}(\phi(x_4, y))}{\partial y^n} \right|_{y=0} = \sum_{u=1}^{n} \sum_{v=0}^{u-1} \frac{C_u^{v} (-1)^v \phi^v(x_4, y)}{\Gamma(u+1)} \frac{\partial^u F_{X_2}(\phi(x_4, y))}{\partial \phi^u} \left. \frac{\partial^u \phi^v(x_4, y)}{\partial y^n} \right|_{y=0} \tag{D.3}
\]

Because of the fact that \( \phi^v(x_4, y) \big|_{y=0} \neq 0 \) if and only if \( v = 0 \) as well as

\[
\left. \frac{\partial^u F_{X_2}(\phi(x_4, y))}{\partial \phi^u} \right|_{y=0} = \begin{cases} 
0, & u < N_2 m_2 \\
\alpha_2^{N_2 m_2}, & u = N_2 m_2
\end{cases} \tag{D.4}
\]

we consider only the case of \( n = u = N_2 m_2 \) and \( v = 0 \), leading to

\[
\frac{\partial^n F_{Y_1}(y)}{\partial y^n} \bigg|_{y=0} = \frac{\Gamma(N_2 m_2 + m_4)}{\Gamma(N_2 m_2 + 1) \Gamma(m_4)} \alpha_4^{N_2 m_2} y^{N_2 m_2} + o(y^{N_2 m_2}) \tag{D.8}
\]
Substituting (D.8) and (D.9) into (B.1) and using the relationship in (7), the MacLaurin expansion of $F_\gamma(y)$ is rewritten as

$$F_\gamma(y) \xrightarrow{y \to 0} 1 - \left[ 1 - \frac{\Gamma(N_1 m_1 + N_2 m_2 + m_4)}{\Gamma(N_2 m_2 + 1) \Gamma(m_4)} \frac{a_2^{N_2 m_2}}{a_4^{N_2 m_2}} \left( \frac{y}{\rho} \right)^{N_2 m_2} + o(y^{N_2 m_2}) \right] \right]$$

$$\times \left[ 1 - \frac{\Gamma(N_1 m_1 + N_3 m_3)}{\Gamma(N_3 m_3 + 1) \Gamma(m_3)} \frac{a_3^{N_3 m_3}}{a_4^{N_3 m_3}} \left( \frac{y}{\rho} \right)^{N_3 m_3} + o(y^{N_3 m_3}) \right]$$

which completes the proof of Theorem 3.

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