Secrecy Performance of Threshold-Based Cognitive Relay Network With Diversity Combining

Khyati Chopra, Ranjan Bose, and Anupam Joshi

Abstract: **In the spectrum sharing mode, the transmitting power of the secondary user (SU) is optimally controlled, such that no additional interference occurs at the primary user (PU). In this paper, the secrecy outage performance is analyzed for such cognitive underlay decode-and-forward (DF) threshold-based relay network. The relayed and the direct signals are combined at the secondary eavesdropper and destination. Unlike other works to date, we have used both selection combining (SC) and maximal ratio combining (MRC) diversity schemes at the destination and eavesdropper with all possible permutations, and the best possible combination for cognitive system secrecy has been validated. Further, we consider threshold-based relaying where, the relay can successfully decode and re-transmit, only if the received signal-to-noise ratio (SNR) meets the particular threshold. We show that the diversity scheme, the threshold SNR, the secrecy rate, and the interference power all have a significant impact on cognitive system secrecy. We have also shown that the secrecy performance is more sensitive to changes in the quality of direct link between source to eavesdropper than source to destination, especially at the higher secrecy rates. The accuracy of the analytical expressions is corroborated by the computer simulation results.**

Index Terms: **Cognitive relay network, maximal ratio combining, selection combining, secrecy outage probability, threshold-based.**

I. Introduction

THE spectrum resources are exhausted due to the unparalleled increase in various wireless communication services. To opportunistically exploit the existing wireless spectrum, cognitive radio (CR) has emerged as a new communication paradigm for future high-coverage, high-capacity and multitier hierarchical networks [1, 2]. The spectrum is shared without any performance degradation of primary users (PUs), by considering that the received interference remains below the predefined interference threshold level at the PU receiver (PU-Rx) [3–5]. The unused spectrum can be efficiently utilized by cognitive radio specifically in underlay [5, 6], for concurrently transmitting data of secondary users (SUs) in the same spectrum band, which is licensed to PUs [3, 4]. The peak interference type of power control modeling for characterizing the underlay cognitive radio network (CRN) has been discussed in [3, 4, 7]. However, due to the highly dynamic nature of the CR network architecture, CR devices are extremely vulnerable to the malicious behavior [2, 3]. Therefore, to ensure a reliable and secure data transmission, critical attention has been given in the literature to applications of the security issues in CRNs [2–4, 6, 8, 9]. Information-theoretic security or physical layer security (PLS) has been developed as an effective secure wireless communications paradigm [3, 4, 10–12], the theoretical foundation of which was laid by Wyner [13].

Diversity is an effective technique to combat the performance degradation in wireless communication systems caused due to fading. Cooperative diversity is incorporated in a multi-path fading environment with the help of relay nodes, to improve the communication reliability and throughput [10, 14, 15]. Maximal ratio combining (MRC) and selection combining (SC) are the diversity combining techniques, where the relayed signals as well as the signal from the source are combined to obtain the diversity gain [14]. Diversity reception scheme such as transmit antenna selection (TAS)/maximal ratio combining is discussed in [16] under high SNR regimes, for security enhancement in multiple-input multiple-output (MIMO) CRNs. High SNR analysis is carried out in [16], while, on the contrary, threshold-based relaying is considered in our work. Authors in [17] have studied secure switch-and-stay combining (SSSC) for two-phase underlay CRN. Unlike our study, direct links from the source to destination and eavesdropper are assumed to be in severe shadowing environments and thus non-existent in [17]. Authors in [18] have studied the secrecy performance of a half-duplex cognitive relay network. In [19], authors have considered physical-layer security protocols in multicast cognitive radio networks. Both in [18, 19], the direct link only between source and eavesdropper is taken into account, while the direct source to destination link is not available.

On the other hand, high SNR approximation is typically considered in the prior literature [16, 20–25], where perfect decoding is assumed at each relay. However, for all the SNR regimes, this assumption might not be appropriate. Decoding error can occur in the system, as the signal strength might be degraded due to fading effect, such that the message is not correctly decoded by the relay. The secrecy performance of the cooperative system is thus affected by the quality of both source-relay and relay-destination link [10, 12, 26]. Whereas, high SNR assumption neglects the effect of the first hop link quality, which can actually be a bottleneck for secrecy performance in the cooperative communication [10, 12, 26]. To address the impact of source-relay link on the system secrecy in a better way , threshold-based relaying has been recently introduced, where, perfect decoding at the relay is only possible if the received signal-to-noise ratio (SNR) at the relay meets the particular threshold [7, 10, 26]. Though the problems of secrecy in CRNs have been addressed by the researchers, the effect of threshold-based relaying and di-

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versity reception has yet not been well understood [27–30]. For mathematical simplicity, the combination of the relayed and the direct signal is not considered in the prior literature [17, 27–30], by assuming that the direct link is in deep shadowing , which is practically not desirable in CRNs. This is because intuitively, due to the interference constraints from the primary user, the source power is random in nature, which indicates that the direct signal path might not be weak always, and therefore it should be considered [7, 31]. Consequently, the QoS needs to be maintained by the relay in underlay CRNs, and it is thus employed even for short distance communication [31]. Recently, our works in [7], studied the secrecy performance of threshold-based cognitive multi-relay system, with direct link only between secondary source and eavesdropper. The more practical scenario would be to include both source to eavesdropper and source to destination direct signal paths, such that two independent versions of the source message can be accessed to employ diversity combining techniques.

Our study is thus significantly different from the others discussed in the literature [3, 10, 18, 19, 27–29, 31–33], as it is motivated to reasonably examine the joint impact of the relayed and direct signal paths on cognitive system secrecy at both the destination and eavesdropper. We have hence presented a detailed and comprehensive secrecy analysis of employing both MRC and SC diversity receivers at the secondary destination and eavesdropper with all possible permutations, and have justified the best possible combination for secrecy of underlay cognitive relay system. It has been shown that how the direct signal paths have a significant impact on the cognitive system secrecy and the secrecy performance becomes more sensitive to the channel quality of source to eavesdropper than source to destination, especially at the higher secrecy rates. To further account for the effect of first hop link quality on system secrecy, threshold-based relaying has also been considered in this paper. We have organized the rest of our paper as follows. Section II describes the underlay cognitive relay threshold-based system model. The outage probability of the cognitive relay system with SC and MRC diversity schemes is evaluated in Section III. In Section IV, numerical results are discussed to support the analytical expressions. Section V concludes this study.

II. System Model

We consider a secondary source SS, that transmits its information to a secondary destination SD, through a single DF secondary relay SR, working in a dual-hop mode as shown in the Fig.1, in the presence of a secondary eavesdropper SE. In this underlay cognitive spectrum sharing, the transmission over the same spectrum by SU and PU are allowed, till there is no detection problem at the primary destination PD, due to the interference caused by the SU [3, 4, 32]. This constraint the powers of SS and SR, such that the interference received at PD should be lower than the maximum tolerable interference power level I_p. In addition, the maximum transmit power constraint is also considered, such that SS and SR powers are less than P, where P is taken as the maximum transmit power [3, 4, 7, 32]. Using both maximum transmit power and interference constraints , the SS and SR powers are limited as
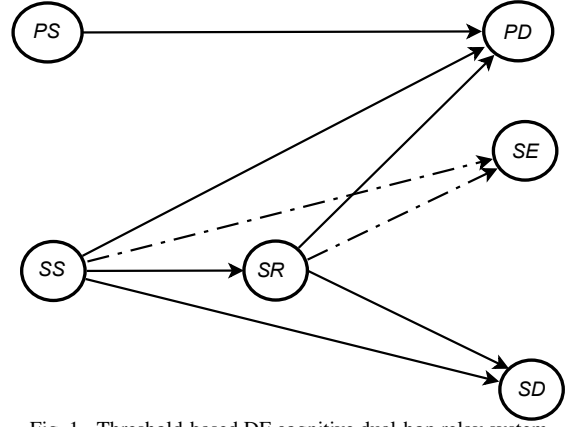

Fig. 1. Threshold-based DF cognitive dual-hop relay system.

$P_s \leq \min\left(\frac{I_p}{|h_{sp}|^2}, P\right), P_r \leq \min\left(\frac{I_p}{|h_{rp}|^2}, P\right)$ respectively. For extremely large values of P, the transmit powers P_s and P_r of SS and SR are modeled as $P_s = \frac{I_p}{|h_{sp}|^2}, P_r = \frac{I_p}{|h_{rp}|^2}$. This peak interference type of power control modeling for characterizing the underlay cognitive network is assumed in our work, which is also widely used in prior literature [3, 4, 7, 32]. We have not ignored the presence of direct $SS - SD$ and $SS - SE$ links in our cognitive system. The random nature of source powers due to interference constraints in the dual-hop CRN, indicates that the direct path signal might not be weak always, and therefore it should be considered [31]. The links between various nodes work in half-duplex mode in our system model and we have modeled them as Rayleigh flat fading mutually independent channels.

The SNR Γ_{xy} , between any two random nodes such as x and y [10, 12] , is given by

$$\Gamma_{xy} = \frac{P_x |h_{xy}|^2}{N_{0_y}}, \tag{1}$$

where the transmit power is denoted by P_x at the node x , the noise variance is given by N_{0_y} at the node y for additive white Gaussian noise (AWGN) . Γ_{xy} is exponentially distributed and $1/\beta_{xy}$ is taken as the mean value, as h_{xy} is Rayleigh distributed, [34]. It is given as $\Gamma_{xy} \sim \mathcal{E}\left(\beta_{\S\dagger}\right)$, where β_{xy} is taken as the parameter of exponential distribution. The $SS - SR$ channels h_{sr}, $SR - SD$ channels h_{rd}, $SR - SE$ channels h_{re}, $SS - PD$ channels h_{sp}, $SR - PD$ channels h_{rp}, $SS - SD$ channels h_{sd} , and $SS - SE$ channels h_{se}, are slowly varying Rayleigh flat fading channels [10, 12]. Without loss of generality, let N_{sr}, N_{rd}, N_{re}, N_{sp}, N_{rp}, N_{sd} and N_{se} denote the variances of AWGN for $SS - SR$, $SR - SD$, $SR - SE$, $SS - PD$, $SR - PD$, $SS - SD$ and $SS - SE$ links respectively. The SNRs Γ_{sr} , Γ_{rd}, Γ_{re}, Γ_{sp}, Γ_{rp}, Γ_{sd} and Γ_{se} are exponentially distributed which can be represented using (1), with link quality taken as $\gamma_{sr} = \frac{|h_{sr}|^2}{N_{sr}}$, $\gamma_{rd} = \frac{|h_{rd}|^2}{N_{rd}}$, $\gamma_{re} = \frac{|h_{re}|^2}{N_{re}}$, $\gamma_{sd} = \frac{|h_{sd}|^2}{N_{sd}}$, $\gamma_{se} = \frac{|h_{se}|^2}{N_{se}}$, $\gamma_{sp} = |h_{sp}|^2$ and $\gamma_{rp} = |h_{rp}|^2$, with average values $1/\beta_{sr}$, $1/\beta_{rd}$, $1/\alpha_{re}$, $1/\beta_{sd}$, $1/\alpha_{se}$, $1/\theta_{sp}$ and $1/\theta_{rp}$ respectively, where the parameters of exponential distribution are β_{sr}, β_{rd}, α_{re}, β_{sd}, α_{se}, θ_{sp} and θ_{rp}.

When instantaneous secrecy rate of this cooperative relay system becomes lower than the required secrecy rate, given as R_s

where, $R_s > 0$ and $\rho = 2^{2R_s}$ [10, 35], an outage event occurs. ρ is used for directly mapping R_s, and the outage probability P_o, is taken as the probability that this outage event has successfully occurred [10, 12]. Without assuming correct decoding at the relay, here we take into consideration that the relay can perfectly decode and re-transmit the message, only if the received SNR meets the particular threshold SNR, taken as γ_{th} for the $SS - SR$ link [10, 21].

Achievable secrecy rate is given as the difference between the information rate of main channel and eavesdropper channel [10, 12, 13]

$$C_s \triangleq \frac{1}{2}\left[\log_2\left(\frac{1 + \Gamma_M}{1 + \Gamma_E}\right)\right]^+, \tag{2}$$

where $(x)^+ \triangleq \max(0, x)$, Γ_M and Γ_E are the respective SNRs at SD and SE. Here, the 1/2 term denotes that in order to finish the dual-hop transmission process, we require two time phase. The relay decodes the message transmitted by the source, in the first time phase. In the second time phase, the message is re-encoded and forwarded by relay to the receiver.

For the random variable Z, which is exponentially distributed with parameter β_{ab}, the CDF is given as

$$F_Z(z) = \mathbb{P}[Z \leq z]$$
$$= 1 - e^{-z\beta_{ab}}, \tag{3}$$

and the corresponding PDF is obtained by differentiating (3) with respect to z as

$$f_Z(z) = \beta_{ab}e^{-z\beta_{ab}}. \tag{4}$$

For MRC, the random variable Z is the sum of two random variables A and B, i.e., $Z = A + B$ where A and B are exponentially distributed with parameters β_{ab} and $\beta_{a'b'}$, the CDF is given as

$$F_Z(z) = \mathbb{P}[A + B \leq z]$$
$$= \mathbb{P}[A \leq z - B]$$
$$= 1 - \frac{\beta_{a'b'}e^{-z\beta_{ab}}}{\beta_{a'b'} - \beta_{ab}} - \frac{\beta_{ab}e^{-z\beta_{a'b'}}}{\beta_{ab} - \beta_{a'b'}}, \tag{5}$$

and the corresponding PDF is obtained by differentiating (5) with respect to z as

$$f_Z(z) = \frac{\beta_{a'b'}\beta_{ab}e^{-z\beta_{ab}}}{\beta_{a'b'} - \beta_{ab}} + \frac{\beta_{ab}\beta_{a'b'}e^{-z\beta_{a'b'}}}{\beta_{ab} - \beta_{a'b'}}. \tag{6}$$

For SC, the random variable Z is the max of two random variables A and B, i.e., $Z = \max(A, B)$ where A and B are exponentially distributed with parameters β_{ab} and $\beta_{a'b'}$, the CDF is given as

$$F_Z(z) = \mathbb{P}[\max(A, B) \leq z]$$
$$= \mathbb{P}[A \leq z]\mathbb{P}[B \leq z]$$
$$= 1 - e^{-z\beta_{ab}} - e^{-z\beta_{a'b'}} + e^{-z(\beta_{ab}+\beta_{a'b'})}, \tag{7}$$

and the corresponding PDF is obtained by differentiating (7)

with respect to z as

$$f_Z(z) = \beta_{ab}e^{-z\beta_{ab}} + \beta_{a'b'}e^{-z\beta_{a'b'}}$$
$$- (\beta_{ab} + \beta_{a'b'})e^{-z(\beta_{ab}+\beta_{a'b'})}. \tag{8}$$

We have investigated four scenarios in our study. First is when SC diversity scheme is employed at both SD and SE, such that when $\Gamma_{sr} \geq \gamma_{th}$, the relay correctly decodes the message and $\Gamma_M^{SC} = \max(\Gamma_{rd}, \Gamma_{sd})$ is the SNR at SD and $\Gamma_E^{SC} = \max(\Gamma_{re}, \Gamma_{se})$ is the SNR at SE. The second is when SC diversity scheme is employed at SD and MRC diversity scheme is employed at SE, such that when $\Gamma_{sr} \geq \gamma_{th}$, the relay correctly decodes the message and $\Gamma_M^{SC} = \max(\Gamma_{rd}, \Gamma_{sd})$ is the SNR at SD and $\Gamma_E^{MRC} = \Gamma_{re} + \Gamma_{se}$ is the SNR at SE. The third is when MRC diversity scheme is employed at SD and SC diversity scheme is employed at SE, such that when $\Gamma_{sr} \geq \gamma_{th}$, the relay correctly decodes the message and $\Gamma_M^{MRC} = \Gamma_{rd} + \Gamma_{sd}$ is the SNR at SD and $\Gamma_E^{SC} = \max(\Gamma_{re}, \Gamma_{se})$ is the SNR at SE. The fourth is when MRC diversity scheme is employed at both SD and SE, such that when $\Gamma_{sr} \geq \gamma_{th}$, the relay correctly decodes the message and $\Gamma_M^{MRC} = \Gamma_{rd} + \Gamma_{sd}$ is the SNR at SD and $\Gamma_E^{MRC} = \Gamma_{re} + \Gamma_{se}$ is the SNR at SE. When $\Gamma_{sr} < \gamma_{th}$, the relay does not transmit at all, thus only direct $SS - SE$ and $SS - SD$ communication link exists, where $\Gamma_M = \Gamma_{sd}$ is taken as the main link SNR at SD and $\Gamma_E = \Gamma_{se}$ is taken as the eavesdropper link SNR at SE for all the four scenarios.

III. Secrecy Outage Probability of Cognitive Single Relay System

This section discusses the P_o for the cognitive threshold-based relay system where, both the direct signal paths between $SS - SD$ and $SS - SE$ exists. The outage probability has been evaluated in this section by finding out the conditional outage probability of cognitive system, when the relay could successfully decodes the source message and when it could not. $\mathbb{E}[\cdot]$ is taken as the expectation operator, which involves the averaging over random variables γ_{sp} and γ_{rp}. Hence, we have followed the law of total probability for obtaining the outage probability for the four scenarios, and it is given as

$$P_o = \mathbb{E}_{\gamma_{rp}}\left[\mathbb{E}_{\gamma_{sp}}\left[\mathbb{P}\left[C_s < R_s | \Gamma_{sr} \geq \gamma_{th}, \gamma_{sp}, \gamma_{rp}\right] \times \right.\right.$$
$$\mathbb{P}[\Gamma_{sr} \geq \gamma_{th}|\gamma_{sp}, \gamma_{rp}] + \mathbb{P}\left[C_s < R_s|\Gamma_{sr} < \gamma_{th}, \gamma_{sp}, \gamma_{rp}\right]$$
$$\left.\left.\times \mathbb{P}\Big[\Gamma_{sr} < \gamma_{th}|\gamma_{sp}, \gamma_{rp}\Big]\right]\right] \tag{9}$$

A. Secrecy Outage With SC at both Destination and Eavesdropper (SC-SC)

The P_o for the first scenario is given as

$$P_o = \mathbb{E}\left[\mathbb{P}\left[\frac{1 + \max\left(\frac{I_p\gamma_{rd}}{\gamma_{rp}}, \frac{I_p\gamma_{sd}}{\gamma_{sp}}\right)}{1 + \max\left(\frac{I_p\gamma_{re}}{\gamma_{rp}}, \frac{I_p\gamma_{se}}{\gamma_{sp}}\right)} < \rho \Big| \Gamma_{sr} \geq \gamma_{th}, \gamma_{sp}, \gamma_{rp}\right]\right.$$
$$\left.\times \left[1 - \mathbb{P}\left[\frac{I_p\gamma_{sr}}{\gamma_{sp}} < \gamma_{th}\Big|\gamma_{sp}, \gamma_{rp}\right]\right]\right]$$

$$+ \mathbb{P}\left[\frac{1 + \frac{I_p \gamma_{sd}}{\gamma_{sp}}}{1 + \frac{I_p \gamma_{se}}{\gamma_{sp}}} < \rho \Big| \Gamma_{sr} < \gamma_{th}, \gamma_{sp}, \gamma_{rp}\right]$$

$$\times \mathbb{P}\left[\frac{I_p \gamma_{sr}}{\gamma_{sp}} < \gamma_{th} \Big| \gamma_{sp}, \gamma_{rp}\right]\right] \tag{10}$$

Expressions for the terms Q_1 to Q_{11} in (11) are presented in the Appendix, after using some algebraic simplifications and performing partial fractions.

B. Secrecy Outage With SC at Destination and MRC at Eavesdropper (SC-MRC)

The P_o for the second scenario is given as

$$P_o = \mathbb{E}\left[\mathbb{P}\left[\frac{1 + \max\left(\frac{I_p \gamma_{rd}}{\gamma_{rp}}, \frac{I_p \gamma_{sd}}{\gamma_{sp}}\right)}{1 + \left(\frac{I_p \gamma_{re}}{\gamma_{rp}} + \frac{I_p \gamma_{se}}{\gamma_{sp}}\right)} < \rho \Big| \Gamma_{sr} \geq \gamma_{th}, \gamma_{sp}, \gamma_{rp}\right]\right.$$

$$\times \left[1 - \mathbb{P}\left[\frac{I_p \gamma_{sr}}{\gamma_{sp}} < \gamma_{th} \Big| \gamma_{sp}, \gamma_{rp}\right]\right]$$

$$+ \mathbb{P}\left[\frac{1 + \frac{I_p \gamma_{sd}}{\gamma_{sp}}}{1 + \frac{I_p \gamma_{se}}{\gamma_{sp}}} < \rho \Big| \Gamma_{sr} < \gamma_{th}, \gamma_{sp}, \gamma_{rp}\right]$$

$$\left.\times \mathbb{P}\left[\frac{I_p \gamma_{sr}}{\gamma_{sp}} < \gamma_{th} \Big| \gamma_{sp}, \gamma_{rp}\right]\right] \tag{12}$$

Expressions for the terms R_1 to R_8 in (13) are presented in the Appendix, after using some algebraic simplifications and performing partial fractions.

C. Secrecy Outage With MRC at Destination and SC at Eavesdropper (MRC-SC)

The P_o for the third scenario is given as

$$P_o = \mathbb{E}\left[\mathbb{P}\left[\frac{1 + \left(\frac{I_p \gamma_{rd}}{\gamma_{rp}} + \frac{I_p \gamma_{sd}}{\gamma_{sp}}\right)}{1 + \max\left(\frac{I_p \gamma_{re}}{\gamma_{rp}}, \frac{I_p \gamma_{se}}{\gamma_{sp}}\right)} < \rho \Big| \Gamma_{sr} \geq \gamma_{th}, \gamma_{sp}, \gamma_{rp}\right]\right.$$

$$\times \left[1 - \mathbb{P}\left[\frac{I_p \gamma_{sr}}{\gamma_{sp}} < \gamma_{th} \Big| \gamma_{sp}, \gamma_{rp}\right]\right]$$

$$+ \mathbb{P}\left[\frac{1 + \frac{I_p \gamma_{sd}}{\gamma_{sp}}}{1 + \frac{I_p \gamma_{se}}{\gamma_{sp}}} < \rho \Big| \Gamma_{sr} < \gamma_{th}, \gamma_{sp}, \gamma_{rp}\right]$$

$$\left.\times \mathbb{P}\left[\frac{I_p \gamma_{sr}}{\gamma_{sp}} < \gamma_{th} \Big| \gamma_{sp}, \gamma_{rp}\right]\right] \tag{14}$$

Expressions for the terms S_1 to S_8 in (15) are presented in the Appendix, after using some algebraic simplifications and performing partial fractions.

D. Secrecy Outage With MRC at both Destination and Eavesdropper (MRC-MRC)

The P_o for the fourth scenario is given as

$$P_o = \mathbb{E}\left[\mathbb{P}\left[\frac{1 + \left(\frac{I_p \gamma_{rd}}{\gamma_{rp}} + \frac{I_p \gamma_{sd}}{\gamma_{sp}}\right)}{1 + \left(\frac{I_p \gamma_{re}}{\gamma_{rp}} + \frac{I_p \gamma_{se}}{\gamma_{sp}}\right)} < \rho \Big| \Gamma_{sr} \geq \gamma_{th}, \gamma_{sp}, \gamma_{rp}\right]\right.$$

$$\times \left[1 - \mathbb{P}\left[\frac{I_p \gamma_{sr}}{\gamma_{sp}} < \gamma_{th} \Big| \gamma_{sp}, \gamma_{rp}\right]\right]$$

$$+ \mathbb{P}\left[\frac{1 + \frac{I_p \gamma_{sd}}{\gamma_{sp}}}{1 + \frac{I_p \gamma_{se}}{\gamma_{sp}}} < \rho \Big| \Gamma_{sr} < \gamma_{th}, \gamma_{sp}, \gamma_{rp}\right]$$

$$\left.\times \mathbb{P}\left[\frac{I_p \gamma_{sr}}{\gamma_{sp}} < \gamma_{th} \Big| \gamma_{sp}, \gamma_{rp}\right]\right] \tag{16}$$

Expressions for the terms T_1 to T_6 in (17) are presented in the Appendix, after using some algebraic simplifications and performing partial fractions. Using these, P_o for all four cases is evaluated and the secrecy performance analysis is done further in the numerical section.

E. Secrecy Outage With No Direct Link

This section discusses secrecy performance of the cognitive relay system, with an assumption that both the direct signal paths $SS-SD$ and $SS-SE$ are not present due to deep shadow fading [7]. The P_o is given as

$$P_o = \mathbb{E}\left[\mathbb{P}\left[\frac{1}{2}\left[\log_2\left(\frac{1 + \Gamma_{rd}}{1 + \Gamma_{re}}\right)\right] < R_s \Big| \Gamma_{sr} \geq \gamma_{th}, \gamma_{sp}, \gamma_{rp}\right]\right.$$

$$\left.\times \mathbb{P}\left[\Gamma_{sr} \geq \gamma_{th} | \gamma_{sp}, \gamma_{rp}\right] + \mathbb{P}\left[\Gamma_{sr} < \gamma_{th} | \gamma_{sp}, \gamma_{rp}\right]\right]$$

$$= \int_0^{+\infty}\int_0^{+\infty}\left[\left(1 - \frac{\alpha_{re} e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{rd}y}}{\rho\beta_{rd} + \alpha_{re}}\right)e^{-\frac{\gamma_{th}\beta_{sr}x}{I_p}}\right.$$

$$\left.+ \left(1 - e^{-\frac{\gamma_{th}\beta_{sr}x}{I_p}}\right)\right]\theta_{sp}e^{-\theta_{sp}x}\theta_{rp}e^{-\theta_{rp}y}dxdy \tag{18}$$

The closed-form expression of the P_o for cognitive relay system from (18) is obtained as

$$P_o = \left(1 - \frac{\alpha_{re}\theta_{rp}\theta_{sp}}{\left(\rho\beta_{rd} + \alpha_{re}\right)\left(\theta_{rp} + \left(\frac{\rho-1}{I_p}\right)\beta_{rd}\right)\left(\theta_{sp} + \frac{\gamma_{th}\beta_{sr}}{I_p}\right)}\right) \tag{19}$$

F. Asymptotic Analysis

For the asymptotic behavior analysis, when $1/\beta_{sr} = 1/\beta_{rd} = 1/\beta \to \infty$, the P_o for cognitive threshold-based single relay system in (19) is given as

$$P_o = \frac{\beta_{rd}\left(\rho\theta_{rp} + \frac{\alpha_{re}(\rho-1)}{I_p}\right)}{\alpha_{re}\theta_{rp}} + \frac{\gamma_{th}\beta_{sr}}{I_p\theta_{sp}}$$

$$P_o = \underbrace{\mathbb{E}\left[e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\right]}_{Q_1} - \underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\gamma_{rp}\alpha_{re}e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{sd}\gamma_{sp}}}{(\rho\beta_{sd}\gamma_{sp}+\alpha_{re}\gamma_{rp})}\right]}_{Q_2}$$

$$-\underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\gamma_{sp}\alpha_{se}e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{sd}\gamma_{sp}}}{(\rho\beta_{sd}\gamma_{sp}+\alpha_{se}\gamma_{sp})}\right]}_{Q_3} + \underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}(\gamma_{sp}\alpha_{se}+\alpha_{re}\gamma_{rp})e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{sd}\gamma_{sp}}}{(\rho\beta_{sd}\gamma_{sp}+\alpha_{se}\gamma_{sp}+\alpha_{re}\gamma_{rp})}\right]}_{Q_4}$$

$$-\underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\gamma_{rp}\alpha_{re}e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{rd}\gamma_{rp}}}{(\rho\beta_{rd}\gamma_{rp}+\alpha_{re}\gamma_{rp})}\right]}_{Q_5} - \underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\gamma_{sp}\alpha_{se}e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{rd}\gamma_{rp}}}{(\rho\beta_{rd}\gamma_{rp}+\alpha_{se}\gamma_{sp})}\right]}_{Q_6}$$

$$+\underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}(\gamma_{sp}\alpha_{se}+\alpha_{re}\gamma_{rp})e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{rd}\gamma_{rp}}}{(\rho\beta_{rd}\gamma_{rp}+\alpha_{se}\gamma_{sp}+\alpha_{re}\gamma_{rp})}\right]}_{Q_7} + \underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\gamma_{rp}\alpha_{re}e^{-\left(\frac{\rho-1}{I_p}\right)(\beta_{sd}\gamma_{sp}+\beta_{rd}\gamma_{rp})}}{(\rho(\beta_{sd}\gamma_{sp}+\beta_{rd}\gamma_{rp})+\alpha_{re}\gamma_{rp})}\right]}_{Q_8}$$

$$+\underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\gamma_{sp}\alpha_{se}e^{-\left(\frac{\rho-1}{I_p}\right)(\beta_{sd}\gamma_{sp}+\beta_{rd}\gamma_{rp})}}{(\rho(\beta_{sd}\gamma_{sp}+\beta_{rd}\gamma_{rp})+\alpha_{se}\gamma_{sp})}\right]}_{Q_9} - \underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}(\gamma_{sp}\alpha_{se}+\alpha_{re}\gamma_{rp})e^{-\left(\frac{\rho-1}{I_p}\right)(\beta_{sd}\gamma_{sp}+\beta_{rd}\gamma_{rp})}}{(\rho(\beta_{sd}\gamma_{sp}+\beta_{rd}\gamma_{rp})+\alpha_{se}\gamma_{sp}+\alpha_{re}\gamma_{rp})}\right]}_{Q_{10}}$$

$$+\underbrace{\mathbb{E}\left[\left(1-\frac{\alpha_{se}e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{sd}\gamma_{sp}}}{\rho\beta_{sd}+\alpha_{se}}\right)\left(1-e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\right)\right]}_{Q_{11}} \tag{11}$$

$$P_o = \underbrace{\mathbb{E}\left[e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\right]}_{R_1} - \underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\gamma_{rp}\alpha_{re}\alpha_{se}\gamma_{sp}e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{sd}\gamma_{sp}}}{(\rho\beta_{sd}\gamma_{sp}+\alpha_{se}\gamma_{sp})(\alpha_{re}\gamma_{rp}-\alpha_{se}\gamma_{sp})}\right]}_{R_2}$$

$$-\underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\gamma_{rp}\alpha_{re}\alpha_{se}\gamma_{sp}e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{sd}\gamma_{sp}}}{(\rho\beta_{sd}\gamma_{sp}+\alpha_{re}\gamma_{rp})(\alpha_{se}\gamma_{sp}-\alpha_{re}\gamma_{rp})}\right]}_{R_3} - \underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\gamma_{rp}\alpha_{re}\alpha_{se}\gamma_{sp}e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{rd}\gamma_{rp}}}{(\rho\beta_{rd}\gamma_{rp}+\alpha_{se}\gamma_{sp})(\alpha_{re}\gamma_{rp}-\alpha_{se}\gamma_{sp})}\right]}_{R_4}$$

$$-\underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\gamma_{rp}\alpha_{re}\alpha_{se}\gamma_{sp}e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{rd}\gamma_{rp}}}{(\rho\beta_{rd}\gamma_{rp}+\alpha_{re}\gamma_{rp})(\alpha_{se}\gamma_{sp}-\alpha_{re}\gamma_{rp})}\right]}_{R_5} + \underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\gamma_{rp}\alpha_{re}\alpha_{se}\gamma_{sp}e^{-\left(\frac{\rho-1}{I_p}\right)(\beta_{sd}\gamma_{sp}+\beta_{rd}\gamma_{rp})}}{(\rho(\beta_{sd}\gamma_{sp}+\beta_{rd}\gamma_{rp})+\alpha_{se}\gamma_{sp})(\alpha_{re}\gamma_{rp}-\alpha_{se}\gamma_{sp})}\right]}_{R_6}$$

$$+\underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\gamma_{rp}\alpha_{re}\alpha_{se}\gamma_{sp}e^{-\left(\frac{\rho-1}{I_p}\right)(\beta_{sd}\gamma_{sp}+\beta_{rd}\gamma_{rp})}}{(\rho(\beta_{sd}\gamma_{sp}+\beta_{rd}\gamma_{rp})+\alpha_{re}\gamma_{rp})(\alpha_{se}\gamma_{sp}-\alpha_{re}\gamma_{rp})}\right]}_{R_7} + \underbrace{\mathbb{E}\left[\left(1-\frac{\alpha_{se}e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{sd}\gamma_{sp}}}{\rho\beta_{sd}+\alpha_{se}}\right)\left(1-e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\right)\right]}_{R_8} \tag{13}$$

$$= \frac{1}{\frac{1}{\beta}}\left[\frac{\rho}{\alpha_{re}}+\frac{(\rho-1)}{I_p\theta_{rp}}+\frac{\gamma_{th}}{I_p\theta_{sp}}\right] \tag{20}$$

We can observe from (20) that P_o is inversely proportional to $1/\beta$, and when the main channel SNR $= 1/\beta$ tends to infinity, P_o tends to zero. P_o as shown in (20) is directly proportional to γ_{th}, $1/\alpha_{re}$ and ρ. We can see that P_o also decreases with an increase of I_p. Also, the diversity order, D [10, 12] is given by

the power of $1/\beta$ in the denominator of (20). As we have not considered any relay selection, it is intuitive that $D = 1$, for this single relay cognitive system.

IV. Numerical Analysis

This section presents the simulation results to validate the analytical expressions. All the secondary and primary nodes are assumed to have the same noise power.

$$P_o = \underbrace{\mathbb{E}\left[e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\right]}_{S_1} - \underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\gamma_{sp}\beta_{sd}\alpha_{se}\gamma_{sp}e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{rd}\gamma_{rp}}}{\left(\rho\beta_{rd}\gamma_{rp}+\alpha_{se}\gamma_{sp}\right)\left(\beta_{sd}\gamma_{sp}-\beta_{rd}\gamma_{rp}\right)}\right]}_{S_2}$$

$$-\underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\gamma_{rp}\beta_{rd}\alpha_{se}\gamma_{sp}e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{sd}\gamma_{sp}}}{\left(\rho\beta_{sd}\gamma_{sp}+\alpha_{se}\gamma_{sp}\right)\left(\beta_{rd}\gamma_{rp}-\beta_{sd}\gamma_{sp}\right)}\right]}_{S_3} - \underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\gamma_{sp}\beta_{sd}\alpha_{re}\gamma_{rp}e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{rd}\gamma_{rp}}}{\left(\rho\beta_{rd}\gamma_{rp}+\alpha_{re}\gamma_{rp}\right)\left(\beta_{sd}\gamma_{sp}-\beta_{rd}\gamma_{rp}\right)}\right]}_{S_4}$$

$$-\underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\gamma_{rp}\beta_{rd}\alpha_{re}\gamma_{rp}e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{sd}\gamma_{sp}}}{\left(\rho\beta_{sd}\gamma_{sp}+\alpha_{re}\gamma_{rp}\right)\left(\beta_{rd}\gamma_{rp}-\beta_{sd}\gamma_{sp}\right)}\right]}_{S_5} + \underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\gamma_{sp}\beta_{sd}(\alpha_{re}\gamma_{rp}+\alpha_{se}\gamma_{sp})e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{rd}\gamma_{rp}}}{\left(\rho\beta_{rd}\gamma_{rp}+\alpha_{se}\gamma_{sp}+\alpha_{re}\gamma_{rp}\right)\left(\beta_{sd}\gamma_{sp}-\beta_{rd}\gamma_{rp}\right)}\right]}_{S_6}$$

$$+\underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\gamma_{rp}\beta_{rd}(\alpha_{re}\gamma_{rp}+\alpha_{se}\gamma_{sp})e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{sd}\gamma_{sp}}}{\left(\rho\beta_{sd}\gamma_{sp}+\alpha_{se}\gamma_{sp}+\alpha_{re}\gamma_{rp}\right)\left(\beta_{rd}\gamma_{rp}-\beta_{sd}\gamma_{sp}\right)}\right]}_{S_7} + \underbrace{\mathbb{E}\left[\left(1-\frac{\alpha_{se}e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{sd}\gamma_{sp}}}{\rho\beta_{sd}+\alpha_{se}}\right)\left(1-e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\right)\right]}_{S_8} \quad (15)$$

$$P_o = \underbrace{\mathbb{E}\left[e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\right]}_{T_1} - \underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\gamma_{sp}\beta_{sd}\alpha_{re}\alpha_{se}\gamma_{sp}e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{rd}\gamma_{rp}}}{\left(\beta_{sd}\gamma_{sp}-\beta_{rd}\gamma_{rp}\right)\left(\alpha_{se}\gamma_{sp}-\alpha_{re}\gamma_{rp}\right)\left(\rho\beta_{rd}+\alpha_{re}\right)}\right]}_{T_2}$$

$$-\underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\gamma_{sp}\gamma_{rp}\beta_{rd}\alpha_{re}\alpha_{se}\gamma_{rp}e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{sd}\gamma_{sp}}}{\left(\beta_{rd}\gamma_{rp}-\beta_{sd}\gamma_{sp}\right)\left(\alpha_{se}\gamma_{sp}-\alpha_{re}\gamma_{rp}\right)\left(\rho\beta_{sd}\gamma_{sp}+\alpha_{re}\gamma_{rp}\right)}\right]}_{T_3}$$

$$-\underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\gamma_{sp}\gamma_{rp}\beta_{sd}\alpha_{re}\alpha_{se}\gamma_{sp}e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{rd}\gamma_{rp}}}{\left(\beta_{sd}\gamma_{sp}-\beta_{rd}\gamma_{rp}\right)\left(\alpha_{re}\gamma_{rp}-\alpha_{se}\gamma_{sp}\right)\left(\rho\beta_{rd}\gamma_{rp}+\alpha_{se}\gamma_{sp}\right)}\right]}_{T_4}$$

$$-\underbrace{\mathbb{E}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\gamma_{rp}\beta_{rd}\alpha_{re}\alpha_{se}\gamma_{rp}e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{sd}\gamma_{sp}}}{\left(\beta_{rd}\gamma_{rp}-\beta_{sd}\gamma_{sp}\right)\left(\alpha_{re}\gamma_{rp}-\alpha_{se}\gamma_{sp}\right)\left(\rho\beta_{sd}+\alpha_{se}\right)}\right]}_{T_5}$$

$$+\underbrace{\mathbb{E}\left[\left(1-\frac{\alpha_{se}e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{sd}\gamma_{sp}}}{\rho\beta_{sd}+\alpha_{se}}\right)\left(1-e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}\right)\right]}_{T_6} \quad (17)$$

Fig. 2 shows the P_o for cognitive system under SC-SC scenario as given in (11), with total SNR $1/\beta$. The figure is plotted with different $R_s = 0.1, 2.0$, $1/\beta_{sd} = 6, 9$ dB, $1/\alpha_{se} = 6, 9$ dB and fixed $\gamma_{th} = 3$ dB, $1/\alpha_{re} = 1/\alpha = 9$ dB , $I_p = 9$ dB, $1/\theta_{sp} = 3$ dB, $1/\theta_{rp} = 3$ dB. It is interesting to observe from the plot that the secrecy performance is improved by increasing $1/\beta_{sd}$ from 6 dB to 9 dB for a given $1/\alpha_{se} = 3$ dB at lower secrecy rates, while, at higher secrecy rates there is no significant improvement. However, the secrecy performance significantly decreases by increasing $1/\alpha_{se}$ from 6 dB to 9 dB for a given $1/\beta_{sd} = 3$ dB both at high and low secrecy rates. The secrecy outage is thus more sensitive to changes in the quality of di-rect link between $SS - SE$ than $SS - SD$, especially at the higher secrecy rates. This makes the direct link between secondary source to eavesdropper more crucial at higher secrecy rates for secure communication.

Fig. 3 shows the comparison of P_o for cognitive system, as given in (11), (13), (15) and (17), with total SNR $1/\beta$. The figure is plotted with different $R_s = 0.1, 1.0$ and fixed $\gamma_{th} = 3$ dB, $1/\alpha_{re} = 1/\alpha = 9$ dB , $I_p = 9$ dB, $1/\beta_{sd} = 3$ dB, $1/\alpha_{se} = 3$ dB, $1/\theta_{sp} = 3$ dB, $1/\theta_{rp} = 3$ dB.It is observed from the figure that secrecy performance of the cognitive relay system is best when diversity scheme MRC is used at SD and SC is used at SE. The performance is worst when diversity scheme SC is
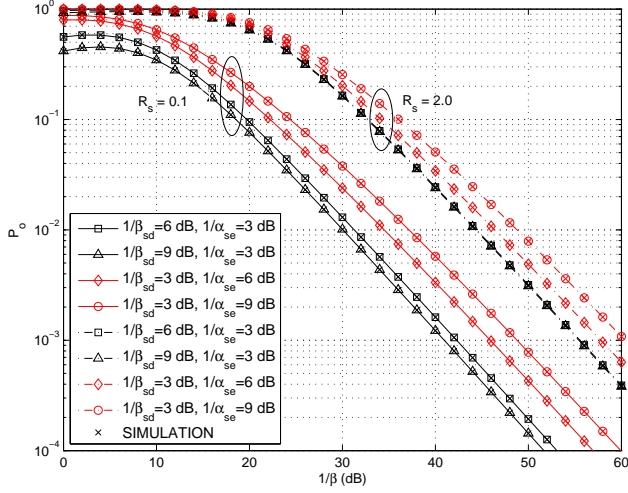
Fig. 2. Secrecy outage probability with $1/\beta$ under SC-SC scenario for $R_s = 0.1, 2.0$, $1/\beta_{sd} = 6, 9$ dB, $1/\alpha_{se} = 6, 9$ dB, $1/\alpha = 9$ dB and $\gamma_{th} = 3$ dB of cognitive relay system.

used at SD and MRC is used at SE. At lower secrecy rates, the performance of the MRC-MRC system and SC-SC system is comparable. However, at higher secrecy rates, SC-SC system performs better than the MRC-MRC system. This is because at higher secrecy rates, when both the destination and eavesdropper employs the same diversity scheme, the secrecy performance of the system is dominated by the diversity scheme used at the eavesdropper. Also, it is shown that P_o increases in function of the required secrecy rate R_s, which is intuitive.

Fig. 4 shows the P_o for cognitive system under SC-SC scenario as given in (11), with total SNR $1/\beta$. The figure is plotted with different $1/\alpha_{se} = 0, 6, 12$ dB, $1/\beta_{sd} = 3, 9$ dB and fixed $R_s = 1.0$, $\gamma_{th} = 3$ dB, $1/\alpha_{re} = 1/\alpha = 3$ dB , $I_p = 9$ dB, $1/\theta_{sp} = 3$ dB, $1/\theta_{rp} = 3$ dB. It can be observed from the plot that the secrecy performance is improved by increasing $1/\beta_{sd}$ from 3 dB to 9 dB for a given $1/\alpha_{se} = 0$ or 6 or 12 dB. It is however interesting to note that when the direct $SS - SE$ link quality is low, i.e., $1/\alpha_{se} = 0$ dB, the amount of improvement in the secrecy performance by improving direct $SS - SD$ link quality is higher. Thus, when there is already low secrecy due to good quality channel of the eavesdropper, it intuitively becomes difficult to improve the secrecy of the system.

Fig. 5 shows the effect of γ_{th} on P_o, as given in (11), (13), (15) and (17). The figure has been plotted with different $1/\alpha_{re} = 1/\alpha = 6, 12$ dB and fixed $R_s = 1.0$, $1/\beta_{sr} = 1/\beta_{rd} = 25$ dB, $1/\alpha_{se} = 3$ dB, $1/\beta_{sd} = 3$ dB , $I_p = 9$ dB , $1/\theta_{sp} = 3$ dB, $1/\theta_{rp} = 3$ dB. It can be observed from the plot that when γ_{th} tends to zero, all curves saturate to a particular value depicted by using horizontal dashed line, which can be evaluated by substituting $\gamma_{th} = 0$ in (11), (13), (15) and (17). This shows that a fixed least P_o could be achieved depending on the input parameters, when the message is perfectly decoded by the relay. When γ_{th} tends to infinity, due to high SNR threshold relay cannot decode the message, and as both $SS - SE$ and $SS - SD$ links exist, P_o tends to $\left(1 - \frac{\alpha_{se}\theta_{sp}}{(\rho\beta_{sd}+\alpha_{se})\left(\theta_{sp}+\left(\frac{\rho-1}{I_p}\right)\beta_{sd}\right)}\right)$. This shows that the direct
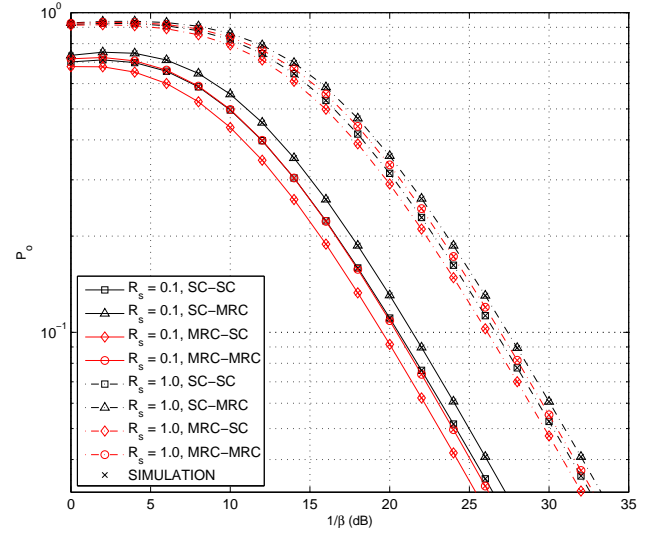

Fig. 3. Comparative analysis of P_o with $1/\beta$ under four scenarios for $R_s = 1.0, 0.1$, $1/\alpha = 9$ dB and $\gamma_{th} = 3$ dB of cognitive system.
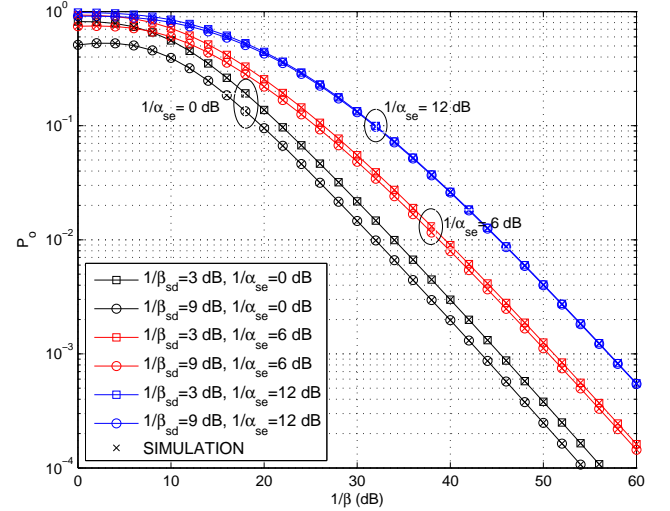

Fig. 4. Secrecy outage probability with $1/\beta$ under SC-SC scenario for $1/\beta_{sd} = 3, 9$ dB, $1/\alpha_{se} = 0, 6, 12$ dB, $R_s = 1.0$, $1/\alpha = 9$ dB and $\gamma_{th} = 3$ dB of cognitive relay system.

links have a significant impact on the system secrecy. Also, it is observed that P_o increases in function of $1/\alpha_{re}$.

Fig. 6 shows the P_o for cognitive balanced system under SC-SC scenario as given in (11), with γ_{th}. The figure is plotted with different $1/\beta_{sd} = 3, 40$ dB , $1/\beta_{sr} = 1/\beta_{rd} = 3, 40$ dB, $R_s = 0.1, 1.0$ and fixed $\gamma_{th} = 3$ dB, $1/\alpha_{se} = 3$ dB, $1/\alpha_{re} = 1/\alpha = 3$ dB , $I_m = 9$ dB, $1/\theta_{sp} = 3$ dB, $1/\theta_{rp} = 3$ dB. It can be observed from the plot that as γ_{th} increases, the outage probability decreases when the quality of $SR - SD$ channel is very low in comparison to the quality of $SS - SD$ channel, i.e., $1/\beta_{rd} = 3$ dB and $1/\beta_{sd} = 40$ dB. Whereas, the outage probability increases when the quality of $SR - SD$ channel is very high in comparison to the quality of $SS - SD$ channel, i.e., $1/\beta_{rd} = 40$ dB and $1/\beta_{sd} = 3$ dB. This can be explained as follows. When γ_{th} increases, the probability of the relay to get
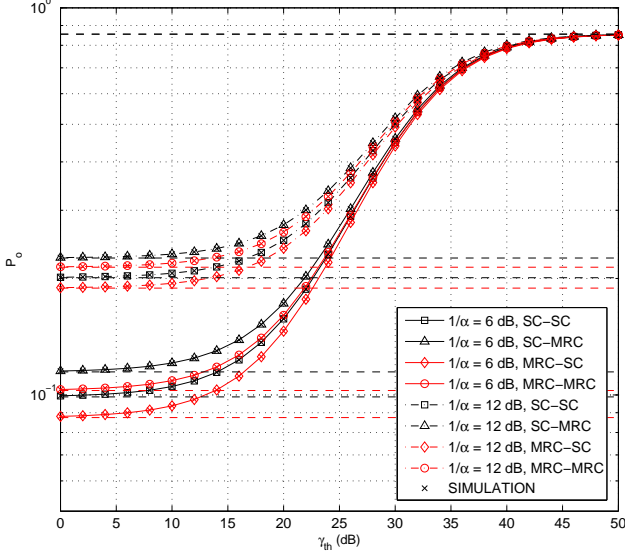
Fig. 5. Secrecy outage probability of the cognitive system with γ_{th} under four scenarios for $1/\alpha = 6, 12$ dB , $R_s = 1.0$.

Fig. 6. Secrecy outage probability of the cognitive relay system with γ_{th} under SC-SC scenario for $1/\beta_{sd} = 3, 40$ dB, $1/\beta_{sr} = 1/\beta_{rd} = 3, 40$ dB, $R_s = 0.1, 1.0, 1/\alpha = 3$ dB.

Fig. 7. Secrecy outage probability of the cognitive system with I_p in SC-SC scenario for $1/\beta = 25, 30, 35$ dB , $R_s = 0.1, 1.0$ and $\gamma_{th} = 3$ dB.

selected decreases. Hence, when the quality of the $SS - SD$ channel is not good in comparison to $SR - SD$ channel, the SNR at the destination decreases and the secrecy outage probability increases. On the other hand, with an increase in γ_{th}, there is decrease in the transmission towards the eavesdropper also, which decreases SNR at the eavesdropper. Thus, when the quality of $SS - SD$ channel is far better than the quality of $SR - SD$ channel, the SNR at the destination is increased. As a result, the secrecy outage probability decreases. It can also be observed from the plot that when γ_{th} tends to zero or infinity, all curves saturate to a particular value depicted by using horizontal dashed lines.

Fig. 7 shows P_o for the cognitive system, as expressed in (11) for the SC-SC scenario , with I_p. The figure has been plotted with different $1/\beta_{sr} = 1/\beta_{rd} = 1/\beta = 25, 30, 35$ dB, $R_s = 1.0, 0.1$ and fixed $\gamma_{th} = 3$ dB , $1/\alpha_{re} = 1/\alpha = 9$ dB, $1/\theta_{sp} = 3$ dB, $1/\theta_{rp} = 3$ dB . We can observe from the plot that P_o decreases [3], with the increase in the I_p. This can be explained as with an increasing I_p, higher power can be transmitted by the SU, leading to a decrease of P_o. We can observe from the figure that when I_p is increased beyond a certain value, P_o for the SC-SC scenario converges to its respective P_o floor [3]. For the other scenarios also, this observation holds true. It can be observed that the improvement in the main link average SNR, decreases the P_o of cognitive relay system. P_o increases in function of R_s, which is also intuitive.

V. Conclusion

The exact closed-form expressions are presented in this paper for the secrecy outage probability of threshold-based DF cognitive underlay relay system. We have assumed peak interference type of power control at the secondary relay and source. Unlike prior work, the relayed and the direct signals are combined at the eavesdropper and destination in our study and the secrecy performance with permutations of both MRC and SC diversity
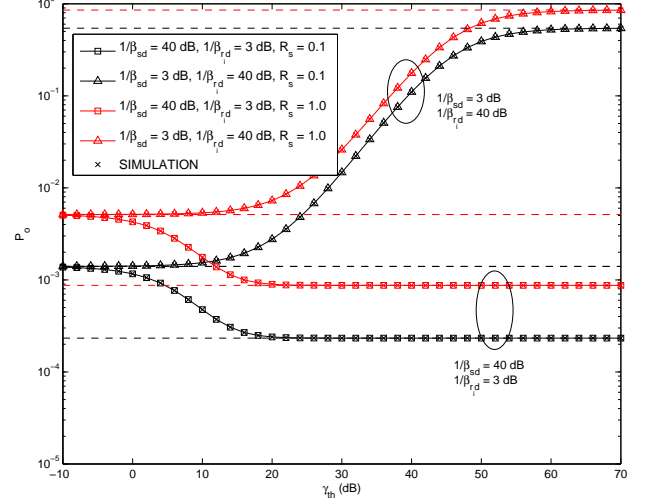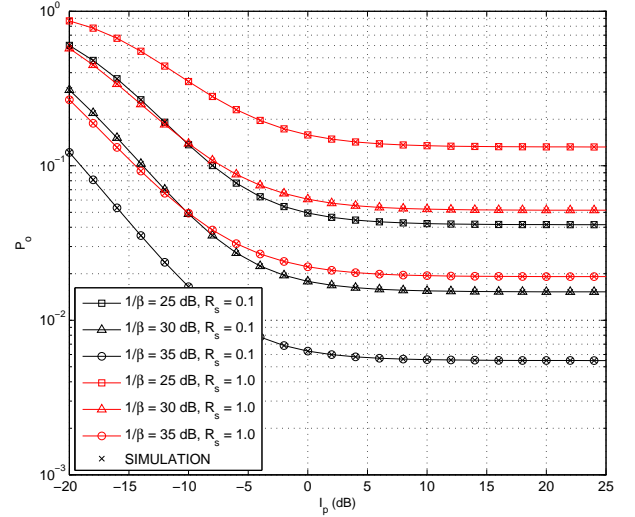
schemes is investigated. Our results corroborate that MRC at SD and SC at the eavesdropper gives the best performance. We also demonstrate that at at higher secrecy rates, SC-SC system performs better than the MRC-MRC system. We have shown that the secrecy performance of cognitive relay system is significantly affected by the threshold SNR, interference power, required secrecy rate and diversity scheme (MRC/SC). We also conclude that the direct link between source and eavesdropper plays a more crucial role in the secrecy performance of the system than between source and destination. Our research on analyzing the secrecy performance of this cognitive threshold-based relay system with the effect of channel knowledge at the transmitter is ongoing. Furthermore, in future this work can also be extended for multi-eavesdropper and multi-destination system.

VI. Appendix

A. Some standard integrals used for evaluation of expressions

The exponential random variables $|h_{sp}|^2$ and $|h_{rp}|^2$ are represented as X and Y for convenience. We have used the integration of the product of exponential integral function $Ei(\cdot)$, where $Ei(x) = \int_{-\infty}^{x} \frac{e^t}{t} dt$ with exponential function and powers [36], given as

$$\int_0^\infty x e^{-ax} E_i(bx) dx = \frac{-1}{a^2}\left[\ln\left(\frac{a}{b} - 1\right) - \left(\frac{a}{a-b}\right)\right] \quad (21)$$

$$\int_0^\infty x e^{-ax} E_1(bx) dx = \frac{1}{a^2}\left[\ln\left(1 + \frac{a}{b}\right) - \left(\frac{a}{a+b}\right)\right] \quad (22)$$

B. Evaluation of Q_1 in (11)

$$\mathbb{E}_{X,Y}\left[e^{-\frac{\gamma_{th}\beta_{sr}X}{I_p}} \right] = \mathbb{E}_Y\left[\int_0^{+\infty}\left(e^{-\frac{\gamma_{th}\beta_{sr}x}{I_p}}\right)\theta_{sp}e^{-\theta_{sp}x} \right]$$

$$= \left(\frac{\theta_{sp}}{\theta_{sp} + \frac{\gamma_{th}\beta_{sr}}{I_p}}\right) \quad (23)$$

C. Evaluation of Q_2 in (11)

$$\mathbb{E}_{X,Y}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}X}{I_p}}\alpha_{re}Y e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{sd}X}}{(\rho\beta_{sd}X + \alpha_{re}Y)} \right] =$$

$$\int_0^{+\infty}\int_0^{+\infty}\left(\frac{e^{-\frac{\gamma_{th}\beta_{sr}x}{I_p}}\alpha_{re}y e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{sd}x}}{(\rho\beta_{sd}x + \alpha_{re}y)}\right)$$

$$\times \theta_{sp}e^{-\theta_{sp}x}\theta_{rp}e^{-\theta_{rp}y}dxdy$$

$$= \int_0^{+\infty}\left(\frac{\alpha_{re}\theta_{sp}\theta_{rp}}{\rho\beta_{sd}}\right) y e^{-y\left(\theta_{rp} - \frac{\alpha_{re}z_q}{\beta_{sd}\rho}\right)}$$

$$\times E_1\left(\frac{\alpha_{re}z_q y}{\beta_{sd}\rho}\right) dy \quad (24)$$

where $z_q = \left(\frac{\rho-1}{I_p}\right)\beta_{sd} + \theta_{sp} + \frac{\gamma_{th}\beta_{sr}}{I_p}$.

D. Evaluation of Q_3 in (11)

$$\mathbb{E}_{X,Y}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}X}{I_p}}\alpha_{se}X e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{sd}X}}{(\rho\beta_{sd}X + \alpha_{se}X)} \right] =$$

$$\int_0^{+\infty}\int_0^{+\infty}\left(\frac{e^{-\frac{\gamma_{th}\beta_{sr}x}{I_p}}\alpha_{se}x e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{sd}x}}{(\rho\beta_{sd}x + \alpha_{se}x)}\right)$$

$$\times \theta_{sp}e^{-\theta_{sp}x}\theta_{rp}e^{-\theta_{rp}y}dxdy$$

$$= \frac{\theta_{rp}\theta_{sp}\alpha_{se}}{z_q\theta_{rp}(\beta_{sd}\rho + \alpha_{se})}$$

where $z_q = \left(\frac{\rho-1}{I_p}\right)\beta_{sd} + \theta_{sp} + \frac{\gamma_{th}\beta_{sr}}{I_p}$.

E. Evaluation of Q_4 in (11)

$$\mathbb{E}_{X,Y}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}X}{I_p}}(\alpha_{se}X + \alpha_{re}Y) e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{sd}X}}{(\rho\beta_{sd}X + \alpha_{se}X + \alpha_{re}Y)} \right] =$$

$$\int_0^{+\infty}\int_0^{+\infty}\left(\frac{e^{-\frac{\gamma_{th}\beta_{sr}x}{I_p}}(\alpha_{se}x + \alpha_{re}y) e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{sd}x}}{(\rho\beta_{sd}x + \alpha_{se}x + \alpha_{re}y)}\right)$$

$$\times \theta_{sp}e^{-\theta_{sp}x}\theta_{rp}e^{-\theta_{rp}y}dxdy$$

$$= \int_0^{+\infty}\left(\frac{\alpha_{se}\theta_{sp}\theta_{rp}}{\alpha_{re}}\right) x e^{-x\left(z_q - \frac{\theta_{rp}(\beta_{sd}\rho + \alpha_{se})}{\alpha_{re}}\right)} \times$$

$$E_1\left(\frac{\theta_{rp}(\beta_{sd}\rho + \alpha_{se})x}{\alpha_{re}}\right) dx + \int_0^{+\infty}\left(\frac{\alpha_{re}\theta_{sp}\theta_{rp}}{\beta_{sd}\rho + \alpha_{se}}\right) \times$$

$$y e^{-y\left(\theta_{rp} - \frac{z_q\alpha_{re}}{(\beta_{sd}\rho + \alpha_{se})}\right)} E_1\left(\frac{z_q\alpha_{re}y}{(\beta_{sd}\rho + \alpha_{se})}\right) dy \quad (25)$$

where $z_q = \left(\frac{\rho-1}{I_p}\right)\beta_{sd} + \theta_{sp} + \frac{\gamma_{th}\beta_{sr}}{I_p}$.

F. Evaluation of Q_8 in (11)

$$\mathbb{E}_{X,Y}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}X}{I_p}}\alpha_{re}Y e^{-\left(\frac{\rho-1}{I_p}\right)(\beta_{sd}X + \beta_{rd}Y)}}{(\rho(\beta_{sd}X + \beta_{rd}Y) + \alpha_{re}Y)} \right] =$$

$$\int_0^{+\infty}\int_0^{+\infty}\left(\frac{e^{-\frac{\gamma_{th}\beta_{sr}x}{I_p}}\alpha_{re}y e^{-\left(\frac{\rho-1}{I_p}\right)(\beta_{sd}x + \beta_{rd}y)}}{(\rho(\beta_{sd}x + \beta_{rd}y) + \alpha_{re})}\right)$$

$$\times \theta_{sp}e^{-\theta_{sp}x}\theta_{rp}e^{-\theta_{rp}y}dxdy$$

$$= \int_0^{+\infty}\left(\frac{\alpha_{re}\theta_{sp}\theta_{rp}}{\rho\beta_{sd}}\right) y e^{-y\left(z_{q_2} - \frac{z_{q_1}(\beta_{rd}\rho + \alpha_{re})}{\beta_{sd}\rho}\right)}$$

$$\times E_1\left(\frac{z_{q_1}(\beta_{rd}\rho + \alpha_{re})y}{\beta_{sd}\rho}\right) dy \quad (26)$$

where $z_{q_1} = \left(\frac{\rho-1}{I_p}\right)\beta_{sd} + \theta_{sp} + \frac{\gamma_{th}\beta_{sr}}{I_p}$ and $z_{q_2} = \left(\frac{\rho-1}{I_p}\right)\beta_{rd} + \theta_{rp}$.

G. Evaluation of Q_{10} in (11)

$$\mathbb{E}_{X,Y}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}X}{I_p}}(\alpha_{se}X + \alpha_{re}Y) e^{-\left(\frac{\rho-1}{I_p}\right)(\beta_{sd}X + \beta_{rd}Y)}}{(\rho(\beta_{sd}X + \beta_{rd}Y) + \alpha_{se}X + \alpha_{re}Y)} \right] =$$

$$\int_0^{+\infty}\int_0^{+\infty}\left(\frac{e^{-\frac{\gamma_{th}\beta_{sr}x}{I_p}}(\alpha_{se}x + \alpha_{re}y) e^{-\left(\frac{\rho-1}{I_p}\right)(\beta_{sd}x + \beta_{rd}y)}}{(\rho(\beta_{sd}x + \beta_{rd}y) + \alpha_{se}x + \alpha_{re}y)}\right)$$

$$\times \theta_{sp}e^{-\theta_{sp}x}\theta_{rp}e^{-\theta_{rp}y}dxdy$$

$$= \int_0^{+\infty}\left(\frac{\alpha_{se}\theta_{sp}\theta_{rp}}{(\beta_{rd}\rho + \alpha_{re})}\right) x e^{-x\left(z_{q_1} - \frac{z_{q_2}(\beta_{sd}\rho + \alpha_{se})}{\beta_{rd}\rho + \alpha_{re}}\right)} \times$$

$$E_1\left(\frac{z_{q_2}(\beta_{sd}\rho + \alpha_{se})x}{\beta_{rd}\rho + \alpha_{re}}\right) dx + \int_0^{+\infty}\left(\frac{\alpha_{re}\theta_{sp}\theta_{rp}}{\beta_{sd}\rho + \alpha_{se}}\right) \times$$

$$y e^{-y\left(z_{q_2} - \frac{z_{q_1}(\beta_{rd}\rho + \alpha_{re})}{\beta_{sd}\rho + \alpha_{se}}\right)} E_1\left(\frac{z_{q_1}(\beta_{rd}\rho + \alpha_{re})y}{\beta_{sd}\rho + \alpha_{se}}\right) dy \quad (27)$$

where $z_{q_1} = \left(\frac{\rho-1}{I_p}\right)\beta_{sd} + \theta_{sp} + \frac{\gamma_{th}\beta_{sr}}{I_p}$ and $z_{q_2} = \left(\frac{\rho-1}{I_p}\right)\beta_{rd} + \theta_{rp}$.

H. Evaluation of Q_{11} in (11)

$$\mathbb{E}_{X,Y}\left[\left(1 - \frac{\alpha_{se}e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{sd}X}}{\rho\beta_{sd}+\alpha_{se}}\right)\left(1 - e^{-\frac{\gamma_{th}\beta_{sr}X}{I_p}}\right)\right] =$$

$$\mathbb{E}_Y\left[\int_0^{+\infty}\left(\left(1 - \frac{\alpha_{se}e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{sd}x}}{\rho\beta_{sd}+\alpha_{se}}\right)\times\right.\right.$$
$$\left.\left.\left(1 - e^{-\frac{\gamma_{th}\beta_{sr}x}{I_p}}\right)\right)\theta_{sp}e^{-\theta_{sp}x}\right]$$

$$= 1 - \frac{\theta_{sp}}{\theta_{sp}+\frac{\gamma_{th}\beta_{sr}}{I_p}}$$
$$- \frac{\alpha_{se}\theta_{sp}}{(\rho\beta_{sd}+\alpha_{se})\left(\theta_{sp}+\left(\frac{\rho-1}{I_p}\right)\beta_{sd}\right)}$$
$$+ \frac{\alpha_{se}\theta_{sp}}{(\rho\beta_{sd}+\alpha_{se})\left(\theta_{sp}+\frac{\gamma_{th}\beta_{sr}}{I_p}+\left(\frac{\rho-1}{I_p}\right)\beta_{sd}\right)} \tag{28}$$

The other expressions for Q_5, Q_6, Q_7 and Q_9 can be readily obtained by interchanging $\beta_{sd} \leftrightarrow \beta_{rd}$, $\alpha_{se} \leftrightarrow \alpha_{re}$, and $\theta_{sp} \leftrightarrow \theta_{rp}$, in Q_3, Q_2, Q_4 and Q_8 respectively, while keeping the probability of selection term, i.e. $e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}$ intact. The expressions are omitted due to space limitations.

I. Evaluation of R_4 in (13)

$$\mathbb{E}_{X,Y}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}X}{I_p}}\alpha_{re}Y\alpha_{se}Xe^{-\left(\frac{\rho-1}{I_p}\right)\beta_{rd}Y}}{(\rho\beta_{rd}Y+\alpha_{se}X)(\alpha_{re}Y-\alpha_{se}X)}\right] =$$

$$\int_0^{+\infty}\int_0^{+\infty}\left(\frac{e^{-\frac{\gamma_{th}\beta_{sr}x}{I_p}}\alpha_{re}y\alpha_{se}xe^{-\left(\frac{\rho-1}{I_p}\right)\beta_{rd}y}}{(\rho\beta_{rd}y+\alpha_{se}x)(\alpha_{re}y-\alpha_{se}x)}\right)$$
$$\times \theta_{sp}e^{-\theta_{sp}x}\theta_{rp}e^{-\theta_{rp}y}dxdy$$

$$= \int_0^{+\infty}\left(\frac{\alpha_{re}\theta_{sp}\theta_{rp}\alpha_{re}}{\alpha_{se}(\beta_{rd}\rho+\alpha_{re})}\right)ye^{-y\left(z_r+\frac{\left(\theta_{sp}+\frac{\gamma_{th}\beta_{sr}}{I_p}\right)\alpha_{re}}{\alpha_{se}}\right)}\times$$

$$E_i\left(\frac{\left(\theta_{sp}+\frac{\gamma_{th}\beta_{sr}}{I_p}\right)\alpha_{re}y}{\alpha_{se}}\right)dy - \int_0^{+\infty}\left(\frac{\alpha_{re}\theta_{sp}\theta_{rp}\beta_{rd}\rho}{\alpha_{se}(\beta_{rd}\rho+\alpha_{re})}\right)\times$$

$$ye^{-y\left(z_r-\frac{\left(\theta_{sp}+\frac{\gamma_{th}\beta_{sr}}{I_p}\right)\beta_{rd}\rho}{\alpha_{se}}\right)}E_1\left(\frac{\left(\theta_{sp}+\frac{\gamma_{th}\beta_{sr}}{I_p}\right)\beta_{rd}\rho y}{\alpha_{se}}\right)dy \tag{29}$$

where $z_r = \left(\frac{\rho-1}{I_p}\right)\beta_{rd}+\theta_{rp}$.

J. Evaluation of R_5 in (13)

$$\mathbb{E}_{X,Y}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}X}{I_p}}\alpha_{re}Y\alpha_{se}Xe^{-\left(\frac{\rho-1}{I_p}\right)\beta_{rd}Y}}{(\rho\beta_{rd}Y+\alpha_{re}Y)(\alpha_{se}X-\alpha_{re}Y)}\right] =$$

$$\int_0^{+\infty}\int_0^{+\infty}\left(\frac{e^{-\frac{\gamma_{th}\beta_{sr}x}{I_p}}\alpha_{re}y\alpha_{se}xe^{-\left(\frac{\rho-1}{I_p}\right)\beta_{rd}y}}{(\rho\beta_{rd}y+\alpha_{re}y)(\alpha_{se}x-\alpha_{re}y)}\right)$$
$$\times \theta_{sp}e^{-\theta_{sp}x}\theta_{rp}e^{-\theta_{rp}y}dxdy$$

$$= \int_0^{+\infty}\left(\frac{\alpha_{se}\theta_{sp}\theta_{rp}}{\rho\beta_{rd}+\alpha_{re}}\right)xe^{-x\left(\theta_{sp}+\frac{\gamma_{th}\beta_{sr}}{I_p}+\frac{\alpha_{se}z_r}{\alpha_{re}}\right)}$$
$$\times E_i\left(\frac{\alpha_{se}z_r x}{\alpha_{re}}\right)dx \tag{30}$$

where $z_r = \left(\frac{\rho-1}{I_p}\right)\beta_{rd}+\theta_{rp}$.

K. Evaluation of R_7 in (13)

$$\mathbb{E}_{X,Y}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}X}{I_p}}\alpha_{re}Y\alpha_{se}Xe^{-\left(\frac{\rho-1}{I_p}\right)(\beta_{sd}X+\beta_{rd}Y)}}{(\rho(\beta_{sd}X+\beta_{rd}Y)+\alpha_{re}Y)(\alpha_{se}X-\alpha_{re}Y)}\right] =$$

$$\int_0^{+\infty}\int_0^{+\infty}\left(\frac{e^{-\frac{\gamma_{th}\beta_{sr}x}{I_p}}\alpha_{re}y\alpha_{se}xe^{-\left(\frac{\rho-1}{I_p}\right)(\beta_{sd}x+\beta_{rd}y)}}{(\rho(\beta_{sd}x+\beta_{rd}y)+\alpha_{re}y)(\alpha_{se}x-\alpha_{re}y)}\right)$$
$$\times \theta_{sp}e^{-\theta_{sp}x}\theta_{rp}e^{-\theta_{rp}y}dxdy$$

$$= \int_0^{+\infty}\left(\frac{\alpha_{se}\theta_{sp}\theta_{rp}\alpha_{se}}{\beta_{rd}\rho\alpha_{se}+\beta_{sd}\rho\alpha_{re}+\alpha_{re}\alpha_{se}}\right)\times$$
$$xe^{-x\left(z_{r_1}+\frac{z_{r_2}\alpha_{se}}{\alpha_{re}}\right)}E_i\left(\frac{z_{r_2}\alpha_{se}x}{\alpha_{re}}\right)dx$$

$$- \int_0^{+\infty}\left(\frac{\alpha_{re}\theta_{sp}\theta_{rp}\alpha_{se}\beta_{sd}\rho}{(\beta_{rd}\rho\alpha_{se}+\beta_{sd}\rho\alpha_{re}+\alpha_{re}\alpha_{se})(\beta_{rd}\rho+\alpha_{re})}\right)$$
$$xe^{-x\left(z_{r_1}-\frac{z_{r_2}\beta_{sd}\rho}{\beta_{rd}\rho+\alpha_{re}}\right)}E_1\left(\frac{z_{r_2}\beta_{sd}\rho x}{\beta_{rd}\rho+\alpha_{re}}\right)dx \tag{31}$$

where $z_{r_1} = \left(\frac{\rho-1}{I_p}\right)\beta_{sd}+\theta_{sp}+\frac{\gamma_{th}\beta_{sr}}{I_p}$ and $z_{r_2} = \left(\frac{\rho-1}{I_p}\right)\beta_{rd}+\theta_{rp}$. The other expressions for R_2, R_3 and R_6 can be readily obtained by interchanging $\beta_{sd} \leftrightarrow \beta_{rd}$, $\alpha_{se} \leftrightarrow \alpha_{re}$, and $\theta_{sp} \leftrightarrow \theta_{rp}$, in R_5, R_4 and R_7 respectively, while keeping the probability of selection term, i.e. $e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}$ intact. R_1 and R_8 terms are similar to Q_1 and Q_{11} respectively.

L. Evaluation of S_2 in (15)

$$\mathbb{E}_{X,Y}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}X}{I_p}}\beta_{sd}X\alpha_{se}Xe^{-\left(\frac{\rho-1}{I_p}\right)\beta_{rd}Y}}{(\rho\beta_{rd}Y+\alpha_{se}X)(\beta_{sd}X-\beta_{rd}Y)}\right] =$$

$$\int_0^{+\infty}\int_0^{+\infty}\left(\frac{e^{-\frac{\gamma_{th}\beta_{sr}x}{I_p}}\beta_{sd}x\alpha_{se}xe^{-\left(\frac{\rho-1}{I_p}\right)\beta_{rd}y}}{(\rho\beta_{rd}y+\alpha_{se}x)(\beta_{sd}x-\beta_{rd}y)}\right)$$
$$\times \theta_{sp}e^{-\theta_{sp}x}\theta_{rp}e^{-\theta_{rp}y}dxdy$$

$$= \int_0^{+\infty} \left(\frac{\beta_{sd}\alpha_{se}\theta_{sp}\theta_{rp}}{\beta_{rd}\rho\beta_{sd} + \beta_{rd}\alpha_{se}} \right) \times$$

$$\left(xe^{-x\left(\theta_{sp} + \frac{\gamma_{th}\beta_{sr}}{I_p} + \frac{z_s\beta_{sd}}{\beta_{rd}}\right)} E_i\left(\frac{z_s\beta_{sd}x}{\beta_{rd}}\right) dx \right.$$

$$\left. + xe^{-x\left(\theta_{sp} + \frac{\gamma_{th}\beta_{sr}}{I_p} - \frac{z_s\alpha_{se}}{\beta_{rd}\rho}\right)} E_1\left(\frac{z_s\alpha_{se}x}{\beta_{rd}\rho}\right) dx \right) \qquad (32)$$

where $z_s = \left(\frac{\rho-1}{I_p}\right)\beta_{rd} + \theta_{rp}$.

M. Evaluation of S_4 in (15)

$$\mathbb{E}_{X,Y}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}X}{I_p}}\beta_{sd}X\alpha_{re}Ye^{-\left(\frac{\rho-1}{I_p}\right)\beta_{rd}Y}}{(\rho\beta_{rd}Y + \alpha_{re}Y)(\beta_{sd}X - \beta_{rd}Y)} \right] =$$

$$\int_0^{+\infty}\int_0^{+\infty} \left(\frac{e^{-\frac{\gamma_{th}\beta_{sr}x}{I_p}}\beta_{sd}x\alpha_{re}ye^{-\left(\frac{\rho-1}{I_p}\right)\beta_{rd}y}}{(\rho\beta_{rd}y + \alpha_{re}y)(\beta_{sd}x - \beta_{rd}y)} \right)$$

$$\times \theta_{sp}e^{-\theta_{sp}x}\theta_{rp}e^{-\theta_{rp}y}dxdy$$

$$= \int_0^{+\infty} \left(\frac{\alpha_{re}\beta_{sd}\theta_{sp}\theta_{rp}}{\beta_{rd}(\rho\beta_{rd} + \alpha_{re})} \right) xe^{-x\left(\theta_{sp} + \frac{\gamma_{th}\beta_{sr}}{I_p} + \frac{z_s\beta_{sd}}{\beta_{rd}}\right)}$$

$$\times E_i\left(\frac{z_s\beta_{sd}x}{\beta_{rd}}\right) dx \qquad (33)$$

where $z_s = \left(\frac{\rho-1}{I_p}\right)\beta_{rd} + \theta_{rp}$.

N. Evaluation of S_6 in (15)

$$\mathbb{E}_{X,Y}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}X}{I_p}}\beta_{sd}X(\alpha_{re}Y + \alpha_{se}X)e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{rd}Y}}{(\rho\beta_{rd}Y + \alpha_{se}X + \alpha_{re}Y)(\beta_{sd}X - \beta_{rd}Y)} \right] =$$

$$\int_0^{+\infty}\int_0^{+\infty} \left(\frac{e^{-\frac{\gamma_{th}\beta_{sr}x}{I_p}}\beta_{sd}x(\alpha_{re}y + \alpha_{se}x)e^{-\left(\frac{\rho-1}{I_p}\right)\beta_{rd}y}}{(\rho\beta_{rd}y + \alpha_{se}x + \alpha_{re}y)(\beta_{sd}x - \beta_{rd}y)} \right)$$

$$\times \theta_{sp}e^{-\theta_{sp}x}\theta_{rp}e^{-\theta_{rp}y}dxdy$$

$$= \int_0^{+\infty} \left(\frac{\beta_{sd}\alpha_{se}\theta_{sp}\theta_{rp}}{\beta_{rd}\rho\beta_{sd} + \beta_{rd}\alpha_{se} + \beta_{sd}\alpha_{re}} \right) \times$$

$$\left(xe^{-x\left(\theta_{sp} + \frac{\gamma_{th}\beta_{sr}}{I_p} + \frac{z_s\beta_{sd}}{\beta_{rd}}\right)} E_i\left(\frac{z_s\beta_{sd}x}{\beta_{rd}}\right) dx \right.$$

$$+ \int_0^{+\infty} xe^{-x\left(\theta_{sp} + \frac{\gamma_{th}\beta_{sr}}{I_p} - \frac{z_s\alpha_{se}}{\beta_{rd}\rho + \alpha_{re}}\right)} E_1\left(\frac{z_s\alpha_{se}x}{\beta_{rd}\rho + \alpha_{re}}\right) dx \right)$$

$$+ \int_0^{+\infty} \left(\frac{-\beta_{rd}\alpha_{re}\theta_{sp}\theta_{rp}}{\beta_{rd}\rho\beta_{sd} + \beta_{rd}\alpha_{se} + \beta_{sd}\alpha_{re}} \right) \times$$

$$ye^{-y\left(z_s + \frac{\left(\theta_{sp} + \frac{\gamma_{th}\beta_{sr}}{I_p}\right)\beta_{rd}}{\beta_{sd}}\right)} E_i\left(\frac{\left(\theta_{sp} + \frac{\gamma_{th}\beta_{sr}}{I_p}\right)\beta_{rd}y}{\beta_{sd}}\right) dy$$

$$+ \int_0^{+\infty} \left(\frac{\beta_{sd}(\alpha_{re} + \beta_{rd}\rho)\alpha_{re}\theta_{sp}\theta_{rp}}{\alpha_{se}(\beta_{rd}\rho\beta_{sd} + \beta_{rd}\alpha_{se} + \beta_{sd}\alpha_{re})} \right) \times$$

where $z_s = \left(\frac{\rho-1}{I_p}\right)\beta_{rd} + \theta_{rp}$. The other expressions for S_3, S_5 and S_7 can be readily obtained by interchanging $\beta_{sd} \leftrightarrow \beta_{rd}$, $\alpha_{se} \leftrightarrow \alpha_{re}$, and $\theta_{sp} \leftrightarrow \theta_{rp}$, in S_4, S_2 and S_6 respectively, while keeping the probability of selection term, i.e. $e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}$ intact. S_1 and S_8 terms are similar to Q_1 and Q_{11} respectively.

O. Evaluation of T_2 in (17)

$$\mathbb{E}_{X,Y}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}X}{I_p}}\beta_{sd}X\alpha_{re}\alpha_{se}Xe^{-\left(\frac{\rho-1}{I_p}\right)\beta_{rd}Y}}{(\beta_{sd}X - \beta_{rd}Y)(\alpha_{se}X - \alpha_{re}Y)(\rho\beta_{rd} + \alpha_{re})} \right] =$$

$$\int_0^{+\infty}\int_0^{+\infty} \left(\frac{e^{-\frac{\gamma_{th}\beta_{sr}x}{I_p}}\beta_{sd}x\alpha_{re}\alpha_{se}xe^{-\left(\frac{\rho-1}{I_p}\right)\beta_{rd}y}}{(\beta_{sd}x - \beta_{rd}y)(\alpha_{se}x - \alpha_{re}y)(\rho\beta_{rd} + \alpha_{re})} \right)$$

$$\times \theta_{sp}e^{-\theta_{sp}x}\theta_{rp}e^{-\theta_{rp}y}dxdy$$

$$= \int_0^{+\infty} \left(\frac{-\beta_{sd}\alpha_{se}\alpha_{re}\theta_{sp}\theta_{rp}}{(\rho\beta_{rd} + \alpha_{re})(\beta_{sd}\alpha_{re} - \alpha_{se}\beta_{rd})} \right) \times$$

$$\left(xe^{-x\left(\left(\theta_{sp} + \frac{\gamma_{th}\beta_{sr}}{I_p}\right) + \frac{z_{t_1}\beta_{sd}}{\beta_{rd}}\right)} E_i\left(\frac{z_{t_1}\beta_{sd}x}{\beta_{rd}}\right) dx \right.$$

$$\left. - xe^{-x\left(\left(\theta_{sp} + \frac{\gamma_{th}\beta_{sr}}{I_p}\right) + \frac{z_{t_1}\alpha_{se}}{\alpha_{re}}\right)} E_i\left(\frac{z_{t_1}\alpha_{se}x}{\alpha_{re}}\right) dx \right) \qquad (35)$$

where $z_{t_1} = \left(\frac{\rho-1}{I_p}\right)\beta_{rd} + \theta_{rp}$.

P. Evaluation of T_3 in (17)

$$\mathbb{E}_{X,Y}\left[\frac{e^{-\frac{\gamma_{th}\beta_{sr}X}{I_p}}XY\beta_{rd}\alpha_{re}\alpha_{se}Ye^{-\left(\frac{\rho-1}{I_p}\right)\beta_{sd}X}}{(\beta_{rd}Y - \beta_{sd}X)(\alpha_{se}X - \alpha_{re}Y)(\rho\beta_{sd}X + \alpha_{re}Y)} \right] =$$

$$\int_0^{+\infty}\int_0^{+\infty} \left(\frac{e^{-\frac{\gamma_{th}\beta_{sr}x}{I_p}}xy\beta_{rd}\alpha_{re}\alpha_{se}ye^{-\left(\frac{\rho-1}{I_p}\right)\beta_{sd}x}}{(\beta_{rd}y - \beta_{sd}x)(\alpha_{se}x - \alpha_{re}y)(\rho\beta_{sd}x + \alpha_{re}y)} \right)$$

$$\times \theta_{sp}e^{-\theta_{sp}x}\theta_{rp}e^{-\theta_{rp}y}dxdy$$

$$= \int_0^{+\infty} \left(\frac{-\beta_{sd}^2\alpha_{se}\alpha_{re}\theta_{sp}\theta_{rp}}{(\beta_{rd}\alpha_{se} - \alpha_{re}\beta_{sd})(\rho\beta_{rd}\beta_{sd} + \alpha_{re}\beta_{sd})} \right) \times$$

$$xe^{-x\left(z_{t_2} + \frac{\theta_{rp}\beta_{sd}}{\beta_{rd}}\right)} E_i\left(\frac{\theta_{rp}\beta_{sd}x}{\beta_{rd}}\right) dx +$$

$$\int_0^{+\infty} \left(\frac{-\alpha_{se}^3\beta_{rd}\theta_{sp}\theta_{rp}}{(\alpha_{re}\beta_{sd} - \beta_{rd}\alpha_{se})(\rho\alpha_{re}\beta_{sd} + \alpha_{re}\alpha_{se})} \right) \times$$

$$xe^{-x\left(z_{t_2} + \frac{\theta_{rp}\alpha_{se}}{\alpha_{re}}\right)} E_i\left(\frac{\theta_{rp}\alpha_{se}x}{\alpha_{re}}\right) dx +$$

$$\int_0^{+\infty} \left(\frac{-\rho^2\beta_{sd}^2\alpha_{se}\beta_{rd}\theta_{sp}\theta_{rp}}{(\beta_{sd} + \rho\beta_{rd}\beta_{sd})(\alpha_{re}\alpha_{se} + \rho\alpha_{re}\beta_{sd})} \right) \times$$

$$xe^{-x\left(z_{t_2} - \frac{\theta_{rp}\rho\beta_{sd}}{\alpha_{re}}\right)} E_1\left(\frac{\theta_{rp}\rho\beta_{sd}x}{\alpha_{re}}\right) dx \qquad (36)$$

where $z_{t_2} = \left(\frac{\rho-1}{I_p}\right)\beta_{sd} + \theta_{sp} + \frac{\gamma_{th}\beta_{sr}}{I_p}$. The other expressions for T_4 and T_5 can be readily obtained by interchanging $\beta_{sd} \leftrightarrow \beta_{rd}$, $\alpha_{se} \leftrightarrow \alpha_{re}$, and $\theta_{sp} \leftrightarrow \theta_{rp}$, in T_3 and T_2 respectively, while keeping the probability of selection term, i.e. $e^{-\frac{\gamma_{th}\beta_{sr}\gamma_{sp}}{I_p}}$ intact. T_1 and T_6 terms are similar to Q_1 and Q_{11} respectively.

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