Network-Coded Two-Way Relaying in Spectrum Sharing Systems with Quality-of-Service Requirements

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***Abstract*—We investigate the performance of a dual-hop two-way cognitive radio system, where the secondary users (SUs) exchange information in an underlay mode with the assistance of a half-duplex relay utilizing physical-layer network coding over finite GF(2). Moreover, we consider a practical scenario of interference from the primary users (PUs) affecting the relay and source nodes. The analysis provides a generalization of previous works as it considers an extended transmission system where the channels can consist of a combination of independent and identically distributed (i.i.d.) and independent but non-identically distributed (i.n.i.d.) Nakagami-m fading models. Also, unlike prior works, this paper focuses on the performance of both the PUs and the SUs. Closed-form expressions for the symbol error probability (SEP) and outage probability of the intended PU are obtained. In addition, we derive exact closed-form expressions for the SEP with consideration of special cases of practical interest (e.g., no interference power, interference-limited and single dominant interference cases) for the SUs. Furthermore, an upper bound on the achievable rate of the secondary system is provided. Subsequently, closed-form approximating expression for the SEP of the secondary system at high signal-to-noise ratios is obtained. Simulation results are provided and attest to the accuracy of the analytical results.**

***Index Terms*—Cognitive radio networks, network coding, symbol error probability, two-way relaying.**

I. Introduction

In the design of modern wireless communication systems, achieving higher data rates and more reliable transmissions have become pivotal goals. While some recent studies predict multi-fold increase in the data traffic by 2020 [1–3], mobile operators must currently deal with resource congestion and energy limitations of existing systems. In this context, cooperative communication has emerged as an advanced paradigm to achieve robustness and high data rate transmissions [4].

Among the many cooperative communication schemes that have been proposed in recent years, two-way relaying offers many advantages in terms of capacity increase, coverage extension and energy savings. One of the most widely embraced protocols in two-way relaying is the physical-layer network coding (PNC) in which two source nodes simultaneously transmit their information message to an intermediate relay over a multiple access channel (MAC) in the first stage, and the relay retransmits the XOR'ed version of the received messages to the source nodes over a broadcast channel (BC) in the second stage [5]. Despite a higher complexity, the PNC relaying protocol can offer lower bit error rates, which is a desirable attribute for future wireless cellular networks. For this purpose, we, henceforth, evaluate the performance of PNC relaying schemes.

Meanwhile, the spectrum resources are extremely scarce. Cognitive radio (CR) together with dynamic spectrum access (DSA) provide an advanced strategy for addressing the spectrum scarcity problem of wireless networks by allowing the sharing of resources between different classes of users [6]. One of the most common approaches for DSA in spectrum-sharing systems is in the form of an underlay scheme, whereby secondary users (SUs) are allowed to coexist with primary users (PUs) as long as the primary's quality-of-service (QoS) is not affected. Since the underlay approach does not necessarily rely on detection of spectrum white space, it is of special interest [7]. Besides, most wireless networks operate according to a frequency reuse principle, which makes co-channel interference (CCI) a dominant factor. Hence, the transmit power of the SUs is not only dependent on the radio channel between them, but also on the interference channels from the PU to the SUs and on the primary channel as well.

Based on these considerations, much research efforts were devoted to the performance study of various schemes for relaying SU's messages in underlay cognitive radio networks (CRNs), taking into account interference from and to the PUs. In [8–17], the purpose was to investigate the effect of primary transmissions on the performance of traditional CRNs. For instance, in [8], a closed-form expression for the outage probability (OP), under peak interference power constraint in the presence of multiple unidirectional primary transceivers, was derived assuming Rayleigh fading. The performance metrics in an amplify-and-forward (AF) CRN with best relay selection were studied in [10]. [11] presented a closed-form expression for the OP of a secondary network implementing decode-and-forward (DF) relaying. In [12], the OP of a unidirectional cognitive multiple-input multiple-output (MIMO) relaying system was analyzed. The asymptotic OP for three relay-selection strategies were obtained in [13]. The authors in [15], examined the outage performance of DF CRNs. [16] studied the performance of a multi-relay spectrum sharing system, where the diversity order was shown to be

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equal to one regardless of the number of relaying nodes, and [17] investigated the impact of multiuser diversity on the outage performance of DF CRNs.

Compared to the traditional relaying considered in the above works, two-way relaying techniques can potentially double the spectral efficiency [18]. For example, [19–23] derived the OP of two-way relaying systems in the presence of CCI and additive white Gaussian noise (AWGN) at the relay(s) and the end-sources. [24] studied the problem of relay selection and optimal resource allocation for two-way AF and DF relaying in spectrum sharing systems, and [25] proposed a transmit beamforming technique for an underlay CRN, where the CR system uses part of the primary spectrum, while a MIMO secondary base station acts as a relay for the primary network. A cognitive relay precoder based on the mean square error (MSE) criterion was designed in [26], where only imperfect channel state information (CSI) was assumed available. In [27], a relay selection strategy for two-way AF relaying was presented. The OP of incremental AF and DF relaying in underlay spectrum sharing systems over Nakagami-m fading channels was derived in [28]. A MIMO two-way relay scheme for CRN was proposed in [29], where an AF relay is optimally selected to maximize the sum rate of the SUs while taking into account the interference level of the PU.

While previous works enhanced the knowledge on cognitive relaying, they did not elaborate on the performance of both the primary network and the two-way DF relaying secondary network when the interacting SUs and relay are affected by multiple primary interferers. This scenario can occur, for instance, in a cellular network where two mobile users are communicating via a base station or another type of relay using the spectrum holes of a nearby primary network. Motivated by these considerations, we herein pursue a detailed performance analysis of dual-hop two-way DF relaying in spectrum-sharing systems with multiple primary interferers. The contributions of the paper can be summarized as follows: (i) In the two-way dual-hop secondary network, the source nodes and the relay are affected by multiple interferers originating from the primary network in a Nakagami-m fading environment. This practical but intricate setup has scarcely been considered in the related literature [1]. Assuming Nakagami-m fading channels, we consider a general scenario in which the fading can be i.i.d. or i.n.i.d., and obtain exact closed-form expressions for the OP and the average SEP of the PU. (ii) The average SEP of the secondary network under binary phase shift keying (BPSK) modulation is derived. Furthermore, the average SEP behavior is analyzed in detail for several practical cases of interest, including i.i.d. and i.n.i.d. fading channels, the interference-free case and the scenario with a single dominant interferer. (iii) We explore the achievable rate performance of the two-way cognitive DF relaying assuming availability of CSI at the receiving nodes. Upper bounds on the achievable rate of the secondary system are derived based on Jensen's inequality. (iv) For additional insights onto the impact of system parameters, such as fading parameters and the number of primary interferers, we derive the asymptotic SEP for different cases. The results indicate that an equal number of interferers at each SU node yields better SEP performance than the un-equal case, over the whole SNR range of interest. (v) Simulations are presented to corroborate the analysis, and to provide interesting horizons on the impact of noise, interference, fading parameters and primary outage threshold, on performance.

The rest of the paper is organized as follows: Section II introduces the system model and fading statistics. In Section III, we pursue the performance analysis of the primary network and derive an exact closed-form expression for the SEP and an upper-bound on the sum rate. The asymptotic analysis for the secondary network is developed in Section IV. Asymptotic performance analysis provided in Section V. Section VI presents a set of numerical results, and Section VII concludes the paper.

[1]Performance analysis of two-way spectrum sharing systems in Nakagami-m environments has its own challenges. That is why many papers appeared even with the same topics as in unidirectional networks suffering from Rayleigh fading [30, 31]. There are also many works on bidirectional relay networks which are only noise limited or interference limited, or assuming Rayleigh fading [32, 33]. Therefore, none of the prior works presented such practical and comprehensive analysis of the proposed scenario.

II. System Model

We examine the impact of multiple primary interferers on the performance of a unidirectional primary network as well as of a CR two-way relay network. The intended primary network consists of a transmitter node, $\tilde{P}$, and a receiver node, P. The CRN consists of two source nodes, S_1 and S_2, which exchange information via a relay R employing PNC, as shown in Fig. 1. We assume that the direct channel between S_1 and S_2 has a negligibly small SNR due to severe fading. The amplitudes of all channels undergo flat Nakagami-m fading and the channels are assumed to be reciprocal in the forward and backward directions. The PNC scheme consists of two stages: during the MAC stage, sources S_1 and S_2 simultaneously transmit to R; in the BC stage, R broadcasts the XOR'ed version of the received symbols to the sources.

In our formulation, h, g and h_P denote the random channel coefficients from S_1 to R, from S_2 to R and from the intended PU, $\tilde{P}$, to its receiver P, respectively. Also, $f_{R,j}$, $f_{S_1,j}$, $f_{S_2,j}$ represent the channel coefficients from the jth interferer to R, S_1 and S_2, respectively. Additionally, f_{P,S_1}, f_{P,S_2}, $f_{P,R}$ and $f_{P,j}$ are the flat fading coefficients from S_1 to P, S_2 to P, R to P and from the jth primary interferer to P, respectively.

The amplitudes of all the links have Nakagami-m distributions, where $m \geq 0.5$ represents the fading severity parameter. Therefore, the corresponding SNRs are random variables (RVs) following Gamma distributions with shape parameter m and mean Ω, denoted as $G(m, \Omega)$. The distributions of the various channel squared magnitudes can be expressed, via their corresponding parameters as: $|h|^2 \overset{d}{\sim} G\left(m_h, \Omega_h\right)$, $|g|^2 \overset{d}{\sim} G\left(m_g, \Omega_g\right)$, $|f_{R,j}|^2 \overset{d}{\sim} G\left(m_{R,j}, \Omega_{R,j}\right)$, $|f_{S_1,j}|^2 \overset{d}{\sim} G(m_{S_1,j}, \Omega_{S_1,j})$, $|f_{S_2,j}|^2 \overset{d}{\sim} G(m_{S_2,j}, \Omega_{S_2,j})$, $|h_P|^2 \overset{d}{\sim} G\left(m_P, \Omega_P\right)$, $|f_{P,S_1}|^2 \overset{d}{\sim} G\left(m_{P,S_1}, \Omega_{P,S_1}\right)$, $|f_{P,S_2}|^2 \overset{d}{\sim} G\left(m_{P,S_2}, \Omega_{P,S_2}\right)$, $|f_{P,j}|^2 \overset{d}{\sim} G(m_{P,j}, \Omega_{P,j})$ and $|f_{P,R}|^2 \overset{d}{\sim} G(m_{P,R}, \Omega_{P,R})$, where symbol $\overset{d}{\sim}$ denotes "distributed as". Also,

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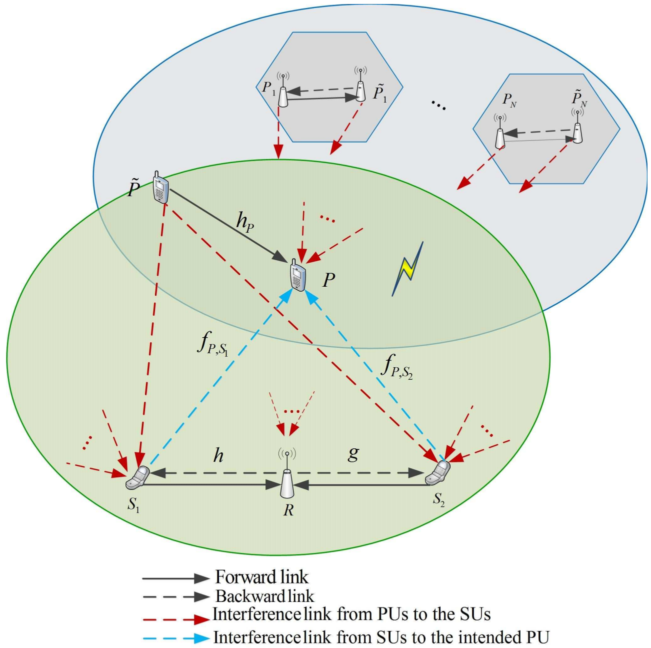

Fig. 1. A two-way cognitive cooperative network in the presence of multiple primary interferers.

we define the scale parameter $\beta_x = \frac{m_x}{\Omega_x}, x \in \{(S_1,j),(S_2,j),(R,j),(P,j),(P,R),(P,S_1),(P,S_2),h,g,P\}$. In the MAC stage, S_1 and S_2 send their respective messages x_1 and x_2 to R. During this stage, L_P PUs out of the existing ones which exchange messages with their respective receivers, interfere with node P. In such a case, there is no need for state feedback to synchronize the primary and secondary networks. The sources and the relay are affected by L_{S_i}, $i \in \{1,2\}$ and L_R interferers, respectively. The interferers, which are the PUs in the proximity of the secondary network, may be i.i.d. or i.n.i.d. Under this scenario, the signal received by R in the MAC stage is given by

$$y_R = \sqrt{E_S}hx_1 + \sqrt{E_S}gx_2 + \sum_{j=1}^{L_R}\sqrt{E_{R,j}}f_{R,j}d_{R,j} + n_R, \quad (1)$$

where E_S is the transmit energy at S_1 and S_2, $E_{R,j}$ is the transmit energy at the jth interferer in the vicinity of R. x_1, x_2 and $d_{R,j}$ represent the unit-energy symbols transmitted from S_1, S_2 and the jth interferer, respectively, and $n_R \sim \mathcal{CN}(0, N_0)$ represents the AWGN at R. The signal received by the intended primary receiver P, can be expressed as

$$y_{P,S} = \sqrt{E_P}h_P x_P + \sum_{j=1}^{L_P}\sqrt{E_{P,j}}f_{P,j}d_{P,j} + \sqrt{E_S}f_{P,S_1}x_1 + \sqrt{E_S}f_{P,S_2}x_2 + n_P, \quad (2)$$

where E_P denotes the transmit energy at the intended primary transmitter, $E_{P,j}$ is the transmit energy at the jth primary interferer in the proximity of the primary node P, while x_P and $d_{P,j}$ represent the modulated symbols with unit energy emitted by the intended primary transmitter and jth interferer in the vicinity of P, respectively, and $n_P \sim \mathcal{CN}(0, N_0)$ is the AWGN at P.

By employing the minimum Euclidean distance rule, the relay proceeds for joint detection of the received signal y_R, as expressed by [34]

$$[\bar{x}_1, \bar{x}_2] = \underset{[s_1,s_2]:\, s_1,s_2 \in \mathcal{A}}{\arg\min} \left| y_R - \left(\sqrt{E_S}hs_1 + \sqrt{E_S}gs_2\right)\right|, \quad (3)$$

where $\bar{x}_1$ and $\bar{x}_2$ are the estimates of x_1 and x_2, respectively, and $|\mathcal{A}|$=Q denotes the cardinality of the Q-ary constellation. The relaying node R selects the best map out of a well-designed finite mapping book according to the channel condition. Then, $\bar{x}_1$ and $\bar{x}_2$ are decoded and $\bar{X}_1$ and $\bar{X}_2$ obtained. Next, using the PNC protocol over the finite GF(2), the relay encodes the XOR'ed version of the decoded binary symbols and produces

$$\hat{y}_R = \bar{X}_1 \oplus \bar{X}_2, \quad (4)$$

where $\oplus$ is the bitwise XOR operation. Then, R encodes $\hat{y}_R$ and produces x_R which is broadcasted to S_1 and S_2 in the BC stage. After perfect cancelation of self-interference, the received signals at the two sources and node P will be

$$y_{S_1} = \sqrt{E_R}hx_R + \sum_{j=1}^{L_{S_1}}\sqrt{E_{S_1,j}}f_{S_1,j}d_{S_1,j} + n_{S_1}, \quad (5)$$

$$y_{S_2} = \sqrt{E_R}gx_R + \sum_{j=1}^{L_{S_2}}\sqrt{E_{S_2,j}}f_{S_2,j}d_{S_2,j} + n_{S_2}, \quad (6)$$

$$y_{R,P} = \sqrt{E_P}h_P x_P + \sum_{j=1}^{L_P}\sqrt{E_{P,j}}f_{P,j}d_{P,j} + \sqrt{E_R}f_{P,R}x_R + n_P, \quad (7)$$

where $E_{S_1,j}$ and $E_{S_2,j}$ denote the transmit power of the jth interferer affecting S_1 and S_2, $d_{S_1,j}$ and $d_{S_2,j}$ are the jth interference unit-power symbols affecting S_1 and S_2, $n_{S_1} \sim \mathcal{CN}(0, N_0)$ and $n_{S_2} \sim \mathcal{CN}(0, N_0)$ are AWGN at nodes S_1 and S_2, respectively, and E_R is the transmit power of the relay.

Based on (5) and (6) the received signal-to-interference plus noise ratio (SINR) at S_1 and S_2 can be expressed by

$$\gamma_{R,S_1} = \frac{E_R|h|^2}{\sum_{j=1}^{L_{S_1}} E_{S_1,j}|f_{S_1,j}|^2 + N_0}, \quad (8)$$

$$\gamma_{R,S_2} = \frac{E_R|g|^2}{\sum_{j=1}^{L_{S_2}} E_{S_2,j}|f_{S_2,j}|^2 + N_0}. \quad (9)$$

Next, the performance analysis with respect to (w.r.t.) the PU is presented.

III. Performance Analysis of the Primary Network

A. Outage Probability and Power Allocation

We aim at obtaining the OP of the intended PU, based on which the power allocation of the SUs is investigated. One of the major challenges of spectrum sharing systems is that the SUs should satisfy the QoS requirements of the primary network. In our case, the reliability requirements of the PUs shall be ensured. Specifically, the OP of primary transmissions shall be guaranteed to be below a pre-defined threshold λ [35],

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$$P_{\rm Pri}^{\rm out} = \Pr\left\{ \log_2\left(1+\frac{E_P|h_P|^2}{\sum\limits_{j=1}^{L_P} E_{P,j}|f_{P,j}|^2+E_S|f_{P,S_1}|^2+E_S|f_{P,S_2}|^2+N_0}\right)\leq R_{\rm P}\right\}\leq\lambda, \quad (10)$$

as in (10),[2] where $R_{\rm P}$ is the primary transmission rate. In the sequel, we refer to λ as the primary OP threshold. It is noteworthy that we assume that some of the channels can be i.i.d. whereas others are i.n.i.d., which provides a generalization of the channel models used in some earlier works, e.g., [23]. The following proposition states the OP of the SINR of the PU and power constraint of the secondary sources.

Proposition 1: According to the preceding equation, the OP of the PU can be obtained as

$$F_{P,S}(\gamma_{\rm th}) = 1-\sum_{j=1}^{L_{FP}}\sum_{k=1}^{M_{P,j}}\sum_{t=1}^{L_{FSP}}\sum_{w=1}^{M_{P,S_t}}\sum_{n=0}^{m_P-1}\sum_{r=0}^{n}\sum_{q=0}^{r} \times\frac{\bar{\gamma}_P^n\Gamma(n+k-r)\Gamma(w+q)\theta_{tw}\alpha_{jk}}{\Gamma(n+1)\Gamma(w)\Gamma(k)}\binom{n}{r}\binom{r}{q} \times\frac{\gamma_{\rm th}^n\exp(-\bar{\gamma}_P\gamma_{\rm th})}{(\bar{\gamma}_P\gamma_{\rm th}+\bar{\gamma}_{P,j})^{n+k-r}(\bar{\gamma}_P\gamma_{\rm th}+\bar{\gamma}_{P,S_t})^{w+q}}\leq\lambda, \quad (11)$$

where $\gamma_{\rm th}=2^{R_{\rm P}}-1, \bar{\gamma}_P=\beta_P N_0 E_P^{-1}, \alpha_{jk}=(\Gamma(M_{P,j}-k+1))^{-1}\psi_j^{(M_{P,j}-k)}(-\bar{\gamma}_{P,j}), \psi_j(s)=\bar{\gamma}_{P,j}^{M_{P,j}}\times\prod_{\substack{l=1\\l\neq j}}^{L_{FP}}(s/\bar{\gamma}_{P,l}+1)^{-M_{P,l}}$, $\bar{\gamma}_{P,S_t}=\beta_{P,S_t}N_0E_S^{-1}, \theta_{tw}=(\Gamma(M_{P,S_t}-w+1))^{-1}\sigma_j^{(M_{P,S_t}-w)}(-\bar{\gamma}_{P,S_t})$ and $\sigma_j(s)=\bar{\gamma}_{P,S_j}^{M_{P,S_j}}\prod_{\substack{l=1\\l\neq j}}^{L_{FSP}}(s/\bar{\gamma}_{P,S_l}+1)^{M_{P,S_l}}$. In addition, L_{FSP} is the number of secondary interferers affecting P which have different values of $\bar{\gamma}_{P,S_t}$, and L_{FP} is the number of primary interferers at node P, which may have different values of $\bar{\gamma}_{P,j}=\beta_{P,j}N_0E_{P,j}^{-1}$. M_{P,S_1}, M_{P,S_2} and $M_{P,j}$ are, respectively, the sum of the shape parameters of the interferers' channels at S_1, S_2 and P, with equal values of $\bar{\gamma}_{P,S_1}$, $\bar{\gamma}_{P,S_2}$ and $\bar{\gamma}_{P,j}$. Besides, throughout this paper $f^{(i)}(x)$ represents the ith derivative of $f(x)$ w.r.t. x.

Proof: See Appendix I. ■

In the adopted power control scheme, we employ a static method to control the transmit power of the SUs. As such, the SUs utilize the maximum average admissible power for transmission. Finally, for a given value of the primary OP threshold λ, the power of the secondary sources is derived by solving (11) w.r.t. E_S using popular computing softwares, such as Matlab and Mathematica.

Note that the allowed values of E_R are obtained by applying the same strategy as in evaluating the power constraint of the two sources. According to (7), and similar to the proof of Proposition 1, it can be shown that the OP of the PU's SINR in the BC phase is given by (12), based on which the power constraint of the relay is achieved:

$$F_{P,R}(\gamma_{\rm th}) = 1-\sum_{j=1}^{L_{FP}}\sum_{k=1}^{M_{P,j}}\sum_{n=0}^{m_P-1}\sum_{r=0}^{n}\sum_{q=0}^{r}\binom{n}{r}\binom{r}{q} \times\frac{\bar{\gamma}_P^n\bar{\gamma}_{P,R}^{-m_{P,R}}\Gamma(n+k-r)\Gamma(m_{P,R}+q)\alpha_{jk}}{\Gamma(n+1)\Gamma(m_{R,P})\Gamma(k)} \times\frac{\gamma_{\rm th}^n\exp(-\bar{\gamma}_P\gamma_{\rm th})}{(\bar{\gamma}_P\gamma_{\rm th}+\bar{\gamma}_{P,j})^{n+k-r}(\bar{\gamma}_P\gamma_{\rm th}+\bar{\gamma}_{P,R})^{m_{P,R}+q}}\leq\lambda, \quad (12)$$

where $\bar{\gamma}_{P,R}=\beta_{P,R}N_0E_R^{-1}$. By solving (12) w.r.t. E_R, the admissible power values for the relay can be obtained. We note that the outage performance of the PU is investigated for two reasons. Firstly, the OP is a key performance measure for CRN operating under time-varying and slow flat fading conditions and, secondly, it can be used to solve the power allocation problem for the SUs, as considered in this work.

B. Symbol Error Probability

The error rates of several modulation schemes employed in practice represented in terms of the Q-function as $aQ\left(\sqrt{2b\gamma}\right)$, where a and b are modulation-specific constants [37]; for instance, $a=1$ and $b=1$ for binary phase-shift keying (BPSK). One method to evaluate the SEP in fading environments is to make use of the CDF-based approach, which allows us to write the average SEP of the two-way relaying system, assuming BPSK modulation, as

$$P_e=\mathbb{E}\left[aQ\left(\sqrt{2b\gamma}\right)\right]=\frac{a\sqrt{b}}{2\sqrt{\pi}}\int_0^\infty\frac{e^{-b\gamma}}{\sqrt{\gamma}}F_\gamma(\gamma)\,d\gamma, \quad (13)$$

where $\mathbb{E}[.]$ represents expectation over the SINR distribution. To compute the SEP, we need to perform partial fraction expansion on (11), which results in

$$F(\gamma)=1-\sum_{j=1}^{L_{FP}}\sum_{k=1}^{M_{P,j}}\sum_{n=0}^{m_p-1}\sum_{p=0}^{n}\sum_{q=0}^{p}\binom{n}{p}\binom{p}{q}\gamma^n \times\frac{\bar{\gamma}_{R,P}^{m_{RP}}\Gamma(n+k-p)\Gamma(m_{R,P}+q)\alpha_{jk}}{\Gamma(n+1)\Gamma(m_{R,P})\Gamma(k)\bar{\gamma}_P^{m_{R,P}+k+q-p}}\exp(-\bar{\gamma}_P\gamma) \times\left[\sum_{l=1}^{n+k-p}\varrho_l\left(\gamma+\frac{\bar{\gamma}_{P,j}}{\bar{\gamma}_P}\right)^{-l}+\sum_{m=1}^{m_{R,P}+q}\vartheta_m\left(\gamma+\frac{\bar{\gamma}_{R,P}}{\bar{\gamma}_P}\right)^{-m}\right], \quad (14)$$

[2]The power allocation of the SUs in many prior works, e.g., [10, 36], is obtained based on the instantaneous interference threshold at the primary receiver, i.e., $P_{S_1}=I_P/|h_{P-S_1}|^2$, $P_{S_2}=I_P/|h_{P-S_2}|^2$, $P_R=I_P/|h_{P-R}|^2$ where I_P is the threshold. This requires knowledge of the instantaneous CSI of the link between the secondary nodes and the primary nodes. In practical setups with high mobility, the channel experiences fast fading. In such cases, it is difficult to estimate the instantaneous CSI and, importantly, additional channel resources are required to implement the state feedback of the channel estimates. In our proposed OP-based power allocation, we only need to assume that a SU (S_1, S_2 and R) has knowledge of the average channel gains of the link from itself to the PU. In contrast to the fast variations of instantaneous channel gains, the average channel gains of the PU, which relate to the nominal system parameters only, such as the transmission distance, transmit/receive antenna gain, wavelength of electromagnetic wave, etc., are relatively stable and can be estimated within the CRN.

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$$P_{\text{Pri}}^{e} = a\left[1-\sqrt{\frac{b}{\pi}}\sum_{j=1}^{L_{FP}}\sum_{k=1}^{M_{P,j}}\sum_{n=0}^{m_p-1}\sum_{p=0}^{n}\sum_{q=0}^{p}\frac{\bar{\gamma}_{R,P}^{m_{RP}}\Gamma(n+k-p)\Gamma(m_{R,P}+q)\alpha_{jk}}{\Gamma(n+1)\Gamma(m_{R,P})\Gamma(k)\bar{\gamma}_{P}^{m_{R,P}+k+q-p}}\binom{n}{p}\binom{p}{q}\right.$$
$$\left.\times\left(\sum_{l=1}^{n+k-p}\varrho_l\left(\frac{\bar{\gamma}_{P,j}}{\bar{\gamma}_P}\right)^{n-l+\frac{1}{2}}\mathbb{G}_{l,\bar{\gamma}_{P,j}(b+\bar{\gamma}_P)/\bar{\gamma}_P}+\sum_{m=1}^{m_{R,P}+q}\vartheta_m\left(\frac{\bar{\gamma}_{R,P}}{\bar{\gamma}_P}\right)^{n-m+\frac{1}{2}}\mathbb{G}_{m,\bar{\gamma}_{R,P}(b+\bar{\gamma}_P)/\bar{\gamma}_P}\right)\right]. \tag{15}$$

where $\varrho_l = (\Gamma(n+k-p-l+1))^{1}\varsigma^{(n+k-p-l)}(-\frac{\bar{\gamma}_{P,j}}{\bar{\gamma}_P})$, $\varsigma(\gamma) = (\bar{\gamma}_P\gamma+\bar{\gamma}_{R,P})^{-m_{R,P}-q}$, $\vartheta_m = (\Gamma(m_{R,P}+q-m+1))^{-1}\varepsilon^{(m_{R,P}+q-m)}(-\frac{\bar{\gamma}_{R,P}}{\bar{\gamma}_P})$ and $\varepsilon(\gamma) = (\bar{\gamma}_P\gamma+\bar{\gamma}_{P,j})^{p-k-n}$. Then, substituting (14) into (13) and utilizing [38], the SEP of the PU can be found in closed-from as shown in (15), where $\mathbb{G}_{x,y} = \Phi(n+1/2, n-x+3/2; y)$ and $\Phi(x;y;z)$ is the confluent hypergeometric function of the second kind [38, Eq. (9.211.4)].

IV. Performance Analysis of the Secondary Network

In this section, we investigate the SEP and achievable rate of the secondary two-way PNC relaying system. An exact SEP result at S_1 is obtained, followed by an upper bound on the achievable rate of the system. Since BPSK is easy to implement, is fairly resistant to noise and is the most robust of all PSK modulations, especially for low data-rate applications, it has been adopted in various third-generation (3G) standards, such as European Telecommunications Standards Institute (ETSI) in Europe, the Association of Radio Industries and Business (ARIB) in Japan and various wireless LAN standards, IEEE 802.11b, RFID and Bluetooth. BPSK modulation is therefore considered in this work for the performance analysis of the secondary network.

A. Symbol Error Probability

The average SEP of the two-way relay system for BPSK modulation can be obtained from (13). To begin, notice that errors at the relay occur when the S_1-R message is decoded correctly but the S_2-R message is not, or vice versa. In addition, an error at S_1 occurs when the information sent from R-S_1 is erroneous but correctly detected by S_1, or when the information sent from R-S_1 is correct but decoded with error at S_1. The following proposition summarizes the SEP at S_1 for the asymmetric two-way relay channel [3].

Proposition 2: Denote the instantaneous SEP at R, w.r.t. links S_1-R and S_2-R by $P^b(\gamma_{S_1,R})$ and $P^b(\gamma_{S_2,R})$, respectively, and that at S_1 w.r.t. link R-S_1 by $P^b(\gamma_{R,S_1})$. Also, let $P^b(\gamma_R)$ be the probability that $\hat{y}_R$ is in error. Further, let $e_{\gamma_{i,j}}$ and $\bar{e}_{\gamma_{i,j}}$ symbolize, respectively, that the received signal at node j w.r.t. link i-j is detected incorrectly and correctly. Then, the SEP of the asymmetric two-way network coded relaying system at S_1 is given by

$$P_{S_1}^{e} = P^b(\gamma_R)\bar{P}^b(\gamma_{R,S_1}) + P^b(\gamma_{R,S_1})\bar{P}^b(\gamma_R), \tag{16}$$

where $\bar{P}^b(.) = 1-P^b(.)$ and

$$\begin{aligned}P^b(\gamma_R) =& P^b(\gamma_{S_1,R}|\bar{e}_{\gamma_{S_2,R}})\bar{P}^b(\gamma_{S_2,R})\\ &+ P^b(\gamma_{S_2,R}|\bar{e}_{\gamma_{S_1,R}})\bar{P}^b(\gamma_{S_1,R}),\end{aligned} \tag{17}$$

$$P^b(\gamma_{R,S_1}) = \mathcal{J}_{S_1,h,S,\lambda_{jk}}, \tag{18}$$

$$P^b(\gamma_{S_1,R}|\bar{e}_{\gamma_{S_2,R}}) = \mathcal{J}_{R,h,R,\mu_{jk}}, \tag{19}$$

$$P^b(\gamma_{S_1,R}|e_{\gamma_{S_2,R}}) = \mathcal{H}_{h,g}, \tag{20}$$

where $\mathcal{J}_{S_1,h,S,\lambda_{jk}}$ and $\mathcal{H}_{h,g}$ are shown on the top of next page, while $\bar{\gamma}_{h,R} = \beta_h N_0 E_S^{-1}$, $\bar{\gamma}_{g,R} = \beta_g N_0 E_S^{-1}$, $\bar{\gamma}_{S_1,j} = \beta_{S_1,j}N_0 E_{S_1,j}^{-1}$, $\bar{\gamma}_{R,j} = \beta_{R,j}N_0E_{R,j}^{-1}$, $\lambda_{jk} = (\Gamma(M_{S_1,j}-k+1))^{-1}\rho_j^{(M_{S_1,j}-k)}(-\bar{\gamma}_{S_1,j})$, $\rho_j(s) = \bar{\gamma}_{S_1,j}^{M_{S_1,j}}\prod_{l=1, l\neq j}^{L_{FS_1}}(s/\bar{\gamma}_{S_1,l}+1)^{-M_{S_1,l}}$, $\mu_{jk} = (\Gamma(M_{R,j}-k+1))^{-1}\varphi_j^{(M_{R,j}-k)}(-\bar{\gamma}_{R,j})$, $\varphi_j(s) = \bar{\gamma}_{R,j}^{M_{R,j}}\prod_{l=1, l\neq j}^{L_{FR}}(s/\bar{\gamma}_{R,l}+1)^{-M_{R,l}}$, $\eta_{0k} = (\Gamma(m_g-k+1))^{-1}\omega_0^{(m_g-k)}(-\bar{\gamma}_{g,R}/2)$, $\omega_0(s) = \left(\frac{\bar{\gamma}_{g,R}}{2}\right)^{m_g}\prod_{l=1}^{L_{FR}}(s/\bar{\gamma}_{R,l}+1)^{-M_{R,l}}$, $\eta_{jk} = (\Gamma(M_{R,j}-k+1))^{-1}\Psi_j^{(M_{R,j}-k)}(-\bar{\gamma}_{R,j})$ and $\Psi_j(s) = (2s/\bar{\gamma}_{g,R}+1)^{-m_g}\bar{\gamma}_{R,j}^{M_{R,j}}\prod_{l=1, l\neq j}^{L_{FR}}(s/\bar{\gamma}_{R,l}+1)^{-M_{R,l}}$. The quantity L_{Fx} denotes, the number of primary interferers at node x which may have different values of $\bar{\gamma}_{x,j}$. In addition, $M_{x,j}$, $x \in \{S_1, R\}$, is the sum of the shape parameters of interferer channels affecting node x with equal values of $\bar{\gamma}_{x,j}$. Notice that $\bar{P}^b(\gamma_{S_2,R})$, $P^b(\gamma_{S_2,R}|\bar{e}_{\gamma_{S_1,R}})$ and their corresponding CDFs and also the related equations can be obtained by replacing the subscript $g \leftrightarrow h$ in that of S_1. It is worth mentioning that since the relay simultaneously decodes the message information as in (3), the decoding processes are dependent of each other and we therefore used the conditional probability in obtaining $P_{S_1}^{e}$ [39, 40].

Proof: See Appendix II. ■

For the symmetrical case when $\bar{\gamma}_{h,R} = \bar{\gamma}_{g,R}$, by substituting $P^b(\gamma_{S_1,R}|\bar{e}_{\gamma_{S_2,R}}) = P^b(\gamma_{S_2,R}|\bar{e}_{\gamma_{S_1,R}})$ and $P^b(\gamma_{S_1,R}|e_{\gamma_{S_2,R}}) = P^b(\gamma_{S_2,R}|e_{\gamma_{S_1,R}})$ in (91) and (92), and then substituting the results in (17), $P^b(\gamma_R)$ is simplified as

$$P^b(\gamma_R) = 2\frac{P^b(\gamma_{S_1,R}|\bar{e}_{\gamma_{S_2,R}})[1-P^b(\gamma_{S_2,R}|e_{\gamma_{S_1,R}})]}{P^b(\gamma_{S_1,R}|\bar{e}_{\gamma_{S_2,R}})+[1-P^b(\gamma_{S_2,R}|e_{\gamma_{S_1,R}})]}. \tag{23}$$

Next, we consider three special cases of interest where further simplifications are obtained.

[3] Obtaining the end-to-end performance metrics renders the analysis a very challenging mathematical problem. Therefore, it will be impossible to obtain any engineering insights. In addition, we recall that obtaining the performance metrics at S_1 is a standard approach adopted in the majority of works reported in the literature of two-way relaying, that enables the, otherwise tedious, analytical study of these configurations [20].

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$$\mathcal{J}_{S_1,h,S,\lambda_{jk}} = a\left[1-\sqrt{b/\pi}\sum_{j=1}^{L_{FS_1}}\sum_{k=1}^{M_{S_1,j}}\sum_{n=0}^{m_h-1}\sum_{i=0}^{n}\frac{\bar{\gamma}_{h,S}^{n}\lambda_{jk}\Gamma(k+i)\Gamma(n+\frac{1}{2})}{\Gamma(n+1)\Gamma(k)\bar{\gamma}_{S_1,j}^{k+i}}\binom{n}{i}\left(\frac{\bar{\gamma}_{S_1,j}}{\bar{\gamma}_{h,S}}\right)^{n+\frac{1}{2}}\mathbb{G}_{k+i,\bar{\gamma}_{S_1,j}(b+\bar{\gamma}_{h,S})/\bar{\gamma}_{h,S}}\right]. \quad (21)$$

$$\mathcal{H}_{h,g} = a\Bigg[1-\sqrt{\pi/b}\sum_{n=0}^{m_h-1}\sum_{k=1}^{m_g}\sum_{i=0}^{n}\frac{\bar{\gamma}_{h,R}^{n}\eta_{0k}\Gamma(k+i)\Gamma(n+\frac{1}{2})}{\Gamma(n+1)\Gamma(k)}\binom{n}{i}\left(\frac{2}{\bar{\gamma}_{g,R}}\right)^{k+i}\left(\frac{\bar{\gamma}_{g,R}}{2\bar{\gamma}_{h,R}}\right)^{n+\frac{1}{2}}$$
$$\times\mathbb{G}_{k+i,\bar{\gamma}_{g,R}(b+\bar{\gamma}_{h,R})/(2\bar{\gamma}_{h,R})}+\sum_{j=1}^{L_{FR}}\sum_{k=1}^{M_{R,j}}\sum_{n=0}^{m_h-1}\sum_{i=0}^{n}\frac{\bar{\gamma}_{h,R}^{n}\eta_{jk}\Gamma(k+i)\Gamma(n+\frac{1}{2})}{\Gamma(n+1)\Gamma(k)}$$
$$\times\binom{n}{i}\left(\frac{1}{\bar{\gamma}_{R,j}}\right)^{k+i}\left(\frac{\bar{\gamma}_{R,j}}{\bar{\gamma}_{h,R}}\right)^{n+\frac{1}{2}}\mathbb{G}_{k+i,\bar{\gamma}_{R,j}(b+\bar{\gamma}_{h,R})/\bar{\gamma}_{h,R}}\Bigg]. \quad (22)$$

*1) **Interference-free Case**:*

Corollary 1: Here, we present our main results on the error probability performance of the CR dual-hop relaying system, when none of the nodes is impaired by interference ($E_{S_1,j} = E_{S_2,j} = E_{R,j} = E_I = 0\ \forall j$). As a consequence, the equations obtained in Proposition 2 are simplified as

$$P^b(\gamma_{R,S_1}) = \mathcal{I}_{h,S}, \quad (24)$$
$$P^b(\gamma_{S_1,R}|\bar{e}_{\gamma_{S_2,R}}) = \mathcal{I}_{h,R}, \quad (25)$$
$$P^b(\gamma_{S_1,R}|e_{\gamma_{S_2,R}}) = \mathcal{U}_{h,g}, \quad (26)$$

where

$$\mathcal{I}_{h,S} = a\left[1-\sqrt{b/\pi}\sum_{n=0}^{m_h-1}\frac{\Gamma(n+\frac{1}{2})\bar{\gamma}_{h,S}^{n}}{\Gamma(n+1)(b+\bar{\gamma}_{h,S})^{n+\frac{1}{2}}}\right], \quad (27)$$

$$\mathcal{U}_{h,g} = a\Bigg[1-\sqrt{b/\pi}\sum_{n=0}^{m_g-1}\sum_{i=0}^{n}\frac{\Gamma(m_h+i)\Gamma(n+\frac{1}{2})}{\sqrt{\bar{\gamma}_{g,R}}\Gamma(m_h)\Gamma(n+1)}$$
$$\times\binom{n}{i}\left(\frac{\bar{\gamma}_{h,R}}{2}\right)^{n-i+\frac{1}{2}}\mathbb{G}_{m_h+i,\bar{\gamma}_h/2}\Bigg]. \quad (28)$$

*2) **Single Interferer Case**:*

Corollary 2: If only one dominant source of interference affects each node of the secondary network, the CDFs can be written as

$$F_{\gamma_{R,S_1}}(\gamma) = \mathcal{A}_{S_1,h,S}, \quad (29)$$
$$F_{\gamma_{S_1,R|\bar{e}_{S_2,R}}}(\gamma) = \mathcal{A}_{R,h,R}, \quad (30)$$
$$F_{\gamma_{S_1,R|e_{S_2,R}}}(\gamma) = \mathcal{B}_{h,g}, \quad (31)$$

where

$$\mathcal{A}_{S_1,h,S} = 1-\sum_{n=0}^{m_h-1}\sum_{i=0}^{n}\frac{\bar{\gamma}_{h,S}^{n}\bar{\gamma}_{S_1,1}^{m_{S_1,1}}\Gamma(m_{S_1,1}+i)}{\Gamma(n+1)\Gamma(m_{S_1,1})}$$
$$\times\binom{n}{i}\frac{\gamma^n\exp(-\bar{\gamma}_{h,S}\gamma)}{(\bar{\gamma}_{h,S}\gamma+\bar{\gamma}_{S_1,1})^{m_{S_1,1}+i}}, \quad (32)$$

$$\mathcal{B}_{h,g} = 1-\sum_{n=0}^{m_h-1}\sum_{i=0}^{n}\sum_{k=1}^{m_g}\frac{\bar{\gamma}_{h,R}^{n}\eta_{0k}\Gamma(k+i)}{\Gamma(n+1)\Gamma(k)}$$
$$\times\binom{n}{i}\frac{\gamma^n\exp(-\bar{\gamma}_{h,R})}{(\bar{\gamma}_{h,R}\gamma+\frac{\bar{\gamma}_{g,R}}{2})^{k+i}}$$
$$-\sum_{n=0}^{m_h-1}\sum_{i=0}^{n}\sum_{k=1}^{m_{R,1}}\frac{\bar{\gamma}_{h,R}^{n}\eta_{1k}\Gamma(k+i)}{\Gamma(n+1)\Gamma(k)}$$
$$\times\binom{n}{i}\frac{\gamma^n\exp(-\bar{\gamma}_{h,R})}{(\bar{\gamma}_{h,R}\gamma+\bar{\gamma}_{R,1})^{k+i}}. \quad (33)$$

Moreover, the error probability is simplified as

$$P^b(\gamma_{R,S_1}) = \mathcal{C}_{S_1,h,S}, \quad (34)$$
$$P^b(\gamma_{S_1,R}|\bar{e}_{\gamma_{S_2,R}}) = \mathcal{C}_{R,h,R}, \quad (35)$$
$$P^b(\gamma_{S_1,R}|e_{\gamma_{S_2,R}}) = \mathcal{D}_{h,g}, \quad (36)$$

where $\mathcal{C}_{S_1,h,S}$ and $\mathcal{D}_{h,g}$ shown on the top of next page.

*3) **I.I.D. Channel Case**:*

Corollary 3: The interferers' channels can be assumed to be complex circularly symmetric i.i.d. Gaussian distributed. This assumption is very generic and has been employed in the literatures for performance analysis and resource allocation [41]. Then, the CDFs can be further simplified as

$$F_{\gamma_{R,S_1}}(\gamma) = \mathcal{L}_{S_1,h,S}, \quad (39)$$
$$F_{\gamma_{S_1,R|\bar{e}_{S_2,R}}}(\gamma) = \mathcal{L}_{R,h,R}, \quad (40)$$
$$F_{\gamma_{S_1,R|e_{S_2,R}}}(\gamma) = \mathcal{V}_{h,g}, \quad (41)$$

where

$$\mathcal{L}_{S_1,h,S} = 1-\sum_{n=0}^{m_h-1}\sum_{i=0}^{n}\frac{\bar{\gamma}_{h,S}^{n}\bar{\gamma}_{S_1}^{M_{S_1}}\Gamma(M_{S_1}+i)}{\Gamma(n+1)\Gamma(M_{S_1})}$$
$$\times\binom{n}{i}\frac{\gamma^n}{(\bar{\gamma}_{h,S}\gamma+\bar{\gamma}_{S_1})^{M_{S_1}+i}}\exp(-\bar{\gamma}_{h,S}\gamma), \quad (42)$$

$$\mathcal{V}_{h,g} = 1-\sum_{n=0}^{m_h-1}\sum_{i=0}^{n}\sum_{k=1}^{m_g}\frac{\bar{\gamma}_{h,R}^{n}\eta_{0k}\Gamma(k+i)}{\Gamma(n+1)\Gamma(k)}$$

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$$\mathcal{C}_{S_1,h,S} =a\left[1-\sqrt{b/\pi}\sum_{n=0}^{m_h-1}\sum_{i=0}^{n}\frac{\bar{\gamma}_{h,S}^n\Gamma(m_{S_1,1}+i)\Gamma(n+\frac{1}{2})}{\Gamma(n+1)\Gamma(m_{S_1,1})\bar{\gamma}_{S_1,1}^i}\binom{n}{i}\left(\frac{\bar{\gamma}_{S_1,1}}{\bar{\gamma}_{h,S}}\right)^{n+\frac{1}{2}}\mathbb{G}_{m_{S_1,1}+i,\bar{\gamma}_{S_1,1}(b+\bar{\gamma}_{h,S})/\bar{\gamma}_{h,S}}\right]. \quad (37)$$

$$\begin{aligned}\mathcal{D}_{h,g} =a\Bigg[1-\sqrt{b/\pi}&\sum_{n=0}^{m_h-1}\sum_{i=0}^{n}\sum_{k=1}^{m_g}\frac{\bar{\gamma}_{h,R}^n\eta_{0k}\Gamma(k+i)\Gamma(n+\frac{1}{2})}{\Gamma(n+1)\Gamma(k)}\binom{n}{i}\left(\frac{2}{\bar{\gamma}_{g,R}}\right)^{k+i}\left(\frac{\bar{\gamma}_{g,R}}{2\bar{\gamma}_{h,R}}\right)^{n+\frac{1}{2}}\\ &\times\mathbb{G}_{k+i,\bar{\gamma}_{g,R}(b+\bar{\gamma}_{h,R})/(2\bar{\gamma}_{h,R})}+\sum_{n=0}^{m_h-1}\sum_{i=0}^{n}\sum_{k=1}^{m_{R,1}}\binom{n}{i}\frac{\Gamma(k+i)\Gamma(n+\frac{1}{2})}{\Gamma(n+1)\Gamma(k)}\\ &\times\frac{\bar{\gamma}_{h,R}^n\eta_{1k}}{\bar{\gamma}_{R,1}^{k+i}}\left(\frac{\bar{\gamma}_{R,1}}{\bar{\gamma}_{h,R}}\right)^{n+\frac{1}{2}}\mathbb{G}_{k+i,\bar{\gamma}_{R,1}(b+\bar{\gamma}_{h,R})/\bar{\gamma}_{h,R}}\Bigg]. \quad (38)\end{aligned}$$

$$\begin{aligned}&\times\binom{n}{i}\frac{\gamma^n}{\left(\bar{\gamma}_{h,R}\gamma+\frac{\bar{\gamma}_{g,R}}{2}\right)^{k+i}}\exp\left(-\bar{\gamma}_{h,R}\right)\\ &-\sum_{n=0}^{m_h-1}\sum_{i=0}^{n}\sum_{k=1}^{M_R}\frac{\bar{\gamma}_{h,R}^n\eta_{1k}\Gamma(k+i)}{\Gamma(n+1)\Gamma(k)}\\ &\times\binom{n}{i}\frac{\gamma^n}{\left(\bar{\gamma}_{h,R}\gamma+\bar{\gamma}_R\right)^{k+i}}\exp\left(-\bar{\gamma}_{h,R}\right), \quad (43)\end{aligned}$$

while $M_{S_1}=L_{S_1}m_{S_1,j}$, $\bar{\gamma}_{S_1}=\beta_{S_1}N_0E_{IS_1}^{-1}$, $M_R=L_Rm_{R,j}$ and $\bar{\gamma}_R=\beta_RN_0E_{IR}^{-1}$. Moreover, the error probability is simplified as

$$P^b(\gamma_{R,S_1}) =\mathcal{Q}_{S_1,h,S}, \quad (44)$$
$$P^b(\gamma_{S_1,R}|\bar{e}_{\gamma_{S_2,R}}) =\mathcal{Q}_{R,h,R}, \quad (45)$$
$$P^b(\gamma_{S_1,R}|e_{\gamma_{S_2,R}}) =\mathcal{P}_{h,g}, \quad (46)$$

where

$$\begin{aligned}\mathcal{Q}_{S_1,h,S} =a\Bigg[1-\sqrt{b/\pi}&\sum_{n=0}^{m_h-1}\sum_{i=0}^{n}\frac{\bar{\gamma}_{h,S}^n\Gamma(M_{S_1}+i)\Gamma(n+\frac{1}{2})}{\Gamma(n+1)\Gamma(M_{S_1})\bar{\gamma}_{S_1}^i}\\ &\times\binom{n}{i}\left(\frac{\bar{\gamma}_{S_1}}{\bar{\gamma}_{h,S}}\right)^{n+\frac{1}{2}}\mathbb{G}_{M_{S_1}+i,\bar{\gamma}_{S_1}(b+\bar{\gamma}_{h,S})/\bar{\gamma}_{h,S}}\Bigg], \quad (47)\end{aligned}$$

$$\begin{aligned}\mathcal{P}_{h,g} =a\Bigg[1-\sqrt{b/\pi}\Bigg(&\sum_{n=0}^{m_h-1}\sum_{i=0}^{n}\sum_{k=1}^{m_g}\frac{\bar{\gamma}_{h,R}^n\eta_{0k}\Gamma(k+i)\Gamma(n+\frac{1}{2})}{\Gamma(n+1)\Gamma(k)}\\ &\times\binom{n}{i}\left(\frac{2}{\bar{\gamma}_{g,R}}\right)^{k+i}\left(\frac{\bar{\gamma}_{g,R}}{2\bar{\gamma}_{h,R}}\right)^{n+\frac{1}{2}}\mathbb{G}_{k+i,\bar{\gamma}_{g,R}(b+\bar{\gamma}_{h,R})/(2\bar{\gamma}_{h,R})}\\ &+\sum_{n=0}^{m_h-1}\sum_{i=0}^{n}\sum_{k=1}^{M_R}\binom{n}{i}\frac{\Gamma(k+i)\Gamma(n+\frac{1}{2})}{\Gamma(n+1)\Gamma(k)}\\ &\times\frac{\bar{\gamma}_{h,R}^n\eta_{1k}}{\bar{\gamma}_{R,1}^{k+i}}\left(\frac{\bar{\gamma}_R}{\bar{\gamma}_{h,R}}\right)^{n+\frac{1}{2}}\mathbb{G}_{k+i,\bar{\gamma}_R(b+\bar{\gamma}_{h,R})/\bar{\gamma}_{h,R}}\Bigg)\Bigg]. \quad (48)\end{aligned}$$

B. Achievable Rate

Achievable Rate in the Shannon sense is another metric that is presented in this paper. Rate is a suitable performance measure for applications that are delay insensitive. Based on the cut-set bound, we can compute the outer bound of the capacity region for the two-way PNC relaying system. Assuming perfect CSI at the receiving nodes, the outer bound of the capacity region is expressed as [42, 43]:

$$R_1\leq\min\{C_{R,S_2},C_{S_1,R}\}, \quad (49)$$

$$R_2\leq\min\{C_{R,S_1},C_{S_2,R}\}, \quad (50)$$

where $C_{S_1,R}$, C_{R,S_2}, $C_{S_2,R}$ and C_{R,S_1} are the capacity of links S_1-R, R-S_2, S_2-R and R-S_1, respectively. Finding closed-form expressions for $C_{S_1,R}$, C_{R,S_2}, $C_{S_2,R}$ and C_{R,S_1} requires the evaluation of $C_\gamma=0.5\mathbb{E}\{\log(1+\gamma)\}$, which becomes intractable or computationally impractical. To circumvent this difficulty, we use an alternative approach based on Jensen's inequality, which leads to much simpler expressions. Specifically, we can show that we can obtain the following expressions:

$$C_{R,S_2} =\mathcal{F}_{S_2,g,S,\bar{\lambda}_{jk}}, \quad (51)$$
$$C_{R,S_1} =\mathcal{F}_{S_1,h,S,\lambda_{jk}}, \quad (52)$$
$$C_{S_1,R} =\mathcal{F}_{R,h,R,\mu_{jk}}, \quad (53)$$
$$C_{S_2,R} =\mathcal{F}_{R,g,R,\mu_{jk}}, \quad (54)$$

where

$$\begin{aligned}\mathcal{F}_{S_2,g,S,\bar{\lambda}_{jk}} =&\sum_{j=1}^{L_{FS_2}}\sum_{k=1}^{M_{S_2,j}}\sum_{n=0}^{m_g-1}\sum_{i=0}^{n}\frac{\bar{\gamma}_{g,S}^n\bar{\lambda}_{jk}\Gamma(k+i)}{\Gamma(k)\bar{\gamma}_{S_2,j}^{k+i}}\\ &\times\binom{n}{i}\left(\frac{\bar{\gamma}_{S_2,j}}{\bar{\gamma}_{g,S}}\right)^{n+1}\Phi\left(n+1,n-k-i+2,\bar{\gamma}_{S_2,j}\right), \quad (55)\end{aligned}$$

while $\bar{\gamma}_{S_2,j}=\beta_{S_2,j}N_0E_{S_2,j}^{-1}$, $\bar{\lambda}_{jk}=(\Gamma(M_{S_2,j}-k+1))^{-1}\nu_j^{(M_{S_2,j}-k)}(-\bar{\gamma}_{S_2,j})$ and $\nu_j\left(s\right)=\bar{\gamma}_{S_2,j}^{M_{S_2,j}}\prod_{\substack{l=1\\l\neq j}}^{L_{FS_2}}\left(s/\bar{\gamma}_{S_2,l}+1\right)^{-M_{S_2,l}}$. Here, L_{FS_2} is the number of primary interferers affecting S_2 which have different values of $\bar{\gamma}_{S_2,j}$, and $M_{S_2,j}$ is the summation of the shape parameters of the interferer channels at S_2 with equal values of $\bar{\gamma}_{S_2,j}$. A rate pair (R_1,R_2) is achievable only if the expressions in (49) and (50) are satisfied with equality.

V. Asymptotic Analysis

A. Lower Bound Analysis

The performance of the two-way PNC relay system can further be quantified by analyzing the error performance based on (8) in the high SNR regime. Under this condition, which

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occurs when $E_{IS_1,j} \gg N_0$ and $E_{IR,j} \gg N_0$, (8) and (93) in Appendix II can be upper bounded as

$$\gamma_{R,S_1} < \gamma^{\text{up}}_{R,S_1} = \frac{E_R |h|^2}{\sum_{j=1}^{L_{S_1}} E_{S_1,j} |f_{S_1,j}|^2}, \tag{56}$$

$$\gamma_{S_1,R|\bar{e}_{S_2,R}} < \gamma^{\text{up}}_{S_1,R|\bar{e}_{S_2,R}} = \frac{E_S |h|^2}{\sum_{j=1}^{L_R} E_{R,j} |f_{R,j}|^2}. \tag{57}$$

Accordingly, the CDFs of the received SINR at node S_1, can be expressed as

$$F_{\gamma^{\text{up}}_{R,S_1}}(\gamma) = \Xi_{S_1,h,R,\lambda_{jk}}, \tag{58}$$

$$F_{\gamma^{\text{up}}_{S_1,R|\bar{e}_{S_2,R}}}(\gamma) = \Xi_{R,h,S,\mu_{jk}}, \tag{59}$$

where

$$\Xi_{S_1,h,R,\lambda_{jk}} = 1 - \sum_{j=1}^{L_{FS_1}} \sum_{k=1}^{M_{S_1,j}} \sum_{n=0}^{m_h-1} \frac{\beta_h^n \lambda_{jk} \Gamma(n+k)}{E_R^n \Gamma(n+1)\Gamma(k)} \gamma^n \times \left(\frac{\beta_h}{E_R}\gamma + \frac{\beta_{S_1,j}}{E_{S_1,j}} \right)^{-(n+k)}. \tag{60}$$

With the aim to highlight the impact of the fading parameters on the error performance, specific asymptotic regimes are considered below:

*1) **Case 1**:* In this case, we characterize the impact of the amount of received interference power on the error performance of the two-way PNC relay system. To begin, consider the case when the power of the interferers are negligible compared with the useful signal power, i.e., $E_I \ll E_S$. As such, we have the following simplification:

$$\gamma_{S_1,R|e_{S_2,R}} < \gamma^{\text{up}}_{S_1,R|e_{S_2,R}} = \frac{E_S |h|^2}{2E_S |g|^2}. \tag{61}$$

Then, $F_{\gamma^{\text{up}}_{S_1,R|e_{S_2,R}}}(\gamma)$ can be obtained as

$$F_{\gamma^{\text{up}}_{S_1,R|e_{S_2,R}}}(\gamma) = \xi_{h,g}, \tag{62}$$

where

$$\xi_{h,g} = 1 - \sum_{n=0}^{m_h-1} \frac{\beta_h^n \Gamma(m_g+n)}{\Gamma(n+1)\Gamma(m_g)} \left(\frac{\beta_g}{2}\right)^{m_g} \gamma^n \times \left(\beta_h \gamma + \frac{\beta_g}{2} \right)^{-(m_g+n)}. \tag{63}$$

For this case, a lower bound expression for the SEP is formulated in the following proposition.

Proposition 3: The lower bound on the SEP performance of the system in the asymptotically high SNR regime for Case 1 is given by (16) where

$$P^b(\gamma_{R,S_1}) = \mathcal{W}_{S_1,h,R,\lambda_{jk}}, \tag{64}$$

$$P^b(\gamma_{S_1,R}|\bar{e}_{\gamma_{S_2,R}}) = \mathcal{W}_{R,h,S,\mu_{jk}}, \tag{65}$$

$$P^b(\gamma_{S_1,R}|e_{\gamma_{S_2,R}}) = \aleph_{g,h}, \tag{66}$$

with $\mathcal{W}_{S_1,h,R,\lambda_{jk}}$ and $\aleph_{g,h}$ shown on the top of next page.

Proof: The proof is similar to that of Proposition 2. ■

*2) **Case 2**:* Consider the case where the power of the useful signal is much smaller than that of the interferers, i.e., $E_S \ll E_I$. For this case, $\gamma_{S_1,R|e_{S_2,R}}$ can be approximated as

$$\gamma_{S_1,R|e_{S_2,R}} < \gamma^{\text{up}}_{S_1,R|e_{S_2,R}} = \frac{E_S |h|^2}{\sum_{j=1}^{L_R} E_{R,j} |f_{R,j}|^2}. \tag{69}$$

Here, $\gamma^{\text{up}}_{S_1,R|e_{S_2,R}} = \gamma^{\text{up}}_{S_1,R|\bar{e}_{S_2,R}}$, which implies that $F_{\gamma^{\text{up}}_{S_1,R|e_{S_2,R}}}(\gamma) = F_{\gamma^{\text{up}}_{S_1,R|\bar{e}_{S_2,R}}}(\gamma)$.

One may conclude that in this case increasing the SNR has no impact on the average SEP. In fact, since $E_S \ll E_I$, the quality of the secondary links is much worse than that of the primary-to-secondary links. Therefore, the performance of the secondary relay network does not improve by increasing the SNR. The diversity order in this case is equal to 0.

B. Simplified Analysis

Since the derived expressions are complex, herein, we present simplified closed-form formulae for the SEP based on a linearization approach as in [44]. Using Taylor series, the behavior of the PDF of the SINR around the origin can be expanded as follows:

$$F_{\gamma_{R,S_1}}(\gamma) \approx \mathcal{Z}_{S_1,h,S,\lambda_{jk}}, \tag{70}$$

$$F_{\gamma_{S_1,R|\bar{e}_{S_2,R}}}(\gamma) \approx \mathcal{Z}_{R,h,R,\mu_{jk}}, \tag{71}$$

$$F_{\gamma_{S_1,R|e_{S_2,R}}}(\gamma) \approx \mathcal{T}_{h,g}, \tag{72}$$

where

$$\mathcal{Z}_{S_1,h,S,\lambda_{jk}} = \frac{\bar{\gamma}_{h,S}^{m_h} \gamma^{m_h}}{\Gamma(m_h+1)} \sum_{j=1}^{L_{FS_1}} \sum_{k=1}^{M_{S_1,j}} \sum_{i=0}^{m_h} \binom{m_h}{i} \frac{\lambda_{jk}\Gamma(k+i)}{\Gamma(k)\bar{\gamma}_{S_1,j}^{k+i}}, \tag{73}$$

$$\mathcal{T}_{h,g} = \sum_{n=0}^{m_h-1} \frac{\eta_{m_g}\Gamma(m_g+n)}{\Gamma(n+1)\Gamma(m_g)} \left(2\beta_h\beta_g^{-1}\right)^n \gamma^n \times \left(1+2\beta_h\beta_g^{-1}\gamma\right)^{-(m_g+n)} \left(1-\beta_h N_0 E_S^{-1}\gamma\right), \tag{74}$$

$$\mathcal{Z}_{S_1,h,S,\lambda_{jk}} = \frac{\bar{\gamma}_{h,S}^{m_h} \gamma^{m_h}}{\Gamma(m_h+1)} \sum_{j=1}^{L_{FS_1}} \sum_{k=1}^{M_{S_1,j}} \sum_{i=0}^{m_h} \binom{m_h}{i} \frac{\lambda_{jk}\Gamma(k+i)}{\Gamma(k)\bar{\gamma}_{S_1,j}^{k+i}},$$

$$\mathcal{T}_{h,g} = \sum_{n=0}^{m_h-1} \frac{\eta_{m_g}\Gamma(m_g+n)}{\Gamma(n+1)\Gamma(m_g)} \left(2\beta_h\beta_g^{-1}\right)^n \gamma^n \times \left(1+2\beta_h\beta_g^{-1}\gamma\right)^{-(m_g+n)} \left(1-\beta_h N_0 E_S^{-1}\gamma\right), \tag{75}$$

and $\eta_{m_g} = \left(2\bar{\gamma}_{g,R}^{-1}\right)^{m_g} \eta_{0m_g}$. Accordingly, using the CDF-based approach as in Proposition 2, we obtain

$$P^b(\gamma_{R,S_1}) = \frac{a\Gamma(m_h+\frac{1}{2})}{b^{m_h}\sqrt{\pi}} \mathcal{Z}_{S_1,h,S,\lambda_{jk}}, \tag{76}$$

$$P^b(\gamma_{S_1,R}|\bar{e}_{\gamma_{S_2,R}}) = \frac{a\Gamma(m_h+\frac{1}{2})}{b^{m_h}\sqrt{\pi}} \mathcal{Z}_{R,h,R,\mu_{jk}}, \tag{77}$$

$$P^b(\gamma_{S_1,R}|e_{\gamma_{S_2,R}}) = a\left[1 - \sqrt{b/\pi}\,\mathcal{Y}_{g,h}\right], \tag{78}$$

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$$\mathcal{W}_{S_1,h,R,\lambda_{jk}} = a\Bigg[1-\sqrt{b/\pi}\sum_{j=1}^{L_{FS_1}}\sum_{k=1}^{M_{S_1,j}}\sum_{n=0}^{m_h-1}\frac{\lambda_{jk}\Gamma(n+k)\Gamma(n+\frac{1}{2})}{\Gamma(n+1)\Gamma(k)}\left(\frac{E_{S_1,j}}{\beta_{S_1,j}}\right)^k\sqrt{\frac{\beta_{S_1,j}E_R}{\beta_h E_{S_1,j}}} \times\Phi\left(n+1,3/2-k,b\beta_{S_1,j}E_R/\left(\beta_h E_{S_1,j}\right)\right)\Bigg]. \quad (67)$$

$$\aleph_{g,h} = a\left[1-\sqrt{b/\pi}\sqrt{\frac{\beta_g}{2\beta_h}}\sum_{n=0}^{m_h-1}\frac{\Gamma(m_g+n)\Gamma(n+\frac{1}{2})}{\Gamma(n+1)\Gamma(m_g)}\Phi\left(n+1,3/2-m_g,b\beta_g/\left(2\beta_h\right)\right)\right]. \quad (68)$$

where

$$\mathcal{Y}_{g,h} = \sqrt{\frac{\beta_g}{2\beta_h}}\sum_{n=0}^{m_h-1}\frac{\eta_{m_g}\Gamma(m_g+n)\Gamma(n+\frac{1}{2})}{\Gamma(n+1)\Gamma(m_g)}, \times\left[\Phi\left(n+\frac{1}{2};\frac{3}{2}-m_g;\frac{b\beta_g}{2\beta_h}\right)-(n+\frac{1}{2})(\frac{\beta_g}{2\beta_h}) \times\bar{\gamma}_{h,R}\Phi\left(n+\frac{3}{2};\frac{5}{2}-m_g;\frac{b\beta_g}{2\beta_h}\right)\right]. \quad (79)$$

Finally, by substituting the results into (16), a simpler closed-form expression for the average SEP of the system can be obtained.

VI. Numerical Results and Discussion

Monte-Carlo simulations are performed to validate the analytical results. For ease, we denote the number of interferers affecting the secondary nodes by $L=[L_{S_1},L_{S_2},L_R]$, and that impacting the PU by $L=[L_P]$. In the following simulation evaluations, γ_{th} is set to 3dB and the noise power are normalized to be 0dB. Also, in all figures the horizontal axis is the primary transmit SNR, $\bar{\gamma}_P$.

The outage and error performance comparison between the analytical results and the simulation results corresponding to the intended PU is illustrated in Fig. 2 and Fig. 3 respectively, for different values of L and fading parameter $m=2$. In these figures, the useful power of the PU and the interference power profile satisfy $E_P-E_{P,j}=30$dB, where $E_{P,j}$ is the transmit energy at the jth $(j\in\{1,2,...,L_P\})$ primary interferer in the proximity of node P. First, the agreement between the plots from the analysis and those from simulations confirm the accuracy of the analysis. As observed, the interference form the other PUs' has an adverse influence on the outage and the SEP of the intended PU. It is evident that the OP and SEP improve with increasing received SNR at the PU. The transmit power of the SUs is controlled for the target reliability at the primary. Therefore, as the primary OP threshold λ decreases, the performance of the SUs would degrade.

Figs. 4 to 8 show the SEP versus SNR for the two-way PNC cognitive relaying system, for Case 1, i.e., when $E_I\ll E_S$. To examine the accuracy of the expressions in Corollaries 1-3, Fig. 4 shows the results for the i.i.d. case with the corresponding lower bound and asymptotic results, as well as the SEP obtained through simulations. Two sets of plots are presented, for a primary OP threshold $\lambda=0.1$ and 0.01, while $m=2$. Fig. 5 depicts a similar set of results for $\lambda=0.01$ and $m=1,2$. As observed, the analytical results yield an excellent match across the entire SNR range.

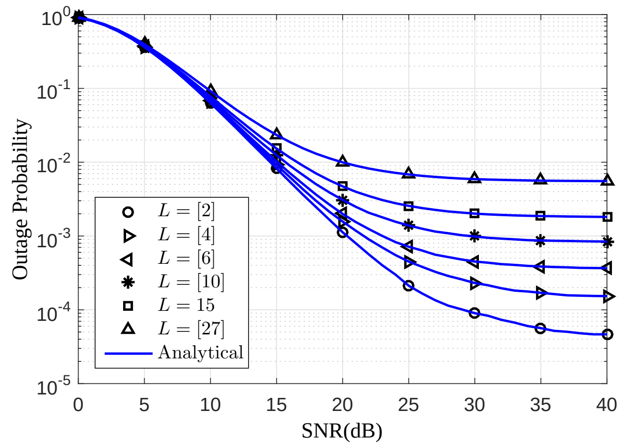

Fig. 2. OP of the PU for different numbers of co-channel interferers.

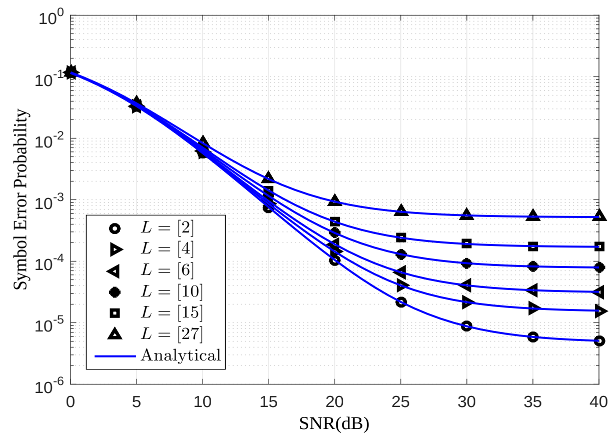

Fig. 3. SEP of the PU for different numbers of co-channel interferers.

Fig. 6 illustrates corresponding sets of results for the i.n.i.d. case, for $m=1$ and 2 and with $\lambda=0.01$. Similar conclusions as above can be drawn. For completeness, the case of Rayleigh fading is shown. From Fig. 5 and Fig. 6, it can be deduced that when the interferers' channels are i.n.i.d., the performance improvement is significant compared with the case when the interferers' channels are i.i.d.

Figs. 7 and 8 depict the results when the channels consist of a combination of i.i.d. and i.n.i.d. Nakagami-m fading to examine Corollaries 1-3, for $m=1,2$ and $\lambda=0.1,0.01$. In addition, the average SEP performance under Case 2, i.e. when $E_S\ll E_I$, is a horizontal line matched exactly at 1/2 shown in Figs. 4 to 8. As observed for these two practical Cases 1 and 2, when $E_S\ll E_I$ the secondary network is almost in outage and

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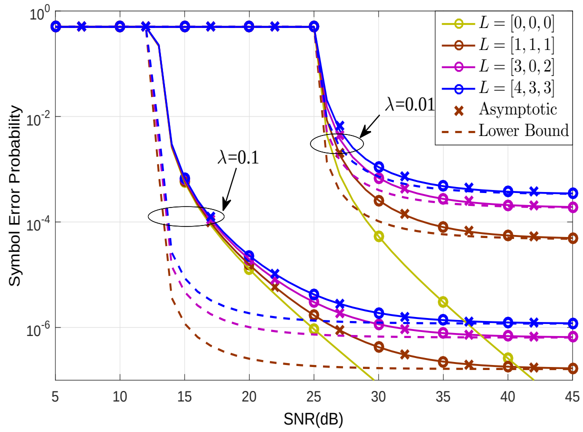

Fig. 4. SEP of the secondary in the i.i.d. case for different primary OP threshold $\lambda \in \{0.1, 0.01\}$ and numbers of interferers (L).

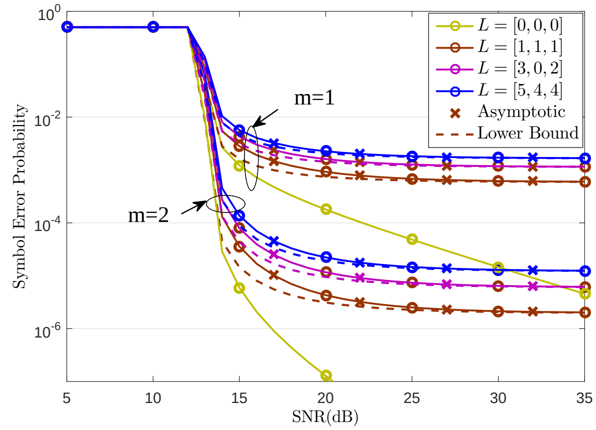

Fig. 6. SEP of the two-way PNC relay network in the i.n.i.d. case, for $m \in \{1, 2\}$ and different numbers of interferers.

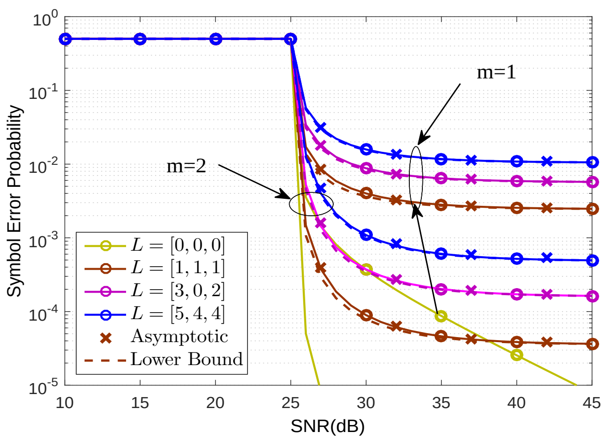

Fig. 5. SEP of the secondary in the i.i.d. case and for different fading parameter $m \in \{1, 2\}$ and numbers of interferers (L).

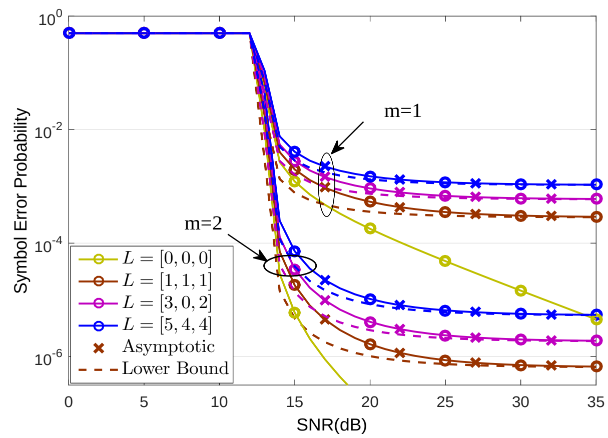

Fig. 7. SEP of the secondary in the i.i.d. and i.n.i.d. cases, for $m \in \{1, 2\}$ and different numbers of interferers.

exhibits poor error performance (see the parts of the curves before the cutoff points), while when $E_I \ll E_S$ (Case 1) and assuming that the interference power is increasing with the transmit power of the relay and the secondary sources, the SEP improvement is visible only in the medium SNR range. With an increase in the transmit power E_S, the error probability reaches a floor at high SNR. Therefore, the PNC cognitive relaying system is more vulnerable to noise than to interference for low and moderate SNRs, whereas it is more susceptible to interference at high SNR.

Additionally, some interesting observations are drawn from Figs. 4 to 8, as summarized next: (i) There is a close match between the asymptotic results and the simulations, even for low SNRs. Besides, in the low-to-medium SNR range, as the SNR increases the SEP performance improves because the dominant factor is the AWGN. (ii) The performance of the interference-free system ($L = [0, 0, 0]$) as well as that of the single-interferer case ($L = [1, 1, 1]$) are included as benchmark. In these two special cases, the simulation results are in good agreement with the analytical ones (Corollary 1 and 2, respectively). (iii) For the special scenario where the SUs terminals transmit with the same power characteristics as the interfering terminals, implying that the interference-to-noise ratio (INR) and the SNR tend to infinity simultaneously as the additive noise power becomes negligible, the presence of interference at the secondary nodes induces a floor level at high SNR in the SEP performance, which is reflected in a zero diversity order (as indicated by the slope of the curves), while for the interference-free case error floors do not occur. This demonstrates that the use of interference cancellation is crucial for attaining the beneficial effects of diversity. (iv) It can be concluded from the results in Figs. 4-8 that the number of interfering signals has no effect on the SEP in the low SNR range, whereas a degradation can be seen as the SNR increases. (v) As expected, there is a significant improvement in performance as the fading parameters (m) and the primary's OP threshold (λ) increase. (vi) Since both the source nodes and the relay experience interferences from the primary side, the floor point on the error performance is reached at lower SNR values.

We now turn our attention to Fig. 9, which illustrates the achievable rate performance of the system for different distributions of interferers, when their total is constant (here fixed to 27), and different values of λ, for $m = 2$. It can clearly be seen that with the increase of λ a better performance is achieved. WThe gap between the simulation and analytical results is due to the use of the Jensen's inequality in

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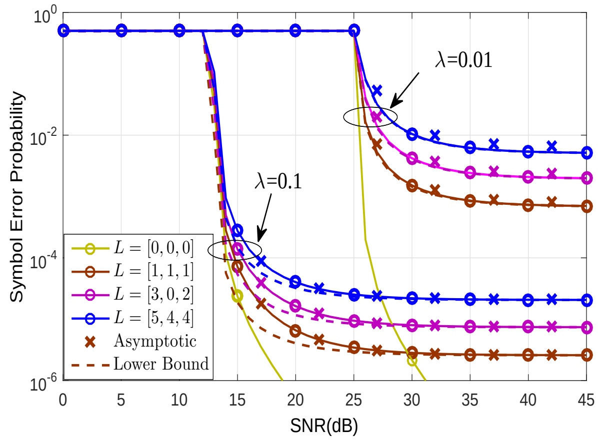

Fig. 8. SEP of the secondary in the i.i.d. and i.n.i.d. cases, for different primary OP threshold $\lambda \in \{0.1, 0.01\}$ and numbers of interferers.

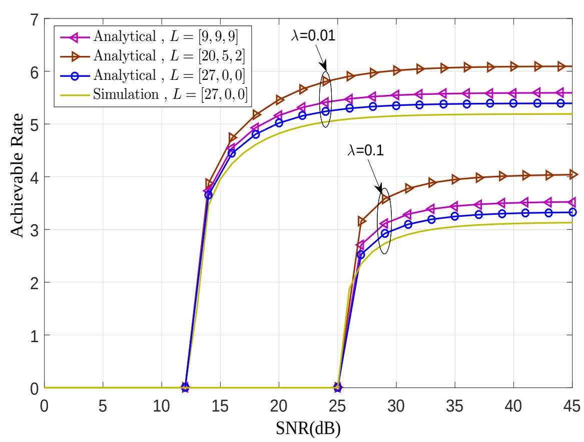

Fig. 9. Achievable rate for different primary OP threshold $\lambda \in \{0.1, 0.01\}$ and numbers of interferers.

the derivation of expressions (51)-(54). The unmarked curve shows the rate R_1 of the system when $C_{\gamma_{R,S_1}}$, $C_{\gamma_{R,S_2}}$, $C_{\gamma_{S_1}}$ and $C_{\gamma_{S_2}}$ are computed by simulation (for clarity, only the case of $L = [27, 0, 0]$ is shown). As expected, an equal number of interferers at each node of the secondary network gives better performance. Also, the worse performance occurs for $L = [27, 0, 0]$, i.e. when only S_1 is affected by interference.

VII. Conclusion

This paper considered a traditional primary network co-existing with a two-way cognitive relay network where two SU source nodes communicate with each other through a relay using a PNC protocol while sharing the spectrum with multiple PUs. We investigated the effects of interference created by multiple primary transceivers and by the CRN on the performance of both a target PU and the SUs. The desired signals were assumed to be subject to Nakagami-m fading. Furthermore, it was assumed that there is an arbitrary number of interferers subject to both i.i.d. and i.n.i.d. Nakagami-m fading, with each interfering signal having a different power and undergoing a different amount of fading. Exact closed-form expressions for the OP and SEP of a target PU were derived. For the SUs, closed-form expressions for the SEP and its lower bound, as well as an upper bound on the achievable rates were derived. Cases of interference-free and single interference reception at the SUs were studied by deriving new expressions for the average SEP valid for BPSK modulation. Simple asymptotic expressions for the error performance were also developed. It was shown that interference at the secondary nodes leads to floor levels in the SEP, which occur because the higher the SNR the higher the interference on information-bearing link. The simulation results indicate that the fading parameters have significant impact on the OP and SEP performances. Furthermore, for low SNR values, the error performance is not sensitive to the number of co-channel interfering signals. Comparisons with simulation results showed that the newly developed analytical expressions for the average SEP accurately predict the system's performance.

Appendix I
Proof of Proposition 1

According to (10) and making the change of variables $x = \frac{E_P}{N_0}|h_P|^2$, $y = \sum_{j=1}^{L_{FP}} E_{P,j}|f_{P,j}|^2$ and $z = E_S\left(|f_{P,S_1}|^2 + |f_{P,S_2}|^2\right)$, the PDFs of these RVs are given by $f_X(x) = \bar{\gamma}_P^{m_P}\frac{x^{m_P-1}}{\Gamma(m_P)}\exp\left(-\bar{\gamma}_P x\right)$, $f_Y(y) = \sum_{j=1}^{L_{FP}}\sum_{k=1}^{M_{P,j}}\frac{\alpha_{jk}}{\Gamma(k)}y^{k-1}\exp\left(-\bar{\gamma}_{P,j}y\right)$ and $f_Z(z) = \sum_{t=1}^{L_{FSP}}\sum_{w=1}^{M_{P,S_t}}\frac{\theta_{tw}}{\Gamma(w)}z^{w-1}\exp(-\bar{\gamma}_{P,S_t}z)$. According to (10), the CDF of the primary SINR is obtained as

$$\begin{aligned}
F_P(\gamma) &= \mathbb{E}_y\left[\mathbb{E}_z\left[\mathbb{E}_w\left[Pr\left(x \le \gamma\left(y+w+z+\sigma^2_{P_i}\right)|y,z,w\right)\right]\right]\right] \\
&= \int_0^\infty\int_0^\infty\int_0^{\gamma(y+z+1)} f_X(x)f_Y(y)f_Z(z)dxdydz \\
&= \int_0^\infty\int_0^\infty F_x\left(\gamma\left(y+z+1\right)\right)f_Y(y)f_Z(z)f_W(w)dydzdw \\
&= \int_0^\infty\int_0^\infty\left[1-\sum_{n=0}^{m_P-1}\frac{\left(\bar{\gamma}_P(y+z+1)\gamma\right)^n}{\Gamma(n+1)}\right. \\
&\qquad\left.\times\exp\left(-\bar{\gamma}_P(y+z+1)\gamma\right)\right]f_Y(y)f_Z(z)dydz \\
&= \int_0^\infty\int_0^\infty\left[1-\sum_{j=1}^{m_P-1}\sum_{r=0}^{n}\sum_{q=0}^{r}\frac{\bar{\gamma}_P^n\gamma^n}{\Gamma(n+1)}\binom{n}{r}\binom{r}{q}\right. \\
&\quad\left.\times\exp(-\bar{\gamma}_P\gamma)z^q\exp(-\bar{\gamma}_P z\gamma)y^{n-r}\exp(-\bar{\gamma}_P y\gamma)\right] \\
&\quad\times f_Y(y)f_Z(z)dydz, \qquad (80)
\end{aligned}$$

where $\mathbb{E}[.]$ represents expectation. (80) can be split into two separate integrals as follows

$$I_0 = \int_0^\infty\int_0^\infty f_Y(y)f_Z(z)dydz = 1 \qquad (81)$$

$$I_1 = \sum_{j=1}^{m_P-1}\sum_{r=0}^{n}\sum_{q=0}^{r}\frac{\bar{\gamma}_P^n\gamma^n}{\Gamma(n+1)}\binom{n}{r}\binom{r}{q}\exp(-\bar{\gamma}_P\gamma)$$

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$$\times \int_0^\infty z^q \exp(-\bar{\gamma}_P z\gamma) f_Z(z) dz$$
$$\times \int_0^\infty y^{n-r} \exp(-\bar{\gamma}_P y\gamma) f_Y(y) dy. \quad (82)$$

Finally, the CDF of the primary SINR is expressed as shown in (83). In terms of (83), the OP of the SINR of the PU can be directly expressed as

$$P_{\rm Pri}^{\rm out} = F_P(\gamma_{\rm th}). \quad (84)$$

To ensure that the primary's communications is reliable, the corresponding OP shall remain below a threshold λ and we must have

$$P_{\rm Pri}^{\rm out} \le \lambda \Rightarrow P_{\rm Pri}^{\rm out} - \lambda \le 0. \quad (85)$$

Finally, by solving (85) w.r.t. E_S, the power constraint of S_1 and S_2 can be achieved as shown in (11).

Appendix II
Proof of Proposition 2

To begin, the CDF of γ_{R,S_1} in (8) is obtained as

$$F_{\gamma_{R,S_1}}(\gamma) = \mathcal{K}_{S_1,h,S,\lambda_{jk}}, \quad (86)$$

where

$$\mathcal{K}_{S_1,h,S,\lambda_{jk}} = 1 - \sum_{j=1}^{L_{FS_1}} \sum_{k=1}^{M_{S_1,j}} \sum_{n=0}^{m_h-1} \sum_{i=0}^{n} \frac{\bar{\gamma}_{h,S}^n \lambda_{jk} \Gamma(k+i)}{\Gamma(n+1)\Gamma(k)}$$
$$\times \binom{n}{i} \frac{\gamma^n}{\left(\bar{\gamma}_{h,S}\gamma + \bar{\gamma}_{S_1,j}\right)^{k+i}} \exp(-\bar{\gamma}_{h,S}\gamma). \quad (87)$$

By substituting (86) into (13), with [45, Eq. 9.211.4], and doing some manipulations, we arrive at (18). Next, we derive $P^b(\gamma_R)$. We have

$$P^b(\gamma_R) = P^b(\gamma_{S_1,R}|\bar{e}_{\gamma_{S_2,R}})\bar{P}^b(\gamma_{S_2,R}) + P^b(\gamma_{S_2,R}|\bar{e}_{\gamma_{S_1,R}})\bar{P}^b(\gamma_{S_1,R}). \quad (88)$$

$P^b(\gamma_{S_1,R})$ and $P^b(\gamma_{S_2,R})$ can be further expressed as

$$P^b(\gamma_{S_1,R}) = P^b(\gamma_{S_1,R}|e_{\gamma_{S_2,R}})P^b(\gamma_{S_2,R}) + P^b(\gamma_{S_1,R}|\bar{e}_{\gamma_{S_2,R}})\bar{P}^b(\gamma_{S_2,R}), \quad (89)$$
$$P^b(\gamma_{S_2,R}) = P^b(\gamma_{S_2,R}|e_{\gamma_{S_1,R}})P^b(\gamma_{S_1,R}) + P^b(\gamma_{S_2,R}|\bar{e}_{\gamma_{S_1,R}})\bar{P}^b(\gamma_{S_1,R}). \quad (90)$$

With the help of (89) and (90), we obtain (91) and (92). To find $P^b(\gamma_{S_1,R}|\bar{e}_{\gamma_{S_2,R}})$, $P^b(\gamma_{S_1,R}|e_{\gamma_{S_2,R}})$, $P^b(\gamma_{S_2,R}|\bar{e}_{\gamma_{S_1,R}})$ and $P^b(\gamma_{S_2,R}|e_{\gamma_{S_1,R}})$, we make use of the CDF-based approach. To this end, the SINRs $\gamma_{S_1,R|\bar{e}_{S_2,R}}$, $\gamma_{S_1,R|e_{S_2,R}}$, $\gamma_{S_2,R|\bar{e}_{S_1,R}}$ and $\gamma_{S_2,R|e_{S_1,R}}$ need to be obtained. According to (3), these SINRs at the relay are given by

$$\gamma_{S_1,R|\bar{e}_{S_2,R}} = \frac{E_S|h|^2}{\sum_{j=1}^{L_R} E_{R,j}|f_{R,j}|^2 + N_0}, \quad (93)$$
$$\gamma_{S_1,R|e_{S_2,R}} = \frac{E_S|h|^2}{2E_S|g|^2 + \sum_{j=1}^{L_R} E_{R,j}|f_{R,j}|^2 + N_0}, \quad (94)$$

and their corresponding CDFs can be obtained as

$$F_{\gamma_{S_1,R|\bar{e}_{S_2,R}}}(\gamma) = \mathcal{K}_{R,h,R,\mu_{jk}}, \quad (95)$$
$$F_{\gamma_{S_1,R|e_{S_2,R}}}(\gamma) = \mathcal{N}_{h,g}, \quad (96)$$

where

$$\mathcal{N}_{h,g} = 1 - \sum_{n=0}^{m_h-1} \sum_{k=1}^{m_g} \sum_{i=0}^{n} \frac{\bar{\gamma}_{h,R}^n \eta_{0k} \Gamma(k+i)}{\Gamma(n+1)\Gamma(k)} \binom{n}{i}$$
$$\times \frac{\gamma^n}{\left(\bar{\gamma}_{h,R}\gamma + \frac{\bar{\gamma}_{g,R}}{2}\right)^{k+i}} \exp(-\bar{\gamma}_{h,R}\gamma)$$
$$- \sum_{j=1}^{L_{FR}} \sum_{k=1}^{M_{R,j}} \sum_{n=0}^{m_h-1} \sum_{i=0}^{n} \frac{\bar{\gamma}_{h,R}^n \eta_{jk} \Gamma(k+i)}{\Gamma(n+1)\Gamma(k)} \binom{n}{i}$$
$$\times \frac{\gamma^n}{\left(\bar{\gamma}_{h,R}\gamma + \bar{\gamma}_{R,j}\right)^{k+i}} \exp(-\bar{\gamma}_{h,R}\gamma). \quad (97)$$

Substituting (95), (96), $F_{\gamma_{S_2,R|\bar{e}_{S_1,R}}}(\gamma)$ and $F_{\gamma_{S_2,R|e_{S_1,R}}}(\gamma)$ into (13), we reach the equations shown in Proposition 2.

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$$F_P(\gamma) = 1 - \sum_{j=1}^{L_{FP}} \sum_{k=1}^{M_{P,j}} \sum_{t=1}^{L_{FSP}} \sum_{w=1}^{M_{P,S_t}} \sum_{n=0}^{m_P - 1} \sum_{r=0}^{n} \sum_{q=0}^{r} \frac{\bar{\gamma}_P^n \Gamma(n+k-r)\Gamma(t+q)\theta_{tw}\alpha_{jk}}{\Gamma(n+1)\Gamma(w)\Gamma(k)} \binom{n}{r}\binom{r}{q} \times \frac{\gamma^n}{(\bar{\gamma}_P\gamma + \bar{\gamma}_{P,j})^{n+k-r} (\bar{\gamma}_P\gamma + \bar{\gamma}_{P,S_t})^{w+q}} \exp(-\bar{\gamma}_P\gamma). \tag{83}$$

$$P^b(\gamma_{S_1,R}) = \frac{P^b(\gamma_{S_1,R}|\bar{e}_{\gamma_{S_2,R}}) + P^b(\gamma_{S_2,R}|\bar{e}_{\gamma_{S_1,R}}) \left(P^b(\gamma_{S_1,R}|e_{\gamma_{S_2,R}}) - P^b(\gamma_{S_1,R}|\bar{e}_{\gamma_{S_2,R}})\right)}{1 - \left[P^b(\gamma_{S_1,R}|e_{\gamma_{S_2,R}}) - P^b(\gamma_{S_1,R}|\bar{e}_{\gamma_{S_2,R}})\right] \left[P^b(\gamma_{S_2,R}|e_{\gamma_{S_1,R}}) - P^b(\gamma_{S_2,R}|\bar{e}_{\gamma_{S_1,R}})\right]}. \tag{91}$$

$$P^b(\gamma_{S_2,R}) = \frac{P^b(\gamma_{S_2,R}|\bar{e}_{\gamma_{S_1,R}}) + P^b(\gamma_{S_1,R}|\bar{e}_{\gamma_{S_2,R}}) \left(P^b(\gamma_{S_2,R}|e_{\gamma_{S_1,R}}) - P^b(\gamma_{S_2,R}|\bar{e}_{\gamma_{S_1,R}})\right)}{1 - \left[P^b(\gamma_{S_1,R}|e_{\gamma_{S_2,R}}) - P^b(\gamma_{S_1,R}|\bar{e}_{\gamma_{S_2,R}})\right] \left[P^b(\gamma_{S_2,R}|e_{\gamma_{S_1,R}}) - P^b(\gamma_{S_2,R}|\bar{e}_{\gamma_{S_1,R}})\right]}. \tag{92}$$

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