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Outage Probability of Single-Carrier Cooperative Spectrum Sharing Systems with Decode-and-Forward Relaying and Selection Combining

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***Index Terms*—Spectrum sharing, single-carrier system, interference constraint, signal-to-noise ratio, outage probability, relay networks, cognitive radio networks.**

I. Introduction

COGNITIVE RADIO (CR) networks [1] have been proposed to opportunistically access available spectral bands by secondary users (SUs) without interfering with the primary user (PU) under limited availability of radio spectrum. Cooperative relaying techniques [2]–[6] have been proposed in spectrum-sharing CR systems to efficiently use limited spectral resources. Under limitations on the peak-received power at the primary receivers, the average symbol error rate (SER) of the SU network is studied in [2]. The outage probability of the selective-decode-and-forward (DF) CR system under an outage constraint for the PU is studied in [3] with and without a direct link between the SU-source (S) and SU-destination (D). The effect of the primary transmitter on the secondary network has been investigated in [4] for non-cooperative spectrum sharing system. Relay selection and optimum power allocation (OPA) under interference limitations are considered in [6]. Imperfect channel knowledge with asymmetric fading is studied in the performance analysis of spectrum sharing CR systems in [5] and [7].

The cyclic prefixed single-carrier (CP-SC)-based transmission scheme described in [8] and [9] has been proposed as a good candidate for wireless systems. Such systems exhibit less sensitivity to the frequency offset, lower peak-to-average power ratio (PAPR), lower power-backing off, and a less restrictive requirement of linear amplifiers having large dynamic ranges in contrast to orthogonal frequency division multiplexing (OFDM) transmission [8], [10], [11]. A channel estimation technique for SC transmission is proposed in [11] and [12]. In the presence of cochannel interference (CCI), performance analysis for the CP-SC system has been conducted in [13]. In [14], [15], and [16], a space-time/frequency-block code (STBC/SFBC) and cyclic delay diversity (CDD) are employed to provide transmit diversity to the CP-SC system. By introducing the CP to the front of the transmission symbol block, the channel becomes a right circulant matrix in the time domain after the removal of the signal part related to the CP. Using the properties of right circulant channel matrices [17] of CP-SC transmission [18], the performance of the CP-SC system with opportunistic scheduling has been analyzed in [18]. Recently, CP-SC transmission in cooperative relaying systems has been reported in a number of works [15], [19]–[23]. Distributed SFBC is proposed in [20] for the CP-SC system with a two-hop amplify-and-forward (AF) relaying protocol. An adaptive DF (ADF) relaying protocol is proposed in [19] for the cooperative CP-SC system. However, this work has not investigated the impact of interference power constraints imposed by the PU on the secondary system performance. In [21] and [23], a two-hop AF relaying protocol is applied to the CP-SC system.

In addition, for multiple relays and multiple terminals, best relay and best terminal selection are, respectively, applied to achieve a better throughput. In [22], CP-SC transmission is further applied in two-way AF relaying networks. For these two-way CP-SC systems, a training symbol is optimally designed for channel estimation. For a selected source-relay-destination link via best terminal selection, OPA

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is proposed in [23] by maximizing the achievable average rate. However, since CP-SC-based cooperative systems have not been proposed for spectrum sharing relaying systems with the DF relaying protocol and selection combining at the destination, in this paper, we analyze the performance of a CP-SC spectrum sharing relaying system with the DF relaying protocol and selection combining. The motivation to use the selection combining for a diversity enhancement is explained as follows. Due to the stringent constraints from primary networks, the transmit power at secondary transmitters is strictly monitored which significantly degrades the system performance. Thus, combining the signals from relaying and direct links is essential for improving the cognitive network's performance.

In contrast to the previous works in [15], [19] and [21]–[23], we focus on the performance of spectrum sharing CP-SC systems under maximum allowable interference at the PU and transmit power with the DF relaying protocol and selection combining. Our main contributions can be summarized as follows:

- We propose a CP-SC-based cooperative spectrum sharing system that employs the DF relaying protocol and selection combining at the SU-destination. To the authors' knowledge, there has been no previous work for this proposed system. It is shown in [24] that the end-to-end signal-to-noise ratio (e2e-SNR) for a link between the SU-source (S) and the PU becomes a random variable (RV), and that it is too complex to develop a feasible performance analysis. Motivated by this challenging problem, we first obtain an exact closed-form expression for the conditional cumulative distribution function (CDF) of the e2e-SNR of the DF relaying protocol and selection combining scheme. And then using the properties of right circulant channel matrices in the CP-SC system, we develop the unconditional closed-form CDF for the e2e-SNRs. Note that the employed DF relaying protocol is somewhat similar to the ADF relaying protocol proposed in [19] for a single relay node in the non-spectrum-sharing system.
- In developing the performance analysis, we take into account two separate cases: a limited transmission power and an unlimited transmission power case. In both cases, a maximum allowable interference at the PU is considered to determine the peak transmit power at the SU-source and SU-relay (R). A limited transmission power satisfying a maximum allowable interference at the PU is motivated by several previous works [25]–[27]. The authors in [25] study the outage probability for selective relaying systems using AF, selective-DF, and partial selective-AF relaying protocols. In particular, in [27], a relay selection diversity is investigated without a direct link between the SU-source and SU-destination. By considering the existence of direct link and a single relay, under unlimited transmit power at the secondary transmitters, selection combining has been applied for the AF and DF relaying protocols in [24] and [28], respectively.
- For the proposed CP-SC-based spectrum sharing system, we derive closed-form expressions for the outage probability. To find the outage diversity, we also conduct an asymptotic analysis of the outage probability. It will be seen that in the proposed system, the asymptotic outage diversity is determined by the multipath diversity gain in the secondary networks in the limited and unlimited transmission power cases. However, it is also shown that when interference is independent of the limited transmission power, an error floor in the outage probability is observed [26], which uses the DF relaying protocol without selection combining.

The rest of the paper is organized as follows. In Section II, we first present the system and channel model for CP-SC-based cooperative spectrum sharing relaying systems employing the two-hop DF relaying protocol and selection combining at the SU-destination. The effective e2e-SNR is derived in Section III and then the outage probability analysis of the proposed spectrum sharing system is conducted in Section IV. Simulation results are provided in Section V. Conclusions are drawn in Section VI.

Notation: The superscripts $(\cdot)^*$, $(\cdot)^T$, and $(\cdot)^H$ denote complex conjugation, transposition and conjugate transposition, respectively; $\mathbb{E}_a\{\cdot\}$ denotes expectation with respect to a; $\boldsymbol{I}_N$ is an $N \times N$ identity matrix; $\mathbf{0}$ denotes an all-zero matrix of appropriate dimensions; $\mathcal{CN}\left(\mu, \sigma^2\right)$ denotes the complex Gaussian distribution with mean μ and variance σ^2; $\mathbb{C}^{m \times n}$ denotes the vector space of all $m \times n$ complex matrices; a right circulant matrix $\boldsymbol{A}$ in $\mathbb{C}^{n \times n}$ is defined by the first size-n column vector $\boldsymbol{a}_n \in \mathbb{C}^{n \times 1}$; a zero-padded size-$N$ column vector from $\boldsymbol{a}_n$ is denoted by $\tilde{\boldsymbol{a}}_n$, i.e., $\tilde{\boldsymbol{a}}_n \overset{\triangle}{=} [(\boldsymbol{a}_n)^T, \mathbf{0}_{1\times(N-n)}]^T$; $\|\boldsymbol{a}_n\|$ denotes the Euclidean norm of a vector $\boldsymbol{a}_n$; $F_\varphi(\cdot)$ denotes the CDF of the random variable φ, whereas the probability density function (PDF) of φ is denoted by $f_\varphi(\cdot)$.

Definition 1: Let the right circulant channel matrix $\boldsymbol{H} \in \mathbb{C}^{N\times N}$ be defined by $\tilde{\boldsymbol{h}}_{N_f} \in \mathbb{C}^{N\times 1}$, then we have $\tilde{\varphi} \overset{\triangle}{=} \frac{\mathrm{trace}(\|\boldsymbol{H}\|^2)}{N} = \|\boldsymbol{h}_{N_f}\|^2$, where $\tilde{\mathbf{h}}_{N_f}$ is zero-padded length-N channel vector from $\mathbf{h}_{N_f} \in \mathbb{C}^{N_f\times 1}$. When $\boldsymbol{h}_{N_f}$ is composed of independent and identically distributed (i.i.d.) complex Gaussian RVs with zero means and unit variances, the RV $\tilde{\varphi}$ has a chi-squared distribution with $2N_f$ degrees of freedom [18], and we express the distribution of $\tilde{\varphi}$ as $\tilde{\varphi} \sim \chi^2(2N_f)$. In addition, we express the distribution for $\varphi \overset{\triangle}{=} \tilde{\varphi}/a$ as $\varphi \sim \chi^2(2N_f, a)$ for a positive real-valued constant a.

II. System and Channel Model

In the CP-SC spectrum sharing relaying system under consideration, two-hop DF relaying is used as a relaying protocol in two time slots. We use the following channel models in the proposed spectrum sharing system:

- All multipath channels are assumed to be known exactly in the system and defined by $\boldsymbol{h}_{N_A}^A$ with $A \in \{(\mathrm{S},\mathrm{D}), (\mathrm{S},\mathrm{R}), (\mathrm{R},\mathrm{D}), (\mathrm{S},\mathrm{P}), (\mathrm{R},\mathrm{P})\}$. A channel length over a link A is denoted by $N_A \in$

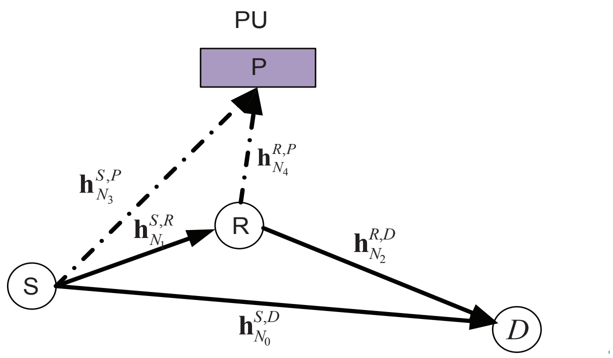

Fig. 1. System model of a CP-SC spectrum sharing relaying system with the DF relaying protocol and selection combining.

$\{N_0, N_1, N_2, N_3, N_4\}$. Based on this notation, $\boldsymbol{h}^{\mathrm{S,D}}_{N_0}$ denotes a size-N_0 multipath channel vector from the SU-source and to the SU-destination, whereas $\boldsymbol{h}^{\mathrm{S,P}}_{N_3}$ denotes a multipath channel vector from the SU-source to the PU. Its channel size is N_3. A path loss component over the non-identical link A is given by $a_A \in \{a_0 \triangleq a^{\mathrm{S,D}}, a_1 \triangleq a^{\mathrm{S,R}}, a_2 \triangleq a^{\mathrm{R,D}}, a_3 \triangleq a^{\mathrm{S,P}}, a_4 \triangleq a^{\mathrm{R,P}}\}$.

- In each individual link $\boldsymbol{h}^{A}_{N_A}$, we assume a quasi-static fading channel where a multipath channel vector $\boldsymbol{h}^{A}_{N_A}$ is composed of i.i.d. complex Gaussian RVs with zero means and the same variance a^{A}.
- The maximum channel length is denoted by $N_{\max} \triangleq \max(N_0, N_1, N_2, N_3, N_4)$.

The transmission symbol block is given by $\boldsymbol{d}_N$ satisfying $\mathbb{E}_{\boldsymbol{d}_N}\{\boldsymbol{d}_N\} = \boldsymbol{0}_N$ and $\mathbb{E}_{\boldsymbol{d}_N}\{\boldsymbol{d}_N \boldsymbol{d}_N^H\} = \boldsymbol{I}_N$. In the sequel, N denotes the size of the transmission symbol block $\boldsymbol{d}_N$. To eliminate intersymbol interference, a CP comprising $N_c \geq N_{\max}$ symbols is prefixed to the front of the symbol block $\boldsymbol{d}_N$. The following assumptions are also employed in the spectrum sharing network:

- The maximum allowable interference constraint at the PU is given by I_p.
- The SU-source and SU-relay have their own transmission power constraint P_T.

A. First hop transmission

In the first hop, the SU-source transmits $\boldsymbol{d}_N$ to the SU-relay under the maximum allowable interference I_p and within its own power constraint. The received signals at the SU-relay and SU-destination are given by [18], respectively,

$$\begin{aligned} \boldsymbol{y}^{\mathrm{S,R}}_N &= \sqrt{P_s a_1}\boldsymbol{H}^{\mathrm{S,R}}\boldsymbol{d}_N + \boldsymbol{n}^{\mathrm{S,R}}_N \text{ and} \\ \boldsymbol{y}^{\mathrm{S,D}}_N &= \sqrt{P_s a_0}\boldsymbol{H}^{\mathrm{S,D}}\boldsymbol{d}_N + \boldsymbol{n}^{\mathrm{S,D}}_N \end{aligned} \quad (1)$$

where $\boldsymbol{H}^{\mathrm{S,R}} \in \mathbb{C}^{N\times N}$ is the right circulant matrix determined by a multipath channel vector $\tilde{\boldsymbol{h}}^{\mathrm{S,R}}_{N_1} \in \mathbb{C}^{N\times 1}$. Similarly, a circulant channel matrix $\boldsymbol{H}^{\mathrm{S,D}} \in \mathbb{C}^{N\times N}$ is determined by a multipath channel vector $\tilde{\boldsymbol{h}}^{\mathrm{S,D}}_{N_0} \in \mathbb{C}^{N\times 1}$. Recall that $\tilde{\boldsymbol{h}}^{\mathrm{S,R}}_{N_1}$ and $\tilde{\boldsymbol{h}}^{\mathrm{S,D}}_{N_0}$ are zero-padded vectors from $\boldsymbol{h}^{\mathrm{S,R}}_{N_1}$ and $\boldsymbol{h}^{\mathrm{S,D}}_{N_0}$. In addition, $\boldsymbol{n}^{\mathrm{S,R}}_N \sim \mathcal{CN}(\boldsymbol{0}, \sigma_n^2 \boldsymbol{I}_N)$ and $\boldsymbol{n}^{\mathrm{S,D}}_N \sim \mathcal{CN}(\boldsymbol{0}, \sigma_n^2 \boldsymbol{I}_N)$. Note that in (1), the signal parts related to the CP are removed from the received signals. Under the transmission power and maximum interference I_p, the power allocation at the SU-source is given by

$$P_s = \min\left(\tilde{P}_T, \frac{\tilde{I}_p}{\frac{a_3}{\sigma_n^2}\|\boldsymbol{h}^{\mathrm{S,P}}_{N_3}\|^2}\right) \quad (2)$$

where $\tilde{P}_T \triangleq P_T/\sigma_n^2$ and $\tilde{I}_p \triangleq I_p/\sigma_n^2$. In the sequel, to simplify our notation, the subscript $(\cdot)_N$ for column vectors will be suppressed.

B. Second hop transmission

In the SU-relay, if the signal from the SU-source is correctly decoded, then the received signal at the SU-destination from the SU-relay is given by [18]

$$\boldsymbol{y}^{\mathrm{R,D}} = \sqrt{P_r a_2}\boldsymbol{H}^{\mathrm{R,D}}\boldsymbol{d} + \boldsymbol{n}^{\mathrm{R,D}} \quad (3)$$

where P_r is the allocated transmission power at the SU-relay, a circulant channel matrix $\boldsymbol{H}^{\mathrm{R,D}} \in \mathbb{C}^{N\times N}$ is defined by $\tilde{\boldsymbol{h}}^{\mathrm{R,D}}_{N_2} \in \mathbb{C}^{N\times 1}$, and $\boldsymbol{n}^{\mathrm{R,D}} \sim \mathcal{CN}(\boldsymbol{0}, \sigma_n^2 \boldsymbol{I}_N)$. The signal parts related to the CP are removed in obtaining (3). Similar to the power allocation at the SU-source, the power allocation at the SU-relay, P_r, is given by

$$P_r = \min\left(\tilde{P}_T, \frac{\tilde{I}_p}{\frac{a_4}{\sigma_n^2}\|\boldsymbol{h}^{\mathrm{R,P}}_{N_4}\|^2}\right). \quad (4)$$

III. Derivation of the statistics of the effective e2e-SNR

Based on Eqs. (1) and (3), we compute the e2e-SNR for the direct link in the SU network as follows:

$$\gamma_0 \triangleq P_s a_0 \varphi_0 \quad (5)$$

where $\varphi_0 \triangleq \frac{\|\boldsymbol{h}^{\mathrm{S,D}}_{N_0}\|^2}{\sigma_n^2}$. We used the properties of right circulant matrices [18], [21] in the computation of (5). For the DF relaying protocol, the SNR of the relaying link, i.e., SU-source$\rightarrow$SU-relay$\rightarrow$SU-destination, is then given by [29]

$$\gamma_r = \min(\gamma_{s,r}, \gamma_{r,d}) \quad (6)$$

where $\gamma_{s,r} \triangleq \frac{P_s a_1 \|\boldsymbol{h}^{\mathrm{S,R}}_{N_1}\|^2}{\sigma_n^2} = \min\left(\tilde{P}_T, \frac{\tilde{I}_p}{a_3 \varphi_3}\right) a_1 \varphi_1$ and $\gamma_{r,d} \triangleq \frac{P_r a_2 \|\boldsymbol{h}^{\mathrm{R,D}}_{N_2}\|^2}{\sigma_n^2} = \min\left(\tilde{P}_T, \frac{\tilde{I}_p}{a_4 \varphi_4}\right) a_2 \varphi_2$, with the definitions of $\varphi_1 \triangleq \frac{\|\boldsymbol{h}^{\mathrm{S,R}}_{N_1}\|^2}{\sigma_n^2}$, $\varphi_2 \triangleq \frac{\|\boldsymbol{h}^{\mathrm{R,D}}_{N_2}\|^2}{\sigma_n^2}$, $\varphi_3 \triangleq \frac{\|\boldsymbol{h}^{\mathrm{S,P}}_{N_3}\|^2}{\sigma_n^2}$, and $\varphi_4 \triangleq \frac{\|\boldsymbol{h}^{\mathrm{R,P}}_{N_4}\|^2)}{\sigma_n^2}$. The selection combining technique is applied at the SU-destination to combine the two signals from relaying and direct links. That is, of the two received signals, the strongest signal is selected at the SU-destination. Thus, the effective e2e-SNR at the SU-destination can be expressed as

$$\gamma_d = \max(\gamma_0, \gamma_r) = \max(\gamma_0, \min(\gamma_{s,r}, \gamma_{r,d})). \quad (7)$$

The channel related RVs $\varphi_0, \varphi_1, \varphi_2, \varphi_3$, and φ_4 are distributed according to chi-squared distributions with $2N_A$ degrees of freedom when the channel vectors are composed of i.i.d. complex Gaussian RVs with zero means and unit variances, so that we express $\varphi_0 \sim \chi^2(2N_0,\rho)$, $\varphi_1 \sim \chi^2(2N_1,\rho)$, $\varphi_2 \sim \chi^2(2N_2,\rho)$, $\varphi_3 \sim \chi^2(2N_3,\rho)$, and $\varphi_4 \sim \chi^2(2N_4,\rho)$ with $\rho \triangleq 1/\sigma_n^2$. The PDF and CDF of $\varphi \sim \chi^2(2N,a)$ are given by, respectively,

$$\begin{aligned} f_{\varphi}(\gamma) &= \frac{1}{a^N\Gamma(N)}\gamma^{N-1}e^{-\frac{\gamma}{a}}\mathrm{U}(\gamma) \text{ and} \\ F_{\varphi}(\gamma) &= 1-e^{-\frac{\gamma}{a}}\sum_{i=0}^{N-1}\frac{1}{i!}\left(\frac{\gamma}{a}\right)^i\mathrm{U}(\gamma) \end{aligned} \tag{8}$$

where $\mathrm{U}(\cdot)$ denotes the unit step function and $\Gamma(x) \triangleq \int_0^\infty e^{-t}t^{x-1}dt$.

Based on the employed channel models, the conditional CDF $F_{\gamma_{s,r}}(x|\varphi_3)$ of $\gamma_{s,r}$ is provided in the following lemma.

Lemma 1: When the channel vectors are composed of i.i.d. complex Gaussian RVs with zero means and unit variances, $F_{\gamma_{s,r}}(\gamma|\varphi_3)$ is given by

$$F_{\gamma_{s,r}}(\gamma|\varphi_3) = \begin{cases} F_{\varphi_1}\left(\frac{\gamma}{(a_1\tilde{P}_T)}\right) & \text{if } \varphi_3 \le \frac{\tilde{I}_p}{a_3\tilde{P}_T}, \\ F_{\varphi_1}\left(\frac{(a_3\gamma\varphi_3)}{(a_1\tilde{I}_p)}\right) & \text{if } \varphi_3 \ge \frac{\tilde{I}_p}{a_3\tilde{P}_T}. \end{cases} \tag{9}$$

Proof: Since

$$\begin{aligned} F_{\gamma_{s,r}}(\gamma|\varphi_3) = P_r\left(\varphi_1 \le \frac{\gamma}{a_1\tilde{P}_T}, \frac{\tilde{I}_p}{\varphi_3} \ge a_3\tilde{P}_T\right) + \\ P_r\left(\frac{\varphi_1}{\varphi_3} \le \frac{a_3\gamma}{a_1\tilde{I}_p}, \frac{\tilde{I}_p}{\varphi_3} \le a_3\tilde{P}_T\right) \end{aligned} \tag{10}$$

we obtain (9). ■

For the notational purpose, we define the following terms: $a_{0,P} \triangleq a_0\tilde{P}_T$, $a_{1,P} \triangleq a_1\tilde{P}_T$, $a_{2,P} \triangleq a_2\tilde{P}_T$, $a_{3,P} \triangleq a_3\tilde{P}_T$, and $a_{4,P} \triangleq a_4\tilde{P}_T$. In addition, $a_{0,I} \triangleq a_0\tilde{I}_p$, $a_{1,I} \triangleq a_1\tilde{I}_p$, $a_{2,I} \triangleq a_2\tilde{I}_p$, $a_{3,I} \triangleq a_3\tilde{I}_p$, and $a_{4,I} \triangleq a_4\tilde{I}_p$.

The conditional CDF of $\gamma_{r,d}$, denoted by $F_{\gamma_{r,d}}(\gamma|\varphi_3)$, is given by the following lemma.

Lemma 2: When the channel vectors are composed of i.i.d. complex Gaussian RVs with zero means and unit variances, $F_{\gamma_{r,d}}(\gamma|\varphi_3)$ is given by

$$\begin{aligned} F_{\gamma_{r,d}}(\gamma|\varphi_3) = \frac{\gamma(N_2,\frac{\gamma}{\rho a_{2,P}})}{\Gamma(N_2)}\frac{\gamma(N_4,\frac{\tilde{I}_p}{\rho a_{4,P}})}{\Gamma(N_4)} + \frac{\Gamma(N_4,\frac{\tilde{I}_p}{\rho a_{4,P}})}{\Gamma(N_4)} - \\ \sum_{l=0}^{N_2-1}\frac{1}{\Gamma(N_4)l!}\left(\frac{a_4\gamma}{a_{2,I}}\right)^l\left(1+\frac{a_4\gamma}{a_{2,I}}\right)^{-(N_4+l)} \\ \Gamma\left(N_4+l,\left(1+\frac{a_4\gamma}{a_{2,I}}\right)\frac{\tilde{I}_p}{\rho a_{4,P}}\right) \end{aligned} \tag{11}$$

where $\Gamma(\alpha,x) \triangleq \int_x^\infty e^{-t}t^{\alpha-1}dt$, and $\gamma(\alpha,x) \triangleq \int_0^x e^{-t}t^{\alpha-1}dt$.

Proof: A proof of this lemma is provided in Appendix A. ■

Using Lemma 1 and Lemma 2, the CDF of $\gamma_{DF} \triangleq \min(\gamma_{s,r},\gamma_{r,d})$, which is equivalent to the e2e-SNR for the DF relaying protocol over the SU-relay link, is given by

$$\begin{aligned} &F_{\gamma_{DF}}(\gamma|\varphi_3) \\ &= 1-\left(1-F_{\gamma_{s,r}}(\gamma|\varphi_3)\right)\left(1-F_{\gamma_{r,d}}(\gamma|\varphi_3)\right) \\ &= 1-\left(1-F_{\gamma_{s,r}}(\gamma|\varphi_3)\right)\left(1-F_{\gamma_{r,d}}(\gamma)\right) \\ &= \begin{cases} 1-\left(1-F_{\varphi_1}\left(\frac{\gamma}{a_{1,P}}\right)\right)\left(1-F_{\gamma_{r,d}}(\gamma)\right) \\ \text{if } \varphi_3 \le \frac{\tilde{I}_p}{a_{3,P}}, \\ 1-\left(1-F_{\varphi_1}\left(\frac{a_3\gamma\varphi_3}{a_1\tilde{I}_p}\right)\right)\left(1-F_{\gamma_{r,d}}(\gamma)\right) \\ \text{if } \varphi_3 \ge \frac{\tilde{I}_p}{a_{3,P}}. \end{cases} \end{aligned} \tag{12}$$

Note that when $\varphi_3 \le \frac{\tilde{I}_p}{a_{3,P}}$, $F_{\gamma_{DF}}(\gamma|\varphi_3)$ is independent of φ_3. Applying a similar approach to that used in the derivation of Lemma 1, the conditional CDF $F_{\gamma_0}(\gamma|\varphi_3)$ for the direct SU-link is given by

$$F_{\gamma_0}(\gamma|\varphi_3) = \begin{cases} F_{\varphi_0}\left(\frac{\gamma}{a_{0,P}}\right) & \text{if } \varphi_3 \le \frac{\tilde{I}_p}{a_{3,P}}, \\ F_{\varphi_0}\left(\frac{a_3\gamma\varphi_3}{a_{0,I}}\right) & \text{if } \varphi_3 \ge \frac{\tilde{I}_p}{a_{3,P}}. \end{cases} \tag{13}$$

Having derived (9), (11), (12), and (13) for the corresponding e2e-SNRs for all distinct links in the system, the unconditional CDF for the cooperative e2e-SNR γ_d is given by the following theorem.

Theorem 1: When the channel vectors are composed of i.i.d. complex Gaussian RVs with zero means and unit variances, an exact closed-form expression for $F_{\gamma_d}(\gamma) = P_r(\gamma_d \le \gamma)$ is given by

$$F_{\gamma_d}(\gamma) = I_0 + I_1 - I_2 - I_3 + I_4 \tag{14}$$

where $\gamma_T \triangleq \frac{\tilde{I}_p}{a_{3,P}}$, and I_0, I_1, I_2, I_3, and I_4 are defined at the top of the next page.

Proof: A proof of this theorem is provided in Appendix B. ■

Next, we will investigate the system, in which the secondary nodes (SU-source and SU-relay) have an unlimited transmission power; that is, $P_s = \frac{\tilde{I}_p}{a_3\varphi_3}$ and $P_r = \frac{\tilde{I}_p}{a_4\varphi_4}$. As a result, the e2e-SNRs are given by

$$\tilde{\gamma}_0 = \frac{a_{0,I}}{a_3\varphi_3}\varphi_0,\ \tilde{\gamma}_{s,r} = \frac{a_{1,I}}{a_3\varphi_3}\varphi_1,\ \text{and } \tilde{\gamma}_{r,d} = \frac{a_{2,I}}{a_4\varphi_4}\varphi_2. \tag{20}$$

The corresponding cooperative e2e-SNR using selection combining and the DF relaying protocol is given by

$$\tilde{\gamma}_d = \max(\tilde{\gamma}_0, \min(\tilde{\gamma}_{s,r},\tilde{\gamma}_{r,d})) \tag{21}$$

where the conditional CDF of $\tilde{\gamma}_{r,d}$ given φ_3 is given by the following lemma.

Lemma 3: The conditional CDF $F_{\tilde{\gamma}_{r,d}}(\gamma|\varphi_3)$ is evaluated as follows:

$$F_{\tilde{\gamma}_{r,d}}(\gamma|\varphi_3) = 1-\Theta(\gamma) \tag{22}$$

where $\Theta(\gamma) \triangleq \sum_{l=0}^{N_2-1}\frac{1}{l!}\left(\frac{a_4\gamma}{a_{2,I}}\right)^l\frac{\Gamma(N_4+l)}{\Gamma(N_4)}\left(1+\frac{a_4\gamma}{a_{2,I}}\right)^{-(N_4+l)}$.

Proof: Using [30, Eq. (6-42)] and [31, Eq. (8.351.3)], we can obtain (22). ■

Since the CDF $F_{\tilde{\gamma}_d}(\gamma|\varphi_3)$ is given by $F_{\tilde{\gamma}_d}(\gamma|\varphi_3) = \left[1-\left[1-F_{\tilde{\gamma}_{s,r}}(\gamma|\varphi_3)\right]\Theta(\gamma)\right]F_{\tilde{\gamma}_0}(\gamma|\varphi_3)$, an exact closed-form expression for the CDF of $\tilde{\gamma}_d$ is given by the following

$$I_0 \triangleq F_{\varphi_0}\left(\frac{\gamma}{a_{0,P}}\right)\left(1-\left(1-F_{\varphi_1}\left(\frac{\gamma}{a_{1,P}}\right)\right)\left(1-F_{\gamma_{r,d}}(\gamma)\right)\right)F_{\varphi_3}(\gamma_T) \quad (15)$$

$$I_1 \triangleq \left(1-F_{\varphi_3}(\gamma_T)\right) \quad (16)$$

$$I_2 \triangleq \left(1-F_{\gamma_{r,d}}(\gamma)\right)\sum_{j=0}^{N_1-1}\frac{1}{\Gamma(N_3)j!}\left(\frac{a_3\gamma}{a_{1,I}}\right)^j\left(1+\frac{a_3\gamma}{a_{1,I}}\right)^{-(N_3+j)}\Gamma\left(N_3+j,\left(1+\frac{a_3\gamma}{a_{1,I}}\right)\left(\frac{\gamma_T}{\rho}\right)\right) \quad (17)$$

$$I_3 \triangleq \sum_{i=0}^{N_0-1}\frac{1}{\Gamma(N_3)i!}\left(\frac{a_3\gamma}{a_{0,I}}\right)^i\left(1+\frac{a_3\gamma}{a_{0,I}}\right)^{-(N_3+i)}\Gamma\left(N_3+i,\left(1+\frac{a_3\gamma}{a_{0,I}}\right)\left(\frac{\gamma_T}{\rho}\right)\right) \quad (18)$$

$$I_4 \triangleq \left(1-F_{\gamma_{r,d}}(\gamma)\right)\sum_{i=0}^{N_0-1}\sum_{j=0}^{N_1-1}\frac{1}{\Gamma(N_3)i!j!}\left(\frac{a_3\gamma}{a_{1,I}}\right)^j\left(\frac{a_3\gamma}{a_{0,I}}\right)^i\left(1+\frac{a_3\gamma}{a_{0,I}}+\frac{a_3\gamma}{a_{1,I}}\right)^{-(N_3+i+j)}$$
$$\Gamma\left(N_3+i+j,\left(1+\frac{a_3\gamma}{a_{0,I}}+\frac{a_3\gamma}{a_{1,I}}\right)\left(\frac{\gamma_T}{\rho}\right)\right). \quad (19)$$

theorem.

Theorem 2: The CDF of $\tilde{\gamma}_d$ is given by

$$F_{\tilde{\gamma}_d}(\gamma) = \int_0^\infty F_{\tilde{\gamma}_d}(\gamma|x)\, f_{\varphi_3}(x)\,dx = 1-\Theta(\gamma)J_1 - J_2 + \Theta(\gamma)J_3 \quad (23)$$

where

$$J_1 \triangleq \sum_{m=0}^{N_1-1}\frac{\Gamma(N_3+m)\left(\frac{a_3\gamma}{a_{1,I}}\right)^m}{\Gamma(N_3)m!}\left(1+\frac{a_3\gamma}{a_{1,I}}\right)^{-(N_3+m)} \quad (24)$$

$$J_2 \triangleq \sum_{m=0}^{N_0-1}\frac{\Gamma(N_3+m)\left(\frac{a_3\gamma}{a_{0,I}}\right)^m}{\Gamma(N_3)m!}\left(1+\frac{a_3\gamma}{a_{0,I}}\right)^{-(N_3+m)} \quad (25)$$

$$J_3 \triangleq \sum_{i=0}^{N_1-1}\sum_{j=0}^{N_0-1}\frac{\Gamma(i+j+N_3)}{i!j!\Gamma(N_3)}\left(\frac{a_3\gamma}{a_{1,I}}\right)^i\left(\frac{a_3\gamma}{a_{0,I}}\right)^j\left(1+\frac{a_3\gamma}{a_{1,I}}+\frac{a_3\gamma}{a_{0,I}}\right)^{-(i+j+N_3)}. \quad (26)$$

Proof: We can easily obtain (23) similarly to the derivations used in the previous lemmas and theorem. ■

Based on the derived CDFs, the outage probability and its asymptotic diversity gain will be analyzed in the following section.

IV. Outage Probability analysis of the spectrum sharing system

Using Theorem 1, we define the outage probability $P_{out}(\gamma_{th})$ for a fixed threshold γ_{th}. We can show the outage probability as follows:

$$P_{out}(\gamma_{th}) = P_r(\gamma_d \le \gamma_{th}) = F_{\gamma_d}(\gamma_{th}). \quad (27)$$

However, since the derived $F_{\gamma_d}(\gamma)$ is too complex to investigate the outage probability behavior as functions of $\tilde{P}_T$ and $\tilde{I}_p$, we turn our attention to an asymptotic region ($\tilde{P}_T \to \infty$), in which we first approximate the CDF of the RV $\varphi \sim \chi^2(2N,\rho)$ as follows [26], [31, Eq. (8.354.1)]: $F_\varphi\left(\frac{\gamma}{\tilde{P}_T}\right) \overset{\tilde{P}_T\to\infty}{\approx} \frac{1}{\Gamma(N+1)}\left(\frac{\gamma}{\rho\tilde{P}_T}\right)^N \triangleq F_{\bar{\varphi}}\left(\frac{\gamma}{\tilde{P}_T}\right)$. Based on this asymptotic CDF, we conduct an asymptotic performance analysis next.

To make an asymptotic outage probability analysis when $\tilde{I}_p$ is proportional to a limited $\tilde{P}_T$, let us define $\tilde{I}_p = \mu\tilde{P}_T$, where μ is a positive constant. The asymptotic CDF of the cooperative e2e-SNR γ_D is given by

$$F_{\tilde{\gamma}_d}(\gamma) \overset{\tilde{P}_T\to\infty}{\approx} F_{\gamma_d}(\gamma) = \begin{cases} Y_0X_0X_1\left(\frac{\gamma}{\tilde{P}_T}\right)^{N_0+N_1} + Y_0X_0X_2\left(\frac{\gamma}{\tilde{P}_T}\right)^{N_0+N_2} \\ \text{if } \varphi_3 \le \gamma_T, \\ Y_1X_0X_1\left(\frac{\gamma}{\tilde{P}_T}\right)^{N_0+N_1} + Y_2X_0X_2\left(\frac{\gamma}{\tilde{P}_T}\right)^{N_0+N_2} \\ \text{if } \varphi_3 \ge \gamma_T \end{cases} \quad (28)$$

where

$$Y_0 \triangleq F_{\varphi_3}\left(\frac{\mu}{a_3}\right),$$
$$Y_1 \triangleq \frac{\rho^{N_0+N_1}}{\Gamma(N_3)}\left(\frac{a_3}{\mu}\right)^{N_0+N_1}\Gamma\left(N_0+N_1+N_3,\frac{\gamma_T}{\rho}\right), \text{ and}$$
$$Y_2 \triangleq \frac{\rho^{N_0}}{\Gamma(N_3)}\left(\frac{a_3}{\mu}\right)^{N_0}\Gamma\left(N_0+N_3,\frac{\gamma_T}{\rho}\right)$$

with X_0, X_1, and X_2 being defined in Appendix C. A derivation of (28) is also provided in Appendix C.

Theorem 3: When the maximum allowable interference $\tilde{I}_p$ is proportional to $\tilde{P}_T$, the asymptotic outage diversity is given by $G_d \triangleq -\lim_{\tilde{P}_T\to\infty}\frac{\log(P_{out}^{as}(\gamma_{th}))}{\log(\tilde{P}_T)} = N_0 + \min(N_1, N_2)$.

Proof: The asymptotic outage probability is evaluated as follows:

$$P_{out}^{as}(\gamma_{th}) \overset{\tilde{P}_T\to\infty}{\approx} P_{out}(\gamma_{th}) = F_{\tilde{\gamma}_d}(\gamma_{th}). \quad (29)$$

From (28), we yield

$$P_{out}^{as}(\gamma_{th}) = \begin{cases} Y_0 X_0 X_1 \left(\frac{\gamma_{th}}{\tilde{P}_T}\right)^{N_0+N_1} + Y_0 X_0 X_2 \left(\frac{\gamma_{th}}{\tilde{P}_T}\right)^{N_0+N_2} \\ \text{if } \varphi_3 \leq \gamma_T, \\ Y_1 X_0 X_1 \left(\frac{\gamma_{th}}{\tilde{P}_T}\right)^{N_0+N_1} + Y_2 X_0 X_2 \left(\frac{\gamma_{th}}{\tilde{P}_T}\right)^{N_0+N_2} \\ \text{if } \varphi_3 \geq \gamma_T. \end{cases} \quad (30)$$

Thus, we have $G_d = N_0 + \min(N_1, N_2)$. ■

Note that when $\tilde{I}_p$ is proportional to $\tilde{P}_T$, an asymptotic outage diversity is mainly determined by the multipath diversity gain of the CP-SC system, and the e2e-SNR of the link from the SU-source to the PU does not affect the asymptotic outage diversity. Moreover, since $\tilde{I}_p = \mu \tilde{P}_T$, with a positive μ, the effect of interference can be canceled out by $\tilde{P}_T$ in the system to achieve the outage diversity.

Next, we make an asymptotic outage probability analysis when $\tilde{I}_p$ is independent of the limited $\tilde{P}_T$. In this case, $\gamma_{s,r}$ and $\gamma_{r,d}$ are, respectively, given by $\gamma_{s,r} = \min\left(\tilde{P}_T, \frac{\tilde{I}_p}{a_3\varphi_3}\right) a_1\varphi_1 = \frac{a_{1,I}\varphi_1}{a_3\varphi_3}$ and $\gamma_{r,d} = \min\left(\tilde{P}_T, \frac{\tilde{I}_p}{a_4\varphi_4}\right) a_2\varphi_2 = \frac{a_{2,I}\varphi_2}{a_4\varphi_4}$. Without derivations of the asymptotic CDFs for these e2e-SNRs, we can focus on the asymptotic outage diversity. From the above asymptotic CDFs, we can readily find that $\gamma_{s,r}$ and $\gamma_{r,d}$ are no longer functions of the limited $\tilde{P}_T$, so that the outage diversity in terms of $\tilde{P}_T$ cannot be achieved over the SU-source→SU-relay→SU-destination link. Also, since the e2e-SNR of the direct link, γ_0, becomes $\gamma_0 = \frac{a_{0,I}\varphi_0}{a_3\varphi_3}$, we have no outage diversity as well. From this knowledge, when $\tilde{I}_p$ is independent of $\tilde{P}_T$, there is no outage diversity gain. In this case, the interference $\tilde{I}_p$ acts as cochannel interference to cause an error floor in the outage probability.

When the transmission power is unlimited, an asymptotic outage probability is given in the following Theorem.

Theorem 4: The asymptotic outage probability is given by

$$\tilde{P}_{out}^{as}(\gamma_{th}) \overset{\tilde{I}_p \to \infty}{\approx} \tilde{P}_{out}(\gamma_{th}) = Z_0 \left(\gamma_{th}/\tilde{I}_p\right)^{N_0+N_1} + Z_1 \left(\gamma_{th}/\tilde{I}_p\right)^{N_0+N_2} \quad (31)$$

where $Z_0 \triangleq \frac{\Gamma(N_0+N_1+N_3)}{\Gamma(N_0+1)\Gamma(N_1+1)\Gamma(N_3)} \left(\frac{(a_3)^2}{a_0 a_1}\right)^{N_0+N_1}$ and $Z_1 \triangleq \frac{\Gamma(N_2+N_4)\Gamma(N_0+N_3)}{\Gamma(N_2+1)\Gamma(N_4)\Gamma(N_3)} \left(\frac{a_4}{a_2}\right)^{N_2} \left(\frac{a_3}{a_0}\right)^{N_0}$. Further, the asymptotic outage diversity is given by $\tilde{G}_d \triangleq -\lim_{\tilde{I}_p \to \infty} \frac{\log(\tilde{P}_{out}^{as}(\gamma_{th}))}{\log(\tilde{I}_p)} = N_0 + \min(N_1, N_2)$.

Proof: A proof of this theorem is provided in Appendix D. ■

V. Simulation Results

In the simulations, we have used $N = 256$ and $N_c = 16$ for the symbol block size and the CP length, respectively. Quadrature phase-shift keying (QPSK) modulation is employed for data symbols. In the simulations, a channel vector is generated by $\boldsymbol{h}_{N_A}^{A} \sim \mathcal{CN}(\mathbf{0}, \boldsymbol{I}_{N_A})$ for $A \in \{(\mathrm{S},\mathrm{D}), (\mathrm{S},\mathrm{R}), (\mathrm{R},\mathrm{D}), (\mathrm{S},\mathrm{P}), (\mathrm{R},\mathrm{P})\}$ with the channel length $N_A \in \{N_0, N_1, N_2, N_3, N_4\}$. In addition, the two-dimensional-plane topology to locate the positions of all nodes is applied. For example, S, R, and D are placed in a straight line with the following coordinators $(0,0)$, $\left(\frac{1}{2}, \frac{1}{2}\right)$, and $(1,0)$, respectively. The PU is located at $[x = 0.4, y = 0.4]$. The pathloss component for the channel between two nodes B and C, with $\mathrm{B},\mathrm{C} \in \{\mathrm{S},\mathrm{R},\mathrm{D},\mathrm{P}\}$, is exponentially decaying as $a^{\mathrm{B,C}} = d_{\mathrm{B,C}}^{-\epsilon}$, where $d_{\mathrm{B,C}}$ is the distance between B and C and ϵ is the path loss exponent. We assume $\epsilon = 4$ in all simulation scenarios. A fixed $\gamma_{th} = 4$ dB is used in the computation of the outage probability. The curves obtained via actual link simulations are denoted by **Sim.**, whereas analytically derived curves are denoted by **An.**. We first consider a limited transmission power case. In this case, Fig. 2 shows the derived outage probability based on Theorem 1 and the outage probabilities obtained from simulations for various values of (N_1, N_2). We use fixed $(N_0 = 2, N_3 = 3, N_4 = 4)$. We can observe good matches between the derived outage probabilities and simulated outage probabilities for different antenna configurations in the system. From these observations, we can find the accuracy of our derived CDFs. In addition, an asymptotically derived outage probabilities are plotted. As $\tilde{P}_T \to \infty$, better closeness between the exact outage probabilities and the asymptotic outage probabilities can be observed. This figure also shows a better outage probability as $\min(N_1, N_2)$ increases. Since the slope changes as a function of $\min(N_1, N_2)$, we can find that the outage diversity gain is determined by the multipath diversity gain, which has the same diversity behavior as the conventional non-spectrum-sharing system with the DF relaying protocol [3] and [19].

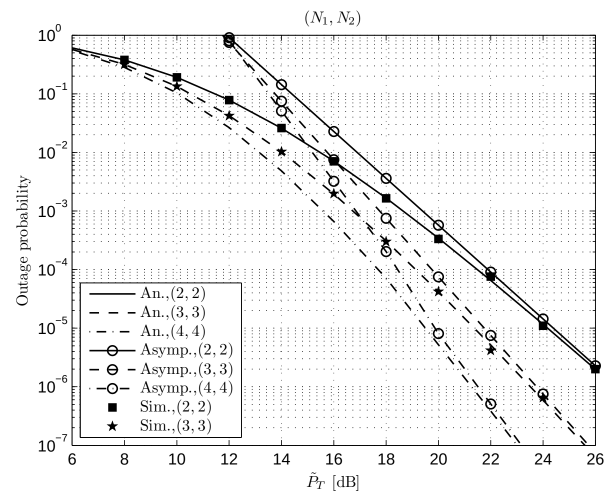

Fig. 2. Outage probability for various numbers of channel taps N_1 and N_2 in the system.

Fig. 3 is the corresponding plot for the outage probability. We use fixed $N_3 = 3$ and $N_4 = 4$. For various values of (N_0, N_1, N_2), this plot shows the asymptotic outage diversity of the proposed spectrum sharing system with the DF protocol and selection combining. As N_0 or $\min(N_1, N_2)$ increases a better outage probability is obtained due to a higher multipath

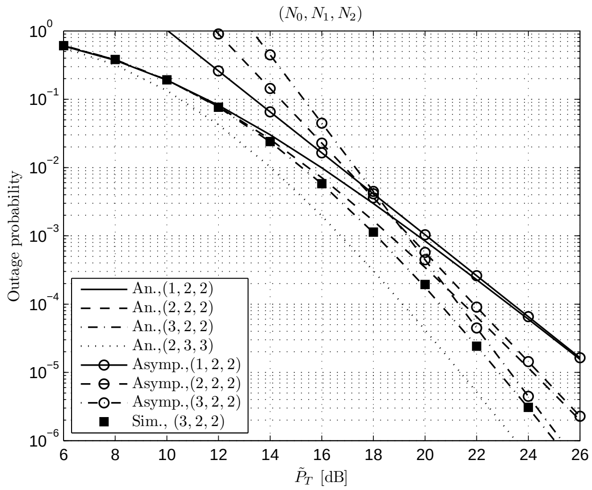

Fig. 3. Outage probability for various numbers of channel taps N_0, N_1, and N_2 in the system.

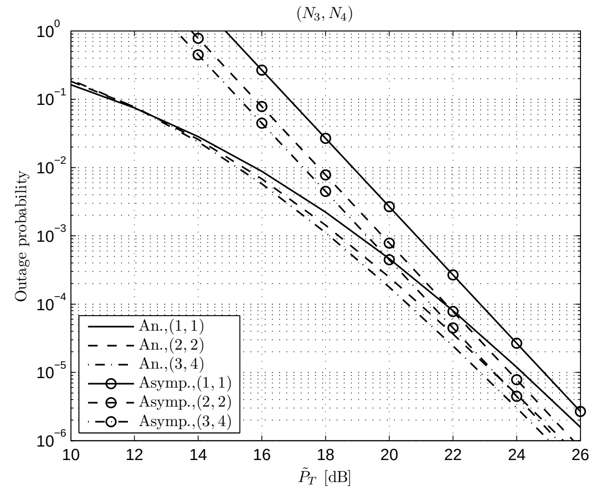

Fig. 5. Outage probability for various numbers of channel taps N_3 and N_4 in the system.

diversity gain as in the cooperative non-spectrum-sharing systems [19].

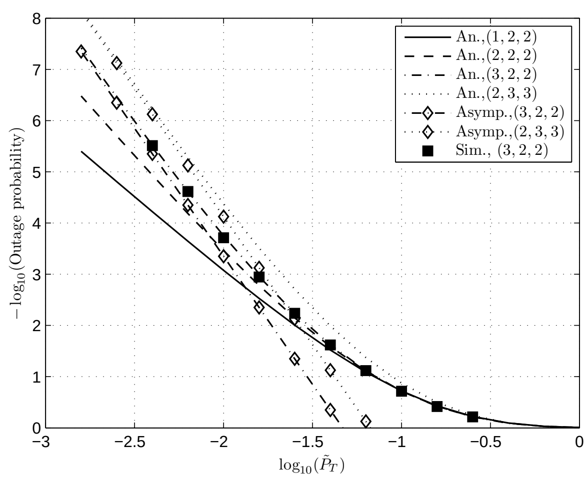

Fig. 4. Outage diversity gain analysis for Fig. 3.

Fig. 4 shows analytically derived outage probabilities, simulated outage probabilities, and their asymptotic outage probabilities on a $\log - \log$ plot. Slopes in this figure give us the outage diversity gain in a function of $\tilde{P}_T$. For $\{(N_0, N_1, N_2)|(1,2,2),(2,2,2),(3,2,2),(2,3,3)\}$, asymptotic diversity gains can be measured as $G_d \approx (3,4,5,5)$ in $[24,\ldots,28]$ dBs, so that $G_d \approx N_0 + \min(N_1, N_2)$ can be verified. Especially, $N_0 = 3, N_1 = 2, N_2 = 2$ has almost the same slope as $N_0 = 2, N_1 = 3, N_2 = 3$. As $\tilde{P}_T \to \infty$, we have $G_d = N_0 + \min(N_1, N_2)$ when $\tilde{I}_p$ is proportional to the unlimited transmission power $\tilde{P}_T$.

Fig. 5 shows several observations on the outage probability. Fixed channels are used for $\boldsymbol{h}_{N_1}^{\mathrm{S,R}}$,$\boldsymbol{h}_{N_0}^{\mathrm{S,D}}$, and $\boldsymbol{h}_{N_2}^{\mathrm{R,D}}$ with $N_0 = 2$, $N_1 = 2$, and $N_2 = 3$. For various values of (N_3, N_4) for interfering channels from the SU-source and SU-relay, $(\boldsymbol{h}_{N_3}^{\mathrm{S,P}}, \boldsymbol{h}_{N_4}^{\mathrm{R,P}})$, a better outage probability can be obtained as the multipath gain for these interfering channels increases. This better outage probability can be obtained when $\tilde{I}_p$ is proportional to the unlimited transmission power $\tilde{P}_T$. However, as seen from Fig. 6, an outage probability floor occurs when $\tilde{I}_p$ is independent of $\tilde{P}_T$. Although we can obtain a better outage probability with a larger channel size up to N_c in the secondary user network, the outage probability floor still appears. A stronger $\tilde{I}_p$ results in a better outage probability. But in this case, $\tilde{I}_p$ acts as cochannel interference in the spectrum sharing system, and therefore outage diversity cannot be achieved.

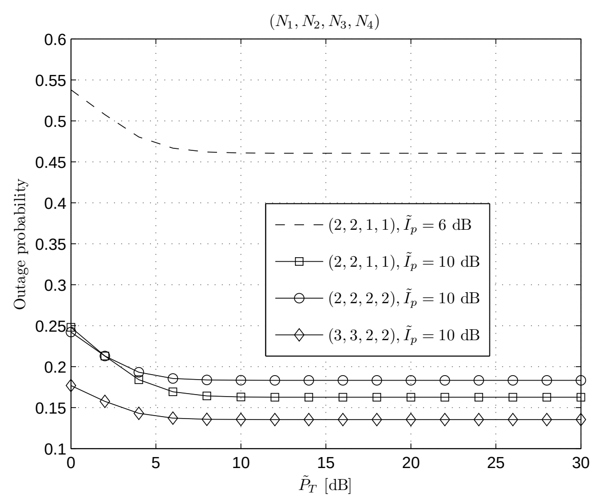

Fig. 6. Outage probability for various numbers of channel taps in the system.

For the unlimited transmission power case, we have obtained the following simulation results. Fig. 7 shows the accuracy of the analytically derived outage probability compared to the simulated outage probability. We use fixed $N_3 = N_4 = 1$. As functions of (N_0, N_1, N_2), this figure indicates that a better outage probability can be obtained as either N_0 or

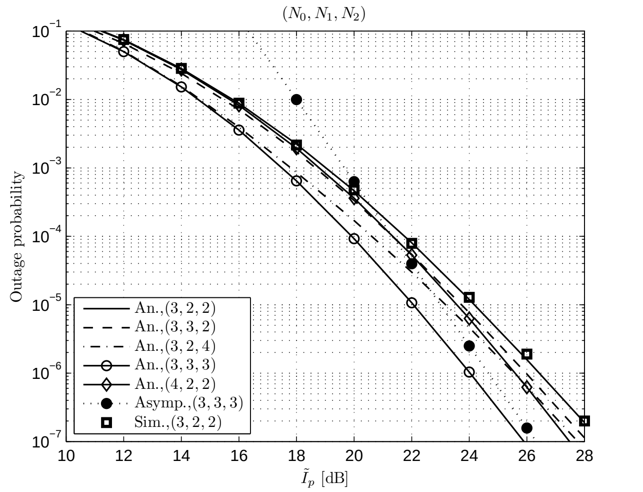

Fig. 7. Outage probability for various numbers of channel taps N_0, N_1, and N_2 in the system.

$\min(N_1, N_2)$ increases. Although outage probabilities are distinct in different sizes for N_0, N_1, and N_2, we can see that $(N_0 = 3, N_1 = 2, N_2)$ has the same slope as $(N_0 = 3, N_1 = 3, N_2 = 2)$ and $(N_0 = 3, N_1 = 2, N_2 = 4)$ since the diversity gain achieved by the DF relaying protocol is the same for these three cases. However, $(N_0 = 3, N_1 = 3, N_2 = 3)$ has a better outage probability than the other three cases due to a higher diversity gain resulting from selection combining and the DF relaying protocol. From this knowledge, the slope of $(N_0 = 4, N_1 = 2, N_2 = 2)$ is equivalent to that of $(N_0 = 3, N_1 = 3, N_2 = 3)$ in the high interference region.

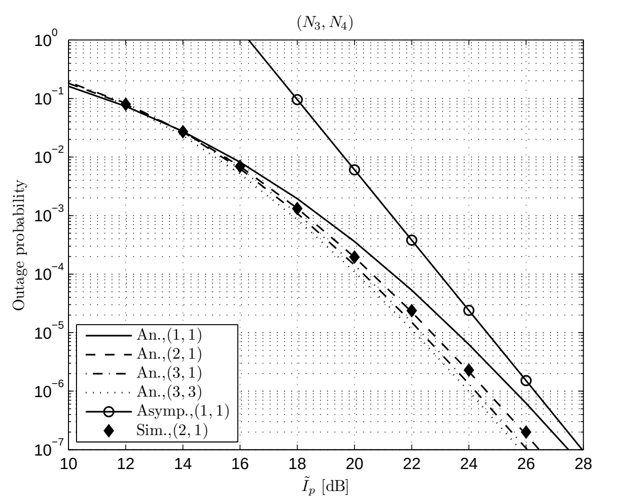

Fig. 8. Outage probability for various numbers of channel taps N_3 and N_4 in the system.

Next, we investigate the effects of N_3 and N_4 on the outage probability as in the limited transmission power. At fixed $N_0 = 4$, $N_1 = 2$, and $N_2 = 2$, Fig. 8 shows the outage probability. Although the slopes are equal for the cases $(N_3 = 1, N_4 = 1)$, $(N_3 = 2, N_4 = 1)$, $(N_3 = 3, N_4 = 1)$, and $(N_3 = 3, N_4 = 3)$ in the high interference region, a better outage probability can be obtained as any of (N_3, N_4) increases. With measuring slopes in Fig. 7 and Fig. 8, we can show the diversity gain $\tilde{G}_d = N_0 + \min(N_1, N_2)$. In this case, outage probability floors are not observed as in the limited transmission power case.

VI. Conclusions

In this paper, we have exploited the cooperative diversity for cyclic prefixed single-carrier systems in a spectrum sharing environment with the DF relaying protocol. For this purpose, we have derived closed-form expressions for the CDFs in unlimited transmission power and limited transmission power cases. Corresponding asymptotic CDFs of the e2e-SNRs have been derived also to obtain an asymptotic outage diversity. When the interference is proportional to the limited transmission power, the achievable outage diversity is shown to be equivalent to the diversity gain for the system with an unlimited transmission power. From the mathematical derivation and simulations, it has been verified that the multipath diversity gain of the CP-SC system determines the outage diversity gain of the spectrum sharing CP-SC system under constraints on the maximum allowable interference in the primary user and on the transmission power.

Appendix A
Proof of Lemma 2

Since $\gamma_{r,d}$ is independent of φ_3, we obtain (A.1) at the top of the next page. Substituting $f_{\varphi_4}(x) = \frac{1}{\rho^{N_4}\Gamma(N_4)} e^{-\frac{x}{\rho}} x^{N_4-1} \mathrm{U}(x)$, $F_{\varphi_2}\left(\frac{a_4\gamma x}{a_{2,I}}\right) = \frac{\gamma(N_4, \frac{a_4\gamma x}{\rho a_{2,I}})}{\Gamma(N_2)}$, and $F_{\varphi_2}\left(\frac{\gamma}{a_{2,P}}\right) = \frac{\gamma(N_2, \frac{\gamma}{\rho a_{2,P}})}{\Gamma(N_2)}$ into (A.1) and using [31, Eq. (8.351.2)], we obtain (11).

Appendix B
Proof of Theorem 1

From (7), it is given that

$$F_{\gamma_d}(\gamma|\varphi_3) = F_{\gamma_{DF}}(\gamma|\varphi_3)\, F_{\gamma_0}(\gamma|\varphi_3). \tag{B.1}$$

Using (12) and (13), (B.1) yields

$$F_{\gamma_d}(\gamma|\varphi_3) = \begin{cases} F_{\varphi_0}\left(\frac{\gamma}{a_{0,P}}\right)\left(1 - \left[1 - F_{\varphi_1}\left(\frac{\gamma}{a_{1,P}}\right)\right]\left[1 - F_{\gamma_{r,d}}(\gamma)\right]\right) \\ \text{if } \varphi_3 \le \gamma_T, \\ F_{\varphi_0}\left(\frac{(a_3\gamma\varphi_3)}{a_{0,I}}\right)\left(1 - \left[1 - F_{\varphi_1}\left(\frac{(a_3\gamma\varphi_3)}{a_{1,I}}\right)\right]\left[1 - F_{\gamma_{r,d}}(\gamma)\right]\right) \\ \text{if } \varphi_3 \ge \gamma_T. \end{cases} \tag{B.2}$$

Now the unconditional $F_{\gamma_d}(\gamma)$ is evaluated as (B.3) at the top of the next page. In (B.3), we define

$$I_0 \triangleq F_{\varphi_0}\left(\frac{\gamma}{a_{0,P}}\right) \left(1 - \left[1 - F_{\varphi_1}\left(\frac{\gamma}{a_{1,P}}\right)\right]\left[1 - F_{\gamma_{r,d}}(\gamma)\right]\right) F_{\varphi_3}(\gamma_T). \tag{B.4}$$

$$\begin{aligned}
F_{\gamma_{r,d}}(\gamma|\varphi_3) &= F_{\gamma_{r,d}}(\gamma) P_r\left(\varphi_2 \le \frac{\gamma}{a_{2,P}}, \frac{\tilde{I}_p}{\varphi_4} \ge a_{4,P}\right) + P_r\left(\frac{\varphi_2}{\varphi_4} \le \frac{a_4\gamma}{a_{2,I}}, \frac{\tilde{I}_p}{\varphi_4} \le a_{4,P}\right) \\
&= P_r\left(\varphi_2 \le \frac{\gamma}{a_{2,P}}\right) P_r\left(\varphi_4 \le \frac{\tilde{I}_p}{a_{4,P}}\right) + P_r\left(\varphi_2 \le \frac{a_4\gamma\varphi_4}{a_{2,I}}, \varphi_4 \ge \frac{\tilde{I}_p}{a_{4,P}}\right) \\
&= F_{\varphi_2}\left(\frac{\gamma}{a_{2,P}}\right) F_{\varphi_4}\left(\frac{\tilde{I}_p}{a_{4,P}}\right) + \int_{\frac{\tilde{I}_p}{a_{4,P}}}^{\infty} f_{\varphi_4}(x) \int_0^{\frac{a_4\gamma x}{a_{2,I}}} f_{\varphi_2}(y)\, dy dx \\
&= \frac{\gamma(N_2, \frac{\gamma}{\rho a_{2,P}})}{\Gamma(N_2)} \frac{\gamma(N_4, \frac{\tilde{I}_p}{\rho a_{4,P}})}{\Gamma(N_4)} + \int_{\frac{I_p}{a_{4,P}}}^{\infty} f_{\varphi_4}(x) \int_0^{\frac{a_4\gamma x}{a_{2,I}}} f_{\varphi_2}(y)\, dy dx \\
&= \frac{\gamma(N_2, \frac{\gamma}{\rho a_{2,P}})}{\Gamma(N_2)} \frac{\gamma(N_4, \frac{\tilde{I}_p}{\rho a_{4,P}})}{\Gamma(N_4)} + \int_{\frac{\tilde{I}_p}{a_{4,P}}}^{\infty} f_{\varphi_4}(x) F_{\varphi_2}\left(\frac{a_4\gamma x}{a_{2,I}}\right) dx. \qquad \text{(A.1)}
\end{aligned}$$

$$\begin{aligned}
F_{\gamma_d}(\gamma) = &\int_0^{\gamma_T} F_{\varphi_0}\left(\frac{\gamma}{a_{0,P}}\right)\left(1 - \left[1 - F_{\varphi_1}\left(\frac{\gamma}{a_{1,P}}\right)\right]\left[1 - F_{\gamma_{r,d}}(\gamma)\right]\right) f_{\varphi_3}(x)\, dx + \\
&\int_{\gamma_T}^{\infty} F_{\varphi_0}\left(\frac{a_3\gamma x}{a_{0,I}}\right)\left(1 - \left[1 - F_{\varphi_1}\left(\frac{a_3\gamma x}{a_{1,I}}\right)\right]\left[1 - F_{\gamma_{r,d}}(\gamma)\right]\right) f_{\varphi_3}(x)\, dx \\
&= F_{\varphi_0}\left(\frac{\gamma}{a_{0,P}}\right)\left(1 - \left[1 - F_{\varphi_1}\left(\frac{\gamma}{a_{1,P}}\right)\right]\left[1 - F_{\gamma_{r,d}}(\gamma)\right]\right) F_{\varphi_3}(\gamma_T) + \int_{\gamma_T}^{\infty}\left[1 - e^{-\frac{a_3\gamma x}{\rho a_{0,I}}} \sum_{i=0}^{N_0-1} \frac{1}{i!}\left(\frac{a_3\gamma x}{\rho a_{0,I}}\right)^i\right] \\
&\left[1 - \left[1 - F_{\gamma_{r,d}}(\gamma)\right] e^{-\frac{a_3\gamma x}{\rho a_{1,I}}} \sum_{j=0}^{N_1-1} \frac{1}{j!}\left(\frac{a_3\gamma x}{\rho a_{1,I}}\right)^j\right] f_{\varphi_3}(x)\, dx \\
&= I_0 + I_1 - I_2 + I_3 + I_4. \qquad \text{(B.3)}
\end{aligned}$$

Using the expression for $f_{\varphi_3}(x)$ and [31, Eq. (8.351.2)], we can derive the following terms:

$$\begin{aligned}
I_1 &\triangleq \int_{\gamma_T}^{\infty} f_{\varphi_3}(x)\, dx, \\
I_2 &\triangleq \left[1 - F_{\gamma_{r,d}}(\gamma)\right] \sum_{j=0}^{N_1-1} \frac{1}{j!}\left(\frac{a_3\gamma}{\rho a_{1,I}}\right)^j \\
&\quad \int_{\gamma_T}^{\infty} e^{-\left(\frac{a_3\gamma x}{\rho a_{1,I}}\right)x} x^j f_{\varphi_3}(x)\, dx \\
&= \left[1 - F_{\gamma_{r,d}}(\gamma)\right] \sum_{j=0}^{N_1-1} \frac{1}{\Gamma(N_3) j!}\left(\frac{a_3\gamma}{a_{1,I}}\right)^j \\
&\quad \left(1 + \frac{a_3\gamma}{a_{1,I}}\right)^{-(N_3+j)} \Gamma\left(N_3 + j, \left(1 + \frac{a_3\gamma}{a_{1,I}}\right)\left(\frac{\gamma_T}{\rho}\right)\right), \\
I_3 &\triangleq \sum_{i=0}^{N_0-1} \frac{1}{i!}\left(\frac{a_3\gamma}{\rho a_{0,I}}\right)^i \int_{\gamma_T}^{\infty} e^{-\left(\frac{a_3\gamma}{\rho a_{0,I}}\right)x} x^i f_{\varphi_3}(x)\, dx \\
&= \sum_{i=0}^{N_0-1} \frac{1}{\Gamma(N_3) i!}\left(\frac{a_3\gamma}{a_{0,I}}\right)^i \left(1 + \frac{a_3\gamma}{a_{0,I}}\right)^{-(N_3+i)} \\
&\quad \Gamma\left(N_3 + i, \left(1 + \frac{a_3\gamma}{a_0\tilde{I}_p}\right)\left(\frac{\gamma_T}{\rho}\right)\right), \text{ and} \\
I_4 &\triangleq \left[1 - F_{\gamma_{r,d}}(\gamma)\right] \sum_{i=0}^{N_0-1} \sum_{j=0}^{N_1-1} \frac{1}{i! j!}\left(\frac{a_3\gamma}{\rho a_{1,I}}\right)^j \left(\frac{a_3\gamma}{\rho a_{0,I}}\right)^i \\
&\quad \int_{\gamma_T}^{\infty} e^{-\left(\frac{a_3\gamma}{\rho a_{0,I}} + \frac{a_3\gamma}{\rho a_{1,I}}\right)x} x^{i+j} f_{\varphi_3}(x)\, dx
\end{aligned}$$

APPENDIX C
PROOF OF (28)

From (B.3), it is given that $F_{\gamma_d}(\gamma)$ for $\varphi_3 \le \gamma_T$

$$\begin{aligned}
F_{\gamma_d}(\gamma) &= F_{\varphi_0}\left(\frac{\gamma}{a_{0,P}}\right) \\
&\left(1 - \left[1 - F_{\varphi_1}\left(\frac{\gamma}{a_{1,P}}\right)\right]\left[1 - F_{\gamma_{r,d}}(\gamma)\right]\right) F_{\varphi_3}(\gamma_T) \qquad \text{(C.1)}
\end{aligned}$$

As $\tilde{P}_T \to \infty$, an asymptotic expression of $F_{\gamma_d}(\gamma)$ is given at the top of the next page. In (C.2), we define $X_0 \triangleq \frac{1}{\Gamma(N_0+1)}\left(\frac{1}{\rho a_0}\right)^{N_0}$ and $X_1 \triangleq \frac{1}{\Gamma(N_1+1)}\left(\frac{1}{\rho a_1}\right)^{N_1}$. From (A.1), an asymptotic $F_{\gamma_{r,d}}(\gamma)$ is evaluated as follows:

$$\begin{aligned}
&F_{\bar{\gamma}_{r,d}}(\gamma) \\
&\approx \frac{\gamma(N_4, \frac{\mu}{\rho a_4})}{\Gamma(N_4)} F_{\bar{\varphi}_2}\left(\frac{\gamma}{a_{2,P}}\right) + \int_{\frac{\tilde{I}_p}{a_{4,P}}}^{\infty} f_{\varphi_4}(x) F_{\bar{\varphi}_2}\left(\frac{a_4\gamma x}{a_{2,I}}\right) dx \\
&= X_2\left(\frac{\gamma}{\tilde{P}_T}\right)^{N_2} \qquad \text{(C.3)}
\end{aligned}$$

$$\begin{aligned} F_{\gamma_d}(\gamma) &= F_{\varphi_0}\left(\frac{\gamma}{a_{0,P}}\right)\left(1-\left[1-F_{\varphi_1}\left(\frac{\gamma}{a_{1,P}}\right)\right]\left[1-F_{\gamma_{r,d}}(\gamma)\right]\right)F_{\varphi_3}\left(\frac{\tilde{I}_p}{a_{3,P}}\right) \\ &= F_{\varphi_0}\left(\frac{\gamma}{a_{0,P}}\right)\left(F_{\varphi_1}\left(\frac{\gamma}{a_{1,P}}\right)+F_{\gamma_{r,d}}(\gamma)-F_{\varphi_1}\left(\frac{\gamma}{a_{1,P}}\right)F_{\gamma_{r,d}}(\gamma)\right)F_{\varphi_3}\left(\frac{\tilde{I}_p}{a_{3,P}}\right) \\ &\approx F_{\varphi_0}\left(\frac{\gamma}{a_{0,P}}\right)\left(F_{\varphi_1}\left(\frac{\gamma}{a_{1,P}}\right)+F_{\gamma_{r,d}}(\gamma)\right)F_{\varphi_3}\left(\frac{\tilde{I}_p}{a_{3,P}}\right) \\ &\approx X_0\left(\frac{\gamma}{\tilde{P}_T}\right)^{N_0}\left(X_1\left(\frac{\gamma}{\tilde{P}_T}\right)^{N_1}+F_{\gamma_{r,d}}(\gamma)\right)F_{\varphi_3}\left(\frac{\tilde{I}_p}{a_{3,P}}\right). \end{aligned} \tag{C.2}$$

where

$$X_2 \triangleq \left(\frac{\gamma(N_4, \frac{\mu}{\rho a_4})}{\Gamma(N_4)}\frac{1}{\Gamma(N_2+1)}\left(\frac{1}{\rho a_2}\right)^{N_2} + \frac{\Gamma\left(N_4+N_2, \frac{\tilde{I}_p}{\rho a_{4,P}}\right)}{\Gamma(N_4)\Gamma(N_2+1)}\left(\frac{a_4}{a_2\mu}\right)^{N_2}\right). \tag{C.4}$$

Now substituting (C.3) into (C.2), we obtain

$$\begin{aligned} &F_{\bar{\gamma}_d}(\gamma) \\ &= F_{\varphi_3}\left(\frac{\mu}{a_3}\right)X_0\left(\frac{\gamma}{\tilde{P}_T}\right)^{N_0}\left(X_1\left(\frac{\gamma}{\tilde{P}_T}\right)^{N_1}+X_2\left(\frac{\gamma}{\tilde{P}_T}\right)^{N_2}\right) \\ &= Y_0X_0X_1\left(\frac{\gamma}{\tilde{P}_T}\right)^{N_0+N_1}+Y_0X_0X_2\left(\frac{\gamma}{\tilde{P}_T}\right)^{N_0+N_2}. \end{aligned} \tag{C.5}$$

Again using (B.3), it is given that $F_{\gamma_d}(\gamma)$ for $\varphi_3 \geq \gamma_T$

$$\begin{aligned} &F_{\gamma_d}(\gamma) = \\ &\int_{\gamma_T}^{\infty} F_{\varphi_0}\left(\frac{a_3\gamma x}{a_{0,I}}\right)\left(1-\left[1-F_{\varphi_1}\left(\frac{a_3\gamma x}{a_{1,I}}\right)\right]\right. \\ &\quad\left.\left[1-F_{\gamma_{r,d}}(\gamma)\right]\right)f_{\varphi_3}(x)\,dx \end{aligned} \tag{C.6}$$

which is equivalent to

$$\begin{aligned} &F_{\gamma_d}(\gamma) \\ &= \int_{\gamma_T}^{\infty} F_{\varphi_0}\left(\frac{a_3\gamma x}{a_{0,I}}\right)\left(F_{\varphi_1}\left(\frac{a_3\gamma x}{a_{1,I}}\right)+\right. \\ &\quad\left.F_{\gamma_{r,d}}(\gamma)-F_{\varphi_1}\left(\frac{a_3\gamma x}{a_{1,I}}\right)F_{\gamma_{r,d}}(\gamma)\right)f_{\varphi_3}(x)\,dx \\ &\approx \int_{\gamma_T}^{\infty} F_{\varphi_0}\left(\frac{a_3\gamma x}{a_{0,I}}\right)\left(F_{\varphi_1}\left(\frac{a_3\gamma x}{a_{1,I}}\right)+F_{\gamma_{r,d}}(\gamma)\right) \\ &\quad f_{\varphi_3}(x)\,dx. \end{aligned} \tag{C.7}$$

Now we can compute

$$F_{\bar{\varphi}_0}\left(\frac{a_3\gamma x}{a_{0,I}}\right) = X_0\left(\frac{a_3}{\mu}\right)^{N_0}\left(\frac{\gamma x}{\tilde{P}_T}\right)^{N_0} \tag{C.8}$$

and

$$F_{\bar{\varphi}_1}\left(\frac{a_3\gamma x}{a_{1,I}}\right) = X_1\left(\frac{a_3}{\mu}\right)^{N_1}\left(\frac{\gamma x}{\tilde{P}_T}\right)^{N_1}. \tag{C.9}$$

Upon applying (C.3) in (C.7), the following asymptotic CDF is obtained:

$$\begin{aligned} &F_{\bar{\gamma}_d}(\gamma) \\ &= \int_{\gamma_T}^{\infty} X_0\left(\frac{a_3}{\mu}\right)^{N_0}\left(\frac{\gamma x}{\tilde{P}_T}\right)^{N_0}\left(X_1\left(\frac{a_3}{\mu}\right)^{N_1}\left(\frac{\gamma x}{\tilde{P}_T}\right)^{N_1}+\right. \\ &\left.\left(\frac{\gamma}{\tilde{P}_T}\right)^{N_2}\right)f_{\varphi_3}(x)\,dx. \end{aligned} \tag{C.10}$$

Using again [31, Eq. (8.351.2)], (C.10) is evaluated as follows:

$$\begin{aligned} &F_{\bar{\gamma}_d}(\gamma) \\ &= \frac{\rho^{N_0+N_1}X_0X_1}{\Gamma(N_3)}\left(\frac{a_3}{\mu}\right)^{N_0+N_1}\Gamma\left(N_0+N_1+N_3, \frac{\gamma_T}{\rho}\right) \\ &\quad\left(\frac{\gamma}{\tilde{P}_T}\right)^{N_0+N_1}+\frac{\rho^{N_0}X_0X_2}{\Gamma(N_3)}\left(\frac{a_3}{\mu}\right)^{N_0} \\ &\quad\Gamma\left(N_0+N_3, \frac{\gamma_T}{\rho}\right)\left(\frac{\gamma}{\tilde{P}_T}\right)^{N_0+N_2} \\ &= Y_1X_0X_1\left(\frac{\gamma x}{\tilde{P}_T}\right)^{N_0+N_1}+Y_2X_0X_2\left(\frac{\gamma x}{\tilde{P}_T}\right)^{N_0+N_2}. \end{aligned} \tag{C.11}$$

APPENDIX D
PROOF OF THEOREM 4

As we know, $\tilde{F}_{\bar{\gamma}_{s,r}}(\gamma|\varphi_3) = \frac{1}{\Gamma(N_1+1)}\left(\frac{a_3\varphi_3}{\rho a_{1,I}}\right)^{N_1}$ and

$$\begin{aligned} \tilde{F}_{\bar{\gamma}_{r,d}}(\gamma|\varphi_3) &= \int_0^{\infty} F_{\bar{\varphi}_2}\left(\frac{a_4\gamma x}{a_{2,I}}\right)f_{\varphi_4}(x)\,dx \\ &\approx \int_0^{\infty}\frac{1}{\Gamma(N_2+1)}\left(\frac{a_4\gamma x}{\rho a_{2,I}}\right)^{N_2}\frac{x^{N_4-1}e^{-\frac{x}{\rho}}}{\Gamma(N_4)\rho^{N_4}}dx \\ &= \frac{\Gamma(N_4+N_2)}{\Gamma(N_2+1)\Gamma(N_4)}\left(\frac{a_4\gamma}{a_{2,I}}\right)^{N_2}. \end{aligned} \tag{D.1}$$

The CDF of $\min(\bar{\gamma}_{s,r}, \bar{\gamma}_{r,d})$ is also approximated as $\tilde{F}_{\min(\bar{\gamma}_{s,r},\bar{\gamma}_{r,d})}(\gamma|\varphi_3) \approx \tilde{F}_{\bar{\gamma}_{s,r}}(\gamma|\varphi_3) + \tilde{F}_{\bar{\gamma}_{r,d}}(\gamma|\varphi_3) = \frac{1}{\Gamma(N_1+1)}\left(\frac{a_3\varphi_3}{\rho a_{1,I}}\right)^{N_1} + \frac{\Gamma(N_4+N_2)}{\Gamma(N_2+1)\Gamma(N_4)}\left(\frac{a_4\gamma}{a_{2,I}}\right)^{N_2}$. Again approximating $\tilde{F}_{\bar{\gamma}_0}(\gamma|\varphi_3) \approx \frac{1}{\Gamma(N_0+1)}\left(\frac{a_3\gamma\varphi_3}{\rho a_{0,I}}\right)^{N_0}$, results in

$$\begin{aligned} \tilde{F}_{\bar{\gamma}_d}(\gamma) &= \int_0^{\infty}\tilde{F}_{\min(\bar{\gamma}_{s,r},\bar{\gamma}_{r,d})}(\gamma|x)\tilde{F}_{\bar{\gamma}_0}(\gamma|x)f_{\varphi_3}(x)\,dx \\ &= Z_0\left(\frac{\gamma_{th}}{\tilde{I}_p}\right)^{N_0+N_1}+Z_1\left(\frac{\gamma_{th}}{\tilde{I}_p}\right)^{N_0+N_2}. \end{aligned} \tag{D.2}$$

Thus, we compute $\tilde{P}_{out}^{as} = \tilde{F}_{\tilde{\gamma}_d}(\gamma_{th})$, and then $\tilde{G}_d = -\lim_{\tilde{I}_p\to\infty} \frac{\log(\tilde{P}_{out}^{as}(\gamma_{th}))}{\log(\tilde{I}_p)} = N_0 + \min(N_1, N_2)$, which proves Theorem 4.

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