Computers, Materials & Continua CMC, vol.63, no.1, pp.119-130, 2020

Cooperative Relay Selection Mechanism in Multi-Hop Networks

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Abstract: In this paper, we consider a three-hop relay system based on interference cancellation technique in Underlay cognitive radio (CR) network. Although underlay CR has been shown as a promising technique to better utilize the source of primary users (PUs), its secondary performance will be severely degraded. On one hand, by adapting the Underlay spectrum sharing pattern, secondary users (SUs) would observe the strict power constraints and be interfered by primary users. On the other hand, limited transmit power results in limited transmission range, which greatly degrade the secondary transmission capacity. To solve the problems above, we propose an interference cancellation protocol for multi-hop wireless communication networks in underlay CR, which could develop the long-distance transmission performance and improve the transmission efficiency significantly. As simulation results shows, proposed scheme significantly reduce the secondary outage probability and increase the secondary diversity than the traditional cases.

Keywords: Cognitive relay networks, interference cancellation, power control, secondary outage probability.

1 Introduction

Cognitive radio improves the spectrum efficiency by allowing secondary users access the licensed spectrum. The problem of coexistence between primary and secondary users in cognitive radio networks has been extensively studied in the literature [Chandwani, Jain and Vyavahare (2015); Dang, Zhao and Zhang (2013); Li, Huang, Ma et al. (2018)]. Secondary users can directly access the spectrum without considering the transmit status of primary networks and they should observe the strict transmission power constraints to satisfy the quality of service (QoS) of primary users in underlay approach [Park, Jang and Lee (2011); Chen, Ouyang, Zhu et al. (2018)]. Most of the research focused on the transmission analysis of the primary user [Rajpoot and Tripathi (2017); Watanabe, Ishibashi and Kohno (2017); Park, Jang and Lee (2011)]. However, the potential benefits of underlay CR may be limited due to the secondary transmission power constraint and the interference from primary

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Received: 18 January 2019; Accepted: 18 March 2019.

networks, which degrade the secondary transmission performance and limit the secondary QoS [Wu, Lee and Shin (2013); Darabi, Maham, Zhou et al. (2014)].

Relay-assisted cooperation in cognitive radio network plays a key role in improving the overall efficiency of secondary transmission system by improving the system throughput, energy efficiency, coverage and channel reliability [Prasad, Sankararao, Roy et al. (2016); Bang, Kim and Hong (2015); Toutki, Qaraqe and Abdallah (2013)]. In particular, the cooperative multi-hop relay transmission can greatly expand the secondary transmission range [Li, Cheng, Jing et al. (2013)]. Adding relays to secondary networks could effectively reduce the interference of primary transmitter to secondary network, but cannot completely eliminate it [Khuong (2011)].

Interference cancellation is an effective technique to suppress the effect of primary networks for the case where only a single channel is used for transmission, under the assumption that both the transmitter and receiver have perfect knowledge of channel state information (CSI) [Devroye and Popovski (2011); Taranto and Popovski (2011)]. The performance of CR has been analyzed for Rayleigh fading and Nakagami fading channels [Zou, Yao and Zheng (2011); Hossain, Le and Devroye (2009)]. Interference cancellation based on relay selection can effectively eliminate interference from primary transmitter and improve the secondary transmission efficiency [Zhou, Kerttula, Malm et al. (2015)].

In this paper, we propose three-phase underlay protocol with interference cancellation which is utilize at both secondary relays and secondary destination. This improved scheme aims at mitigating the interference from primary networks to secondary users to expand the transmission range and improve the performance of secondary system. Dual power constraint should be employed with the primary network restrictions on secondary transmitters. Then, we derive the closed-form for outage probability over Rayleigh fading channels and conduct the simulations to demonstrate the superiority of the performance analysis by using Monte Carlo methods. The improved system achieves better secondary performance than [Dai, Liu and Long (2012)] due to the flexible protocol, which is validated by the simulation results.

The remainder of this paper is organized as follows. In Section Ⅱ, we present an overview of the system model for three-hop relay system, while in Section Ⅲ, we provide the analytical results on the performance in terms of secondary outage probability and then derive the closed-form expressions of the improved system. Section Ⅳ provides the numerical and simulation results, while section V drawn the conclusions.

2 System model and protocol

As shown in Fig. 1, we consider a cognitive radio system with the coexistence of primary and secondary networks. Primary source node P delivers signal to destination node P0. In the meanwhile, secondary source node S forwards its signal towards secondary destination node D with assisting of relay clusters R_i .

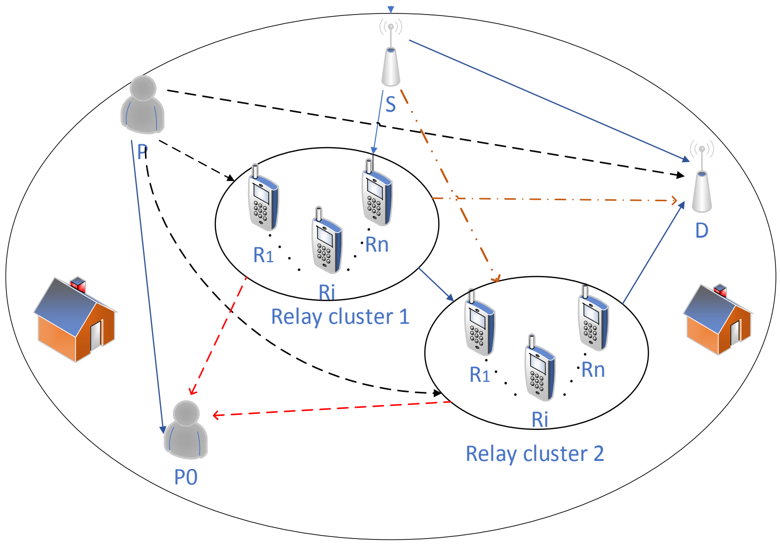

Figure 1: System model of ICS scheme

Relay cluster R_i includes N single-antenna half-duplex relay node and decode-and-forward protocol is considered throughout this correspondence. As can be observed from Fig. 1, primary and secondary networks would interfere with each other. The transmit power of secondary users should be limited for reducing the interference to P0 to guarantee the QoS of primary transmissions measured by primary outage probability. We assume that all the channels are modeled as independent Rayleigh flat fading. We let $h_{i,j}(A \in \{P,S,R_i\}, B \in \{P0,D,R_i\}, i \neq j)$ denote fading coefficient channel from i to j with fading variance σ_{ij}^2. We further denote that I transmit x_i to its destination with data rate R and power E_i. , where the SNR of E_i is denoted as γ_i

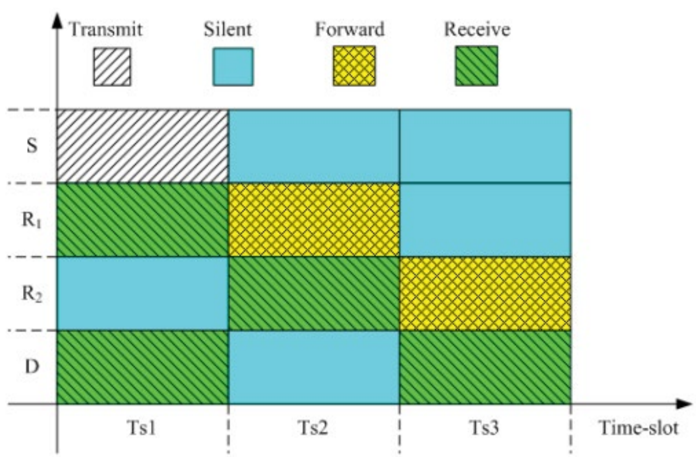

Figure 2: Transmission process of ICS scheme

In this paper, we assumed that S operate in a time division multiple access fashion, where each transmission frame consists of three consecutive phases denoted by Ts1, Ts2 and Ts3. As Fig. 2 shows, we proposed transmission mechanism and it can be described as follows:

In the first time slot Ts1, primary source node P sends data x_P to primary destination P0. While, secondary source node S send data x_S to secondary destination node D, which is interfered by primary network. Then, all relays in relay cluster R_1 attempt to decode signal x_S by utilizing the proposed IC-based decoding technique. Specifically, relays from R_1 directly decode x_S from the original received signal in Ts1. If decoding fails, relays will start the interference mechanism that decode x_P and eliminate the interference component from P. In this case, relays will use the interference cancelled signal to decode x_S again. We define the best decoding set Ω_i for the relays that utilize the improved interference cancellation and decode the signal successfully. At the same time, D attempts to decode x_P from the received signal, and if decoding is successful, D will remove the interference component x_P from the original received data.

In the second time slot Ts2, if the optimal decoding set of R_1 is not an empty set, then R_1-best which can cause the highest received signal to interference and noise ratio (SINR) at R_2 will be selected to assist in the transmission. R_2 uses the same interference cancellation mechanism as R_1.

In the third time slot Ts3, R_2 will send data to D if there are optimal decoding set of R_2. The best relay R_2-best will be chosen to assist transmit data to D Simultaneously. Then, D try to decode x_P from the original signal and removes the interference component x_P. Finally, D performs the maximum ratio combining (MRC) to combine the transmission signals in three time slots and perform the final decoding. There are two special cases, if R_1 or R_2 cannot decode the signal successfully, S will transmit the signal directly to R_2 or D in the next time slot.

3 Signal modeling

The improved protocol has been described in Section II, signals accepted at P0, R_1 and D during the first time slot can be respectively expressed as:

$$y_{P0}(1)=\sqrt{E_P}h_{PP0}x_P(1)+\sqrt{E_S}h_{SP0}x_S+n_{P0}(1) \tag{1}$$

$$y_{R1}(1)=\sqrt{E_S}h_{SR1}x_S+\sqrt{E_P}h_{PR1}x_P+n_{R1}(1) \tag{2}$$

$$y_D(1)=\sqrt{E_S}h_{SD}x_S+\sqrt{E_P}h_{PD}x_P+n_D(1) \tag{3}$$

where superscript 1 means the first transmission time slot Ts1. The improved Interference cancellation mechanism is used to eliminate x_P from original signal. Signal after interference cancellation can be rewritten as:

$$y_{R1}^1(1)=\sqrt{E_S}h_{SR1}x_S+n_{R1}(1) \tag{4}$$

$$y_D^1(1)=\sqrt{E_S}h_{SD}x_S+n_D(1) \tag{5}$$

There exist two situations of secondary transmission depending on whether R_1 can successfully decode the signals during the first time slot Ts1. The best relay Ω_1 will be chosen to transmit x_S to D in Ts2, the received signals of P0 and R_2 in Ts2 can be expressed as:

$$y_{P0}(2) = \sqrt{E_P} h_{PP0} x_P(2) + \sqrt{E_S} h_{SP0} x_S + n_{P0}(2) \tag{6}$$

$$y_{R2}(2) = \sqrt{E_{R1}} h_{R1-R2} x_S(2) + \sqrt{E_P} h_{PR2} x_P + n_{R2}(2) \tag{7}$$

After successful Interference elimination, the signals received at R_2 in Ts2 can be expressed as:

$$y^1_{R2}(2) = \sqrt{E_{R1}} h_{R1-R2} x_S(2) + n_{R2}(2) \tag{8}$$

If R_2 successfully decode the signal by taking IC-based protocol, the signal received at P0 and D can be derived as:

$$y_{P0}(3) = \sqrt{E_P} h_{PP0} x_P(3) + \sqrt{E_{R1}} h_{R1P0} x_{R1} + n_{P0}(3) \tag{9}$$

$$y_D(3) = \sqrt{E_{R2}} h_{R2D} x_S + \sqrt{E_P} h_{PD} x_P + n_D(3) \tag{10}$$

After interference cancellation, signal received at D is given as follows:

$$y^1_D(3) = \sqrt{E_{R2}} h_{R2D} x_{ST} + n_D(3) \tag{11}$$

Eventually, D adopts MRC to combine the signals received in Ts1, Ts2 and Ts3.We assume that once the signal interference cannot be eliminated at D, we will use the original received signal for MRC combining. Better secondary outage probability could be expected due to using the improved interference elimination scheme at both D and P0.

4 Secondary outage probability analysis

The case corresponds to the relays in best decoding set being accessible during the first time slot, i.e.,

$$C_{SR1} = \frac{1}{3}\log_2\left(1+\frac{\gamma_S |\mathrm{h}_{SR1}|^2}{\gamma_P |\mathrm{h}_{PR1}|^2 + 1}\right) \tag{12}$$

And achievable data rates can be expressed as:

$$C_{PR1} = \frac{1}{3}\log_2\left(1+\frac{\gamma_P |\mathrm{h}_{PR1}|^2}{\gamma_S |\mathrm{h}_{SR1}|^2 + 1}\right) \tag{13}$$

Notice that fading factors $|\mathrm{h}_{ST-SR1}|^2$ and $|\mathrm{h}_{PT-SR1}|^2$ are independent and follow the exponential distributions with parameters $\frac{1}{\sigma^2_{SR1}}$ and $\frac{1}{\sigma^2_{PR1}}$ respectively.

As can be shown from (4), accessible data rate at R_1 after successful interference cancellation can be shown as:

$$C_{SR1}^{1}=\frac{1}{3}\log_2\left(1+\gamma_S\left|h_{SR1}\right|^2\right) \tag{14}$$

R_1 can successfully deliver the data x_S by direct decoding or IC-based decoding. The occurrence probability of R_1 successfully decode data x_S during Ts1 can be expressed as:

$$\begin{aligned} P_{R1} &= \Pr\left\{C_{SR1}\geq R_A\right\}+\Pr\left\{C_{SR1}<R_A, C_{PR1}\geq R_B, C_{SR1}\geq R_A\right\} \\ &= \begin{cases} a_1+a_2+a_3-a_4 & ,0<\Delta_A\Delta_B<1 \\ a_1+a_3 & ,\Delta_A\Delta_B\geq 1 \end{cases} \end{aligned} \tag{15}$$

Therefore, we can utilize the table of exponential distribution to calculate the approximate detection probability, that is

$$a_1=\frac{\gamma_S\sigma_{SR1}^2}{\gamma_S\sigma_{SR1}^2+\Delta_A\gamma_P\sigma_{PR1}^2}\exp\left(-\frac{\Delta_A}{\gamma_S\sigma_{SR1}^2}\right) \tag{16}$$

$$a_2=\frac{\Delta_A\gamma_P\sigma_{PR1}^2}{\Delta_A\gamma_P\sigma_{PR1}^2+\gamma_S\sigma_{SR1}^2}\exp\left(\frac{1}{\gamma_P\sigma_{PR1}^2}-\frac{\Psi}{\gamma_S\sigma_{PR1}^2}-\frac{\Psi}{\Delta_A\gamma_P\sigma_{PR1}^2}\right) \tag{17}$$

$$a_3=\frac{\gamma_P\sigma_{PR1}^2}{\gamma_P\sigma_{PR1}^2+\Delta_B\gamma_P\sigma_{SR1}^2}\exp\left(-\frac{\Delta_B}{\gamma_P\sigma_{PR1}^2}-\frac{\Delta_A}{\gamma_S\sigma_{SR1}^2}-\frac{\Delta_A\Delta_B}{\gamma_P\sigma_{PR1}^2}\right) \tag{18}$$

$$a_4=\frac{\gamma_P\sigma_{PR1}^2}{\gamma_P\sigma_{PR1}^2+\Delta_B\gamma_S\sigma_{SR1}^2}\exp\left(-\frac{\Delta_B}{\gamma_P\sigma_{PR1}^2}-\frac{\Psi}{\gamma_S\sigma_{SR1}^2}-\frac{\Psi\Delta_B}{\gamma_P\sigma_{PR1}^2}\right), \tag{19}$$

where $\Delta_A=2^{2R_A}-1$, $\Delta_B=2^{2R_B}-1$ and $\Psi=\frac{\Delta_A\left(1+\Delta_B\right)}{1-\Delta_A\Delta_B}$.

During the second time slot, the detection probability of that R_2 can successfully decode x_S can be expressed as:

$$P_{R2}=\Pr\left\{C_{SR2}\geq R_A\right\}+\Pr\left\{C_{SR2}<R_A, C_{PR2}\geq R_B, C_{SR2}\geq R_A\right\} \tag{20}$$

Therefore, the occurrence probabilities of the case that both of R_1 and R_2 cannot decode the data correctly can be shown as:

$$PC_{\Xi}=\prod_{i=1}^{N}\prod_{j=1}^{M}\left(1-P_{R_i}\right)\times\left(1-P_{R_j}\right) \tag{21}$$

where N and M represent the number of relays in the two clusters respectively. After applying the Interference elimination mechanism at R and D, interference from P can be fully suppressed. From (3), the achievable data rate between P and D in Ts1 is given as $C_{S0}^{P}=\log_2\left(1+\frac{\Upsilon_P\left|h_{PD}\right|^2}{\Upsilon_S\left|h_{SD}\right|^2+1}\right)$. According to Section Ⅱ, if the secondary link is interrupted, that is, relays cannot be successfully decoded, there are two situations depending on whether D could decode the data by IC-based protocol or not. If D fails to use ICS to decode the data, the secondary achievable data rate is shown as $C_{S0}^{1}=\log_2\left(1+\frac{2\Upsilon_S\left|h_{SD}\right|^2}{\Upsilon_P\left|h_{PD}\right|^2+1}\right)$, otherwise, the achievable data rate is $C_{S0}^{2}=\log_2\left(1+2\Upsilon_S\left|h_{SD}\right|^2\right)$ .then the outage probability of the case $\Theta=\Xi$ should be calculated as:

$$Pout_{\Xi}=\Pr\left\{C_{S0}^{1}<R_A,C_{S0}^{P}<R_B\right\}+\Pr\left\{C_{S0}^{2}<R_A,C_{S0}^{P}\geq R_B\right\} \tag{22}$$

On the other hand, when $\Theta=\Omega$ occurs, the achievable data rates between P and D in Ts3 is given as $C_{S0,2}^{P}=\log_2\left(1+\frac{\Upsilon_P\left|h_{PD}\right|^2}{\Upsilon_R\left|h_{RD}\right|^2+1}\right)$. The achievable data rate between S and D has four possible situations as given in Tab. 1. For simplicity, we define $X_1=\Upsilon_S\left|h_{SD}\right|^2$, $X_2=\max_{i\in\Omega_N}\Upsilon_{R2}\left|h_{R2D}\right|^2$, $X_3=\Upsilon_P\left|h_{PD}\right|^2$.

Table 1: Secondary achievable rates of four cases

Situations	Secondary achievable data rates
ICS fails in Ts1, Ts3	$C_{SD}^{C1}=\frac{1}{3}\log_2\left(1+\frac{X_1+X_2}{X_3+1}\right)$
ICS succeeds in Ts1, but fails in Ts3	$C_{SD}^{C2}=\frac{1}{3}\log_2\left(1+X_1+\frac{X_2}{X_3+1}\right)$
ICS fails in Ts1, but succeeds in Ts3	$C_{SD}^{C3}=\frac{1}{3}\log_2\left(1+\frac{X_1}{X_3+1}+X_2\right)$
ICS succeeds in Ts1, Ts3	$C_{SD}^{C4}=\frac{1}{3}\log_2\left(1+X_1+X_2\right)$

Therefore, the secondary outage probability based on relay cooperation scheme can be calculated as:

$$\begin{aligned}Pout_{\Omega}=&\Pr\left\{C_{SD}^{C1}<R_A,C_{S0}^{PT}<R_B,C_{S0,2}^{PT}<R_B\right\}\\&+\Pr\left\{C_{SD}^{C1}<R_A,C_{S0}^{PT}\geq R_B,C_{S0,2}^{PT}<R_B\right\}\\&+\Pr\left\{C_{SD}^{C1}<R_A,C_{S0}^{PT}<R_B,C_{S0,2}^{PT}\geq R_B\right\}\\&+\Pr\left\{C_{SD}^{C1}<R_A,C_{S0}^{PT}\geq R_B,C_{S0,2}^{PT}\geq R_B\right\}\end{aligned} \tag{23}$$

Therefore, the outage probability of system can be calculated as:

$$Pout=Pout_{\Omega}\times PC_{\Omega}^{ICS}+Pout_{\Xi}\times PC_{\Xi}^{ICS} \tag{24}$$

5 Simulation analysis

In this section, we evaluate the proposed information cancellation scheme and show the superiority of proposed scheme by simulations. Note that all the simulation results are for independent Rayleigh flat fading. We consume that each secondary relay clusters insist of 2 relays. For the sake of simplicity, we assume that $\sigma_{PR}^2=\sigma_{PD}^2=0.2$ $\sigma_{PP0}^2=\sigma_{SD}^2=\sigma_{SR1}^2=\sigma_{R1R2}^2=\sigma_{RD}^2=1$ $\sigma_{SP0}^2=\sigma_{RP0}^2$, R_A=0.2, R_B=0.4. We let $Pout_{S0}^{Tra}$ denote the secondary outage probability of traditional protocol and $Pout_{S0}^{\Pr o}$ denote the secondary outage probability in Dai et al. [Dai, Liu and Long (2012)].

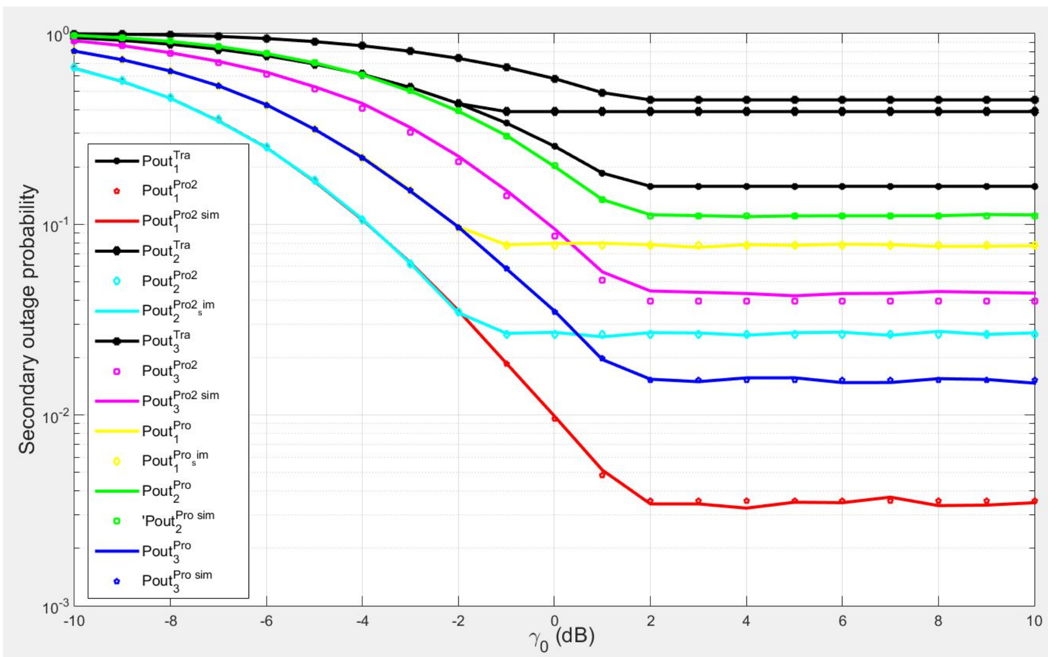

Figure 3: Secondary outage probability *vs.* Υ_0

First, Fig. 3 shows the secondary outage probability *vs.* γ_0 (E_0/σ_0^2) under different kinds of settings for traditional scheme and improved scheme. Note that $Pout_{S0}^{\Pr o2}$ denote the secondary outage probability of three-hop scheme for simplicity. The simulation legend label 1 indicates the simulation condition σ_{SP0}^2=0.2, $R_A=0.2bits/s/Hz$, the label 2 indicates σ_{SP0}^2=0.4, $R_A=0.2bits/s/Hz$, and the label 3 indicates σ_{SP0}^2=0.2, $R_A=0.4bits/s/Hz$. In the simulation, we impose the strict power constraint on secondary users, which is limited by both primary and secondary networks. The secondary power of transmitters is limited by secondary network which allow the maximum transmit power E_{Thr}.

$$E_S=\min(E_S^{Tra},E_{Thr}) \tag{25}$$

$$E_{R_i} = \min(E_{R_i}^{Tra}, E_{Thr}) \tag{26}$$

where the traditional power constraints can be written as:

$$E_S^{Tra} = E_P \sigma_{PP0}^2 \max\left(\frac{1}{1-\xi} e^{\frac{-\Delta_B}{\Upsilon_P \sigma_{PP0}^2}} - 1, 0\right) / (\Delta_B \sigma_{SD}^2) \tag{27}$$

$$E_{R_i}^{Tra} = E_P \sigma_{PP0}^2 \max\left(\frac{1}{1-\xi} e^{\frac{-\Delta_B}{\Upsilon_P \sigma_{PP0}^2}} - 1, 0\right) / (\Delta_B \sigma_{R_i D}^2) \tag{28}$$

where ξ is defined as the outage probability threshold of primary network and is set as 0.04. As shown in Fig. 3, the proposed scheme significantly reduces the secondary outage probability compared with traditional scheme due to the use of interference cancellation. As the γ_0 increases, the secondary outage probability will maintain a steady trend owning to the fact that the QoS of primary network become the main reason for transmit power constraint in high γ_0 regime. We also can observe from Fig. 3 that the secondary outage probability can be reduced when the interference links of SP0 and RP0 become weak. It is due to the fact that more transmit power is distributed to secondary transmitter according to the improved power constraints.

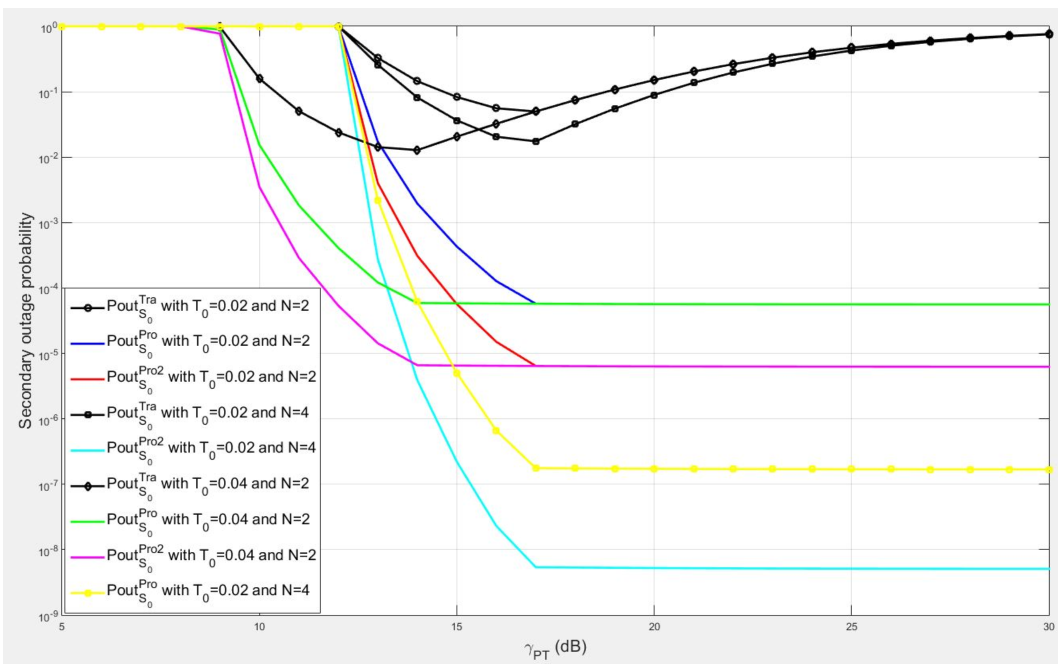

Figure 4: Secondary outage probability *vs.* Υ_P

In Fig. 4 we study the impact of Υ_P on the secondary outage probability by comparing the conventional scheme and improved scheme. T_0 denote the preset threshold ordered by primary networks. Comparing with traditional scheme, the decline of secondary outage probability of improved scheme is more obvious due to the IC-based relay selection scheme. Concerning the multi-hop based on ICS, we compared the improved three-hop scheme with two-hop scheme [Dai, Liu and Long (2012)]. As can be shown in the Fig. 4, the improved scheme can achieve lower secondary outage probability. Note that more flexible IC-based relay selection mechanism could ensure the reliability of secondary transmission link. In order to evaluate the impact of numbers of relays on the secondary system performance, we calculate the system performance in terms of secondary outage probability achieved by traditional scheme, two-hop relay scheme and improved ICS scheme. As relay number increases in each relay cluster, each mechanism will have significant reduction in the secondary outage probability.

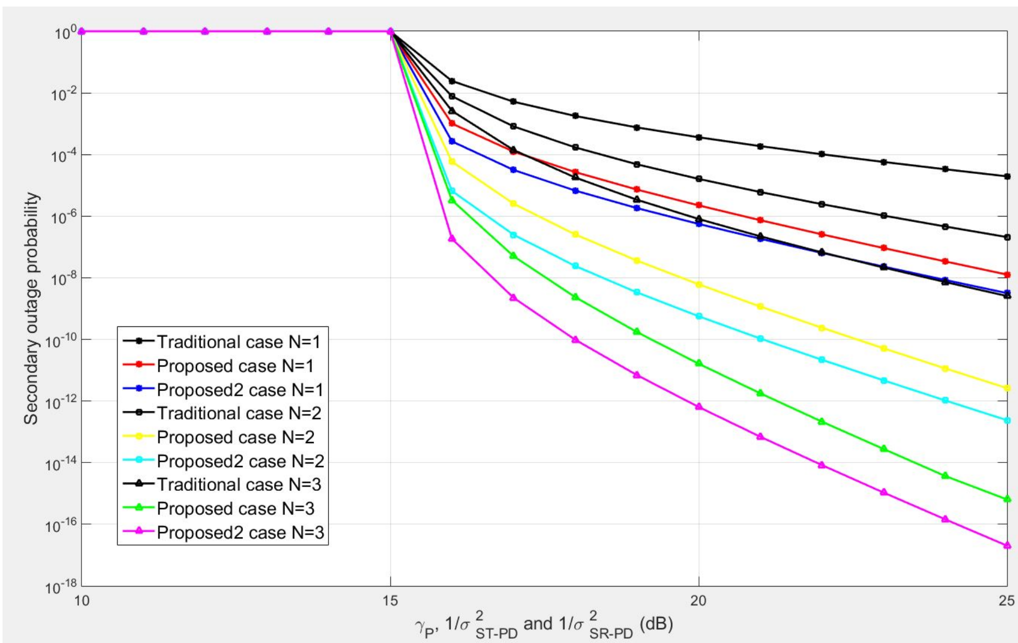

Figure 5: Illustration of generalized diversity gain

If the secondary receiver can reduce the interference close to zero, we can make the definition of the generalized diversity gain as an asymptotic ratio of secondary outage probability to the interference gain as follows:

$$d^{pro} = \lim_{\sigma_{SP0}^2 \to 0} \frac{\log\left(\lim_{\Upsilon_P, 1/\sigma_{RP0}^2} Pout_{SD}^{pro} \right)}{\log\left(\sigma_{SP0}^2\right)} \tag{29}$$

Fig. 5 shows the generalized diversity gain by simulation for conventional and improved scheme, where power constraint imposed by secondary networks will be removed. Fig. 5 shows that the underlying improved protocol achieves a higher degree of diversity than the traditional cases owing to the fact that the interfering link from the primary transmitter to the secondary destination can utilize additional diversity gain by using ICS on the secondary users.

6 Conclusion

In this paper, the proposed IC-based transmission scheme indeed improves the secondary relay transmission efficiency and reduce the secondary outage probability in underlay CRNs. What's more, secondary users transmit signals under dual secondary power limitations which is restricted by both primary and secondary systems. Under the stringent power constraint, improved mechanism aims at improving the secondary performance of multi-hop network. Then, we evaluate the secondary transmission system in terms of secondary outage probability and derive the closed-form expression over Rayleigh fading channels. As simulation results shows, even with the increased hop number of relays, the secondary outage probability is still reduced due to the flexibility of the improved protocol.

Acknowledgement: This work is supported by Sichuan science and Technology Program (2019YFG0212), China Postdoctoral Science Foundation (2019M653401) and Sichuan Science and Technology Program (2018GZ0184).

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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