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Analysis of Underlay Cognitive Radio Networks Based on Interference Cancellation Mechanism

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Abstract: In this paper, we investigate the performance of secondary transmission scheme based on Markov ON-OFF state of primary users in Underlay cognitive radio networks. We propose flexible secondary cooperative transmission schemewith interference cancellation technique according to the ON-OFF status of primary transmitter. For maximal ratio combining (MRC) at destination, we have derived exact closed-form expressions of the outage probability in different situations. The numerical simulation results also reveal that the proposed scheme improve the secondary transmission performance compared with traditional mechanism in terms of secondary outage probability and energy efficiency.

Keywords: Cognitive radio, Markov ON-OFF state, relay selection, outage probability.

1 Introduction and motivation

Cognitive Radio (CR) is one of the most promising techniques to address the shortage of spectrum resources in next generation networks [Li, Huang, Ma et al. (2018); Chen, Motani, Wong et al. (2011)]. Secondary users (SUs) are allowed to access the licensed band of the primary users (PUs) to communicate with each other [Akyildiz, Lee, Vuran et al. (2008); Wang, Hong, Chen et al. (2009)]. Underlay cognitive radio is introduced to improve the spectrum efficiency by allowing secondary user to access the licensed spectrum under the strict constraint to primary networks [Mitola (2000)]. Although secondary users can better utilize the licensed spectrum in underlay approach, the cost is to reduce the secondary transmission quality and the transmission range [Le and Hossain (2008); Luo, Zhang, Zhang et al. (2011)]. In these cases, the interference of primary networks cannot be ignored. The performance of secondary transmission will be reduced remarkably due to the interference from primary networks [Zhang, Jia and Zhang (2009)].

Cooperative relaying transmission is emerging as an effective means to mitigate wireless channel impairments in cognitive radio networks [Meylani, Kurniawan and Arifianto (2017)]. Cooperative transmission attracted considerable research interests in underlay

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sharing approach due to its significant increase in channel capacity and transmission range [Duong, Bao and Zepernick (2011)]. It has shown that user cooperation can improve transmission performance in terms of saving power consumption, increasing the connectivity and extending the transmission coverage [Bao, Duong and Tellambura (2013)] and [Kim, Duong, Tsiftsis et al. (2013)]. It is noted that interference of primary network cannot be eliminated by cooperative relaying [Musavian, Aïssa and Lambotharan (2010)]. Therefore, Secondary transmission performance has been greatly improved by adopting both cooperative relaying and interference cancellation scheme [Zou, Yao and Zheng (2012)].

To the best of our knowledge, the primary transmitter does not occupy the licensed band all the time [Heydari and Heydari (2016)], secondary network suffers from primary interference only when primary transmitters occupy the licensed spectrum [Ghasemi and Sousa (2008); Jayaweera and Li (2009)]. Flexible transmission schme according to different primary transmitter status will save secondary energy consumption and improve transmission efficiency [Quan, Cui, Sayed et al. (2009)].

In this paper, we propose a cooperative DF relaying scheme based on interference cancellation in underlay cognitive radio network, where SUs coexist with PUs. The proposed mechanism can dynamically adjust the secondary transmission mechanism based on interference cancellation according to the status of the primary user. More specifically, SUs decide whether to cancel out the signal of interference from received signal according to the status of PU. We derive closed-form expressions of outage probability (OP) and energy efficiency (EE) over Rayleigh fading channels. The analytical expressions are validated through Monte Carlo simulations.

The outline of this paper is organized as follows. Section Ⅱ presents the system model and Section Ⅲ describes decode-and-forward relaying protocol. The performance of proposed schemein terms of outage probability and energy efficiency are presented in Section Ⅳ Simulation results are provide in Section Ⅴ, followed by concluding remarks summarized in Section Ⅵ.

2 Modeling of the system

As Fig. 1 shows, we consider a cognitive radio network with a primary system and a secondary system. Primary source node PT transmits signal to primary destination node PD. Secondary source node ST communicates with the secondary destination SD via secondary relay cluster SR. It is assumed that the transmission channel between any two users is an independent Rayleigh channel. h_{ij} is used to represent the channel fading coefficient between any two nodes and obeys the exponential distribution.

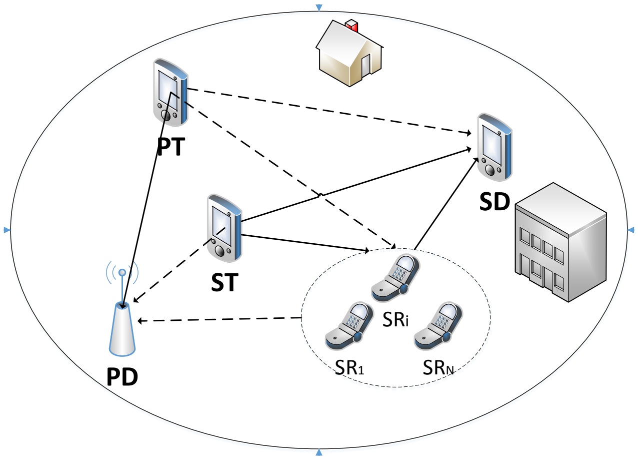

Figure 1: System model of cognitive relay system

On one hand, the secondary network limits the transmission power to ensure the QoS of primary network in underlay spectrum sharing approach. On the other hand, the co-channel transmission causes the primary users to interfere with secondary transmission network. Therefore, SUs should take into the consideration of PU's interference in underlay cognitive radio networks. As Fig. 2 shows, the arrivals of PT offered by channels are governed by Markov two-state process with no following effects.

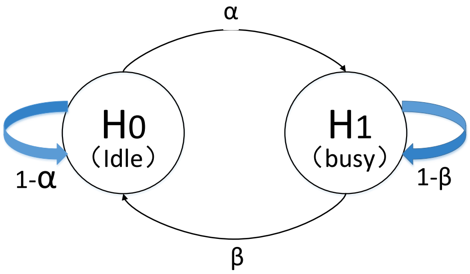

Figure 2: Markov model of primary network

$$\Pr\left(H_{PT}(2)=H_1 \middle| H_{PT}(1)=H_0\right)=\alpha \tag{1}$$

$$\Pr\left(H_{PT}(2)=H_0 \middle| H_{PT}(1)=H_1\right)=\beta \tag{2}$$

Assume that $Hp(i)=H0(i=1,2)$ and $Hp(i)=H1(i=1,2)$ means that the primary user is in idle and transmission state in the i-th transmission time slot respectively.

3 Decode-and-forward relaying protocol

At the beginning of each time slot, the secondary transmitter ST and secondary relay cluster SR perform cooperative spectrum sensing and send sensing information to the fusion center.

After receiving the sensing results, the secondary users adopt different transmission scheme based on interference cancellation according to the decision results sent by the fusion center. The fusion center adopts soft consolidation to aggregate information and make judgements on the status of PT. In the data transmission phase, SUs adopts flexible scheme according to the decision result of fusion center

ST broadcast signal to SR and SD during the first time slot. According to the status of PT, the secondary transmission can be described as follows:

CASE 1: If $H_{PT}(1) = H_0$, that is, the primary user is in an idle state. PT does not cause interference to the secondary system. The fusion center sends information to SR and SD, then SR and SD decode the signal directly without interference cancellation. Relays which successfully decode in relay cluster constitute the optimal decoding set Ω_{SR}.

CASE 2: If $H_{PT}(1) = H_1$, that is, PT is in transmission state and will interfere with the secondary system. Then SR and SD first attempt to decode interference information x_{PT}. If the signal x_{PT} from PT is successfully decoded, it will be cancelled out from original received signal , then SR uses interference cancelled signal to decode x_{ST}. The secondary relays which successfully decode the data by utilizing the interference cancellation technique constitute the best decoding set Ω_{SR}.

If SD can decode x_{PT} successfully, SD will directly remove the interference component from the original received signal. In order to ensure the transmission quality of the primary network, the secondary transmission power is limited by both primary network and secondary network.

During the second time slot, there are still two situations to discuss according to the status of PT.

CASE 1: $H_{PT}(2) = H_0$, SD directly combine the received signals of two transmission time slot by utilizing MRC

CASE 2: $H_{PT}(2) = H_1$, PT is in transmission state. If the best decoding set Ω_{SR} is not empty, the relay in the decoding set with the highest SINR is selected as the best relay to assist secondary transmission. SD attempts to decode the interference signal x_{PT} in the second time slot. If the signal x_{PT} is successfully decoded, it will be cancelled out from the original received signal. Finally, SD combines the signal received from the two time slots.

According to the above discussion, Hp(1)=H0, that is, PT is in an idle state in the first time slot. Signals received at SR and SD can be written as:

$$y_{SR_i}^1(1) = \sqrt{E_{ST}}\mathrm{h}_{ST-SR_i}x_{ST} + n_{SR_i}(1) \tag{3}$$

$$y_{SD}^1(1) = \sqrt{E_{ST}}\mathrm{h}_{ST-SD}x_{ST} + n_{SD}(1) \tag{4}$$

where the superscript 1 denotes the first transmission time slot. Hp(1)=H1, that is, the primary transmitter is in transmission state, signals received by PD, SR and SD are respectively given as:

$$y_{PD}^2(1) = \sqrt{E_{PD}}\mathrm{h}_{PD-PT}x_{PT}(1) + \sqrt{E_{ST}}h_{ST-PD}x_{ST} + n_{PD}(1) \tag{5}$$

$$y_{SR_i}^2(1)=\sqrt{E_{ST}}\mathrm{h}_{ST-SR_i}x_{ST}+\sqrt{E_{PT}}h_{PT-SR_i}x_{PT}(1)+n_{SR_i}(1) \tag{6}$$

$$y_{SD}^2(1)=\sqrt{E_{ST}}\mathrm{h}_{ST-SD}x_{ST}+\sqrt{E_{PT}}h_{PT-SD}x_{PT}(1)+n_{SD}(1) \tag{7}$$

The improved mechanism is used to cancel out interference signal y_{PD}^2 from $y_{SR_i}^2$ and y_{SD}^2, respectively. The interference cancelled signals received by SR and SD can be expressed as:

$$y_{SR_i}^2(1)=\sqrt{E_{ST}}\mathrm{h}_{ST-SR_i}x_{ST}+n_{SR_i}(1) \tag{8}$$

$$y_{SD}^2(1)=\sqrt{E_{ST}}\mathrm{h}_{ST-SD}x_{ST}+n_{SD}(1) \tag{9}$$

In the second time slot, there exists two possible secondary transmission process depending on whether PT is in transmission state or not. If the primary user is in idle state, the signal received by the secondary destination user can be expressed as:

$$y_{SD}^1(2)=\sqrt{E_{SR}}\mathrm{h}_{SR-SD}x_{ST}+n_{SD}(2) \tag{10}$$

where the superscript 2 denotes the second transmission time slot. If the primary user is in the transmission state, it will cause interference to the secondary transmission system, and the signal received by SD can be found as:

$$y_{SD}^2(2)=\sqrt{E_{SR}}\mathrm{h}_{SR-SD}x_{ST}+\sqrt{E_{PT}}h_{PT-SD}x_{PT}(2)+n_{SD}(2) \tag{11}$$

Similarly, y_{SD}^2 after successful interference cancellation can be rewritten as:

$$y_{SD}^2(2)=\sqrt{E_{SR}}\mathrm{h}_{SR-SD}x_{ST}+n_{SD}(2) \tag{12}$$

Finally, SD adopts MRC to combine the signals received in two time slots. It is noted that SD will combine the original signal for MRC if it fails to cancel out the interference.

4 Secondary outage probability analysis

For the first time slot, if Hp(1)=H0, the data achievable rate of ST→SR$_i$ and ST→SD can be respectively written as:

$$C_{ST-SR_i}^{ICM}=\frac{1}{2}\log_2(1+\gamma_{ST}\left|h_{ST-SR_i}\right|^2) \tag{13}$$

$$C_{ST-SD}^{ICM}=\frac{1}{2}\log_2\left(1+\Upsilon_{ST}\left|h_{ST-SD}\right|^2\right) \tag{14}$$

The occurrence probability of that the i-th relay in SR can successfully recover x_{ST} after direct decoding is given as:

$$PD_{SR_i}^1=\Pr\left\{C_{ST-SR_i}^{ICM}\geq R_S\right\} \tag{15}$$

If Hp(1)=H1, SR$_i$ first utilize the original signal from ST to decode x_{ST} directly. If direct decoding fails, SR$_i$ attempts decode x_{PT} and cancels out the interference component from original signal if decoding is successful. Then, SR$_i$ uses interference cancelled signal to decode x_{ST} again. Therefore, the probability of successful decoding in the first time slot is shown as:

$$PD_{SR_i}^2 = \Pr\left\{C_{ST-SR_i}^{ICM} \geq R_S\right\} + \Pr\left\{C_{ST-SR_i}^{ICM} < R_S, C_{PT-SR_i}^{ICM} \geq R_P, C_{ST-SR_i}^{ICM} \geq R_S\right\} \tag{16}$$

$$= \begin{cases} a_1 + a_2 + a_3 - a_4 & ,0 < \Delta_S\Delta_P < 1 \\ a_1 + a_3 & ,\Delta_S\Delta_P \geq 1 \end{cases}$$

where $\Delta_S = 2^{2R_S} - 1$, $\Delta_P = 2^{R_P} - 1$, $\Psi = \dfrac{\Delta_S\left(1+\Delta_P\right)}{1-\Delta_S\Delta_P}$.

$$a_1 = \frac{\gamma_{ST}\sigma_{ST-SR_i}^2}{\gamma_{ST}\sigma_{ST-SR_i}^2 + \Delta_S\gamma_{PT}\sigma_{PT-SR_i}^2}\exp\left(-\frac{\Delta_S}{\gamma_{ST}\sigma_{ST-SR_i}^2}\right) \tag{17}$$

$$a_2 = \frac{\Delta_S\gamma_{PT}\sigma_{PT-SR_i}^2}{\Delta_S\gamma_{PT}\sigma_{PT-SR_i}^2 + \gamma_{ST}\sigma_{ST-SR_i}^2}\exp\left(\frac{1}{\gamma_{PT}\sigma_{PT-SR_i}^2} - \frac{\Psi}{\gamma_{ST}\sigma_{PT-SR_i}^2} - \frac{\Psi}{\Delta_S\gamma_{PT}\sigma_{PT-SR_i}^2}\right) \tag{18}$$

$$a_3 = \frac{\gamma_{PT}\sigma_{PT-SR_i}^2}{\gamma_{PT}\sigma_{PT-SR_i}^2 + \Delta_P\gamma_{PT}\sigma_{ST-SR_i}^2}\exp\left(-\frac{\Delta_P}{\gamma_{PT}\sigma_{PT-SR_i}^2} - \frac{\Delta_S}{\gamma_{ST}\sigma_{ST-SR_i}^2} - \frac{\Delta_S\Delta_P}{\gamma_{PT}\sigma_{PT-SR_i}^2}\right) \tag{19}$$

$$a_4 = \frac{\gamma_{PT}\sigma_{PT-SR_i}^2}{\gamma_{PT}\sigma_{PT-SR_i}^2 + \Delta_P\gamma_{ST}\sigma_{ST-SR_i}^2}\exp\left(-\frac{\Delta_P}{\gamma_{PT}\sigma_{PT-SR_i}^2} - \frac{\Psi}{\gamma_{ST}\sigma_{ST-SR_i}^2} - \frac{\Psi\Delta_P}{\gamma_{PT}\sigma_{PT-SR_i}^2}\right) \tag{20}$$

The probability of having a secondary relay optimal decoding set Ω_{SR} is given as:

$$PC_{\Omega_{SR}}^{ICM} = \prod_{i\in\Omega_{SR}} PD_{SR_i} \prod_{j\in\Omega_{SR}} (1 - PD_{SR_j}) \tag{21}$$

Given the optimal decoding set Ω_{SR}, the conditional outage probability of secondary transmission system is $\mathrm{P\,out}\left\{C_{ST-SD}^{ICM} < R_S \mid \Omega_{SR}\right\}$.

The achievable data rate between ST and SD has four scenarios depending on the status of PT in two time slot.

(1) Hp(1)=H0 & Hp(2)=H0, the primary transmitter is in an idle state in both sub-timeslots $\mathrm{t}_{k,1}$, $\mathrm{t}_{k,2}$. The achievable data rates of link ST→SD can be expressed as:

$$C_{ST-SD}^{S1} = \frac{1}{2}\log_2\left(1 + \Upsilon_{SR_i}\left|\mathrm{h}_{ST-SD}\right|^2 + \max_{i\in\Omega_{SR}}\Upsilon_{SR_i}\left|\mathrm{h}_{SR_i-SD}\right|^2\right) \tag{22}$$

(2) Hp(1)=H1 & Hp(2)=H0, primary transmitter is in transmission state in $\mathrm{t}_{k,1}$ and turn idle in $\mathrm{t}_{k,2}$. The reachable data rate of the link ST→SD depends on whether the interference cancellation performed by the SD is successful or not. The data achievable data rate of link PT→SD is given as:

$$C_{PT-SD}^{S2} = \log_2\left(1+\frac{\Upsilon_{PT}\left|h_{PT-SD}\right|^2}{\gamma_{ST}\left|h_{ST-SD}\right|^2+1}\right) \tag{23}$$

If the interference cancellation is unsuccessful, it can be expressed as:

$$C_{ST-SD}^{S2,1} = \frac{1}{2}\log_2\left(1+\frac{\Upsilon_{ST}\left|\mathrm{h}_{ST-SD}\right|^2}{1+\Upsilon_{PT}\left|\mathrm{h}_{PT-SD}\right|^2}+\max_{i\in\Omega_{SR_i}}\Upsilon_{SR_i}\left|\mathrm{h}_{SR_i-SD}\right|^2\right) \tag{24}$$

If the SD performs interference cancellation successfully, the achievable data rate of the link ST→SD can be expressed as:

$$C_{ST-SD}^{S2,2} = \frac{1}{2}\log_2\left(1+\Upsilon_{ST}\left|\mathrm{h}_{ST-SD}\right|^2+\max_{i\in\Omega_{SR_i}}\Upsilon_{SR_i}\left|\mathrm{h}_{SR_i-SD}\right|^2\right) \tag{25}$$

In this case, the outage probability of the secondary transmission mechanism is given as:

$$Pout^{S2} = \Pr\left\{C_{ST-SD}^{S2,1} < R_S, C_{PT-SD}^{S2} < R_P\right\} + \Pr\left\{C_{ST-SD}^{S2,2} < R_S, C_{PT-SD}^{S2} \ge R_P\right\} \tag{26}$$

$$= \begin{cases} 1+\mathrm{K}_1-\mathrm{K}_2-\mathrm{K}_3-\mathrm{K}_4 & \Delta_S\Delta_P < 2 \\ 1-\mathrm{K}_1+\mathrm{K}_4 & \Delta_S\Delta_P \ge 2 \end{cases}$$

where $\mathrm{K}_1 = \mathrm{K}_2 e^{-\frac{\upsilon_5}{\Upsilon_{PT}\sigma_{PT-SD}^2}-\frac{\upsilon_5\Delta_S}{2\Upsilon_{ST}\sigma_{ST-SD}^2}}$, $\mathrm{K}_2 = \mathrm{K}_6 e^{-\frac{\Delta_S}{2\Upsilon_{ST}\sigma_{ST-SD}^2}}$, $\mathrm{K}_3 = (1-\mathrm{K}_7) e^{\frac{1}{\Upsilon_{ST}\sigma_{ST-SD}^2}-\frac{\mathrm{K}_5}{\Upsilon_{PT}\sigma_{PT-SD}^2}-\frac{\mathrm{K}_5}{\Delta_P\Upsilon_{ST}\sigma_{ST-SD}^2}}$, $\mathrm{K}_4 = \mathrm{K}_7 e^{-\frac{\Delta_P}{\Upsilon_{PT}\sigma_{PT-SD}^2}-\frac{\Delta_S}{2\Upsilon_{ST}\sigma_{ST-SD}^2}-\frac{\Delta_S\Delta_P}{2\Upsilon_{PT}\sigma_{PT-SD}^2}}$, $\mathrm{K}_5 = \frac{\Delta_P(1+\Delta_S)}{2-\Delta_S\Delta_P}$, $\mathrm{K}_6 = \frac{2\Upsilon_{ST}\sigma_{ST-SD}^2}{2\Upsilon_{ST}\sigma_{ST-SD}^2+\Delta_S\Upsilon_{PT}\sigma_{PT-SD}^2}$,

$$\mathrm{K}_7 = \frac{\Upsilon_{PT}\sigma_{PT-SD}^2}{\Upsilon_{PT}\sigma_{PT-SD}^2+\Delta_P\Upsilon_{ST}\sigma_{ST-SD}^2}.$$

(3) Hp(1)=H0 & Hp(2)=H1, primary transmitter is in idle state in $\mathrm{t}_{k,1}$ and turn transmission state in $\mathrm{t}_{k,2}$. Similarly, the reachable data rate of the link PT→SD and the reachable data rate of the link ST→SD can be respectively expressed as:

$$C_{PT-SD}^{S3} = \log_2\left(1+\frac{\Upsilon_{PT}\left|h_{PT-SD}\right|^2}{\max\limits_{i\in\Omega_{SR}}\Upsilon_{SR_i}\left|\mathrm{h}_{SR_i-SD}\right|^2+1}\right) \tag{27}$$

$$C_{ST-SD}^{S3,1} = \frac{1}{2}\log_2\left(1+\Upsilon_{ST}\left|\mathrm{h}_{ST-SD}\right|^2+\frac{\max\limits_{i\in\Omega_{SR}}\Upsilon_{SR}\left|\mathrm{h}_{SR_i-SD}\right|^2}{1+\Upsilon_{PT}\left|\mathrm{h}_{PT-SD}\right|^2}\right) \tag{28}$$

$$C_{ST-SD}^{S3,2} = \frac{1}{2}\log_2\left(1+\Upsilon_{ST}\left|\mathrm{h}_{ST-SD}\right|^2+\max_{i\in\Omega_{SR}}\Upsilon_{SR_i}\left|\mathrm{h}_{SR_i-SD}\right|^2\right) \tag{29}$$

The outage probability of the secondary transmission mechanism can be expressed as:

$$Pout^{S3} = \Pr\left\{C_{ST-SD}^{S3,1} < R_S, C_{PT-SD}^{S3} < R_P\right\} + \Pr\left\{C_{ST-SD}^{S3,2} < R_S, C_{PT-SD}^{S3} \geq R_P\right\}$$
$$= \begin{cases} 1+\mathrm{M}_1 - \mathrm{M}_2 - \mathrm{M}_3 - \mathrm{M}_4 & \Delta_S \Delta_P < 2 \\ 1 - \mathrm{M}_1 + \mathrm{M}_4 & \Delta_S \Delta_P \geq 2 \end{cases} \tag{30}$$

(4) Hp(1)=H1 & Hp(2)=H1, that is, the primary user is in transmission state in both time slot $\mathrm{t}_{k,1}$ and $\mathrm{t}_{k,2}$. The achievable data rate between ST and SD has four possible cases depending on whether SD successfully performs interference cancellation or not in two time slots, Firstly, the data achievable data rates between PT and SD at $\mathrm{t}_{k,1}$ and $\mathrm{t}_{k,2}$ can be obtained respectively from (7) and (11) as:

$$C_{PT-SD}^{S4,1} = \log_2\left(1 + \frac{\Upsilon_{PT}\left|h_{PT-SD}\right|^2}{\gamma_{ST}\left|h_{ST-SD}\right|^2 + 1}\right) \tag{31}$$

$$C_{PT-SD}^{S4,2} = \log_2\left(1 + \frac{\Upsilon_{PT}\left|h_{PT-SD}\right|^2}{\max\limits_{i\in\Omega_{SR}} \Upsilon_{SR_i}\left|\mathrm{h}_{SR_i-SD}\right|^2 + 1}\right) \tag{32}$$

SITUATION 1: SD fails to eliminate the interference in $\mathrm{t}_{k,1}$ and $\mathrm{t}_{k,2}$. The data achievable data rate of the secondary transmission link ST→SD is given as:

$$C_{ST-SD}^{S4,1} = \frac{1}{2}\log_2\left(1 + \frac{\Upsilon_{ST}\left|\mathrm{h}_{ST-SD}\right|^2 + \max\limits_{i\in\Omega_{SR}} \Upsilon_{SR_i}\left|\mathrm{h}_{SR_i-SD}\right|^2}{1+\Upsilon_{PT}\left|\mathrm{h}_{PT-SD}\right|^2}\right) \tag{33}$$

In order to facilitate calculation and expression, we define $z_1 = \gamma_{ST}\left|h_{ST-SD}\right|^2$, $z_2 = \max\limits_{i\in\Omega_{SR}} \Upsilon_{SR_i}\left|\mathrm{h}_{SR_i-SD}\right|^2$, $z_3 = \Upsilon_{PT}\left|h_{PT-SD}\right|^2$. The outage probability of improved scheme can be shown as:

$$Pout^{S4,1} = \Pr\left\{C_{ST-SD}^{S4,1} < R_S, C_{PT-SD}^{S4,1} < R_P, C_{PT-SD}^{S4,2} < R_P\right\} \tag{34}$$
$$= \Pr\left\{\frac{z_1 + z_2}{z_3 + 1} < \Delta_S, \frac{z_3}{z_1 + 1} < \Delta_P, \frac{z_3}{z_2 + 1} < \Delta_P\right\}$$

SITUATION 2: SD succeeds to eliminate the interference in $\mathrm{t}_{k,1}$ and failsin $\mathrm{t}_{k,2}$. The data achievable rate of the secondary transmission link ST→SD and the mechanism's outage probability can be respectively shown as:

$$C_{ST-SD}^{S4,2} = \frac{1}{2}\log_2\left(1 + \Upsilon_{ST}\left|\mathrm{h}_{ST-SD}\right|^2 + \frac{\max\limits_{i\in\Omega_{SR}} \Upsilon_{SR_i}\left|\mathrm{h}_{SR_i-SD}\right|^2}{1+\Upsilon_{PT}\left|\mathrm{h}_{PT-SD}\right|^2}\right) \tag{35}$$

$$Pout^{S4,2} = \Pr\left\{C_{ST-SD}^{S4,2} < R_S, C_{PT-SD}^{S4,1} \geq R_P, C_{PT-SD}^{S4,2} < R_P\right\} \tag{36}$$

SITUATION 3: SD fails to eliminate the interference at $\mathrm{t}_{k,1}$ and succeeds at $\mathrm{t}_{k,2}$ .The data achievable rate of the secondary transmission link ST→SD and the mechanism's outage probability can be shown as:

$$C_{ST-SD}^{S4,3} = \frac{1}{2}\log_2\left(1+\max_{i\in\Omega_{SR}} \Upsilon_{SR_i}\left|\mathrm{h}_{SR-SD}\right|^2 + \frac{\Upsilon_{ST}\left|\mathrm{h}_{ST-SD}\right|^2}{1+\Upsilon_{PT}\left|\mathrm{h}_{PT-SD}\right|^2}\right) \tag{37}$$

$$Pout^{S4,3} = \Pr\left\{C_{ST-SD}^{S4,3} < R_S, C_{PT-SD}^{S4,1} < R_P, C_{PT-SD}^{S4,2} \geq R_P\right\} \tag{38}$$

SITUATION 4: SD succeeds in both $\mathrm{t}_{k,1}$ and $\mathrm{t}_{k,2}$. The data achievable rate of the secondary transmission link ST→SD and the mechanism's outage probability can be respectively shown as:

$$C_{ST-SD}^{S4,4} = \frac{1}{2}\log_2\left(1+\max_{i\in\Omega_{SR}} \Upsilon_{SR_i}\left|\mathrm{h}_{SR-SD}\right|^2 + \Upsilon_{ST}\left|\mathrm{h}_{ST-SD}\right|^2\right) \tag{39}$$

$$Pout^{S4,4} = \Pr\left\{C_{ST-SD}^{S4,4} < R_S, C_{PT-SD}^{S4,1} \geq R_P, C_{PT-SD}^{S4,2} \geq R_P\right\} \tag{40}$$

In this case, according to the interference cancellation situation of SD in two time slots, the outage probability of the secondary transmission system is obtained as:

$$Pout^{S4} = Pout^{S4,1} + Pout^{S4,2} + Pout^{S4,3} + Pout^{S4,4} \tag{41}$$

In summary, according to the transmission status of the primary user, the probability of occurrence of four cases can be obtained as:

CASE 1: $\Pr\left[H_P(1)=H_0, H_P(2)=H_0\right] = p_0(1-\alpha)$ (42)

CASE 2: $\Pr\left[H_P(1)=H_1, H_P(2)=H_0\right] = p_0\alpha$

CASE 3: $\Pr\left[H_P(1)=H_0, H_P(2)=H_1\right] = (1-p_0)\beta$

CASE 4: $\Pr\left[H_P(1)=H_1, H_P(2)=H_1\right] = (1-p_0)(1-\beta)$

Therefore, the total probability formula is applied to calculate the outage probability of four cases:

$$\begin{aligned} Pout^{ICM} &= p_0(1-\alpha)\times Pout^{S1}PC_{\Omega_{SR}} + p_0\alpha\times Pout^{S2}\ PC_{\Omega_{SR}}^{ICM} \\ &\quad + (1-p_0)\beta\times Pout^{S3}PC_{\Omega_{SR}} + (1-p_0)(1-\beta)\times Pout^{S4}PC_{\Omega_{SR}}^{ICM} \end{aligned} \tag{43}$$

5 Results and discussion

In this section, we present some analytical and simulation results to evaluate the performance of improved mechanism and compare with the traditional mechanism [Dai, Liu and Long (2012)]. Assume that $\sigma_{PT-PD}^2 = \sigma_{ST-SD}^2 = \sigma_{ST-SR}^2 = \sigma_{SR-SD}^2 = 1$, $\sigma_{PT-SR}^2 = \sigma_{PT-SD}^2 = 0.2$, R_S=0.2, R_P=0.4. $Pout^{ICM}$ and $Pout^{pro}$ present the OP of mechanism with IC-based direct link and the OP of improved mechanism respectively.

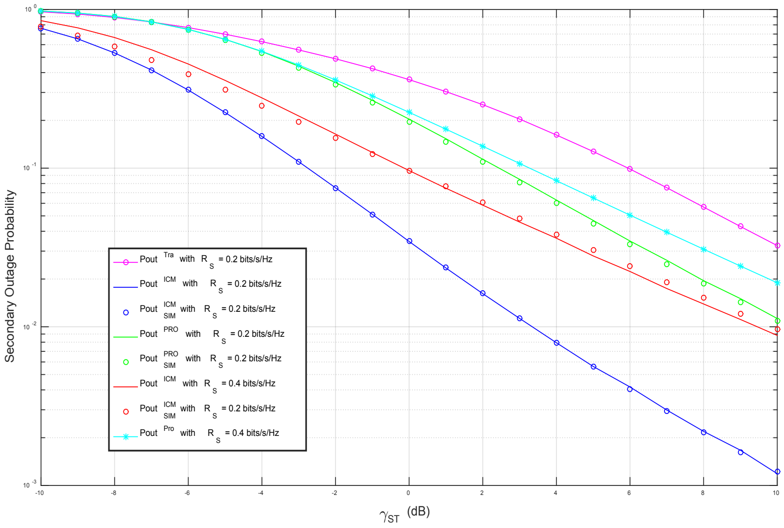

Figure 3: Secondary outage probability *vs.* γ_{ST}

Fig. 3 depicts the secondary outage probability versus γ_{ST} values under different settings. It can be seen that the improved mechanism can significantly reduce the secondary OP compared to the traditional mechanism that ST transmits signal to SD directly without interference cancellation. And $Pout^{pro}$ can keep at a low value due to the IC-base cooperation transmission mechanism compared with $Pout^{ICM}$. Fig. 3 also shows the secondary OP will increase as the secondary data rate R_S is improved.

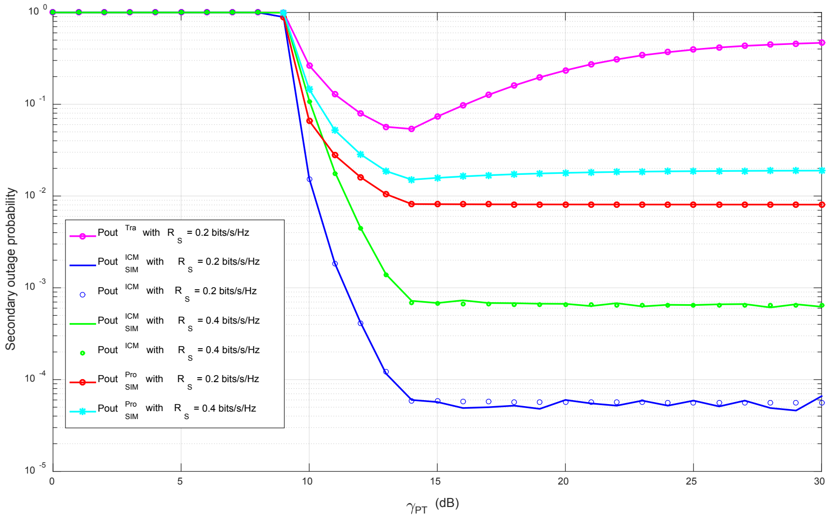

Figure 4: Secondary outage probability *vs.* γ_{PT}

Fig. 4 illustrates the secondary outage probability *vs.* γ_{PT}. Comparing with traditional scheme, the decline of secondary OP of improved mechanism is obvious due to the IC-based cooperation mechanism. Flexible IC-based transmission mechanism could ensure the reliability of secondary transmission. Transmit power constraints of SUs which is limited by PUs can be written as:

$$E_{SU}^{Thr} = E_P \sigma_{PT-PD}^2 \max(\frac{1}{1-\xi} e^{\frac{-\Delta_{PT}}{\gamma_{PT}\sigma_{PT-PD}^2}} - 1, 0) / (\Delta_{PT} \sigma_{SU-PD}^2) \tag{44}$$

Transmit power of SUs can be chosen as $E_{SU} = \min(E_{SU}^{Thr}, E_0)$. E_0 is the Maximum power allowed by the secondary system and is set as 0 dBm.

In low γ_{PT} regions, the secondary outage probability is equal to 1, which due to the fact that the secondary transmission is not permitted in order to ensure the QoS of PT. It is noteworthy that the traditional system performance degrades as expected due to the interference from PT when γ_{PT} is up to 18. However, the secondary OP of improved scheme remains at low level due to the IC-based cooperation mechanism.

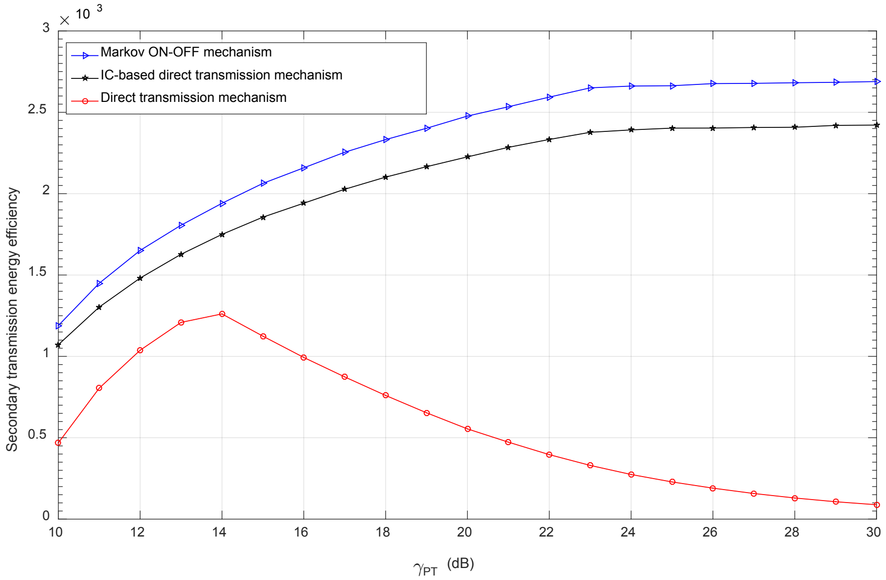

Figure 5: Secondary energy efficiency *vs.* γ_{PT}

Fig. 5 shows the simulation results of secondary energy efficiency versus γ_{PT}. Energy efficiency of secondary system can be calculated as:

$$EE_{DF} = \frac{C_{DF}}{P_{DF}} \tag{45}$$

$$C_{DF} = \min\left\{\frac{1}{2} B \log_2\left(1 + \frac{\gamma_{ST}|h_{ST-SR}|^2}{N_{\text{int}}^1}\right), \frac{1}{2} B \log_2\left(1 + \frac{\gamma_{ST}|h_{ST-SD}|^2}{N_{\text{int}}^1}\right) + \frac{1}{2} B \log_2\left(1 + \frac{\gamma_{SR}|h_{SR-SD}|^2}{N_{\text{int}}^2}\right)\right\} \tag{46}$$

According to the status of PT, the interference signals at SR and SD are respectively expressed as:

$$N_{\text{int}}^{1}=\begin{cases}\gamma_{PT}\left|h_{PT-SR}\right|^{2}+n_{SR} & Hp(i)=H1\\ n_{SR} & Hp(i)=H0\end{cases} \tag{47}$$

$$N_{\text{int}}^{2}=\begin{cases}\gamma_{PT}\left|h_{PT-SD}\right|^{2}+n_{SD} & Hp(i)=H1\\ n_{SD} & Hp(i)=H0\end{cases} \tag{48}$$

The power consumption of SUs are also expressed as P_{cr}^{A} and P_{cr}^{S} depending on whether SUs perform interference cancellation. Then the total energy consumption of receiver is given as:

$$P_{DF}=\left(1+\varepsilon\right)\left(P_{ST}+P_{SR}\right)+P_{cr}+P_{ct} \tag{49}$$

where P_{cr}^{A} =5 dBm, P_{cr}^{S} =0 dBm, and P_{ct} =0 dBm. In low Υ_{PT} regions, the secondary transmission capacity is increased since more available transmit power is allowed in secondary system. As Υ_{PT} increases, the energy efficiency of traditional mechanisms is seriously affected by the interference of PT. However, owning to the improved mechanism, the secondary EE of improved mechanism maintains the stable trend, where SUs power constraint imposed by the secondary system become the dominant factor to affect the secondary outage probability.

6 Conclusion

In this paper, we propose IC-based cooperative scheme for underlay CRNs, where the interference cancellation is utilized at both the secondary relays and the secondary destination. We derive closed-form expressions of outage probability and energy efficiency for both improved scheme and traditional scheme over Rayleigh fading channels. As simulation results show, the secondary system effectively mitigates the interference and improve energy efficiency due to the flexible improved scheme. The proposed IC-based cooperative scheme indeed improves the transmission performance in terms of secondary outage probability and secondary energy efficiency under the strict power constraints. More importantly, considering ON-OFF state of primary transmitter, the improved mechanism can improve the secondary energy efficiency by increasing the capacity of secondary system.

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Appendix.

$$Pout^{S4,1} = \Pr\left\{\frac{z_1+z_2}{z_3+1} < \Delta_S, \frac{z_3}{z_1+1} < \Delta_P, \frac{z_3}{z_2+1} < \Delta_P\right\} \tag{50}$$

$$= \begin{cases} \int_{\Delta P}^{\pi} \left(f_1 - f_2\right) f dz + \int_{0}^{\Delta P} f_3 f dz & \Delta_P \Delta_S < 2 \\ \int_{\Delta P}^{\infty} \left(f_1 - f_2\right) f dz + \int_{0}^{\Delta P} f_3 f dz & \Delta_P \Delta_S \geq 2 \end{cases}$$

where $f_1 = \frac{T\left[\Phi_1(k)\right]}{\gamma_{ST}\sigma_{ST-SD}^2}$, $f_2 = (b_2 - \frac{b_2}{b_1})T\left(c_1\right)$, $f_3 = 1 - b_2 + \frac{T\left[\Phi_2(k)\right]}{\gamma_{ST}\sigma_{ST-SD}^2}$, $b_1 = e^{-\frac{1}{\gamma_{ST}\sigma_{ST-SD}^2}\left(\frac{z_3}{\Delta_P}-1\right)}$, $b_2 = e^{-\frac{\Delta_S(z_3+1)}{\gamma_{ST}\sigma_{ST-SD}^2}}$, $c_1 = e^{-\sum_{i\in S_n(k)}\frac{1}{\gamma_{SR_i}\sigma_{SR_i-SD}^2}\left(\frac{z_3}{\Delta_P}-1\right)}$. Besides, $\Phi_1(k)$ and $\Phi_2(k)$ can be respectively written as:

$$\Phi_1(k) = \begin{cases} \left[\Delta_S\left(z_3+1\right) - 2(\frac{z_3}{\Delta_P} - 1)b_2\right] & \eta_1 = 0 \\ c_2\left(d_2 / d_1 - d_1\right) / \eta_1 & \eta_1 \neq 0 \end{cases} \tag{51}$$

$$\Phi_2(k) = \begin{cases} \Delta_S\left(z_3+1\right)b_2 & \eta_1 = 0 \\ c_2\left(d_2 - 1\right) / \eta_1 & \eta_1 \neq 0 \end{cases} \tag{52}$$

where $\eta_1 = \sum_{i\in S_n(k)} \frac{1}{\gamma_{SR_i}\sigma_{SR_i-SD}^2} - \frac{1}{\gamma_{ST}\sigma_{ST-SD}^2}$, $c_2 = e^{-\sum_{i\in S_n(k)}\frac{\Delta_S(z_3+1)}{\gamma_{SR_i}\sigma_{SR_i-SD}^2}}$,

$d_1 = e^{\eta_1\left(\frac{z_3}{\Delta_P}-1\right)}, d_2 = e^{\eta_1 \Delta_S (z_3+1)}$.

$$Pout^{S4,2} = \Pr\left\{\frac{z_1+z_2}{z_3+1} < \Delta_S, \frac{z_3}{z_1+1} \geq \Delta_P, \frac{z_3}{z_2+1} < \Delta_P\right\} \tag{53}$$

$$= \begin{cases} \int_{\Delta_P}^{\pi_2} (f_4 - f_5) f dz + \int_{\pi_2}^{\pi_3} (f_6 - f_7) f dz & \Delta_P \Delta_S < 1 \\ \int_{\Delta_P}^{\infty} (f_4 - f_5) f dz + \int_{\pi_2}^{\Delta_P} (f_6 - f_7) f dz & \Delta_P \Delta_S \geq 1 \end{cases}$$

$f_4 = \frac{T\left[c_2(e_1-1)/\eta_2\right]}{\gamma_{ST}\sigma^2_{ST-SD}}$ $f_5 = (1-b_1)T(c_1)$, $f_6 = \frac{T\left(c_2(e_2-1)/\eta_2\right)}{\gamma_{ST}\sigma^2_{ST-SD}}$, $f_7 = (1-b_3)T(c_1)$,

$b_3 = e^{-\frac{1}{\gamma_{ST}\sigma^2_{ST-SD}}\left(\Delta_S - \frac{z-\Delta_P}{\Delta_P(1+z)}\right)}$, $\eta_2 = \sum_{i\in S_n(k)} \frac{z+1}{\gamma_{SR_i}\sigma^2_{SR_i-SD}} - \frac{1}{\gamma_{ST}\sigma^2_{ST-SD}}$, $e_1 = e^{\eta_2\left(\frac{z_3}{\Delta_P}-1\right)}$ and

$e_1 = e^{\eta_2\left(\Delta_S - \frac{z_3-\Delta_P}{\Delta_P(z_3+1)}\right)}$.

$$Pout^{S4,3} = \Pr\left\{\frac{z_1+z_2}{z_3+1} < \Delta_S, \frac{z_3}{z_1+1} < \Delta_P, \frac{z_3}{z_2+1} \geq \Delta_P\right\} \tag{54}$$

$$= \begin{cases} \int_{\Delta_P}^{\pi_2} (f_8 + f_9) f dz + \int_{\pi_2}^{\pi_3} f_{10} f dz & \Delta_P \Delta_S < 1 \\ \int_{\Delta_P}^{\pi_2} (f_8 + f_9) f dz + \int_{\pi_2}^{\infty} f_{10} f dz & \Delta_P \Delta_S \geq 1 \end{cases}$$

where $f_8 = b_1 - b_2 + \left(b_1 - \frac{b_5}{b_4}\right)T(c_1)$, $f_9 = \frac{T\left(c_3\left(g_1 - g_1^{(1+\Delta_s)/\Delta_s} / g_2\right)/\eta_3\right)}{\gamma_{ST}\sigma^2_{ST-SD}}$,

$f_{10} = b_1 - b_2 + \frac{T\left[c_3(g_1-g_3)/\eta_3\right]}{\gamma_{ST}\sigma^2_{ST-SD}}$, $b_4 = e^{-\frac{\Delta_S(z_3+1)}{\Delta_p\gamma_{ST}\sigma^2_{ST-SD}}}$, $b_5 = e^{-\frac{(1+\Delta_S)(z_3+1)}{\gamma_{ST}\sigma^2_{ST-SD}}}$,

$c_3 = e^{-\sum_{i\in S_n(k)} \frac{\Delta_S}{\gamma_{SR_i}\sigma^2_{SR_i-SD}}}$, $\eta_3 = \sum_{i\in S_n(k)} \frac{1}{\gamma_{SR_i}\sigma^2_{SR_i-SD}(z+1)} - \frac{1}{\gamma_{ST}\sigma^2_{ST-SD}}$, $g_1 = e^{\eta_1 \Delta_S (z_3+1)}$,

$g_2 = e^{\eta_3\left(\frac{z_3(z_3+1)}{\Delta_P}\right)}$, $g_3 = e^{\eta_3\left(\frac{z}{\Delta_p}-1\right)}$.

$$Pout^{S4,4} = \Pr\left\{ z_1 + z_2 < \Delta_S, \frac{z_3}{z_1+1} < \Delta_P, \frac{z_3}{z_2+1} \geq \Delta_P \right\} \tag{55}$$

$$= \int_{\Delta P}^{\pi 4} f_{11} f dz_3 + \int_{\pi 4}^{\pi 5} \left(f_{12} + f_{13} \right) f dz_3 + \int_{\pi 5}^{\infty} f_{14} f dz_3$$

where $f_{11} = \left(1-b_1\right)\left[1+T\left(c_1\right)\right]$, $f_5 = (1-b_1) + \left(1-\frac{b_6}{b_1}\right)T\left(c_1\right)$, $f_{13} = \frac{T\left[\Phi_3(k)\right]}{\gamma_{ST}\sigma_{ST-SD}^2}$,

$f_{14} = 1 - b_6 + \frac{T\left[\Phi_4(k)\right]}{\gamma_{ST}\sigma_{ST-SD}^2}$ $b_5 = e^{-\frac{\Delta_S}{\gamma_{ST}\sigma_{ST-SD}^2}}$ and $d_3 = \exp(\eta_1 \Delta_S)$.

$$\Phi_1(k) = \begin{cases} b_6\left(2z_3 / \Delta_p - 2 - \Delta_s\right) & \eta_1 = 0 \\ c_3\left(d_1 - d_3 / d_1\right)/\eta_1 & \eta_1 \neq 0 \end{cases} \tag{56}$$

$$\Phi_2(k) = \begin{cases} \Delta_S b_6 & \eta_1 = 0 \\ c_3\left(d_3 - 1\right)/\eta_1 & \eta_1 \neq 0 \end{cases} \tag{57}$$