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Cooperative transmissions for secondary spectrum access in cognitive radios

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SUMMARY

In cognitive radio networks (CRNs), the primary users (PUs) and secondary users (SUs) will interfere with each other, which may severely degrade the performances of both primary and secondary transmissions. In this paper, we propose a *two-phase cognitive transmission* (TCT) protocol for secondary spectrum access in CRNs, aiming at improving the secondary transmission performance while guaranteeing the quality-of-service (QoS) of primary transmissions. In TCT protocol, SUs gain the opportunities to access the licensed spectrum through assisting primary transmissions using superposition coding (SC), where SUs limit their transmit power to satisfy a given primary QoS requirement and also employ interference cancelation technique to mitigate the interference from PUs. Under the constraint of satisfying a required primary outage probability, we derive the closed-form expressions of secondary outage probabilities over Rayleigh fading channels for proposed TCT protocol. Numerical and simulation results reveal that, with a guaranteed primary outage probability, TCT achieves better secondary transmission performance than traditional case. Copyright © 2013 John Wiley & Sons, Ltd.

1 INTRODUCTION

Cognitive radio has been proposed as a promising technology to improve the utilization efficiency of radio spectrum, which allows the secondary users (SUs) to access the licensed spectrum bands without causing harmful interference to the primary users (PUs) 1-8. Generally, SUs need to perform spectrum sensing first and then properly adjust their data transmissions on the basis of the detection results to avoid affecting the operations of PUs in cognitive radio networks (CRNs) 9, 10. Thus, great research interest has grown in different models for spectrum sharing.

Related work

Generally, spectrum sharing paradigms investigated in the literature fall into three categories: the interweave 11-16, underlay 17, 18, and overlay 19, 20 models. Specifically, the interweave model allows SUs to use the licensed spectrum when the PU is considered absent. In 11, the author proposed a two-phase interweave protocol with best-relay selection for CRNs. In 12, 14, reliable spectrum sensing schemes were studied for interweave models, where Javed *et al*. 12 identified the spectrum holes by using the time frequency analysis and digital image processing techniques, whereas Sahai *et al*. 14 reduced the uncertainty about the interference from other opportunistic spectrum users in spectrum sensing via the cooperation among nearby cognitive radios. However, these interweave models are highly sensitive to the detection errors and PU traffic patterns 4, 11.

Unlike in interweave, the SUs in underlay model can directly use the licensed spectrum without considering the states of PUs as long as the induced interference to PUs is kept below a given level. The authors in 17 proposed an adaptive underlay scheme to improve the secondary performance while guaranteeing the quality-of-service (QoS) of primary transmissions. Then, in 18, we proposed a cognitive best-relay communication protocol to ensure the continuity of secondary transmissions for underlay models. As is well known, a major problem of underlay is that SUs may suffer from bad transmission performance due to the strict power constraints imposed on SUs and the interference from PUs 21.

To overcome the shortcoming of underlay, the overlay approach has thus been introduced, where SUs act as relays of PUs to assist primary transmissions in exchange for secondary spectrum access 22. In 19, PUs leased half of each time slot to SUs for overlay transmissions. Motivated by Han *et al*. 19, the authors of 20 investigated a two-way relaying protocol to achieve overlay spectrum sharing without degrading the primary transmission performance. In overlay model, SUs usually have to spare a certain portion of each time slot to only receive the primary signals without sending the secondary signals although they do not need to reduce the transmit power 19-22, which is actually inefficient for secondary spectrum access. In addition, the overlay model may still experience a degradation in secondary transmission performance because of the mutual interference between PUs and SUs.

Our main contributions

To enhance the secondary performance of overlay model, we propose a *two-phase cognitive transmission* (TCT) protocol for CRNs in this paper, where SUs get the chance to use the licensed spectrum through limiting their transmit power to ensure the PU QoS and assisting primary transmissions. The main contributions of this paper can be summarized as follows:

1. The proposed TCT protocol allows SUs to transmit secondary signals in the whole duration of each time slot, which greatly improves the spectrum utilization in secondary systems as compared with traditional overlay cases 19-22 where PUs only lease part of each time slot for secondary transmissions.
2. We naturally integrate superposition coding (SC), interference cancelation (IC), and power control techniques in proposed TCT protocol to improve the secondary transmission performance in overlay CRNs while guaranteeing the PU QoS.
3. Under the constraint of satisfying a given primary outage probability requirement, we derive the closed-form expressions of secondary outage probabilities over Rayleigh fading channels for proposed TCT protocol.

In fact, the proposed TCT protocol is a mixture of underlay and overlay models as it needs to not only limit the SU transmit power according to the PU QoS requirement but also know the radio protocols of PUs for assisting primary transmissions. Simulation results show that the TCT protocol outperforms the traditional overlay case 19, which suggests that it deserves to jointly design underlay and overlay spectrum sharing models for better secondary transmission performance in CRNs.

The remainder of this paper is organized as follows. In Section 2, we describe the system model and details of proposed TCT protocol. Then, in Section 3, we derive the closed-form expressions of secondary outage probabilities over Rayleigh fading channels with a guaranteed primary outage probability for proposed TCT protocol. Finally, numerical and simulation results are provided in Section 4 followed by conclusions in Section 5.

2 SYSTEM MODEL AND PROTOCOL DESCRIPTIONS

As shown in Figure 1, the considered CRN of proposed TCT protocol consists of a primary transmitter–receiver pair $P – P_0$ and two SUs $\{U,V\}$, where U and V are allowed to communicate with each other over the licensed spectrum without affecting the operations of PUs. We assume that $I(I \in \{P,U,V\})$ transmits the signal $x_I(E\{\mid x_I \mid^2\} = 1)$ to $J(J \in \{P_0,U,V\}, J \neq I)$ with the power E_I and data rate R_I. We further assume that the additive white Gaussian noise at $J(J \in \{P_0,U,V\})$ is denoted by n_J, which is with zero mean and power spectrum density N_0. Besides, we suppose that the transmit signal-to-noise ratio (SNR) of I is denoted by γ_I, that is, $\gamma_I = E_I / N_0$.

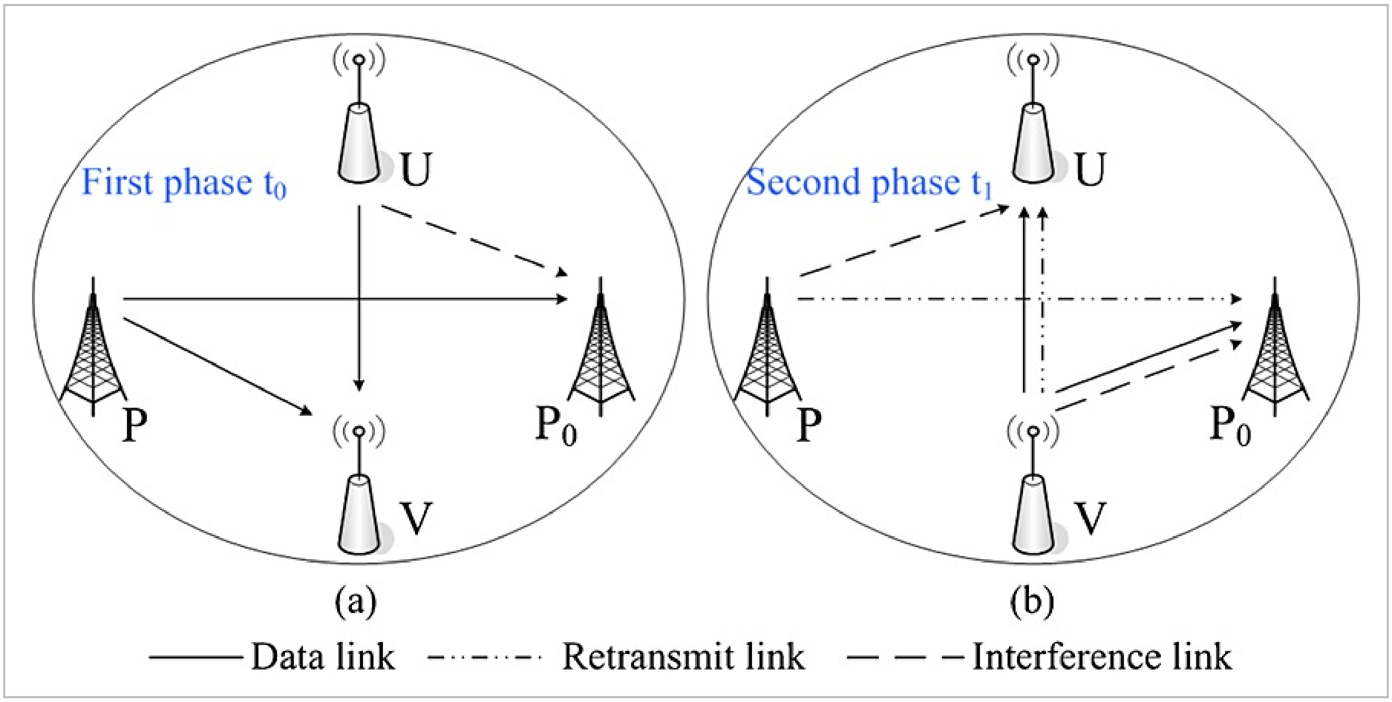

Figure 1

Open in figure viewer | PowerPoint

System model: (a) transmission process of proposed TCT protocol in the first phase t_0. (b) Transmission process of proposed TCT protocol in the second phase t_1.

In this paper, the channels are modeled as independent Rayleigh flat fading 23, where we let h_{IJ} ($I \neq J$) denote the fading coefficient of the channel from I to J. Note that $|h_{IJ}|^2$ obeys an exponential distribution with the parameter $1/\sigma_{I,J}^2$, where $\sigma_{I,J}^2$ denotes the fading variance of the channel from I to J. Furthermore, we assume that SUs can follow the radio protocols of PUs 19-22, and the receivers use maximum ratio combining (MRC) to combine their received signals. Throughout this paper, slotted transmissions are adopted wherein each time slot is divided into two phases denoted as t_0 and t_1, respectively 17-20. The transmission process of proposed TCT protocol is described as follows:

- In the first phase t_0, P broadcasts x_P to P_0 and V. Meanwhile, U sends x_U to V, where U will cause interference to P_0, and thus its transmit power E_U should be reduced to ensure the PU QoS. Then V employs an IC-based decoding method to retrieve x_P and x_U, respectively. Taking the decoding of x_P for example, V first attempts to decode x_P by using its originally received signal in t_0. When V fails to decode x_P directly, it will attempt to decode x_U. In this case, if V successfully decodes x_U, it will cancel out x_U from its originally received signal and then use the interference canceled signal to decode x_P again. Note that the decoding of x_U follows the similar process as the decoding of x_P. Finally, V applies SC to combine the primary signal x_P with the power $\alpha E_V (0 \leqslant \alpha \leqslant 1)$ and its own signal x_V with the power $\beta E_V (\beta = 1 - \alpha)$, where the fraction β should be limited to guarantee the PU QoS.

- In the second phase t_1, V will broadcast its SC-encoded signal to P_0 and U if it successfully decodes x_P in t_0. Otherwise, if V fails to decode x_P in t_0, it will only transmit its own signal x_V to U in t_1 and, at the same time, P will retransmit x_P to P_0. To mitigate the interference from P, the similar IC-based decoding method as used at V in t_0 is employed at U to recover x_V in t_1.

It is noted that, as shown in 19, traditional overlay protocol does not allow SUs to transmit their signals in t_0, where SUs can achieve secondary spectrum access only when they help the PU to relay the primary signal in t_1. On the other hand, the IC and power control techniques are not jointly considered in the traditional protocol. Moreover, there does not exist a retransmission process during t_1 in the traditional case when the SU, which serves as a relay of PUs, fails to decode the primary signal during t_0. Clearly, by using the SC, IC, and power control techniques, SUs can transmit their signals during both t_0 and t_1 while ensuring the PU QoS in proposed TCT protocol, which means that TCT can achieve higher spectrum utilization than traditional overlay cases where SUs are allowed to transmit their own signals only in part of each time slot as indicated in 19-22.

3 PERFORMANCE ANALYSIS OF PROPOSED TCT PROTOCOL

Outage probability

As mentioned in Section 2, during t_0, P broadcasts x_P to P_0 and V while U sends x_U to V. Thus, the signals received at P_0 and V in t_0 are respectively written as

$$y_{P_0} = \sqrt{E_P} h_{PP_0} x_P + \sqrt{E_U} h_{UP_0} x_U + n_{P_0} \tag{1}$$

$$y_V = \sqrt{E_P} h_{PV} x_P + \sqrt{E_U} h_{UV} x_U + n_V \tag{2}$$

From 2, the achievable data rates of the links from P to V and from U to V can be respectively obtained as

$$C_{PV} = \frac{1}{2}\log_2\left(1 + \frac{\gamma_P |h_{PV}|^2}{\gamma_U |h_{UV}|^2 + 1}\right) \tag{3}$$

$$C_{UV} = \frac{1}{2}\log_2\left(1 + \frac{\gamma_U |h_{UV}|^2}{\gamma_P |h_{PV}|^2 + 1}\right) \tag{4}$$

Then the IC-based decoding method as given in Section 2 is employed at V to recover x_P and x_U from $y_{V,0}$ in 2, respectively. More specifically, taking the decoding of x_P for example, V first attempts to decode x_P using $y_{V,0}$. If x_P cannot be directly decoded from $y_{V,0}$, V will use $y_{V,0}$ to decode x_U and then cancel out the interference component $\sqrt{E_U} h_{UV} x_U$ from $y_{V,0}$ if the decoding is successful, where the interference canceled signal is expressed as

$$y'_{V,0} = \sqrt{E_P} h_{PV} x_P + n_V \tag{5}$$

Finally, V uses $y'_{V,0}$ to decode x_P. In this case, from 5, the achievable data rate of the link from P to V after successful IC is calculated as

$$C'_{PV} = \frac{1}{2}\log_2\left(1 + \gamma_P |h_{PV}|^2\right) \tag{6}$$

Thus, the probability of successful decoding of x_P at V in t_0 is given by

$$\begin{aligned} P_{V,P} &= \Pr\{C_{PV} \geqslant R_P\} + \Pr\{C_{PV} < R_P, C_{UV} \geqslant R_U, C'_{PV} \geqslant R_P\} \\ &= \begin{cases} A_0 + A_1 + A_2 - A_3, 0 < \Delta_P \Delta_U < 1 \\ A_0 + A_1, \Delta_P \Delta_U \geqslant 1 \end{cases} \end{aligned} \tag{7}$$

In 7, A_0, A_1, A_2, and A_3 are respectively expressed as

$$A_0 = \frac{\gamma_P \sigma_{PV}^2}{\gamma_P \sigma_{PV}^2 + \Delta_P \gamma_U \sigma_{UV}^2} \exp\left(-\frac{\Delta_P}{\gamma_P \sigma_{PV}^2}\right) \tag{8}$$

$$A_1 = \frac{\gamma_U \sigma_{UV}^2}{\gamma_U \sigma_{UV}^2 + \Delta_U \gamma_P \sigma_{PV}^2} \exp\left(-\frac{\Delta_U}{\gamma_U \sigma_{UV}^2} - \frac{\Delta_P}{\gamma_P \sigma_{PV}^2} - \frac{\Delta_P \Delta_U}{\gamma_U \sigma_{UV}^2}\right) \tag{9}$$

$$A_2 = \frac{\Delta_P \gamma_U \sigma_{UV}^2}{\Delta_P \gamma_U \sigma_{UV}^2 + \gamma_P \sigma_{PV}^2} \exp\left(\frac{1}{\gamma_U \sigma_{UV}^2} - \frac{b}{\gamma_P \sigma_{PV}^2} - \frac{b}{\Delta_P \gamma_U \sigma_{UV}^2}\right) \tag{10}$$

$$A_3 = \frac{\gamma_U \sigma_{UV}^2}{\gamma_U \sigma_{UV}^2 + \Delta_U \gamma_P \sigma_{PV}^2} \exp\left(-\frac{\Delta_U}{\gamma_U \sigma_{UV}^2} - \frac{b}{\gamma_P \sigma_{PV}^2} - \frac{\Delta_U b}{\gamma_U \sigma_{UV}^2}\right) \tag{11}$$

where $\Delta_U = 2^{2R_U}$ and $b = \frac{\Delta_P(1+\Delta_U)}{1-\Delta_P \Delta_U}$.

On the other hand, following the similar IC-based decoding process, the achievable data rate of the link from U to V after successful IC is obtained from 2 as

$$C'_{UV} = \frac{1}{2}\log_2\left(1 + \gamma_U |h_{UV}|^2\right) \tag{12}$$

Therefore, the probability of successful decoding of x_U at V in t_0 can be derived as

$$P_{V,U} = \Pr\{C_{UV} \geqslant R_U\} + \Pr\{C_{UV} < R_U, C_{PV} \geqslant R_P, C'_{UV} \geqslant R_U\}$$
$$= \begin{cases} B_0 + B_1 + B_2 - B_3, 0 < \Delta_P \Delta_U < 1 \\ B_0 + B_1, \Delta_P \Delta_U \geqslant 1 \end{cases} \tag{13}$$

Here, B_0, B_1, B_2, and B_3 in 13 are respectively given as

$$B_0 = \frac{\gamma_U \sigma_{UV}^2}{\gamma_U \sigma_{UV}^2 + \Delta_U \gamma_P \sigma_{PV}^2} \exp\left(-\frac{\Delta_U}{\gamma_U \sigma_{UV}^2}\right) \tag{14}$$

$$B_1 = \frac{\gamma_P \sigma_{PV}^2}{\gamma_P \sigma_{PV}^2 + \Delta_P \gamma_U \sigma_{UV}^2} \exp\left(-\frac{\Delta_P}{\gamma_P \sigma_{PV}^2} - \frac{\Delta_U}{\gamma_U \sigma_{UV}^2} - \frac{\Delta_P \Delta_U}{\gamma_P \sigma_{PV}^2}\right) \tag{15}$$

$$B_2 = \frac{\Delta_U \gamma_P \sigma_{PV}^2}{\Delta_U \gamma_P \sigma_{PV}^2 + \gamma_U \sigma_{UV}^2} \exp\left(\frac{1}{\gamma_P \sigma_{PV}^2} - \frac{c}{\gamma_U \sigma_{UV}^2} - \frac{c}{\Delta_U \gamma_P \sigma_{PV}^2}\right) \tag{16}$$

$$B_3 = \frac{\gamma_P \sigma_{PV}^2}{\gamma_P \sigma_{PV}^2 + \Delta_P \gamma_U \sigma_{UV}^2} \exp\left(-\frac{\Delta_P}{\gamma_P \sigma_{PV}^2} - \frac{c}{\gamma_U \sigma_{UV}^2} - \frac{\Delta_P c}{\gamma_P \sigma_{PV}^2}\right) \tag{17}$$

where $c = \frac{\Delta_U(1+\Delta_P)}{1-\Delta_P \Delta_U}$.

Thus, from 13, the secondary outage probability of the link from U to V is

$$Pout_{UV} = 1 - P_{V,U} \tag{18}$$

From Section 2, we know that there exist two possible cases for the data transmissions in t_1 depending on whether V can successfully decode the primary signal x_P in t_0 or not, which are respectively described as follows.

- **Case 1** (V successfully decodes x_P in t_0): As shown in Section 2, V uses SC to combine the primary signal x_P with its own signal x_V and then broadcasts the SC-encoded signal $\sqrt{\alpha E_V} x_P + \sqrt{\beta E_V} x_V$ to P_0 and U in t_1. Thus, the signals received at P_0 and U during t_1 in this case can be respectively written as

$$y_{P_0,0} = \left(\sqrt{\alpha E_V} x_P + \sqrt{\beta E_V} x_V\right) h_{VP_0} + n_{P_0} \tag{19}$$

$$y_{U,0} = \left(\sqrt{\alpha E_V} x_P + \sqrt{\beta E_V} x_V\right) h_{VU} + n_U \tag{20}$$

  Using MRC to combine the received signals in 1 and 19 at P_0, the achievable data rate of the link from P to P_0 is given by

$$C_{PP_0,0} = \frac{1}{2}\log_2\left(1 + \frac{\gamma_P |h_{PP_0}|^2}{\gamma_U |h_{UP_0}|^2 + 1} + \frac{\alpha \gamma_V |h_{VP_0}|^2}{\beta \gamma_V |h_{VP_0}|^2 + 1}\right) \tag{21}$$

Hence, the primary outage probability in this case is derived as

$$Pout_{PP_0,0} = \Pr\{C_{PP_0,0} < R_P\} = \begin{cases} 1-\varphi(\infty), 0<\alpha<\frac{\Delta_P}{1+\Delta_P} \\ 1-\exp\left(-\frac{d}{\gamma_V\sigma_{VP_0}^2}\right)-\varphi(d), \frac{\Delta_P}{1+\Delta_P}\leqslant\alpha<1 \end{cases} \tag{22}$$

where $d=\frac{\Delta_P}{\alpha-\beta\Delta_P}$ and

$$\varphi(t) = \int_0^t \frac{\gamma_P\sigma_{PP_0}^2}{\gamma_V\sigma_{VP_0}^2\left(\gamma_P\sigma_{PP_0}^2+\gamma_U\sigma_{UP_0}^2\left(\Delta_P-\frac{\alpha x}{\beta x+1}\right)\right)} \exp\left(-\frac{\Delta_P-\frac{\alpha x}{\beta x+1}}{\gamma_P\sigma_{PP_0}^2}-\frac{x}{\gamma_V\sigma_{VP_0}^2}\right)\mathrm{d}x \tag{23}$$

On the other hand, at *U*, a similar IC-based decoding method as used at *V* is employed to reduce the interference from *P* in t_1. Then the secondary achievable data rates of the link from *V* to *U* before IC and after successful IC in this case are respectively given as

$$C_{VU,0} = \frac{1}{2}\log_2\left(1+\frac{\beta\gamma_V|h_{VU}|^2}{\alpha\gamma_V|h_{VU}|^2+1}\right) \tag{24}$$

$$C'_{VU,0} = \frac{1}{2}\log_2\left(1+\beta\gamma_V|h_{VU}|^2\right) \tag{25}$$

Besides, the primary achievable data rate of the link from *V* to *U* is

$$C_{PU,0} = \frac{1}{2}\log_2\left(1+\frac{\alpha\gamma_V|h_{VU}|^2}{\beta\gamma_V|h_{VU}|^2+1}\right) \tag{26}$$

Thus, the secondary outage probability of the link from *V* to *U* in this case is written as

$$Pout_{VU,0} = \Pr\{C_{VU,0}<R_V\} - \Pr\{C_{VU,0}<R_V, C_{PU,0}\geqslant R_P, C'_{VU,0}\geqslant R_V\} \tag{27}$$

The two terms at the right-hand side of 27 can be respectively calculated as

$$\Pr\{C_{VU,0}<R_V\} = \begin{cases} 1, e_0\leqslant 0 \\ 1-\exp\left(-\frac{1}{e_0\gamma_V\sigma_{VU}^2}\right), e_0>0 \end{cases} \tag{28}$$

$$\Pr\{C_{VU,0} < R_V, C_{PU,0} \geqslant R_P, C'_{VU,0} \geqslant R_V\}$$
$$= \begin{cases} 0, e_1 \leqslant 0 \\ \exp\left(-\frac{1}{e_2\gamma_V\sigma_{VU}^2}\right), e_1 > 0, e_0 \leqslant 0, e_1 \geqslant e_2 \\ \exp\left(-\frac{1}{e_1\gamma_V\sigma_{VU}^2}\right), e_1 > 0, e_0 \leqslant 0, e_1 < e_2 \\ \exp\left(-\frac{1}{e_2\gamma_V\sigma_{VU}^2}\right) - \exp\left(-\frac{1}{e_0\gamma_V\sigma_{VU}^2}\right), e_1 > 0, e_0 > 0, e_1 \geqslant e_2 \\ \exp\left(-\frac{1}{e_1\gamma_V\sigma_{VU}^2}\right) - \exp\left(-\frac{1}{e_0\gamma_V\sigma_{VU}^2}\right), e_1 > 0, e_0 > 0, e_0 < e_1 < e_2 \end{cases} \tag{29}$$

where $e_0 = \beta / \Delta_V - \alpha$, $e_1 = \alpha / \Delta_P - \beta$ and $e_2 = \beta / \Delta_V$.

- **Case 2** (V fails to decode x_P in t_0): V only sends its own signal x_V to U with all its available power in t_1. Meanwhile, P retransmits x_P to P_0. Therefore, the received signals at P_0 and U during t_1 in this case are respectively expressed as

$$y_{P_0,1} = \sqrt{E_P}h_{PP_0}x_P + \sqrt{E_V}h_{VP_0}x_V + n_{P_0} \tag{30}$$

$$y_{U,1} = \sqrt{E_V}h_{VU}x_V + \sqrt{E_P}h_{PU}x_P + n_U \tag{31}$$

Then, by combining 1 and 30 using MRC at P_0, the achievable data rate of the link from P to P_0 is given as

$$C_{PP_0,1} = \frac{1}{2}\log\left(1 + \frac{\gamma_P|h_{PP_0}|^2}{\gamma_U|h_{UP_0}|^2 + 1} + \frac{\gamma_P|h_{PP_0}|^2}{\gamma_V|h_{VP_0}|^2 + 1}\right) \tag{32}$$

Therefore, the primary outage probability in this case can be derived as

$$\begin{aligned} & Pout_{PP_0,1} \\ & = \Pr\{C_{PP_0,1} < R_P\} \\ & = 1 - \iint\limits_{x>0,y>0} \frac{1}{\gamma_V\gamma_U\sigma_{VP_0}^2\sigma_{UP_0}^2}\exp\left(-\frac{\Delta_P}{\gamma_P\sigma_{PP_0}^2\left(\frac{1}{x+1} + \frac{1}{y+1}\right)} - \frac{x}{\gamma_V\sigma_{VP_0}^2} - \frac{y}{\gamma_U\sigma_{UP_0}^2}\right)\mathrm{d}x\mathrm{d}y \end{aligned} \tag{33}$$

Similarly, from 31, the secondary achievable data rates of the link from V to U before IC and after successful IC, and the primary achievable data rate of the link from V to U are respectively written as

$$C_{VU,1} = \frac{1}{2}\log_2\left(1 + \frac{\gamma_V|h_{VU}|^2}{\gamma_P|h_{PU}|^2 + 1}\right) \tag{34}$$

$$C'_{VU,1} = \frac{1}{2}\log_2\left(1 + \gamma_V |h_{VU}|^2\right) \tag{35}$$

$$C_{PU,1} = \frac{1}{2}\log_2\left(1 + \frac{\gamma_P |h_{PU}|^2}{\gamma_V |h_{VU}|^2 + 1}\right) \tag{36}$$

As a consequence, the secondary outage probability of the link from *V* to *U* in this case is given as

$$\begin{aligned} Pout_{VU,1} &= \Pr\{C_{VU,1} < R_V\} - \Pr\{C_{VU,1} < R_V, C_{PU,1} \geqslant R_P, C'_{VU,1} \geqslant R_V\} \\ &= \begin{cases} D_0 - D_1 + D_2 - D_3, \Delta_P \Delta_V < 1 \\ D_0 - D_1, \Delta_P \Delta_V \geqslant 1 \end{cases} \end{aligned} \tag{37}$$

where D_0, D_1, D_2, andD_3 are respectively expressed as

$$D_0 = 1 - \frac{\gamma_V \sigma^2_{VU}}{\gamma_V \sigma^2_{VU} + \Delta_V \gamma_P \sigma^2_{PU}} \exp\left(-\frac{\Delta_V}{\gamma_V \sigma^2_{VU}}\right) \tag{38}$$

$$D_1 = \frac{\gamma_P \sigma^2_{PU}}{\gamma_P \sigma^2_{PU} + \Delta_P \gamma_V \sigma^2_{VU}} \exp\left(-\frac{\Delta_P}{\gamma_P \sigma^2_{PU}} - \frac{\Delta_V}{\gamma_V \sigma^2_{VU}} - \frac{\Delta_P \Delta_V}{\gamma_P \sigma^2_{PU}}\right) \tag{39}$$

$$D_2 = \frac{\gamma_P \sigma^2_{PU}}{\gamma_P \sigma^2_{PU} + \Delta_P \gamma_V \sigma^2_{VU}} \exp\left(-\frac{\Delta_P}{\gamma_P \sigma^2_{PU}} - \frac{d}{\gamma_V \sigma^2_{VU}} - \frac{\Delta_P d}{\gamma_P \sigma^2_{PU}}\right) \tag{40}$$

$$D_3 = \frac{\Delta_V \gamma_P \sigma^2_{PU}}{\Delta_V \gamma_P \sigma^2_{PU} + \gamma_V \sigma^2_{VU}} \exp\left(\frac{1}{\gamma_P \sigma^2_{PU}} - \frac{d}{\gamma_V \sigma^2_{VU}} - \frac{d}{\Delta_V \gamma_P \sigma^2_{PU}}\right) \tag{41}$$

Here, $d = \frac{\Delta_V(1+\Delta_P)}{1-\Delta_P\Delta_V}$. Following the total probability law, the primary outage probability can be calculated from 22 and 33 as

$$Pout_{PP_0} = P_{V,P} Pout_{PP_0,0} + (1 - P_{V,P}) Pout_{PP_0,1} \tag{42}$$

In a similar way, from 27 and 37, we can obtain the secondary outage probability of the link from *V* to *U* as

$$Pout_{VU} = P_{V,P} Pout_{VU,0} + (1 - P_{V,P}) Pout_{VU,1} \tag{43}$$

Power control

In TCT protocol, the secondary transmissions between *U* and *V* will cause interference to primary transmissions. Hence, the transmit power of *U* and the power allocated to x_V at *V* should be limited to satisfy a given PU QoS requirement, where we assume that the PU QoS is quantified by primary outage probability performance, that is, the primary outage probability should be kept below a predefined threshold $T_0$17, 18. Besides, we employ a static power control method for SUs in this paper, where an SU uses the maximum allowable power to transmit its signals 17, 24. Then the static power control problems of SUs for proposed TCT protocol can be formulated as

$$\begin{cases} \max E_U \\ \text{s.t. } Pout_{PP_0} \leqslant T_0 \\ \quad E_U \geqslant 0 \end{cases} \tag{44}$$

$$\begin{cases} \max \beta \\ \text{s.t. } Pout_{PP_0} \leqslant T_0 \\ \quad 0 \leqslant \beta \leqslant 1 \end{cases} \tag{45}$$

Optimization problem 44 is used to maximize the allowable transmit power of U for TCT protocol under the constraint of satisfying a required primary outage probability T_0 when β is given. On the other hand, for a given E_U, the transmit power of V assigned to x_V in TCT protocol can be maximized by 45 while ensuring the PU QoS. The solutions for the optimization problems 44 and 45 are respectively given in Theorem 1.

Theorem 1. We first define the functions $\phi_1(E_U) \triangleq Pout_{PP_0}(E_U)$ and $\phi_2(\beta) \triangleq Pout_{PP_0}(\beta)$ for notation simplicity. Then the solutions of 44 and 45 are respectively given as

$$E_U = \begin{cases} 0, \phi_1(0) > T_0 \\ \phi_1^{-1}(T_0), \phi_1(0) \leqslant T_0 \end{cases} \tag{46}$$

$$\beta = \begin{cases} 0, \phi_2(0) > T_0 \\ 1, \phi_2(1) < T_0 \\ \phi_2^{-1}(T_0), \phi_2(0) \leqslant T_0 \&\& \phi_2(1) \geqslant T_0 \end{cases} \tag{47}$$

where ϕ_1^{-1} and ϕ_2^{-1} are the inverse functions of ϕ_1 and ϕ_2, respectively.

Proof. Clearly, for a given β, the primary outage probability $Pout_{PP_0}$ increases with E_U increasing, which is because more interference is induced to primary transmissions as E_U increases. On the other hand, for a given E_U, $Pout_{PP_0}$ will increase as β is improved due to a reduction of the transmit power assigned to x_P at V in this case. Figure 2 depicts the primary outage probability versus E_U and β for proposed TCT protocol. One can easily observe from Figure 2 that the primary outage probability increases with E_U and β increasing. Thus, both the theoretical analysis and the simulation results show that ϕ_1 and ϕ_2 are the monotonically increasing functions of E_U and β, respectively.

As ϕ_1 is a monotonically increasing function of E_U, $\phi_1(E_U) > T_0$ holds for $E_U \geqslant 0$ if $\phi_1(0) > T_0$. In this case, the secondary transmission from U to V is not allowed so as to protect the primary transmissions as much as possible; thus E_U should be chosen as $E_U = 0$. Otherwise, if $\phi_1(0) \leqslant T_0$, we can derive E_U from 44 as $E_U = \phi_1^{-1}(T_0)$. Thus, 46 is proved.

Besides, as ϕ_2 is a monotonically increasing function of β, we have $\phi_2(\beta) > T_0$ for $0 \leqslant \beta \leqslant 1$ if $\phi_2(0) > T_0$. In this case, to protect the primary operations as much as possible, all the available transmit power of V should be allocated to the primary signal x_P and thus β is set to 0. Clearly, if $\phi_2(1) < T_0$, $\phi_2(\beta) < T_0$ holds for $0 \leqslant \beta \leqslant 1$. In this case, to optimize the secondary transmission performance, β is chosen as 1, that is, all V's available transmit power is allocated to the secondary signal x_V. Finally, if $\phi_2(0) \leqslant T_0$ and $\phi_2(1) \geqslant T_0$, we can obtain β from 45 as $\beta = \phi_2^{-1}(T_0)$ as ϕ_2 is a monotonically increasing function of β. Thus, 47 is proved.□

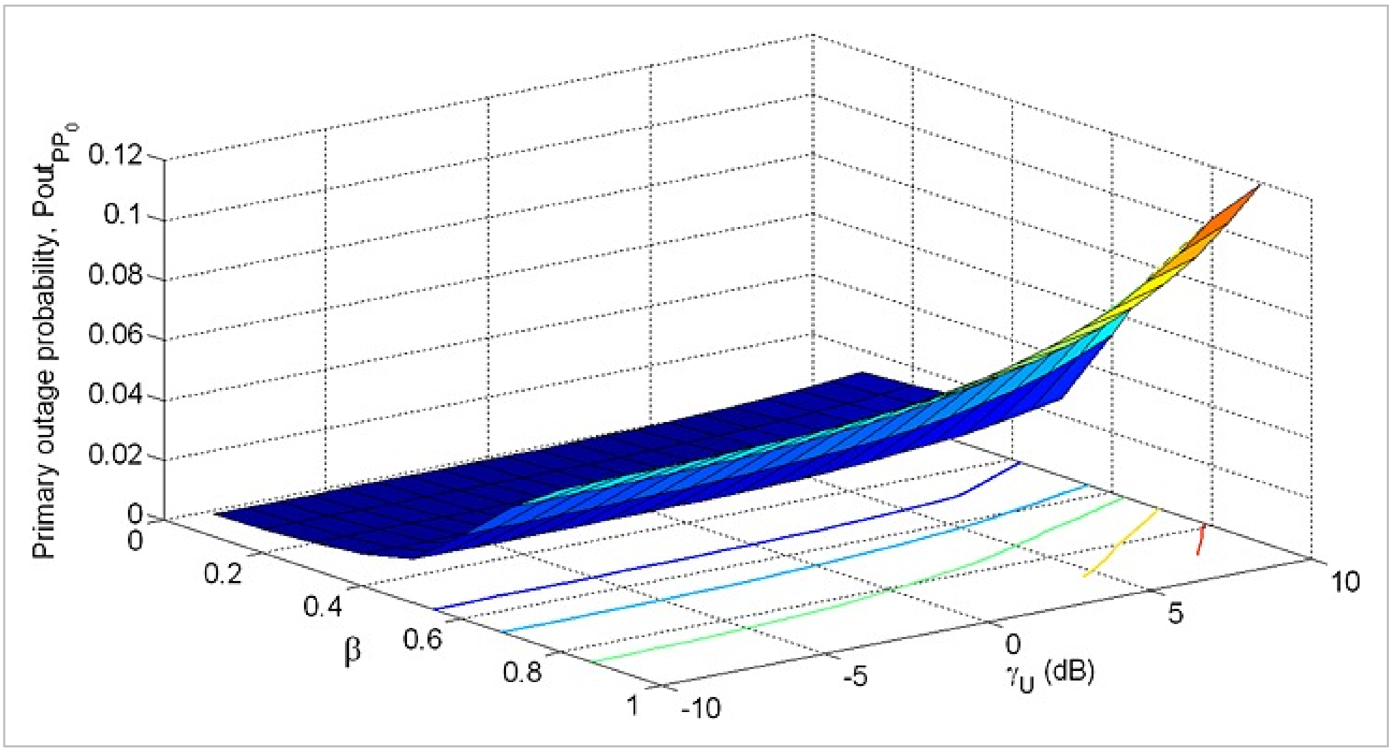

Figure 2

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Primary outage probability versus γ_U and β for TCT protocol with the primary data rate $R_P = 0.4$ bits/s/Hz, secondary data rates $R_U = R_V = 0.1$ bits/s/Hz, P's transmit SNR $\gamma_P = 10$ dB, V's transmit SNR $\gamma_V = 10$ dB, the channel variances $\sigma^2_{PP_0} = \sigma^2_{PU} = \sigma^2_{PV} = 1, \sigma^2_{VU} = \sigma^2_{VP_0} = 1, \sigma^2_{UV} = 1$, and $\sigma^2_{UP_0} = 0.1$.

It is noted that, to satisfy a given PU QoS requirement, we should set E_U and β according to Theorem 1 for TCT protocol. From the preceding discussions, we can expect that, under the constraint of ensuring the PU QoS, TCT can achieve better secondary transmission performance than the traditional overlay case as shown in 19, which will be further validated by the simulation results obtained in Section 4.

4 SIMULATION RESULTS AND DISCUSSIONS

In this section, we will evaluate the performance of proposed TCT protocol by some numerical and simulation results, and then also compare it with the traditional overlay case as presented in 19 under the constraint of satisfying a given PU QoS requirement T_0. The main simulation parameters used in the TCT and traditional overlay protocols are listed as follows:

1. The primary data rate of P is $R_P = 0.4$ bits/s/Hz.
2. The secondary data rates of U and V are set to $R_U = R_V = 0.1$ bits/s/Hz.
3. The transmit SNR of V is $\gamma_V = 10$ dB.
4. The channel variances are $\sigma^2_{PP_0} = \sigma^2_{PV} = 1$, $\sigma^2_{VU} = \sigma^2_{VP_0} = 1$, $\sigma^2_{UV} = 1$, and $\sigma^2_{PU} = \sigma^2_{UP_0} = 0.1$.

It is noted that we let the lines represent the theoretical results derived in this paper, and the discrete marks denote the Monte Carlo simulation results, where 100,000 Monte Carlo simulations are performed using MATLAB.

First, we plot the secondary outage probability $Pout_{VU}$ of the link from V to U versus P's transmit SNR γ_P for the proposed TCT and traditional protocols under different settings in Figure 3, where β is limited according to Theorem 1 to satisfy a required primary outage probability T_0. Figure 3 shows that TCT significantly reduces the secondary outage probability of link from V to U as compared with traditional case 19 when limiting β to guarantee the PU QoS, which accounts for the fact that both the IC and power control techniques are employed in TCT. This also validates the advantages of proposed TCT protocol, which jointly considers the underlay and overlay approaches for secondary spectrum access.

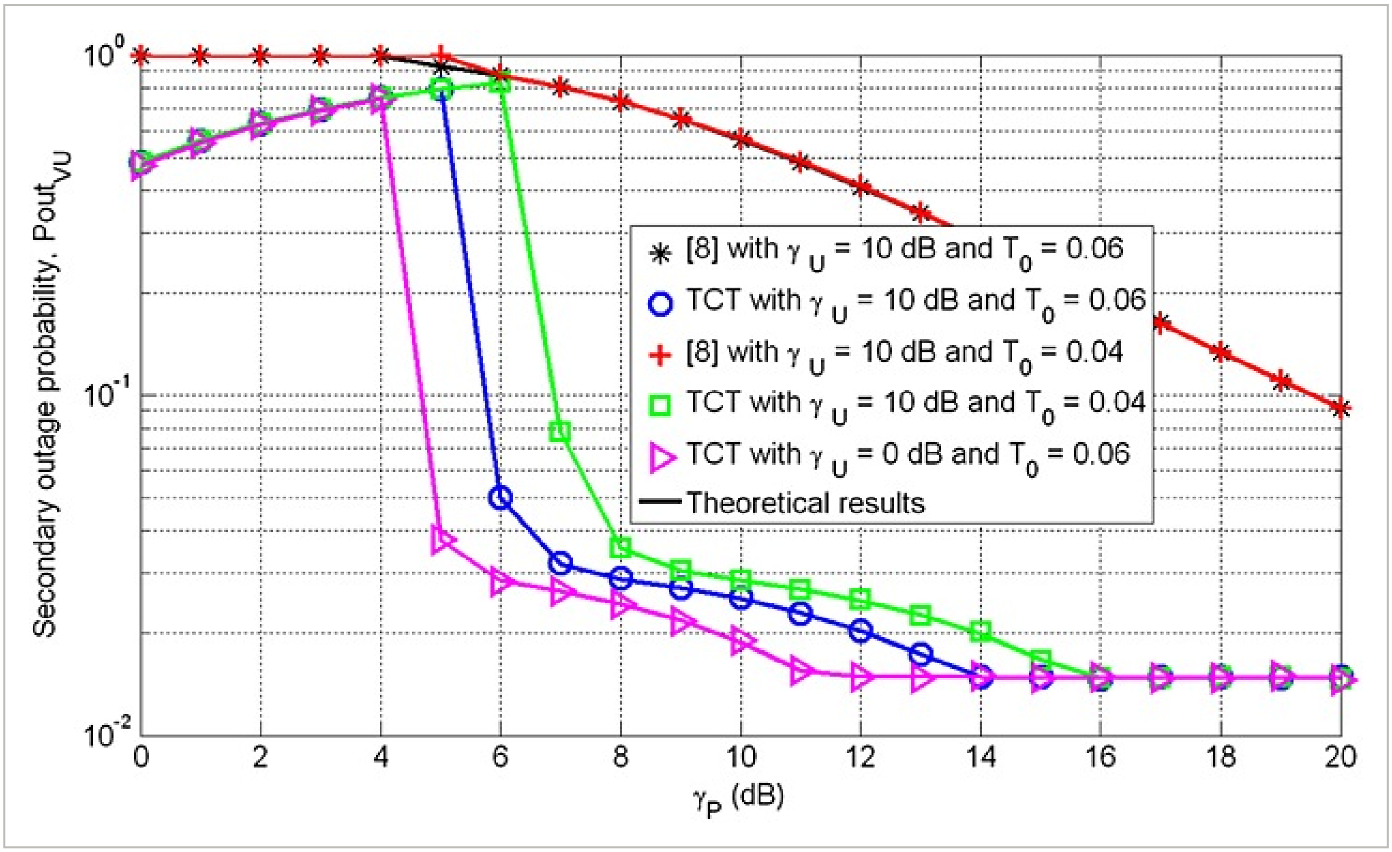

Figure 3

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Secondary outage probability of the link from *V* to *U* versus γ_P for the TCT and traditional protocols with limited β.

Note that there is a cutoff point of γ_P for each curve in Figure 3. Specifically, in traditional protocol, $Pout_{VU}$ is equal to 1 if γ_P is smaller than the cutoff value, which is because β is set to 0, that is, *V* is not allowed to transmit its own signal x_V, to ensure the PU QoS as much as possible in this case. From the Case 2 of Section 3.1, we know that *V* will use all the available power E_V to transmit x_V during t_1 when *V* fails to decode the primary signal x_P during t_0 in TCT protocol, which implies that TCT still can achieve secondary spectrum access for *V* even under $\beta = 0$ because of the Case 2 in Section 3.1. Hence, when γ_P is smaller than the cutoff value, $Pout_{VU}$ in TCT protocol is lower than 1, and it will increase with γ_P growing due to an increase of induced interference from *P* to SUs. It also can be seen from Figure 3 that when γ_P is above its cutoff value, $Pout_{VU}$ will decrease as γ_P rises as *V* can assign more power to its own signal in this context according to Theorem 1. Besides, the cutoff value is reduced as the primary outage probability requirement loosens and at the same time the secondary outage probability performance is also improved, because more power is allowed for *V* to transmit its own signal in this case.

On the other hand, $Pout_{VU}$ is lower when $\gamma_U = 0$ dB than $\gamma_U = 10$ dB in TCT protocol. This accounts for that when γ_U is small, U will cause less interference to primary transmissions, and thus the primary outage probability requirement can be easily satisfied. Then more transmit power of V is allowed to be assigned to x_V in this case, which results in a reduction of $Pout_{VU}$. Moreover, when γ_P is high, as the direct transmission from P to P_0 may be sufficient to satisfy the PU QoS requirement, all the available power E_V can be assigned to x_V, that is, $\beta = 1$. As a consequence, a secondary outage probability floor occurs in high γ_P regions. In this case, the secondary outage probability can be further reduced by increasing γ_V.

Second, Figure 4 shows the secondary outage probability of the link from V to U versus γ_P for the proposed TCT and traditional protocols under different settings, where E_U is limited in TCT protocol and β is limited in traditional case to satisfy a required primary outage probability T_0. From Figure 4, it can be observed that $Pout_{VU}$ is lower in TCT protocol than that in traditional case while ensuring the PU QoS. The reason is that the underlay and overlay approaches are jointly designed in TCT protocol. Clearly, $Pout_{VU}$ is lower under $\beta = 0.8$ than under $\beta = 0.4$ in TCT protocol as more available transmit power of V is assigned to x_V as β is improved. Moreover, $Pout_{VU}$ in TCT will increase slightly with γ_P rising, which is because more interference will be induced from P to U as γ_P increases.

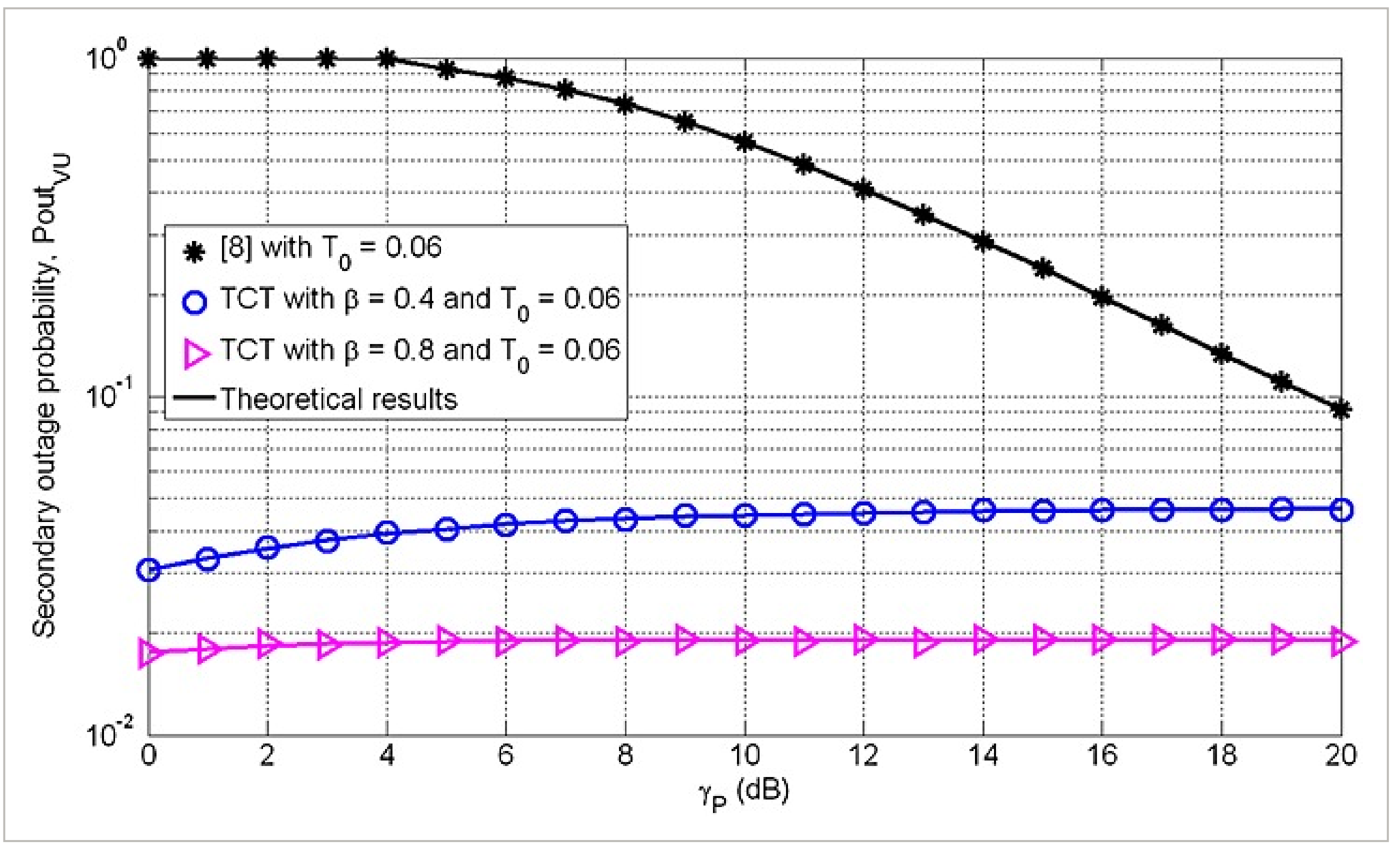

Figure 4

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Secondary outage probability of the link from V to U versus γ_P for the TCT protocol with limited E_U and the traditional case with limited β.

Finally, we depict the secondary outage probability of the link from U to V versus γ_P for TCT protocol under different settings in Figure 5 while limiting γ_U to ensure the PU QoS. Figure 5 demonstrates that TCT also can achieve secondary spectrum access in t_0, which results in higher spectrum utilization as compared with the traditional case 19 where SUs are forbidden to transmit their signals in t_0.

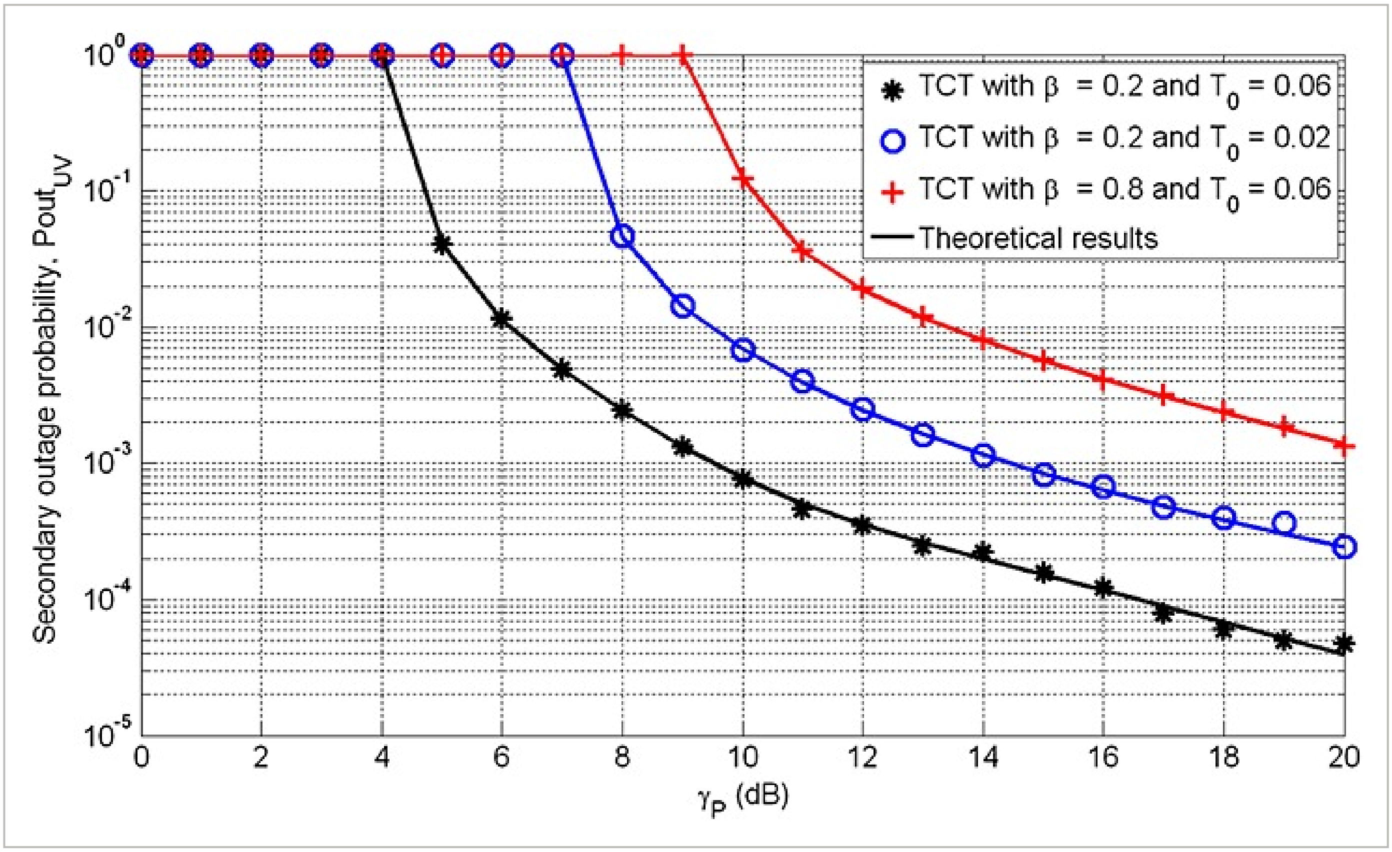

Figure 5

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Secondary outage probability of the link from U to V versus γ_P with limited γ_U for TCT protocol.

For each curve in Figure 5, $Pout_{UV}$ is equal to 1 when γ_P is lower than a cutoff value. This is because when γ_P is lower than the cutoff value, the secondary transmission from U to V in t_0 is not allowed so as to protect the primary transmissions to the utmost. However, when γ_P is above the cutoff value, $Pout_{UV}$ decreases as γ_P is improved, which is because the primary outage probability will decrease as γ_P grows and thus more power will be allowed for U to transmit its signals in this case.

Clearly, $Pout_{UV}$ can be reduced by loosening the primary outage probability requirement due to an increase of the transmit power allowed for U. In addition, $Pout_{UV}$ is higher with $\beta = 0.8$ than with $\beta = 0.2$. This is because when β is high, less power is assigned to the primary signal at V, which results in the primary outage probability increasing. In this case, to ensure the PU QoS, E_U is required to be reduced as suggested by Theorem 1 and thus $Pout_{UV}$ will increase.

5 CONCLUSION

To achieve efficient spectrum sharing in CRNs, we propose a TCT protocol. By jointly considering SC, IC, and power control techniques at the secondary system, we show that TCT can significantly reduce the secondary outage probability and also improve the spectrum utilization as compared with tradition overlay protocol while ensuring the PU QoS. Then we derive the closed-form expressions of secondary outage probabilities over Rayleigh fading channels for TCT protocol under the constraint of satisfying a required primary outage probability. Simulation results show that TCT achieves better secondary transmission performance than traditional case. Note that the performance of TCT can be further improved by utilizing advanced signal processing techniques, such as beamforming, at the primary receiver to mitigate the interference from SUs. Besides, the results obtained in this paper suggest that it deserves to jointly design the underlay and overlay models for better spectrum sharing performance in future studies.

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Citing Literature

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