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Cooperation Diversity for Secrecy Enhancement in Cognitive Relay Wiretap Network Over Correlated Fading Channels

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ABSTRACT In this paper, we investigate the secrecy performance of dual-hop randomize-and-forward (RaF) cognitive relay multi-channel wiretap networks over correlated fading channels, in which the eavesdropper can wiretap the information from source and relays simultaneously. Specifically, in order to enhance the secrecy performance, we introduce two cooperation diversity schemes: 1) traditional partial relay selection (TPRS), where an optimal relay is selected to receive-and-forward the information based on the channel quality between the source and relays and 2) decoding threshold-aided optimal relay selection (DTaORS), where an optimal relay is selected from the threshold-based relay set based on the channel quality between the relays and destination. For these criteria, we analyze the secrecy performance of two cooperation diversity schemes by deriving the exact and asymptotic expressions for the secrecy outage probability of cognitive relay wiretap networks over correlated fading channels. From the results, we conclude that: 1) even though the channel correlation does not influence the secrecy diversity order, it is beneficial to the secrecy coding gain in high main-to-eavesdropper ratio regime; 2) DTaORS with an appropriate decoding rate can achieve better secrecy performance than TPRS. However, affected by the multi-channel wiretap, both of DTaORS and TPRS can not increase the secrecy diversity order any more, which is always equal to 1; and 3) the secrecy performance with a RaF scheme is better than that with a decode-and-forward scheme in multi-channel wiretap scenario.

INDEX TERMS Cognitive radio, secrecy outage probability, cooperation diversity, channel correlation, physical layer security.

I. INTRODUCTION

Driven by the rapidly increasing high-speed demands of services and the growing spectrum shortage problems, cognitive radio, first proposed by Mitola [1], has drawn more and more attentions. The cognitive radio, which includes three different schemes, i.e., underlay, overlay and interweave, can help unlicensed users share the spectrum resources with licensed users and then improve the spectral efficiency [2]–[4]. However, due to the spectrum sharing characteristics, the privacy and security of data transmission in cognitive wireless networks are threatened more seriously than traditional wireless networks [5], [6]. In recent years, with the continuous development of quantum computing, the traditional upper encryption technologies have been unable to meet the needs for confidentiality of wireless communications. Thus, motivated by this observations, physical layer security (PLS) has been proposed from the information-theoretic point of perspective, which utilizes the difference between the main and wiretap channels to enhance the security of information transmission [7], [8]. Nowadays, there has been many works about the PLS of cognitive wireless networks with underlay scheme [9]–[12]. Specifically, Huang *et al.* [13] analyzed the secrecy performance of cognitive multiple-input multiple-output (MIMO) wiretap networks with generalized transmit antenna selection (GTAS) and maximal ratio combining (MRC) scheme. In [14], a jamming noise was designed for the secrecy rate maximization of cognitive multi-input single-output multi-eves (MISOME) networks. Then, in [15], the authors studied the impact of artificial jamming signal on the secrecy performance of full-duplex cognitive wireless networks with two antenna reception schemes and presented the exact and asymptotic expressions for secrecy outage probability (SOP) under the two scenarios.

Cooperation diversity technology, which is first used to enhance the reliability of data transmission, has been proposed as an effective strategy for improving the security [16]–[20]. Nowadays, there are two fundamental relay forwarding protocols, i.e., decoding-and-forward (DF) and amplify-and-forward (AF). Since DF scheme achieves better performance than that of AF scheme, it has been broadly utilized to improve the PLS of cognitive relay networks. Zou *et al.* [21] the impact of an adaptive cooperation diversity scheme with optimal relay selection on the secrecy performance of cognitive DF relay wiretap networks. Then Zou *et al.* [22] extended the analysis in [21] to multi-relay selection scheme and proved that the multi-relay selection achieves better performance than the single-relay selection on the security-reliability trade-off (SRT) performance. In [23], a joint relay and jammer selection was proposed to improve the secrecy performance of cognitive DF relay wiretap networks. It's worth noting that the above works all just considered the single-channel wiretap scenario, where the eavesdropper can only overhear the information from relays. However, once the eavesdropper can simultaneously overhear the information from source and relay, the traditional DF scheme can not achieve a good effect any more. Hence, a new relay forwarding scheme and the corresponding cooperation diversity scheme are needed for the improvement of secrecy performance on cognitive relay multi-channel wiretap networks.

Moreover, a major limitation of the above works is that they all assumed the main channel and the wiretap channel are independent, which is not always reasonable in a real scenario due to the antenna deployments and radio scattering [24]–[26]. Specifically, in [24] and [25], the authors first proved the existence of space correlation properties between different base-stations. Then, a function relationship of two correlated random variables was derived in [27]. Motivated by this, in [28] and [29], the authors investigated the secrecy performance of cooperative relay networks with AF and DF schemes over correlated fading channels, respectively, and proved that the channel correlation is beneficial to SOP in high main-to-eavesdropper ratio (MER) regime. Further, Li *et al.* [30] firstly investigated the impact of correlated fading channels on the secrecy performance of cognitive DF relay wiretap network and utilized generalized relay selection scheme to analyze the influence of different relay selection strategies on the secrecy performance. However, the aforementioned studies all aimed at the single-channel wiretap scenario, i.e., the eavesdropper only overhears the information from relays. To the best of the authors' knowledge, the impact of correlated fading channels on cognitive relay multi-channel wiretap networks, i.e., the eavesdropper can simultaneously overhear the information from both the source and relays, has not been well understood.

Motivated by the above observations, we utilize the cooperation diversity to enhance the security of a cognitive relay multi-channel wiretap network, where a secondary transmitter (ST) communicates with a secondary destination (SD) in the presence of a primary user (PU) and an secondary eavesdropper (SE). To improve the secrecy performance, we consider a randomize-and-forward (RaF) scheme, which is a special variation of DF scheme, at relays to forward the information from ST, in which the ST and relay utilize different codebooks to forward the information so that the eavesdropper can not merge the information overheard from the source and relays. Moreover, we also investigate two cooperation diversity schemes for the considered network, i.e., the traditional partial relay selection (TPRS) and the decoding threshold aided optimal relay selection (DTaORS). The main contributions of our work are summarized as follows:

- Based on the two cooperation diversity schemes, we derived the corresponding exact expressions for SOP of dual-hop RaF cognitive relay multi-channel wiretap networks over correlated fading channels, respectively, which provides us an effective method to investigate the impact of key parameters on the secrecy performance. We find that the secrecy performance achieved by DTaORS with an appropriate decoding rate threshold is better than that achieved by TPRS.
- To achieve more intuitive insights, we also get the asymptotic SOP expressions with the two cooperation diversity schemes in high MER regime. The results demonstrate that the channel correlation does not affect the secrecy diversity order, but has a positive impact on the secrecy coding gain. Moreover, affected by the multi-channel wiretap, the secrecy diversity order is also no longer affected by the cooperation diversity schemes and always equal to 1. In addition, in high MER regime, the asymptotic expressions with TPRS and DTaORS are identical.
- Through simulation analysis, we find that the traditional DF scheme is no longer suitable for the multi-channel wiretap scenario and the channel correlation will damage the secrecy performance of the system with DF. In addition, the RaF scheme can achieve much better performance than DF under the same parameter configurations and the channel correlation can be beneficial to the secrecy performance of the system with RaF.

The rest of this paper is organized as follows. The system model with correlated fading channels and the two cooperation diversity schemes are described in Section II. Section III analyzes the secrecy performance of the system in terms of the exact and asymptotic expressions for SOP. Numerical results and performance analysis are presented in Section IV. Finally, the conclusion is given in Section V.

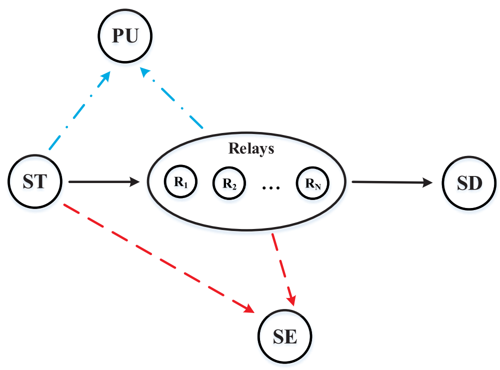

FIGURE 1. Cognitive Relay Wiretap Network.

II. SYSTEM MODEL

We consider a cognitive relay multi-channel wiretap system as shown in Fig. 1, which is composed of a secondary transmitter (ST), a secondary destination (SD), a primary user (PU), a secondary eavesdropper (SE) and N relays $\{\mathrm{R}_n|1 \le n \le N\}$. Among the system, all the nodes have only one antenna, the relays utilize the RaF scheme to receive and forward the information from ST and SE can simultaneously overhear the information from source and relays [31]. Moreover, we consider a more practical scenario, where the channels from ST to relays and SE and the channels from relays to SD and SE are correlated, respectively. All the channels experience quasi-static non-identical Rayleigh fading and the interference at R_n, SD and SE from primary transmitter are neglected due to the limited transmission as in [32] and [33]. In addition, a passive wiretap scenario, just like [35] and [36], is also assumed, which means that the channel statement informations (CSIs) from ST and R_n to SE are not available for the relay selection.

The total transmission includes two phases. Suppose that the relay R_n is selected for the two-phase transmission. In the first phase, the information is transmitted from ST to R_n and the SE can also overhear the information. Thus, the received signals at R_n and SE can be presented as

$$y_{\mathrm{SR}_n} = \sqrt{P_{\mathrm{S}}} h_{\mathrm{SR}_n} x + n_{\mathrm{R}} \tag{1}$$

and

$$y_{\mathrm{SE}} = \sqrt{P_{\mathrm{S}}} h_{\mathrm{SE}} x + n_{1\mathrm{E}}, \tag{2}$$

where x is the confidential information, P_{S} is the actual transmit power at ST, $h_{\mathrm{SR}_n} \sim \mathcal{CN}(0, \lambda_{\mathrm{SR}})$ and $h_{\mathrm{SE}} \sim \mathcal{CN}(0, \lambda_{\mathrm{SE}})$ are the correlated channel fading coefficients of ST$-\mathrm{R}_n$ and ST$-$SE links, respectively. $n_{\mathrm{R}} \sim \mathcal{CN}\left(0, \sigma^2\right)$ and $n_{1\mathrm{E}} \sim \mathcal{CN}\left(0, \sigma^2\right)$ are the additional white Gaussian noise (AWGN) at R_n and SE, respectively.

In the second phase, the selected relay R_n decodes the information and forwards it to SD with a random coding scheme, and the SE can also overhear the information from relays. The received signals at SD and SE are presented as

$$y_{\mathrm{R}_n\mathrm{D}} = \sqrt{P_{\mathrm{R}}} h_{\mathrm{R}_n\mathrm{D}} x + n_{\mathrm{D}} \tag{3}$$

and

$$y_{\mathrm{R}_n\mathrm{E}} = \sqrt{P_{\mathrm{R}}} h_{\mathrm{R}_n\mathrm{E}} x + n_{2\mathrm{E}}, \tag{4}$$

where P_{R} presents the actual transmit power at R_n, $h_{\mathrm{R}_n\mathrm{D}} \sim \mathcal{CN}(0, \lambda_{\mathrm{RD}})$ and $h_{\mathrm{R}_n\mathrm{E}} \sim \mathcal{CN}(0, \lambda_{\mathrm{RE}})$ are the correlated channel fading coefficients of $\mathrm{R}_n$$-$SD and $\mathrm{R}_n$$-$SE links, respectively. $n_{\mathrm{D}} \sim \mathcal{CN}\left(0, \sigma^2\right)$ and $n_{2\mathrm{E}} \sim \mathcal{CN}\left(0, \sigma^2\right)$ are AWGN at SD and SE, respectively.

Note that in the underlay scheme, the secondary transmission can not damage the quality of service (QoS) of PU, thus the actual transmit power at ST and R_n, i.e., P_{S} and P_{R}, are restricted by the interference temperature threshold from PU, i.e.,

$$P_{\mathrm{S}} = \begin{cases} P_{\mathrm{t}}, & |h_{\mathrm{SP}}|^2 \le \frac{Q}{P_{\mathrm{t}}} \\ \frac{Q}{|h_{\mathrm{SP}}|^2}, & |h_{\mathrm{SP}}|^2 > \frac{Q}{P_{\mathrm{t}}} \end{cases} \tag{5}$$

and

$$P_{\mathrm{R}} = \begin{cases} P_{\mathrm{t}}, & \left|h_{\mathrm{R}_n\mathrm{P}}\right|^2 \le \frac{Q}{P_{\mathrm{t}}} \\ \frac{Q}{\left|h_{\mathrm{R}_n\mathrm{P}}\right|^2}, & \left|h_{\mathrm{R}_n\mathrm{P}}\right|^2 > \frac{Q}{P_{\mathrm{t}}}, \end{cases} \tag{6}$$

where P_{t} is the maximal transmit power at ST and R_n, Q is the interference temperature threshold from PU, $h_{\mathrm{SP}} \sim \mathcal{CN}(0, \lambda_{\mathrm{SP}})$ and $h_{\mathrm{R}_n\mathrm{P}} \sim \mathcal{CN}(0, \lambda_{\mathrm{RP}})$ are the channel fading coefficients from PU to ST and R_n, respectively.

According to [27], the conditional probability density function (PDF) of two correlated random variables is presented as

$$f\left(u|\, v\right) = \frac{I_0\left(\frac{2}{1-\rho}\sqrt{\frac{uv\rho}{\bar{u}\bar{v}}}\right)}{(1-\rho)\,\bar{u}} \exp\left(-\frac{\frac{\rho v}{\bar{v}} + \frac{u}{\bar{u}}}{1-\rho}\right), \tag{7}$$

where $u \in \left(|h_{\mathrm{SE}}|^2, \left|h_{\mathrm{R}_n\mathrm{E}}\right|^2\right)$ and $v \in \left(\left|h_{\mathrm{SR}_n}\right|^2, \left|h_{\mathrm{R}_n\mathrm{D}}\right|^2\right)$, $\bar{u}$ and $\bar{v}$ are the corresponding average values, respectively. ρ represents the channel correlation coefficient and $I_0(x)$ is the zeroth order modified Bessel function of the first kind [40].

In order to improve the secrecy performance of the considered system, we introduce two cooperation diversity schemes, i.e., TPRS and DTaORS, for the selection of the best relay R_{n^*}. When TPRS is utilized for the relay selection, the best relay is selected based on the channel quality between ST and R_n,[1] i.e.,

$$n^* = \arg\max_{n\in\Omega_N}\left(\left|h_{\mathrm{SR}_n}\right|^2\right), \tag{8}$$

where $\Omega_N = \{1, 2, \cdots, N\}$ is the set of relays.

[1] A passive eavesdropping scenario is assumed, where the CSI from SE can not be realized by ST and R_n. Hence, we only use the channel quality of main channel as the selection criterion.

In addition, when DTaORS is utilized for the relay selection, the best relay is selected based on a comprehensive channel quality assessment of $\mathrm{ST-R}_n$ and $\mathrm{R}_n\mathrm{-SD}$ links. Firstly, some relays, whose channel capacities meet the decoding rate threshold R_t, will be selected to form a decoding set, $\{R_m|1 \leq m \leq M\}$, based on the channel quality of $\mathrm{ST-R}_n$ link. Then, an optimal relay can be selected from the decoding set based on the channel quality of $\mathrm{R}_n\mathrm{-SD}$ link, i.e.,

$$n^* = \arg\max_{n\in\Omega_M} \left(\left|h_{\mathrm{R}_n\mathrm{D}}\right|^2\right), \tag{9}$$

where $\Omega_M = \{1, 2, \cdots, M\}$ is the decoding set and M is the size of the decoding set. If $M = 0$, which means that no relay can meet the decoding threshold, the transmission breaks down.

Finally, based on the above analysis, the achievable secrecy rate in the first and second phases of cognitive relay multi-channel wiretap network can be given as

$$C_{1\mathrm{s}} = \frac{1}{2}\left[\log_2\left(1+\gamma_{\mathrm{R}_i}\right) - \log_2\left(1+\gamma_{1\mathrm{E}_i}\right)\right]^+ \tag{10}$$

and

$$C_{2\mathrm{s}} = \frac{1}{2}\left[\log_2\left(1+\gamma_{\mathrm{D}_i}\right) - \log_2\left(1+\gamma_{2\mathrm{E}_i}\right)\right]^+, \tag{11}$$

where the parameter $1/2$ demonstrates that the transmission includes two phases, $[x]^+ = \max(x, 0)$, γ_{R_i} is the instantaneous SNR at R_{n^*} in the first phase, γ_{D_i} is the instantaneous SNR at SD in the second phase, $\gamma_{1\mathrm{E}_i}$ and $\gamma_{2\mathrm{E}_i}$ are the instantaneous SNRs at SE in the first and second phases, respectively and $i \in (\mathrm{T}, \mathrm{D})$ represents TPRS and DTaORS, respectively.

III. SECRECY PERFORMANCE ANALYSIS

In this section, we will analyze in detail the secrecy performance of cognitive relay multi-channel wiretap networks over correlated fading channels with TPRS and DTaORS in terms of the exact secrecy outage probability and the asymptotic secrecy outage probability.

A. SECRECY OUTAGE PROBABILITY

According to the definition of RaF protocol, the ST and relay transmit independent randomization signal so that the SE can not merge the information overheard from ST and R_n. Hence, in order to ensure the security, the transmission must be secure in both of the two phases [37]–[39]. According to [39], the secrecy outage probability can be defined as

$$P_{\mathrm{out}}(R_{\mathrm{s}}) = 1 - \Pr\left(C_{1\mathrm{s}} > R_{\mathrm{s}}\right)\Pr\left(C_{2\mathrm{s}} > R_{\mathrm{s}}\right), \tag{12}$$

where R_{s} is the secrecy rate threshold, $C_{1\mathrm{s}}$ and $C_{2\mathrm{s}}$ are the achievable secrecy rates in the first and second phases of the total transmission, respectively.

1) TPRS SCHEME

Considered the common random variables (RV), i.e., $G_1 = |h_{\mathrm{SP}}|^2$ and $G_2 = \left|h_{\mathrm{R}_{n^*}\mathrm{P}}\right|^2$, and the channel correlation properties, the instantaneous received SNRs $\gamma_{\mathrm{R_T}} = \frac{P_{\mathrm{S}}\left|h_{\mathrm{SR}_{n^*}}\right|^2}{\sigma^2}$ and $\gamma_{1\mathrm{E_T}} = \frac{P_{\mathrm{S}}|h_{\mathrm{SE}}|^2}{\sigma^2}$, $\gamma_{\mathrm{D_T}} = \frac{P_{\mathrm{R}}\left|h_{\mathrm{R}_{n^*}\mathrm{D}}\right|^2}{\sigma^2}$ and $\gamma_{2\mathrm{E_T}} = \frac{P_{\mathrm{R}}\left|h_{\mathrm{R}_{n^*}\mathrm{E}}\right|^2}{\sigma^2}$ are no longer independent. Thus, we firstly present the joint conditional PDF of $\gamma_{\mathrm{R_T}}$ and $\gamma_{1\mathrm{E_T}}$ on RV G_1 in **Lemma 1**, and then the PDF of $\gamma_{\mathrm{D_T}}$ and $\gamma_{2\mathrm{E_T}}$ on RV G_2 is given in *Lemma* 2.

Lemma 1: The joint conditional PDF of γ_{R_T} and γ_{1E_T} conditioned on RV G_1 over correlated fading channels with TPRS is derived as

$$\begin{aligned} f_{\gamma_{R_T},\gamma_{1E_T}}(\gamma_1,\gamma_2|G_1) &= \sum_{n=1}^{N}\sum_{l=0}^{\infty}\binom{N}{n}\frac{n(-1)^{n-1}\rho_1^l}{(1-\rho_1)^{2l+1}(l!)^2} \\ &\quad\times\frac{\gamma_1^l\gamma_2^l}{\beta_{SE}^{l+1}\beta_{SR}^{l+1}}\exp\left[-\frac{\gamma_2}{(1-\rho_1)\beta_{SE}}\right. \\ &\quad\left.-\left(\frac{\rho_1}{1-\rho_1}+n\right)\frac{\gamma_1}{\beta_{SR}}\right], \end{aligned} \tag{13}$$

where ρ_1 is the channel correlation coefficient of $ST - R_{n^*}$ and $ST - SE$ links, $\beta_{SR} = \frac{P_S\lambda_{SR}}{\sigma^2}$ and $\beta_{SE} = \frac{P_S\lambda_{SE}}{\sigma^2}$ are the corresponding average values of γ_1 and γ_2.

Proof: See Appendix A. ■

Lemma 2: The joint conditional PDF of γ_{D_T} and γ_{2E_T} conditioned on RV G_2 over correlated fading channels with TPRS is derived as

$$\begin{aligned} &f_{\gamma_{D_T},\gamma_{2E_T}}(\gamma_3,\gamma_4|G_2) \\ &\quad= \sum_{l=0}^{\infty}\frac{\rho_2^l\gamma_3^l\gamma_4^l}{(1-\rho_2)^{2l+1}(l!)^2\beta_{RE}^{l+1}\beta_{RD}^{l+1}} \\ &\qquad\times\exp\left[-\frac{\gamma_4}{(1-\rho_2)\beta_{RE}}-\frac{\gamma_3}{(1-\rho_2)\beta_{RD}}\right], \end{aligned} \tag{14}$$

where ρ_2 is the channel correlation coefficient of $R_{n^*}-SD$ and $R_{n^*}- SE$ links, $\beta_{RD} = \frac{P_R\lambda_{RD}}{\sigma^2}$ and $\beta_{RE} = \frac{P_R\lambda_{RE}}{\sigma^2}$ are the corresponding average values of γ_3 and γ_4.

Proof: When the TPRS scheme is utilized, the best relay is selected based on the CSI of the first phase, which corresponds to a random relay for the second phase. Thus, in the second phase, the PDF of $\gamma_{\mathrm{D_T}}$ is just a fundamental exponential distribution as

$$f_{\gamma_{\mathrm{D_T}}}(\gamma_3|G_2) = \frac{1}{\beta_{\mathrm{RD}}}\exp\left(-\frac{\gamma_3}{\beta_{\mathrm{RD}}}\right). \tag{15}$$

By interchanging the parameters in Eq. (30), i.e., $\rho_1 \to \rho_2$, $\gamma_1 \to \gamma_3$, $\gamma_2 \to \gamma_4$, $\beta_{\mathrm{SR}} \to \beta_{\mathrm{RD}}$, $\beta_{\mathrm{SE}} \to \beta_{\mathrm{RE}}$ and multipling with (15), the joint conditional PDF of $\gamma_{\mathrm{D_T}}$ and $\gamma_{2\mathrm{E_T}}$ in (14) can be derived after simple mathematical manipulations. ■

Then, based on the above analysis, the probability that both the two phases are secure will be given in the follows theorems, respectively.

Theorem 1: The probability that the first phase is secure over correlated fading channels with TPRS can be presented as (16)*, as shown at the top of the next page, where $\gamma_s = 2^{2R_s}$ is the secrecy SNR threshold, $\Gamma(\cdot,\cdot)$ is the upper incomplete Gamma function [40, eq. (8.350.2)].*

Proof: See Appendix B. ■

Theorem 2: The probability that the second phase is secure over correlated fading channels with TPRS can be presented as (17)*, as shown at the top of the next page.*

$$\begin{aligned}\Pr_{\mathrm{TPRS}}\left(C_{1\mathrm{s}}>R_{\mathrm{s}}\right)=&\sum_{n=1}^{N}\sum_{l=0}^{\infty}\sum_{i=0}^{l}\sum_{j=0}^{i}\binom{N}{n}\binom{i}{j}\frac{n(-1)^{n}\,(l+j)!\rho_1^{l}\gamma_s^{j}(\gamma_s-1)^{i-j}}{i!m!(1-\rho_1)^{2l+1}}\left(\frac{\rho_1}{1-\rho_1}+n\right)^{-l-1+i}\lambda_{\mathrm{SE}}^{-j-1}\lambda_{\mathrm{SR}}^{-i}(\sigma)^{2i-2j}\\&\times\left[\frac{1}{(1-\rho_1)\,\lambda_{\mathrm{SE}}}+\left(\frac{\rho_1}{1-\rho_1}+n\right)\frac{\gamma_{\mathrm{s}}}{\lambda_{\mathrm{SR}}}\right]^{-l-j-1}\left\{P_{\mathrm{t}}^{-i+j}\exp\left[-\left(\frac{\rho_1}{1-\rho_1}+n\right)(\gamma_{\mathrm{s}}-1)\frac{\sigma^2}{\lambda_{\mathrm{SR}}P_{\mathrm{t}}}\right]\right.\\&\times\left[1-\exp\left(-\frac{Q}{P_{\mathrm{t}}\lambda_{\mathrm{SP}}}\right)\right]+\frac{Q^{j-i}}{\lambda_{\mathrm{SP}}}\left(\left(\frac{\rho_1}{1-\rho_1}+n\right)(\gamma_{\mathrm{s}}-1)\frac{\sigma^2}{\lambda_{\mathrm{SR}}Q}+\frac{1}{\lambda_{\mathrm{SP}}}\right)^{-i+j-1}\\&\left.\times\Gamma\left[i-j+1,\left(\frac{\rho_1}{1-\rho_1}+n\right)(\gamma_s-1)\frac{\sigma^2}{\lambda_{\mathrm{SR}}P_{\mathrm{t}}}+\frac{Q}{P_{\mathrm{t}}\lambda_{\mathrm{SP}}}\right]\right\}\end{aligned}\tag{16}$$

$$\begin{aligned}\Pr_{\mathrm{TPRS}}\left(C_{2\mathrm{s}}>R_{\mathrm{s}}\right)=&\sum_{l=0}^{\infty}\sum_{i=0}^{l}\sum_{j=0}^{i}\binom{i}{j}\frac{(m+j)!}{m!i!}\gamma_{\mathrm{s}}^{j}(\gamma_{\mathrm{s}}-1)^{i-j}\rho_2^{l}\,(1-\rho_2)^{j+1-i}\lambda_{\mathrm{RD}}^{-i}\lambda_{\mathrm{RE}}^{-l-1}(\sigma)^{2i-2j}\left(\frac{1}{\lambda_{\mathrm{RE}}}+\frac{\gamma_{\mathrm{s}}}{\lambda_{\mathrm{RD}}}\right)^{-l-j-1}\\&\times\left\{P_{\mathrm{t}}^{-i+j}\exp\left(-\frac{(\gamma_{\mathrm{s}}-1)\,\sigma^2}{(1-\rho_2)\,P_{\mathrm{t}}\lambda_{\mathrm{RD}}}\right)\left[1-\exp\left(-\frac{Q}{P_{\mathrm{t}}\lambda_{\mathrm{RP}}}\right)\right]+\frac{Q^{j-i}}{\lambda_{\mathrm{RP}}}\left[\frac{(\gamma_{\mathrm{s}}-1)\,\sigma^2}{(1-\rho_2)\,\lambda_{\mathrm{RD}}Q}+\frac{1}{\lambda_{\mathrm{RP}}}\right]^{-i+j-1}\right.\\&\left.\times\Gamma\left[i-j+1,\frac{(\gamma_{\mathrm{s}}-1)\,\sigma^2}{(1-\rho_2)\,\lambda_{\mathrm{RD}}P_{\mathrm{t}}}+\frac{Q}{P_{\mathrm{t}}\lambda_{\mathrm{RP}}}\right]\right\}\end{aligned}\tag{17}$$

Proof: The proof is similar to **Theorem 1**. ■

2) DTAORS SCHEME

Similar to the introduction of TPRS, we firstly present the joint conditional PDF of $\gamma_{\mathrm{R_D}}$ and $\gamma_{1\mathrm{E_D}}$ in **Lemma 3**, and then the joint conditional PDF of $\gamma_{\mathrm{D_D}}$ and $\gamma_{2\mathrm{E_D}}$ is given in **Lemma 4**.

Lemma 3: For a given size of the decoding set, the joint conditional PDF of γ_{R_D} and γ_{1E_D} conditioned on RV G_1 over correlated fading channels with DTaORS is derived as

$$\begin{aligned}&f_{\gamma_{R_D},\gamma_{1E_D}}(\gamma_1,\gamma_2|G_1)\\&=\sum_{d=0}^{N-M}\sum_{l=0}^{\infty}\binom{N}{M}\binom{N-M}{d}(-1)^d\\&\quad\times\frac{\gamma_1^{l}\gamma_2^{l}\rho_1^{l}}{(1-\rho_1)^{2l+1}\beta_{SR}^{l+1}\beta_{SE}^{l+1}(l!)^2}\exp\left(-\frac{\frac{\gamma_1}{\beta_{SR}}+\frac{\gamma_2}{\beta_{SE}}}{1-\rho_1}\right)\\&\quad\times\exp\left[-\frac{(M+d)\,\gamma_t}{\beta_{SR}}\right],\end{aligned}\tag{18}$$

where $\gamma_t=2^{2R_t}-1$ represents the decoding SNR threshold.

Proof: See Appendix C. ■

Lemma 4: For a given size of the decoding set, the joint conditional PDF of γ_{D_D} and γ_{2E_D} conditioned on RV G_2 over correlated fading channels with DTaORS is derived as

$$\begin{aligned}f_{\gamma_{D_D},\gamma_{2E_D}}(\gamma_3,\gamma_4|G_1)=&\sum_{n=1}^{M}\sum_{l=0}^{\infty}\binom{M}{n}\frac{n(-1)^{n-1}\rho_2^{l}}{(1-\rho_2)^{2l+1}(l!)^2}\\&\times\frac{\gamma_3^{l}\gamma_4^{l}}{\beta_{RD}^{l+1}\beta_{RE}^{l+1}}\exp\left[-\frac{\gamma_4}{(1-\rho_1)\,\beta_{RE}}\right.\\&\left.-\left(\frac{\rho_2}{1-\rho_2}+n\right)\frac{\gamma_3}{\beta_{RD}}\right].\end{aligned}\tag{19}$$

Proof: The proof is similar to **Lemma 1**. ■

Then, we focus on the probability expressions that the first and second phases are secure in the follow theorems.

Theorem 3: The probability that the first phase is secure over correlated fading channels with DTaORS can be presented as (20)*, as shown at the top of the next page.*

Proof: See Appendix D. ■

Theorem 4: For a given size of the decoding set, the probability that the second phase is secure over correlated fading channels with DTaORS can be presented as (21)*, as shown at the top of the next page.*

Proof: The proof is similar to **Theorem 1**. ■

B. ASYMPTOTIC SECRECY OUTAGE PROBABILITY

Although the derived exact SOP can help us to evaluate the secrecy performance of the two proposed schemes, their intractability make us difficult to analyze more deep insights about the impact of parameters. Hence, in this subsection, we turn our attention to investigate the asymptotic secrecy outage probability of the system in high main-to-eavesdropping ratio (MER) regime for extracting two important design parameters, i.e., the achievable secrecy diversity order[2]and the secrecy coding gain.

1) TPRS SCHEME

Considering the average values of the achieved SNRs, i.e., β_{SR}, β_{SE}, β_{RD} and β_{RE}, all tend to be relative large and the MER, i.e., $R=\frac{\beta_{\mathrm{SR}}}{\beta_{\mathrm{SE}}}=\frac{\beta_{\mathrm{RD}}}{\beta_{\mathrm{RE}}}$, also tends to be infinity. Then the asymptotic SOP with TPRS scheme can be represented in the following corollary.

Corollary 1: The asymptotic secrecy outage probability of cognitive relay multi-channel wiretap networks over

[2]The achievable secrecy diversity order is defined as $d_{\mathrm{secrecy}}=-\lim_{R\to\infty}\frac{\log(P_{\mathrm{out}})}{\log(R)}$, which has been widely used as an important parameter in PLS [13], [15].

$$
\begin{aligned}
&\Pr_{\mathrm{DTaORS}}(C_{1\mathrm{s}}>R_{\mathrm{s}})\\
&=\begin{cases}
\sum_{M=1}^{N}\sum_{d=0}^{N-M}\sum_{l=0}^{\infty}\sum_{i=0}^{l}\sum_{t=0}^{i}\binom{N}{M}\binom{N-M}{d}(-1)^{d}\binom{i}{t}\frac{(l+t)!}{l!t!}\gamma_{\mathrm{s}}^{t}(\gamma_{\mathrm{s}}-1)^{i-t}\rho_1^{l}(1-\rho_1)^{t+1-i}\sigma^{2i-2t}\lambda_{\mathrm{SR}}^{-i}\lambda_{\mathrm{SE}}^{-l-1}\\
\left(\frac{1}{\lambda_{\mathrm{SE}}}+\frac{\gamma_{\mathrm{s}}}{\lambda_{\mathrm{SR}}}\right)^{-l-t-1}\Big\{P_{\mathrm{t}}^{-i+t}\exp\left[-\frac{(\gamma_{\mathrm{s}}-1)-(1-\rho_1)\gamma_{\mathrm{t}}\sigma^2}{(1-\rho_1)\lambda_{\mathrm{SR}}P_{\mathrm{t}}}-\frac{(M+d)\gamma_{\mathrm{t}}\sigma^2}{\lambda_{\mathrm{SR}}P_{\mathrm{t}}}\right]\left[1-\exp\left(-\frac{Q}{P_{\mathrm{t}}\lambda_{\mathrm{SP}}}\right)\right]\\
+\frac{Q^{t-i}}{\lambda_{\mathrm{SP}}}\left[\frac{(\gamma_{\mathrm{s}}-1)-(1-\rho_1)\gamma_{\mathrm{t}}\sigma^2}{(1-\rho_1)\lambda_{\mathrm{SR}}Q}+\frac{(M+d)\gamma_{\mathrm{t}}\sigma^2}{\lambda_{\mathrm{SR}}Q}+\frac{1}{\lambda_{\mathrm{SP}}}\right]^{-i+t-1}\Gamma\Big[i-t+1,\Big(\frac{(\gamma_{\mathrm{s}}-1)-(1-\rho_1)\gamma_{\mathrm{t}}\sigma^2}{(1-\rho_1)\lambda_{\mathrm{SR}}P_{\mathrm{t}}}+\frac{Q}{\lambda_{\mathrm{SP}}P_{\mathrm{t}}}\\
+\frac{(M+d)\gamma_{\mathrm{t}}\sigma^2}{\lambda_{\mathrm{SR}}P_{\mathrm{t}}}\Big)\Big]\Big\}, \qquad \frac{\gamma_{\mathrm{t}}+1}{\gamma_{\mathrm{s}}}-1\le 0\\
\sum_{M=1}^{N}\sum_{d=0}^{N-M}\sum_{l=0}^{\infty}\sum_{i=0}^{l}\binom{N}{M}\binom{N-M}{d}(-1)^{d}\Big\{\frac{\rho_1^{l}\gamma_{\mathrm{t}}^{i}\sigma^{2i}}{(1-\rho_1)^{i-1}i!\lambda_{\mathrm{SR}}^{i}}\Big[P_{\mathrm{t}}^{-i}\exp\left(-\frac{\rho_1\gamma_{\mathrm{t}}\sigma^2}{(1-\rho_1)\lambda_{\mathrm{SR}}P_{\mathrm{t}}}-\frac{(M+d)\gamma_{\mathrm{t}}\sigma^2}{\lambda_{\mathrm{SR}}P_{\mathrm{t}}}\right)\\
\left(1-\exp\left(-\frac{Q}{P_{\mathrm{t}}\lambda_{\mathrm{SP}}}\right)\right)+\frac{Q^{-i}}{\lambda_{\mathrm{SP}}}\left(\frac{\rho_1\gamma_{\mathrm{t}}\sigma^2}{(1-\rho_1)\lambda_{\mathrm{SR}}Q}+\frac{(M+d)\gamma_{\mathrm{t}}\sigma^2}{\lambda_{\mathrm{SR}}Q}+\frac{1}{\lambda_{\mathrm{SP}}}\right)^{-i-1}\Gamma\Big(i+1,\frac{\rho_1\gamma_{\mathrm{t}}\sigma^2}{(1-\rho_1)\lambda_{\mathrm{SR}}P_{\mathrm{t}}}\\
+\frac{(M+d)\gamma_{\mathrm{t}}\sigma^2}{\lambda_{\mathrm{SR}}P_{\mathrm{t}}}+\frac{Q}{\lambda_{\mathrm{SP}}P_{\mathrm{t}}}\Big)\Big]-\sum_{j=0}^{l}\frac{\rho_1^{l}\gamma_{\mathrm{t}}^{i}\sigma^{2i+2j}\lambda_{\mathrm{SR}}^{-i}\lambda_{\mathrm{SE}}^{-j}}{i!j!(1-\rho_1)^{i+j-1}}\left(\frac{\gamma_{\mathrm{t}}+1}{\gamma_{\mathrm{s}}}-1\right)^{j}\Big[P_{\mathrm{t}}^{-i-j}\exp\Big(-\frac{\rho_1\gamma_{\mathrm{t}}\sigma^2}{(1-\rho_1)\lambda_{\mathrm{SR}}P_{\mathrm{t}}}\\
-\frac{\sigma^2(\gamma_{\mathrm{t}}+1-\gamma_{\mathrm{s}})}{(1-\rho_1)\lambda_{\mathrm{SE}}\gamma_{\mathrm{s}}P_{\mathrm{t}}}-\frac{(M+d)\gamma_{\mathrm{t}}\sigma^2}{\lambda_{\mathrm{SR}}P_{\mathrm{t}}}\Big)\left(1-\exp\left(-\frac{Q}{P_{\mathrm{t}}\lambda_{\mathrm{SP}}}\right)\right)+\frac{Q^{-i-j}}{\lambda_{\mathrm{SP}}}\Big(\frac{\rho_1\gamma_{\mathrm{t}}\sigma^2}{(1-\rho_1)\lambda_{\mathrm{SR}}Q}+\frac{\sigma^2(\gamma_{\mathrm{t}}+1-\gamma_{\mathrm{s}})}{(1-\rho_1)\lambda_{\mathrm{SE}}\gamma_{\mathrm{s}}Q}\\
+\frac{(M+d)\gamma_{\mathrm{t}}\sigma^2}{\lambda_{\mathrm{SR}}Q}+\frac{1}{\lambda_{\mathrm{SP}}}\Big)^{-i-j-1}\Gamma\Big(i+j+1,\frac{\rho_1\gamma_{\mathrm{t}}\sigma^2}{(1-\rho_1)\lambda_{\mathrm{SR}}P_{\mathrm{t}}}+\frac{\sigma^2(\gamma_{\mathrm{t}}+1-\gamma_{\mathrm{s}})}{(1-\rho_1)\lambda_{\mathrm{SE}}\gamma_{\mathrm{s}}P_{\mathrm{t}}}+\frac{(M+d)\gamma_{\mathrm{t}}\sigma^2}{\lambda_{\mathrm{SR}}P_{\mathrm{t}}}+\frac{Q}{\lambda_{\mathrm{SP}}P_{\mathrm{t}}}\Big)\Big]\\
+\sum_{k=0}^{i}\sum_{s=0}^{k+l}\frac{\rho_1^{l}\gamma_{\mathrm{s}}^{k}(\gamma_{\mathrm{s}}-1)^{i-k}(\gamma_{\mathrm{t}}+1-\gamma_{\mathrm{s}})^{s}(k+l)!\sigma^{2s+2i-2k}}{l!i!s!(1-\rho_1)^{s+i-1-k}\lambda_{\mathrm{SR}}^{i}\lambda_{\mathrm{SE}}^{l+1}\gamma_{\mathrm{s}}^{s}}\left(\frac{1}{\lambda_{\mathrm{SE}}}+\frac{\gamma_{\mathrm{s}}}{\lambda_{\mathrm{SR}}}\right)^{-k-l+s-1}\binom{i}{k}\Big[\left(1-\exp\left(-\frac{Q}{P_{\mathrm{t}}\lambda_{\mathrm{SP}}}\right)\right)\\
\times P_{\mathrm{t}}^{k-s-i}\exp\left(-\frac{\sigma^2(\gamma_{\mathrm{t}}+1-\gamma_{\mathrm{s}})}{(1-\rho_1)\lambda_{\mathrm{SE}}\gamma_{\mathrm{s}}P_{\mathrm{t}}}-\frac{\sigma^2\rho_1\gamma_{\mathrm{t}}}{(1-\rho_1)\lambda_{\mathrm{SR}}P_{\mathrm{t}}}-\frac{(M+d)\gamma_{\mathrm{t}}\sigma^2}{\lambda_{\mathrm{SR}}P_{\mathrm{t}}}\right)+\frac{Q^{k-s-i}}{\lambda_{\mathrm{SP}}}\Big(\frac{\sigma^2(\gamma_{\mathrm{t}}+1-\gamma_{\mathrm{s}})}{(1-\rho_1)\lambda_{\mathrm{SE}}\gamma_{\mathrm{s}}Q}+\frac{1}{\lambda_{\mathrm{SP}}}\\
+\frac{\sigma^2\rho_1\gamma_{\mathrm{t}}}{(1-\rho_1)\lambda_{\mathrm{SR}}Q}+\frac{(M+d)\gamma_{\mathrm{t}}\sigma^2}{\lambda_{\mathrm{SR}}Q}\Big)^{k-s-i-1}\Gamma\Big(s+i-k+1,\frac{\sigma^2(\gamma_{\mathrm{t}}+1-\gamma_{\mathrm{s}})P_{\mathrm{t}}}{(1-\rho_1)\lambda_{\mathrm{SE}}\gamma_{\mathrm{s}}}+\frac{\sigma^2\rho_1\gamma_{\mathrm{t}}P_{\mathrm{t}}}{(1-\rho_1)\lambda_{\mathrm{SR}}}+\frac{(M+d)\gamma_{\mathrm{t}}\sigma^2P_{\mathrm{t}}}{\lambda_{\mathrm{SR}}}\\
+\frac{P_{\mathrm{t}}}{\lambda_{\mathrm{SP}}Q}\Big)\Big]\Big\}, \qquad \frac{\gamma_{\mathrm{t}}+1}{\gamma_{\mathrm{s}}}-1>0
\end{cases}
\end{aligned}
\tag{20}
$$

$$
\begin{aligned}
&\Pr_{\mathrm{DTaORS}}(C_{2\mathrm{s}}>R_{\mathrm{s}})\\
&=\sum_{n=1}^{M}\sum_{l=0}^{\infty}\sum_{i=0}^{l}\sum_{j=0}^{i}\binom{M}{n}\binom{i}{j}(-1)^{n-1}\frac{n(l+j)!\rho_2^{l}\gamma_{\mathrm{s}}^{j}(\gamma_{\mathrm{s}}-1)^{i-j}}{i!l!(1-\rho_2)^{2l+1}}\left(\frac{\rho_2}{1-\rho_2}+n\right)^{-l-1+i}\lambda_{\mathrm{RE}}^{-l-1}\lambda_{\mathrm{RD}}^{-i}\sigma^{2i-2j}\\
&\times\left[\frac{1}{(1-\rho_2)\lambda_{\mathrm{RE}}}+\left(\frac{\rho_2}{1-\rho_2}+n\right)\frac{\gamma_{\mathrm{s}}}{\lambda_{\mathrm{RD}}}\right]^{-l-j-1}\Big\{P_{\mathrm{t}}^{-i+j}\exp\left[-\left(\frac{\rho_2}{1-\rho_2}+n\right)(\gamma_{\mathrm{s}}-1)\frac{\sigma^2}{\lambda_{\mathrm{RD}}P_{\mathrm{t}}}\right]\left[1-\exp\left(-\frac{Q}{\lambda_{\mathrm{RP}}P_{\mathrm{t}}}\right)\right]\\
&+\frac{Q^{j-i}}{\lambda_{\mathrm{RP}}}\left[\left(\frac{\rho_2}{1-\rho_2}+n\right)(\gamma_{\mathrm{s}}-1)\frac{\sigma^2}{\lambda_{\mathrm{RD}}Q}+\frac{1}{\lambda_{\mathrm{RP}}}\right]^{-i+j-1}\\
&\times\Gamma\left[i-j+1,\left(\frac{\rho_2}{1-\rho_2}+n\right)(\gamma_{\mathrm{s}}-1)\frac{\sigma^2}{\lambda_{\mathrm{RD}}P_{\mathrm{t}}}+\frac{Q}{\lambda_{\mathrm{RP}}P_{\mathrm{t}}}\right]\Big\}
\end{aligned}
\tag{21}
$$

correlated fading channels with TPRS scheme can be represented as

$$P_{out}(R_s)\approx\Delta_T R^{-1}, \tag{22}$$

where Δ_T is given by

$$\Delta_T=\begin{cases}(1-\rho_2)\gamma_s, & N>1\\ (2-\rho_1-\rho_2)\gamma_s, & N=1\end{cases} \tag{23}$$

Proof: See Appendix E. ■

2) DTAORS SCHEME

Corollary 2: The asymptotic secrecy outage probability of cognitive relay multi-channel wiretap networks over correlated fading channels with DTaORS scheme can be represented as

$$P_{out}(R_s)\approx\Delta_D R^{-1}, \tag{24}$$

where Δ_D *is given by*

$$\Delta_D = \begin{cases} (1-\rho_2)\,\gamma_s, & N > 1 \\ (2-\rho_1-\rho_2)\,\gamma_s, & N = 1 \end{cases} \tag{25}$$

Proof: When $\beta_{\rm SR}$ tends to be infinite, for a given decoding rate threshold $R_{\rm t}$, the successful decoding probability in (33) can be approximated as

$$\mathrm{P}_M = \binom{N}{M} \exp\left(-\frac{M\gamma_{\rm t}}{\beta_{\rm SR}}\right)\left[1-\exp\left(-\frac{\gamma_{\rm t}}{\beta_{\rm SR}}\right)\right]^{N-M} \approx \begin{cases} 0, & 0 < M < N \\ 1, & M = N \end{cases} \tag{26}$$

Hence, all the relays can decode the information from ST. The joint PDF of $\gamma_{\rm R_D}$ and $\gamma_{\rm 1E_D}$ over correlated fading channels with DTaORS in **Lemma 3** will reduce to

$$f_{\gamma_{\rm R_D},\gamma_{\rm 1E_D}}(\gamma_1,\gamma_2|G_1) \approx \sum_{l=0}^{\infty} \frac{\gamma_1^l \gamma_2^l \rho_1^l}{(1-\rho_1)^{2l+1}\beta_{\rm SR}^{l+1}\beta_{\rm SE}^{l+1}(l!)^2} \times \exp\left(-\frac{\frac{\gamma_1}{\beta_{\rm SR}}+\frac{\gamma_2}{\beta_{\rm SE}}}{1-\rho_1}\right). \tag{27}$$

■

Finally, similar to the derivation process of **Corollary 1**, the asymptotic SOP with DTaORS in (24) can be derived.

Remark 1: From **Corollary 1** and **Corollary 2**, we can find that the channel correlation has a positive impact on the secrecy coding gain, but does not affect the secrecy diversity order. Moreover, the results also demonstrate that when SE can eavesdrop the information from ST and $\rm R_n$ simultaneously, the secrecy diversity order will be no longer affected by the cooperation diversity schemes and always equal to 1. In addition, even though the exact SOPs with TPRS and DTaORS are different, the asymptotic SOPs with the two schemes in high MER regime will tend to be the same. This can be intuitively explained by the fact that in high MER regime, the received SNR at $\rm R_n$ will tend to be very large, thus the decoding rate threshold $R_{\rm t}$ can not filtrate the relays any more.

IV. NUMERICAL RESULTS

In this section, numerical results are provided to evaluate the impact of different key parameters, i.e., the channel correlation coefficient, the relay number, the decoding rate threshold, the maximal transmit power and the interference temperature threshold, on the secrecy performance of the considered system. Unless otherwise stated, the noise variance is set to be $\sigma^2 = 1$. The channel variances of ST−PU link, $\rm R_n$−PU link, ST−SE link and $\rm R_n$−SE link are all set to be unity. The channel variances of ST−$\rm R_n$ link and $\rm R_n$−SD link are both set to be 10. Moreover, the secrecy rate threshold is set to be $R_{\rm s} = 1$bit/s/Hz. As shown in these figures, our derivation results are in exact agreement with the simulation results,[3] which also demonstrates the correctness of our derivation process.

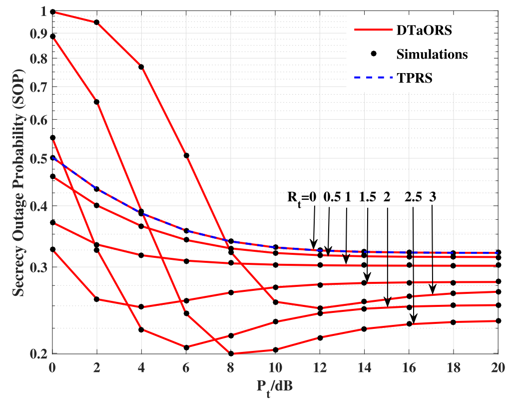

FIGURE 2. **Secrecy outage probability versus $P_{\rm t}$ for $Q = 10$dB, $N = 5$, $\rho_1 = \rho_2 = 0.1$ and $R_{\rm t} = \{0, 0.5, 1, 1.5, 2, 2.5, 3\}$bit/s/Hz.**

Fig. 2 shows the secrecy outage probability versus different $P_{\rm t}$ and $R_{\rm t}$ with a given interference temperature threshold Q. From the figure, we can find that when $R_{\rm t}$ is relatively small, the secrecy performance of DTaORS becomes better with the increasing of $P_{\rm t}$, and the bigger the $R_{\rm t}$, the better the SOP. However, as $R_{\rm t}$ becomes large enough, i.e., $R_{\rm t} > 1.5$bit/s/Hz in the figure, the secrecy performance starts fluctuating with $P_{\rm t}$, which shows down first and then up and exists an inflection point. This is due to the fact that the decoding rate threshold $R_{\rm t}$ can filtrate the information received in the first phase and select the qualified relays to form the decoding set. As $P_{\rm t}$ increases, more qualified relays can be retained for the relay selection in the second phase. In other words, at this moment, the DTaORS can optimize the performance from the whole situation rather than from a separate stage like TPRS. So the SOP shows down with $P_{\rm t}$ in early stage. However, when $P_{\rm t}$ keeps increasing, most even all of the relays can meet the threshold and the threshold is meaningless, then the SOP shows up with $P_{\rm t}$ in later stage. It's worth noting that even though the decoding rate threshold $R_{\rm t}$ is becoming meaningless when $P_{\rm t}$ is large enough, the secrecy performance is also better than TPRS which has no any rate threshold. On the contrary, the practical transmit power is infinite due to the limitation of Q, when $R_{\rm t}$ is so large that the relays merely can meet the condition, the secrecy performance will become worse with the increase of $R_{\rm t}$, i.e., $R_{\rm t} = 3$bit/s/Hz.

Fig. 3 presents the impact of channel correlation coefficients ρ_1 and ρ_2 on the secrecy outage probability with different interference temperature threshold Q. As can be expected, the channel correlation is beneficial to the secrecy performance of both TPRS and DTaORS, and the secrecy performance of DTaORS under an appropriate decoding rate threshold will always be better than that of TPRS. In addition,

[3]In order to guarantee the efficiency and accuracy of simulations, we use a function $T = \text{round}\left(\frac{-10}{\log_{10}\rho}\right)$ as an accurate number of terms for different ρ_1 and ρ_2 to estimate the sum of infinite series in the exact SOP, just like [28] and [30].

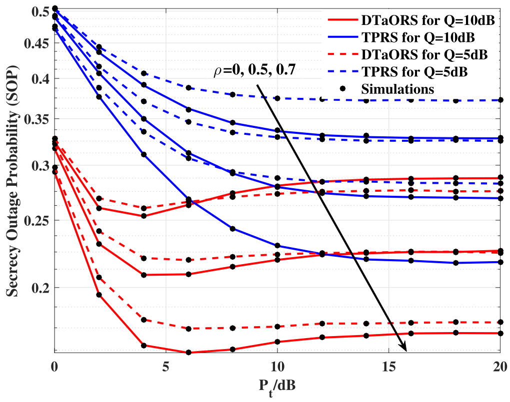

FIGURE 3. Secrecy outage probability versus P_t for $Q = \{5, 10\}$dB, $N = 5$, $R_t = 1.5$bit/s/Hz, and $\rho = \rho_1 = \rho_2 = \{0, 0.5, 0.7\}$.

when P_t is relatively small, the secrecy performance of both the two schemes with $Q = 10$dB is better than that with $Q = 54$dB. This is due to the fact that the practical transmit power is limited by both P_t and Q. However, as P_t becomes relatively large, different from TPRS, in which the secrecy performance with $Q = 10$dB is always better than that with $Q = 5$dB, the secrecy performance of DTaORS with $Q = 10$dB is worse than that with $Q = 5$dB in the case of $\rho = 0$. Moreover, with the increase of ρ, the secrecy performance of DTaORS with $Q = 10$dB is gradually superior to that with $Q = 5$dB in high P_t regime. It's because that the secrecy performance with TPRS always declines with the practical transmit power. Thus, the secrecy performance with larger Q will be always better than that with smaller Q. But when DTaORS is utilized, the SOP shows down first and then up with the increase of P_t like Fig. 2, and an optimal P_t exists for different ρ. Therefore, when the optimal P_t is less than 5dB, the secrecy performance with $Q = 5$dB is better than that with $Q = 10$dB in high P_t regime. and when the optimal P_t is large than 5dB, the secrecy performance with $Q = 10$dB will be better.

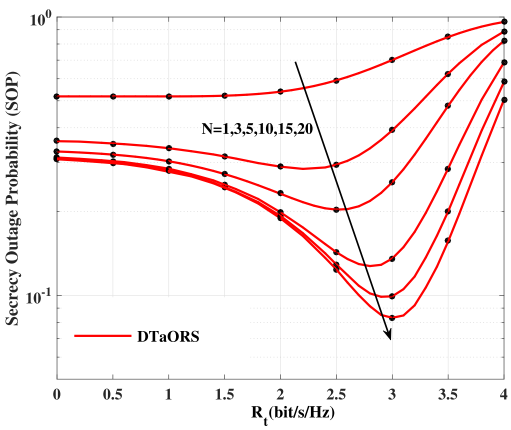

FIGURE 4. Secrecy outage probability versus R_t for $P_t = 10$dB, $Q = 10$dB, $\rho_1 = \rho_2 = 0.1$ and $N = \{1, 3, 5, 10, 15, 20\}$.

Fig. 4 depicts the secrecy outage probability under different R_t and N. As shown in the figure, when $N > 1$, for a given transmit power, the SOP shows down first and then up with the increasing of R_t and there exists an optimal decoding rate threshold value for different N making the SOP minimum. Moreover, we can also find that under different R_t, the secrecy performance will become better with the increasing of N and the optimal R_t also become larger. It is due to the fact that the more the relays, the larger the probability that more relays can meet the decoding threshold, and then more qualified relays can be as candidates for optimal relay selection, which will effectively improve the secrecy performance of the system.

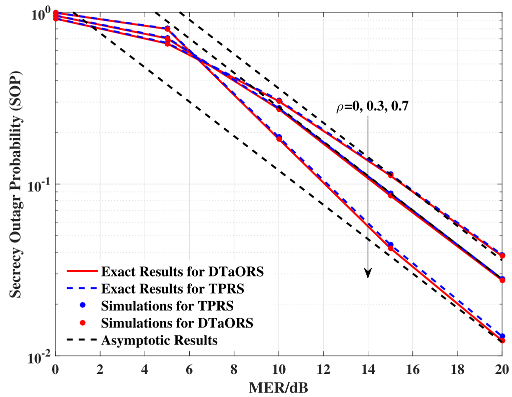

FIGURE 5. Secrecy outage probability versus MER for $N = 5$, $R_t = 1.5$bit/s/Hz and $\rho = \rho_1 = \rho_2 = \{0, 0.3, 0.7\}$.

Fig. 5 plots the secrecy outage probability in high MER regime with different channel correlation coefficients. From the figure, we can find that the asymptotic results are in exact agreement with the exact results and the simulation results, which demonstrates the correctness of our derivation process. In high MER regime, the received SNR at R_n becomes very large, which makes the finite R_t meaningless, thus the secrecy performance of DTaORS and TPRS are identical with each other. In addition, affected by the multi-channel wiretap, the secrecy diversity order is no longer affected by the cooperation diversity scheme and always equals to 1, which accords with the asymptotic results in (23) and (25).

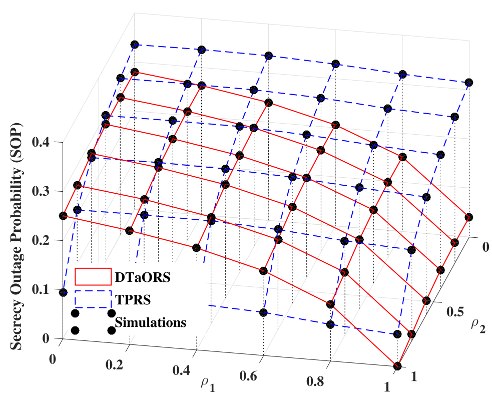

FIGURE 6. Secrecy outage probability versus ρ_1 and ρ_2 for $P_t = 10$dB, $Q = 10$dB, $N = 5$ and $R_t = 1.5$bit/s/Hz.

Fig. 6 examines the joint impacts of ρ_1 and ρ_2 on the secrecy outage probability. From the figure, we can find that

ρ_1 has a more important influence on the secrecy performance of TPRS than ρ_2, and ρ_2 has a more important influence on the secrecy performance of DTaORS in reverse. It depends on the different phases that is utilized for the optimal relay selection. As can be readily observed unless extreme cases, i.e., $\rho_1 = 1$ and $\rho_2 \neq 1$ or ρ_1 is close to 1 and ρ_2 is very small, the secrecy performance of DTaORS is always better than that of TPRS in most cases, which also demonstrates the advantage of DTaORS.

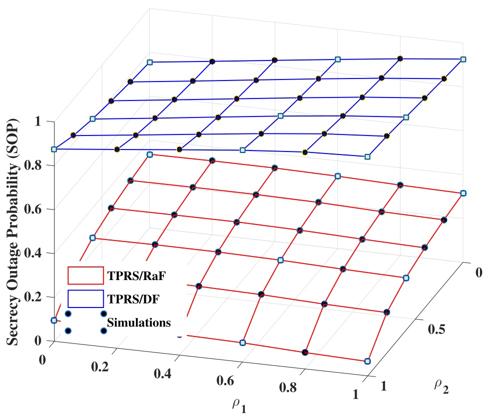

FIGURE 7. Secrecy outage probabilities of TPRS/RaF and TPRS/DF schemes for P_t = 10dB, Q = 10dB, N = 5.

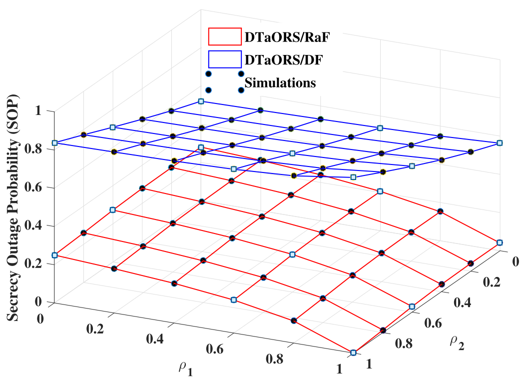

FIGURE 8. Secrecy outage probabilities of DTaORS/RaF and DTaORS/DF schemes for P_t = 10dB, Q = 10dB, N = 5 and R_t = 1.5bit/s/Hz.

Figs. 7 and 8 present the performance comparison of DF and RaF with TPRS and DTaORS schemes, respectively. Having a closer look at these results, we can find that the RaF scheme with TPRS and DTaORS can both get much better secrecy performance than DF scheme, which demonstrates that RaF scheme is more suitable for multi-channel wiretap scenario. Moreover, as can be readily observed that when DF is utilized, the channel correlation coefficients will damage the secrecy performance. It is due to the fact that when the channel correlation exists, the main channel and the wiretapping channel are no longer independent, thus SE can overhear more information from the two transmit phases for information merging, which will further impair the secrecy performance of the system.

V. CONCLUSIONS

In this paper, we have investigate the secrecy performance of cognitive relay multi-channel wiretap networks over correlated fading channels. For the enhancement of secrecy performance, we introduce a relay forwarding protocol, i.e., RaF, and two cooperation diversity schemes, i.e., TPRS and DTaORS. Then, we further analyze the performance of the two cooperation diversity schemes by deriving the exact and asymptotic secrecy outage probability expressions, respectively. Our results show that the channel correlation is beneficial to the secrecy performance in high MER regime, DTaORS can get better performance than TPRS in most cases and RaF is more suitable for the multi-channel wiretap scenario than DF.

APPENDIX

A. PROOF OF LEMMA 1

According to the principle of TPRS scheme, a best relay is selected based on the channel of ST$-$R$_n$ link. Thus, the conditional cumulative distribution function (CDF) and PDF of $\gamma_{\mathrm{R_T}}$ can be derived as

$$F_{\gamma_{R_T}}(\gamma_1|G_1) = \left[1-\exp\left(-\frac{\gamma_1}{\beta_{\mathrm{SR}}}\right)\right]^N \tag{28}$$

and

$$\begin{aligned} f_{\gamma_{\mathrm{R_T}}}(\gamma_1|G_1) &= N\left[1-\exp\left(-\frac{\gamma_1}{\beta_{\mathrm{SR}}}\right)\right]^{N-1}\exp\left(-\frac{\gamma_1}{\beta_{\mathrm{SR}}}\right)\frac{1}{\beta_{\mathrm{SR}}} \\ &= \sum_{n=1}^{N}\binom{N}{n}\frac{n(-1)^{n-1}}{\beta_{\mathrm{SR}}}\exp\left(-\frac{n\gamma_1}{\beta_{\mathrm{SR}}}\right). \end{aligned} \tag{29}$$

Based on Eq. (7), we can get the joint conditional PDF of $\gamma_{\mathrm{R_T}}$ and $\gamma_{\mathrm{1E_T}}$ as

$$\begin{aligned} f_{\gamma_{\mathrm{1E_T}}|\gamma_{\mathrm{R_T}}}(\gamma_2|\gamma_1, G_1) &= \frac{I_0\left(\frac{2}{1-\rho_1}\sqrt{\frac{\gamma_2\gamma_1\rho_1}{\beta_{\mathrm{SR}}\beta_{\mathrm{SE}}}}\right)}{(1-\rho_1)\beta_{\mathrm{SE}}} \\ &\quad\times\exp\left(-\frac{\frac{\rho_1\gamma_1}{\beta_{\mathrm{SR}}}+\frac{\gamma_2}{\beta_{\mathrm{SE}}}}{1-\rho_1}\right). \end{aligned} \tag{30}$$

To this end, we can get the joint conditional PDF in (13), after combining (29) and (30).

B. PROOF OF THEOREM 1

Based on the definition of the secrecy capacity, the probability that the first phase is secure can be presented as

$$\begin{aligned} \Pr(C_{1\mathrm{s}} > R_\mathrm{s}) &= \Pr\left(\frac{1+\gamma_{\mathrm{R_T}}}{1+\gamma_{\mathrm{1E_T}}} > \gamma_\mathrm{s}\right) \\ &= \int_0^\infty\int_{\gamma_\mathrm{s}(1+\gamma_2)-1}^\infty f_{\gamma_{\mathrm{R_T}},\gamma_{\mathrm{1E_T}}}(\gamma_1,\gamma_2)d\gamma_1 d\gamma_2. \end{aligned} \tag{31}$$

By substituting (13) into (31), we can derive the conditional probability as

$$\Pr(C_{1\mathrm{s}} > R_\mathrm{s}|G_1) = \sum_{n=1}^{N}\sum_{l=0}^{\infty}\sum_{i=0}^{l}\sum_{j=0}^{i}\binom{N}{n}\binom{i}{j}\sigma^{2i-2j}$$

$$\times \frac{n(-1)^{n-1}(l+j)!\rho_1^l \gamma_s^j (\gamma_s-1)^{i-j}}{i!l!(1-\rho_1)^{2l+1}} \left(\frac{\rho_1}{1-\rho_1}+n\right)^{-l-1+i}$$
$$\times \lambda_{SE}^{-l-1}\lambda_{SR}^{-i}\left[\frac{1}{(1-\rho_1)\lambda_{SE}}+\left(\frac{\rho_1}{1-\rho_1}+n\right)\frac{\gamma_s}{\lambda_{SR}}\right]^{-l-j-1}$$
$$\times P_S^{-i+j}\exp\left[-\left(\frac{\rho_1}{1-\rho_1}+n\right)(\gamma_s-1)\frac{\sigma^2}{P_S\lambda_{SR}}\right]. \quad (32)$$

To this end, combining (5) and (32) and doing the integral, the unconditional probability can be derived as (16) after some mathematical manipulations.

C. PROOF OF LEMMA 3

For a given decoding rate threshold R_t, the probability that M relays can decode the information from ST successfully can be presented as

$$P_M = \binom{N}{M}\exp\left(-\frac{M\gamma_t}{\beta_{SR}}\right)\left[1-\exp\left(-\frac{\gamma_t}{\beta_{SR}}\right)\right]^{N-M}. \quad (33)$$

Because the DTaORS scheme selects the best relay based on the channel quality of R_n−SD link, thus the selected relay is corresponding to a random relay for ST−R_n link and the joint conditional PDF of γ_{R_D} and γ_{1E_D} can be represented just like (14) as

$$f_{\gamma_{R_D},\gamma_{1E_D}}(\gamma_1,\gamma_2|G_1) = \sum_{l=0}^{\infty}\frac{\rho_1^l\gamma_1^l\gamma_2^l}{(1-\rho_1)^{2l+1}(l!)^2\beta_{SE}^{l+1}\beta_{SR}^{l+1}} \times\exp\left[-\frac{\gamma_2}{(1-\rho_1)\beta_{SE}}-\frac{\gamma_1}{(1-\rho_1)\beta_{SR}}\right]. \quad (34)$$

To this end, the joint conditional PDF of of γ_{R_D} and γ_{1E_D} in (18) can be easily derived, after combining (33) and (34) and appling the Binomial expansion theorem.

D. PROOF OF THEOREM 3

According to the principle of DTaORS scheme, if M $(M>0)$ relays can succeed decoding the information from ST, then the received SNRs on the M relays must meet the condition that $\gamma_{R_D}\geq\gamma_t$. Hence, the conditional probability on RV G_1 that the first phase is secure with DTaORS should be represented as

$$\begin{aligned}
&\Pr_{\text{DTaORS,M}}(C_{1s}>R_s|G_1)\\
&=\Pr\left(C_{1s}>R_s|\gamma_{R_D}>\gamma_t,G_1\right)\\
&=\Pr\left(\gamma_{R_D}>\gamma_s\left(1+\gamma_{1E_D}\right)-1,\gamma_{R_D}>\gamma_t|G_1\right)\\
&\quad\times/\Pr\left(\gamma_{R_D}>\gamma_t|G_1\right)\\
&=\int_0^\infty\int_{\max[\gamma_s(1+\gamma_2)-1,\gamma_t,0]}^\infty f_{\gamma_{R_D},\gamma_{1E_D}}(\gamma_1,\gamma_2|G_1)\,d\gamma_1 d\gamma_2\\
&\quad\times\exp\left(\frac{\gamma_t}{\beta_{SR}}\right).
\end{aligned} \quad (35)$$

According to the values of γ_t and γ_s, the expression for $\max[\gamma_s(1+\gamma_2)-1,\gamma_t,0]$ can be re-expressed as

$$\max[\gamma_s(1+\gamma_2)-1,\gamma_t,0] = \begin{cases}0, & 1+\gamma_t-\gamma_s<0\\ \gamma_t, & 0<\gamma_2<\frac{\gamma_t+1}{\gamma_s}-1, 1+\gamma_t-\gamma_s\geq0\\ \gamma_s(1+\gamma_2)-1, & \gamma_2\geq\frac{\gamma_t+1}{\gamma_s}-1, 1+\gamma_t-\gamma_s\geq0\end{cases} \quad (36)$$

By substituting (36) into (35), the conditional probability in (35) can be further expressed as

$$\Pr_{\text{DTaORS, M}}(C_{1s}>R_s|G_1) = \begin{cases}\int_0^\infty\int_{\gamma_s(1+\gamma_2)-1}^\infty f_{\gamma_{R_D},\gamma_{1E_D}}(\gamma_1,\gamma_2|G_1)\,d\gamma_1 d\gamma_2 \\ \quad\times\exp\left(\frac{\gamma_t}{\beta_{SR}}\right), \quad 1+\gamma_t-\gamma_s\leq0\\ \left(\int_0^{(1+\gamma_t)/\gamma_s-1}\int_{\gamma_t}^\infty f_{\gamma_{R_D},\gamma_{1E_D}}(\gamma_1,\gamma_2|G_1)\,d\gamma_1 d\gamma_2\right.\\ \quad+\int_{(1+\gamma_t)/\gamma_s-1}^\infty\int_{\gamma_s(1+\gamma_2)-1}^\infty f_{\gamma_{R_D},\gamma_{1E_D}}(\gamma_1,\gamma_2|G_1)\\ \quad\left.d\gamma_1 d\gamma_2\right)\times\exp\left(\frac{\gamma_t}{\beta_{SR}}\right), \quad 1+\gamma_t-\gamma_s>0\end{cases} \quad (37)$$

Then by substituting (18) into (37), under a given size of decoding set, the conditional the first phase is secure can be derived as (38) shown at the top of the next page.

Finally, considering all the possible values of M and doing the integral in (38), we can derive the unconditional probability integral expression as

$$\Pr_{\text{DTaORS}}(C_{1s}>R_s) = \int_0^\infty\sum_{M=1}^N\Pr_{\text{DTaORS,M}}(C_{1s}>R_s|G_1)f_{G_1}(g_1)dg_1, \quad (39)$$

where $f_{G_1}(g_1)=\frac{1}{\lambda_{SP}}\exp\left(-\frac{g_1}{\lambda_{SP}}\right)$ is the PDF of $|h_{SP}|^2$.

To this end, the probability expression in (20) can be easily derived, after simple mathematical manipulations.

E. PROOF OF COROLLARY 1

According to Eq. (12), we can rewrite it as

$$P_{out}(R_s)=F_{C_{1s}}(R_s)+F_{C_{2s}}(R_s)-F_{C_{1s}}(R_s)F_{C_{2s}}(R_s), \quad (40)$$

where $F_{C_{1s}}(R_s)=1-\Pr(C_{1s}>R_s)$ and $F_{C_{2s}}(R_s)=1-\Pr(C_{2s}>R_s)$.

In the first phase, when β_{SR} and β_{SE} tend to be relative large, the expression of $F_{C_{1s}}(R_s)$ can be approximated as

$$F_{C_{1s}}(R_s)=\Pr\left(\frac{1+\gamma_{R_T}}{1+\gamma_{1E_T}}<\gamma_s\right) \approx\Pr\left(\frac{\gamma_{R_T}}{\gamma_{1E_T}}<\gamma_s\right). \quad (41)$$

$$
\begin{aligned}
&\Pr_{\mathrm{DTaORS,M}}\left(C_{1\mathrm{s}} > R_{\mathrm{s}}|G_1\right) \\
&= \begin{cases}
\sum_{d=0}^{N-M}\sum_{l=0}^{\infty}\sum_{i=0}^{l}\sum_{t=0}^{i}\binom{N}{M}\binom{N-M}{d}(-1)^d \exp\left[-\frac{(M+d)\,\gamma_{\mathrm{t}}\sigma^2}{P_{\mathrm{S}}\lambda_{\mathrm{SR}}}\right]\binom{i}{t}\gamma_{\mathrm{s}}^{t}(\gamma_{\mathrm{s}}-1)^{i-t}\rho_1^{l}(1-\rho_1)^{t+1-i} \\
\times\frac{(l+t)!}{l!i!}\sigma^{2i-2t}\lambda_{\mathrm{SR}}^{-i}\lambda_{\mathrm{SE}}^{-l-1}\left(\frac{1}{\lambda_{\mathrm{SE}}}+\frac{\gamma_{\mathrm{s}}}{\lambda_{\mathrm{SR}}}\right)^{-l-t-1} P_{\mathrm{s}}^{-i+t}\exp\left[-\frac{\gamma_{\mathrm{s}}-1-(1-\rho_1)\,\gamma_{\mathrm{t}}\sigma^2}{(1-\rho_1)\,\lambda_{\mathrm{SR}}P_{\mathrm{S}}}\right], \\
\qquad\qquad 1+\gamma_{\mathrm{t}}-\gamma_{\mathrm{s}}\le 0 \\
\sum_{d=0}^{N-M}\sum_{l=0}^{\infty}\sum_{i=0}^{l}\binom{N}{M}\binom{N-M}{d}(-1)^d\exp\left[-\frac{(M+d)\,\gamma_{\mathrm{t}}\sigma^2}{P_{\mathrm{S}}\lambda_{\mathrm{SR}}}\right]\Bigg\{\frac{\rho_1^l\gamma_{\mathrm{t}}^i\sigma^{2i}P_{\mathrm{S}}^{-i}}{(1-\rho_1)^{i-1}i!\lambda_{\mathrm{SR}}^{i}}\exp\left[-\frac{\rho_1\gamma_{\mathrm{t}}\sigma^2}{(1-\rho_1)\,P_{\mathrm{S}}\lambda_{\mathrm{SR}}}\right] \\
-\sum_{j=0}^{l}\frac{\rho_1^l\gamma_{\mathrm{t}}^i(\gamma_{\mathrm{t}}+1-\gamma_{\mathrm{s}})^j\sigma^{2i+2j}P_{\mathrm{S}}^{-i-j}}{i!j!(1-\rho_1)^{i+j-1}\gamma_s^j\lambda_{\mathrm{SR}}^i\lambda_{\mathrm{SE}}^j}\exp\left[-\frac{\sigma^2}{(1-\rho_1)\,P_{\mathrm{S}}}\left(\frac{\rho_1\gamma_{\mathrm{t}}}{\lambda_{\mathrm{SR}}}+\frac{\gamma_{\mathrm{t}}+1-\gamma_{\mathrm{s}}}{\gamma_{\mathrm{s}}\lambda_{\mathrm{SE}}}\right)\right]+\sum_{k=0}^{i}\sum_{s=0}^{k+l}\frac{(\gamma_{\mathrm{s}}-1)^{i-k}}{\gamma_{\mathrm{s}}^{s-k}l!i!s!} \\
\frac{\rho_1^l(\gamma_{\mathrm{t}}+1-\gamma_{\mathrm{s}})^s\,(k+l)!\sigma^{2s+i-k}}{(1-\rho_1)^{s+i-1-k}\lambda_{\mathrm{SR}}^i\lambda_{\mathrm{SE}}^{l+1}}\left(\frac{1}{\lambda_{\mathrm{SE}}}+\frac{\gamma_{\mathrm{s}}}{\lambda_{\mathrm{SR}}}\right)^{-k-l+s-1}\binom{i}{k}P_{\mathrm{s}}^{k-s-i}\exp\Bigg[-\frac{\sigma^2}{(1-\rho_1)\,P_{\mathrm{S}}}\Bigg(\frac{\gamma_{\mathrm{t}}+1-\gamma_{\mathrm{s}}}{\gamma_{\mathrm{s}}\lambda_{\mathrm{SE}}} \\
+\frac{\rho_1\gamma_{\mathrm{t}}}{\lambda_{\mathrm{SR}}}\Bigg)\Bigg]\Bigg\}, \qquad\qquad 1+\gamma_{\mathrm{t}}-\gamma_{\mathrm{s}}>0
\end{cases}
\end{aligned}
\tag{38}
$$

Moreover, as β_{SR} tends to be infinity, the PDF of $\gamma_{\mathrm{R_T}}$ in (29) can be approximated as

$$
f_{\gamma_{\mathrm{R_T}}}(\gamma_1) \approx \frac{N}{\beta_{\mathrm{SR}}}\exp\left(-\frac{\gamma_1}{\beta_{\mathrm{SR}}}\right)\left(\frac{\gamma_1}{\beta_{\mathrm{SR}}}\right)^{N-1}. \tag{42}
$$

Then by substituting (42) into (30), the joint PDF of $\gamma_{\mathrm{R_T}}$ and $\gamma_{1\mathrm{E_T}}$ should be rewrited as

$$
\begin{aligned}
&f_{\gamma_{\mathrm{R_T}},\gamma_{1\mathrm{E_T}}}(\gamma_1,\gamma_2) \\
&= \frac{NI_0\left(\frac{2}{1-\rho_1}\sqrt{-\frac{\gamma_1\gamma_2\rho_1}{\beta_{\mathrm{SE}}\beta_{\mathrm{SR}}}}\right)}{(1-\rho_1)\,\beta_{\mathrm{SE}}\beta_{\mathrm{SR}}}\exp\left(-\frac{\frac{\gamma_1}{\beta_{\mathrm{SR}}}+\frac{\gamma_2}{\beta_{\mathrm{SE}}}}{1-\rho_1}\right)\left(\frac{\gamma_1}{\beta_{\mathrm{SR}}}\right)^{N-1} \\
&= \sum_{l=0}^{\infty}\frac{N\rho_1^l\gamma_1^{l+N-1}\gamma_2^l}{(1-\rho_1)^{2l+1}(l!)^2\beta_{\mathrm{SE}}^{-l-1}\beta_{\mathrm{SR}}^{-l-N}}\exp\left(-\frac{\frac{\gamma_1}{\beta_{\mathrm{SR}}}+\frac{\gamma_2}{\beta_{\mathrm{SE}}}}{1-\rho_1}\right).
\end{aligned}
\tag{43}
$$

Let $Z_1 = \frac{\gamma_1}{\gamma_2}$ and $R = \frac{\beta_{\mathrm{SR}}}{\beta_{\mathrm{SE}}}$, then the PDF of Z_1 can be derived as

$$
\begin{aligned}
f_{Z_1}(z) &= \int_0^{\infty}\gamma_2 f_{\gamma_{\mathrm{R_T}},\gamma_{1\mathrm{E_T}}}(z\gamma_2,\gamma_2)\,d\gamma_2 \\
&= \sum_{l=0}^{\infty}\frac{N\rho_1^l\,(2l+N)!}{(1-\rho_1)^{2l+1}(l!)^2R^{l+N}}z^{l+N-1} \\
&\quad\times\left(\frac{\frac{z}{R}+1}{1-\rho_1}\right)^{-2l-N-1}.
\end{aligned}
\tag{44}
$$

When R tends to be infinity, the PDF of Z_1 can be further approximated as

$$
f_{Z_1}(z) \approx \sum_{l=0}^{\infty}\frac{N\rho_1^l\,(2l+N)!}{(l!)^2R^{l+N}}(1-\rho_1)^N z^{l+N-1}. \tag{45}
$$

Finally, the probability that $C_{1\mathrm{s}} < R_{\mathrm{s}}$ can be derived as

$$
\begin{aligned}
F_{C_{1\mathrm{s}}}(R_{\mathrm{s}}) &= \int_0^{\gamma_{\mathrm{s}}} f_{Z_1}(z)\,dz \\
&= \sum_{l=0}^{\infty}\frac{N\rho_1^l\,(2m+N)!}{(l!)^2\,(l+N)}(1-\rho_1)^N R^{-l-N}\gamma_{\mathrm{s}}^{l+N} \\
&\approx (1-\rho_1)^N\gamma_{\mathrm{s}}^N N!R^{-N}.
\end{aligned}
\tag{46}
$$

In the second phase, when β_{RD} and β_{RE} tend to be relative large, the expression of $F_{C_{2\mathrm{s}}}(R_{\mathrm{s}})$ can be approximated just like (41) as

$$
F_{C_{2\mathrm{s}}}(R_{\mathrm{s}}) = \Pr\left(\frac{1+\gamma_{\mathrm{D_T}}}{1+\gamma_{2\mathrm{E_T}}}<\gamma_{\mathrm{s}}\right) \approx \Pr\left(\frac{\gamma_{\mathrm{D_T}}}{\gamma_{2\mathrm{E_T}}}<\gamma_{\mathrm{s}}\right). \tag{47}
$$

Then, similar to (44), let $Z_2 = \frac{\gamma_3}{\gamma_4}$, $R = \frac{\beta_{\mathrm{RD}}}{\beta_{\mathrm{RE}}}$ and combining with Eq. (14), the PDF of Z_2 can be presented as

$$
\begin{aligned}
f_{Z_2}(z) &= \int_0^{\infty}\gamma_4 f_{\gamma_{\mathrm{D_T}},\gamma_{2\mathrm{E_T}}}(z\gamma_4,\gamma_4)\,d\gamma_4 \\
&\approx \sum_{l=0}^{\infty}\frac{\rho_2^l\,(2l+1)!}{(l!)^2}R^{-l-1}z^l\,(1-\rho_2).
\end{aligned}
\tag{48}
$$

Finally, after doing the integral manipulations and ignoring the high-order terms, the probability that $C_2 < R_{\mathrm{s}}$ can be derived as

$$
F_{C_{2\mathrm{s}}}(R_{\mathrm{s}}) = \int_0^{\gamma_{\mathrm{s}}} f_{Z_2}(z)dz \approx (1-\rho_2)\,\gamma_{\mathrm{s}}R^{-1}. \tag{49}
$$

To this end, by substituting (46) and (49) into (40) and ignoring the high-order terms, the asymptotic SOP expression with TORS in (22) can be easily derived after simple manipulations.

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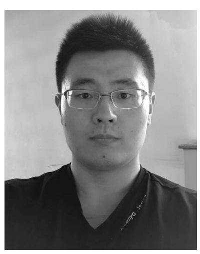

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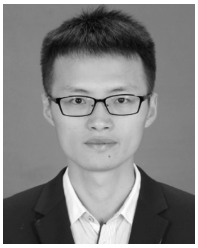

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