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Cooperative Relaying with Interference Cancellation for Secondary Spectrum Access

Zeyang Dai[1], Jian Liu[2, *] and Keping Long[2, 1]
[1] School of Communication & Information Engineering (SCIE), University of Electronic Science and Technology of China (UESTC), Chengdu 611731, China
[e-mail: daizeyang1985@163.com]
[2] Institute of Advanced Network Technology and New Services (ANTS), University of Science and Technology Beijing (USTB), Beijing 100083, China
[e-mail: {liujian, longkeping}@ustb.edu.cn]
*Corresponding author: Jian Liu

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Abstract

Although underlay spectrum sharing has been shown as a promising technique to promote the spectrum utilization in cognitive radio networks (CRNs), it may suffer bad secondary performance due to the strict power constraints imposed at secondary systems and the interference from primary systems. In this paper, we propose a two-phase based cooperative transmission protocol with the interference cancellation (IC) and best-relay selection to improve the secondary performance in underlay models under stringent power constraints while ensuring the primary quality-of-service (QoS). In the proposed protocol, IC is employed at both the secondary relays and the secondary destination, where the IC-based best-relay selection and cooperative relaying schemes are well developed to reduce the interference from primary systems. The closed-form expression of secondary outage probability is derived for the proposed protocol over Rayleigh fading channels. Simulation results show that, with a guaranteed primary outage probability, the proposed protocol can achieve not only lower secondary outage probability but also higher secondary diversity order than the traditional underlay case.

Keywords: Cognitive radio, cooperative communication, underlay, relay selection, power control

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1. Introduction

Cognitive radio (CR) improves the spectrum utilization by allowing the secondary users (SUs) to use the licensed spectrum without adversely affecting the operations of primary users (PUs) in CR networks (CRNs) [1][2][3]. Generally, SUs need to sense the availability of spectrum holes before their transmissions and then they are restricted to transmit over the spectrum bands not occupied by PUs [4]. In [5], a cooperative sensing based cognitive transmission protocol is proposed to enable SUs to use the licensed spectrum when the PU is detected to be absent. However, this spectrum sharing paradigm, usually refered to as *interweave*, is highly sensitive to the spectrum sensing errors and the PU traffic patterns [6]. Specifically, if false alarm occurs, i.e., the PU is considered active when it is indeed absent, secondary transmissions are not allowed in interweave models, which potentially degrades the secondary performance. On the other hand, if the licensed spectrum is frequently occupied by the PUs, SUs seldom have the opportunities to achive seocndary spectrum access.

To overcome the shortcomings of interweave spectrum sharing, the *underlay* approach has thus been introduced, which allows SUs to directly access the licensed spectrum without considering the PU traffic patterns [6]. In underlay model, SUs can simultaneously transmit with PUs over the same spectrum, provided that the SU transmit power is limited to satisfy a required PU quality-of-service (QoS) [6][7][8][9]. In [8], the authors considered best-relay selection in underlay model, aiming at elevating secondary performance while ensuring the PU QoS. Then, in [9], we proposed an adaptive underlay protocol to guarantee the continuity of secondary transmissions, where a SU communicates with its destination through a direct link when PUs are absent but via intermediate relays with power control when PUs are present. However, the secondary performance of these underlay models would be severely degraded by the stringent power constraints imposed on SUs and the interference from PUs.

Recently, the interference cancellation (IC) technique has been applied to underlay models to reduce the interference from PUs [10][11]. In [12], IC is employed in a non-CR network to mitigate the interference from the selected best-relay to other relays. Note that, as suggested by [8], conventional transmission protocols (such as the relay selection and data reception, etc.) in non-CR networks should be properly redesigned in CRNs due to the mutual interference between PUs and SUs. Consequently, unlike [12], this paper considers the IC in CRNs with the objective of reducing the interference from PUs to improve the secondary performance while ensuring the PU QoS in underlay models under the strict power constraints on SUs. The IC-based underlay CRNs are also considered in [10][11], where the single-hop cognitive transmissions without relay selection were invetigated. Different from [10][11], this paper studies two-hop cooperative transmissions with both the IC and best-relay selection techniques for underlay spectrum sharing. Besides, we consider the strict power constraints imposed on SUs, i.e., the SU transmit power is limited by both the primary and secondary systems, which is more practical than [8][9] where the SU transmit power is only limited by the primary system. Our main contributions can be summarized as follows:

1) Under the strict power constraints on SUs, we propose a two-phase underlay protocol with the IC and best-relay selection techniques in this paper, where IC is utilized at both the secondary relays and the secondary destination. Then, the IC-based best-relay selection and cooperative relaying schemes are well developed. Unlike our earlier work [9] which aims at ensuring the continuity of secondary transmissions, this work is with the goal of mitigating the interference from PUs to SUs so as to improve the secondary performance in underlay models. Besides, the proposed IC-based underlay protocol has lower implementation complexity compared to the beamforming-based IC cases [9] since SUs do not need to equip multi-antenna.
2) We evaluate the performance of proposed protocol in terms of outage probability [13][14] and accordingly derive the closed-form expression of secondary ouatge probability over Rayleigh fading channels under the constraint of satisfying a given PU QoS requirement.
3) Finally, we conduct some simulations to confirm the effectiveness of proposed underlay protocol and also compare the performance of proposed protocol with that of [8]. Since the proposed protocol employs IC at SUs, it can be expected to achieve better secondary performance than [8] with a guaranteed PU QoS under the strict power constrainsts on SUs, which will be validated by the simualtion results in Section 4.

The rest of this paper is organized as follows. In Section 2, the system model and proposed protocol are described in details. In Section 3, we analyze the performance of proposed protocol in terms of secondary outage probability and then derive its corresponding closed-form expression. Simulation results are provided in Section 4, followed by concluding remarks summarized in Section 5.

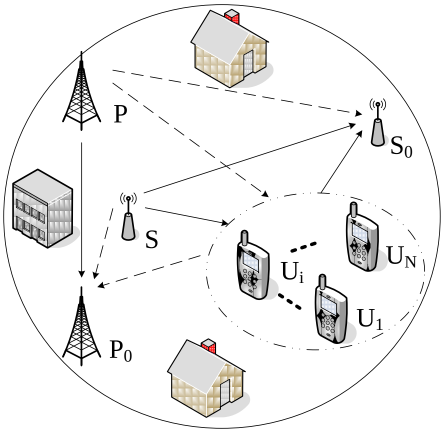

Fig. 1. System model

2. Proposed IC-based Cooperative Relaying Protocol

2.1 System Model and Protocol Descriptions

As shown in **Fig. 1**, we consider a CRN organized by a primary transmitter-receiver pair P - P_0, a secondary transmitter-receiver pair S - S_0 and N secondary relays $\Omega = \{U_1, \cdots, U_N\}$. In this CRN, SUs should limit their transmit power to ensure the PU QoS which is quantified by primary outage probability performance [8][9][10][11][12]. The channels are modeled as independent Rayleigh flat fading [5][6][7][8][9][10][11][12]. We let h_{IJ} ($I \in \{P, S, U_i \mid i = 1, \cdots, N\}$, $J \in \{P_0, S_0, U_i \mid i = 1, \cdots, N\}$, $I \neq J$) denote fading coefficient of the channel from I to J with the fading variance σ_{IJ}^2, and n_J represent the additive white Gaussian noise (AWGN) at J with zero mean and variance σ_0^2. We assume that I transmits x_I ($E\{|x_I|^2\} = 1$) to its destination with the data rate R_I and power E_I, where the signal-to-noise ratio (SNR) of E_I is denoted as $\gamma_I = E_I / \sigma_0^2$. We further assume that the decode-and-forward (DF) protocol is used at the relays. Thus, the signal transmitted at U_i is $x_{U_i} = x_S$ [7][8][9][10][11][12].

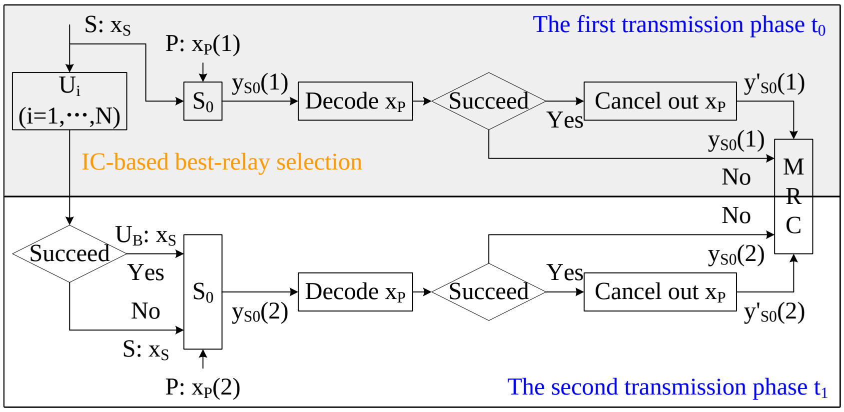

Fig. 2. Transmission process of proposed protocol

In this paper, it is assumed that SUs operate in a time division multiple access fashion [7][8][9][10][11][12], where each medium access control frame consists of two consecutive transmission phases denoted by t_0 and t_1, respectively. The proposed underlay protocol is illustrated by **Fig. 2**, which can be described as follows:

- In the first phase t_0, S broadcasts x_S to the relays and S_0, which is interfered by P. Meanwhile, S will cause interference to P_0. Next, all relays attempt to decode x_S using the proposed IC-based decoding technique. Specifically, U_i first utilizes its originally received signal from S in t_0 to decode x_S directly. If the direct decoding fails, U_i will try to decode x_P and cancel out the interference component induced by x_P from its originally received signal if the decoding is successful, where we assume that S_0 can follow the radio protocols of PUs [7][10][11]. In this case, U_i will use the interfernece cancelled received signal to decode x_S again. The relays which can successfully decode x_S using the proposed IC-based decoding method constitute a set Ξ, called *decoding set*. On the other hand, S_0 attempts to decode x_P and then cancels out the interference component from its originally received signal if the decoding is successful. To ensure the PU QoS, the power E_S should be limited. Besides, E_S can not exceed the maximum power allowed by the secondary system.

- In the second phase t_1, if Ξ is not empty, the best relay U_B which can cause the highest received signal-to-interference-and-noise ratio (SINR) at S_0 will be chosen from Ξ to forward x_S to S_0; otherwise, if Ξ is empty, i.e., all relays fail to decode x_S, S will retransmit x_S to S_0. Clearly, PUs and SUs will interfere with each other in this case. Similarly, S_0 uses its originally received signal in t_1 to decode x_P first and then cancels out the interference component if the decoding is successful. Finally, S_0 adopts maximum ratio combining (MRC) technique to combine its received signals in t_0 and t_1 after IC, and then attempts to decode x_S from the MRC combined signal. Moreover, the power E_{U_B} is constrained by both the primary and secondary systems.

Note that, the proposed protocol naturally integrates the IC technique with the best-relay selection and cooperative relaying in underlay model, which can improve the secondary performance compared to traditional underlay cases [8] under the stringent power constraints on SUs. Since we want to show the advantages of proposed IC-based protocol, the choice of combining method used at S_0 is not critical. Hence, this work can be easily extended to other combining technique cases. Besides, the proposed protocol also suits for other interference scenarios as long as S_0 knows the radio protocols of interference users.

2.2 Signal Modeling

The proposed underlay protocol has been introduced in Section 2. 1. In t_0, the signals received at P_0, U_i and S_0 can be respectively expressed as

$$y_{P_0}\left(1\right)=\sqrt{E_P}h_{PP_0}x_P\left(1\right)+\sqrt{E_S}h_{SP_0}x_S+n_{P_0}\left(1\right) \tag{1}$$

$$y_{U_i}\left(1\right)=\sqrt{E_S}h_{SU_i}x_S+\sqrt{E_P}h_{PU_i}x_P\left(1\right)+n_{U_i}\left(1\right) \tag{2}$$

$$y_{S_0}\left(1\right)=\sqrt{E_S}h_{SS_0}x_S+\sqrt{E_P}h_{PS_0}x_P\left(1\right)+n_{S_0}\left(1\right) \tag{3}$$

where the superscript 1 denotes the first transmission phase. Then, the IC technique as described in Section 2. 1 is used to cancel out $x_P(1)$ from $y_{U_i}(1)$ and $y_{S_0}(1)$ as given in (2) and (3), respectively. Consequently, the interference cancelled received signals of U_i and S_0 in t_0 are obtained as

$$y'_{U_i}(1) = \sqrt{E_S} h_{SU_i} x_S + n_{U_i}(1) \tag{4}$$

$$y'_{S_0}(1) = \sqrt{E_S} h_{SS_0} x_S + n_{S_0}(1) \tag{5}$$

During t_1, as illustrated in Section 2. 1, there exists two possible secondary transmission processes depending on whether Ξ is empty or not. Let Θ represent the empty set and Ω_n denote the nth non-empty sub-collection of Ω. Therefore, $\Xi = \Theta$ indicates that all relays fail to decode x_S and $\Xi = \Omega_n$ implies that the relays within Ω_n can successfully decode x_S. When the case $\Xi = \Theta$ occurs, S will retransmit x_S to S_0 in t_1. Thus, in this case, the signals received at P_0 and S_0 in t_1 can be respectively found as

$$y_{P_0,\Theta}(2) = \sqrt{E_P} h_{PP_0} x_P(2) + \sqrt{E_S} h_{SP_0} x_S + n_{P_0}(2) \tag{6}$$

$$y_{S_0,\Theta}(2) = \sqrt{E_S} h_{SS_0} x_S + \sqrt{E_P} h_{PS_0} x_P(2) + n_{S_0}(2) \tag{7}$$

where the superscript 2 denotes the second transmission phase. Since the proposed IC method is utilized, the recived signal of S_0 after successful IC in t_1 is written from (7) as

$$y'_{S_0,\Theta}(2) = \sqrt{E_S} h_{SS_0} x_S + n_{S_0}(2) \tag{8}$$

On the other hand, when the case $\Xi = \Omega_n$ happens, the best relay U_B will be chosen within Ω_n to forward x_S to S_0 in t_1. Consider that U_i is selected from Ω_n as the best one. In this case, the received signals of P_0 and S_0 in t_1 are respectively expressed as

$$y_{P_0,\Omega_n}(2) = \sqrt{E_P} h_{PP_0} x_P(2) + \sqrt{E_{U_i}} h_{U_iP_0} x_S + n_{P_0}(2) \tag{9}$$

$$y_{S_0,\Omega_n}(2) = \sqrt{E_{U_i}} h_{U_iS_0} x_S + \sqrt{E_P} h_{PS_0} x_P(2) + n_{S_0}(2) \tag{10}$$

Similarly, $y_{S_0,\Omega_n}(2)$ in (10) after successful IC can be rewritten as

$$y'_{S_0,\Omega_n}(2) = \sqrt{E_{U_i}} h_{U_iS_0} x_S + n_{S_0}(2) \tag{11}$$

Finally, S_0 adopts MRC to combine its received signals in t_0 and t_1 after IC. It is noted that if S_0 fails to cancel out the interference from P, it will use its originally received signal for MRC combining. Since IC is employed at both the secondary relays and the secondary destination, we can expect that the proposed underlay protocol is able to achieve better secondary performance than the traditional underlay case [8]. This will be validated by the simulation results in Section 4.

3. Outage Performance Analysis

3. 1 Power Control

In this paper, we impose strcit power constraints on SUs, i.e., the SU transmit power is limited by both the primary and secondary systems, which is different from the traditional underlay cases [8][9] where the SU transmit power is only limited by the primary system. Since we use outage performance to quantify the PU QoS, the primary outage probability should be kept below a predefined threshold T_0. Following [8][9] and from (1), (6) and (9), we can write the traditional power constraits on S and U_i as

$$E_S = E_P \sigma_{PP_0}^2 \delta / \left(\Delta_P \sigma_{SP_0}^2 \right) \tag{12}$$

$$E_{U_i} = E_P \sigma_{PP_0}^2 \delta / \left(\Delta_P \sigma_{U_i P_0}^2 \right) \tag{13}$$

where $\delta = \max\left(\frac{1}{1-T_0} \mathrm{e}^{-\frac{\Delta_P}{\gamma_P \sigma_{PP_0}^2}} - 1, 0 \right)$ and $\Delta_P = 2^{R_P} - 1$. However, in practice, the transmit powers of S and U_i are also limited by the secondary system, i.e., it can not exceed the maximum power E_0 allowed by the secondary system. Thus, E_S and E_{U_i} should be chosen as

$$E_S = \min\left(E_P \sigma_{PP_0}^2 \delta / \left(\Delta_P \sigma_{SP_0}^2 \right), E_0 \right) \tag{14}$$

$$E_{U_i} = \min\left(E_P \sigma_{PP_0}^2 \delta / \left(\Delta_P \sigma_{U_i P_0}^2 \right), E_0 \right) \tag{15}$$

To ensure the PU QoS, S and U_i need to set their transmit powers according to (14) and (15), respectively.

3. 2 Secondary Outage Probability

From (2), we know that the achievable data rates of the links $S \to U_i$ and $P \to U_i$ are respectively obtained as

$$C_{SU_i} = \frac{1}{2} \log_2 \left(1 + \frac{\gamma_S \left| h_{SU_i} \right|^2}{\gamma_P \left| h_{PU_i} \right|^2 + 1} \right) \tag{16}$$

$$C_{PU_i} = \frac{1}{2} \log_2 \left(1 + \frac{\gamma_P \left| h_{PU_i} \right|^2}{\gamma_S \left| h_{SU_i} \right|^2 + 1} \right) \tag{17}$$

Then, from (4), the achievable data rate of the link $S \to U_i$ after successful IC is calculated as

$$C_{SU_i}^{IC} = \frac{1}{2} \log_2 \left(1 + \gamma_S \left| h_{SU_i} \right|^2 \right) \tag{18}$$

As shown in Section 2. 1, U_i can successfully recover x_S through either direct decoding or IC-based decoding. Therefore, in an information-theoretic sense [7][8][9][10][11][12], the occurrence probability of that U_i can successfully decode x_S in t_0 is given as

$$P_{U_i} = \Pr\left\{C_{SU_i} \geq R_S\right\} + \Pr\left\{C_{SU_i} < R_S, C_{PU_i} \geq R_P, C_{SU_i}^{IC} \geq R_S\right\} \\ = \begin{cases} \upsilon_0 + \upsilon_1 + \upsilon_2 - \upsilon_3, 0 < \Delta_S \Delta_P < 1 \\ \upsilon_0 + \upsilon_2, \Delta_S \Delta_P \geq 1 \end{cases} \tag{19}$$

where $\Delta_S = 2^{2R_S} - 1$, $\tau = \frac{\Delta_S\left(1+\Delta_P\right)}{1-\Delta_S\Delta_P}$ and

$$\upsilon_0 = \frac{\gamma_S \sigma_{SU_i}^2}{\gamma_S \sigma_{SU_i}^2 + \Delta_S \gamma_P \sigma_{PU_i}^2} \exp\left(-\frac{\Delta_S}{\gamma_S \sigma_{SU_i}^2}\right) \tag{20}$$

$$\upsilon_1 = \frac{\Delta_S \gamma_P \sigma_{PU_i}^2}{\Delta_S \gamma_P \sigma_{PU_i}^2 + \gamma_S \sigma_{SU_i}^2} \exp\left(\frac{1}{\gamma_P \sigma_{PU_i}^2} - \frac{\tau}{\gamma_S \sigma_{SU_i}^2} - \frac{\tau}{\Delta_S \gamma_P \sigma_{PU_i}^2}\right) \tag{21}$$

$$\upsilon_2 = \frac{\gamma_P \sigma_{PU_i}^2}{\gamma_P \sigma_{PU_i}^2 + \Delta_P \gamma_S \sigma_{SU_i}^2} \exp\left(-\frac{\Delta_P}{\gamma_P \sigma_{PU_i}^2} - \frac{\Delta_S}{\gamma_S \sigma_{SU_i}^2} - \frac{\Delta_S \Delta_P}{\gamma_P \sigma_{PU_i}^2}\right) \tag{22}$$

$$\upsilon_3 = \frac{\gamma_P \sigma_{PU_i}^2}{\gamma_P \sigma_{PU_i}^2 + \Delta_P \gamma_S \sigma_{SU_i}^2} \exp\left(-\frac{\Delta_P}{\gamma_P \sigma_{PU_i}^2} - \frac{\tau}{\gamma_S \sigma_{SU_i}^2} - \frac{\tau \Delta_P}{\gamma_P \sigma_{PU_i}^2}\right) \tag{23}$$

Therefore, the occurrence probabilities of the cases $\Xi = \Theta$ and $\Xi = \Omega_n$ are respectively given as

$$P_\Theta = \prod_{i=1}^{N}\left(1 - P_{U_i}\right) \tag{24}$$

$$P_{\Omega_n} = \prod_{i\in\Omega_n} P_{U_i} \prod_{j\in\bar{\Omega}_n}\left(1 - P_{U_j}\right) \tag{25}$$

where $\bar{\Omega}_n$ is the complementary set of Ω_n.

For notation simplicity, we define $x = \gamma_S \left|h_{SS_0}\right|^2$, $y = \max_{i\in\Omega_n} \gamma_{U_i} \left|h_{U_iS_0}\right|^2$, $z = \gamma_P \left|h_{PS_0}\right|^2$. Then, from (3), the achievable data rate between P and S_0 in t_0 is $C_{S_0}^1 = \log_2\left(1 + \frac{z}{x+1}\right)$. If $\Xi = \Theta$ occurs, the achievable data rate between P and S_0 in t_1 can be obtained from (7) as $C_{S_0}^1$. According to Section 3. 1, under $\Xi = \Theta$, the achievable data rate between S and S_0 has two possible cases depending on whether the IC at S_0 is successful or not in t_0 and t_1. If the IC fails, the secondary achievable data rate is given as $C_{S_0,1} = \frac{1}{2}\log_2\left(1 + \frac{2x}{z+1}\right)$; otherwise, the achievable rate is $C_{S_0,2} = \frac{1}{2}\log_2\left(1 + 2x\right)$. Hence, using the results of Appendix A, the secondary outage probability of proposed protocol conditioned on that the case $\Xi = \Theta$ occurs is given by

$$
\begin{aligned}
Pout_{\Theta} &= \Pr\left\{C_{S_0,1} < R_S, C_{S_0}^1 < R_P\right\} + \Pr\left\{C_{S_0,2} < R_S, C_{S_0}^1 \geq R_P\right\} \\
&= \begin{cases} 1+\beta_1-\beta_2-\beta_3-\beta_4, \Delta_P\Delta_S < 2 \\ 1-\beta_1+\beta_4, \Delta_P\Delta_S \geq 2 \end{cases}
\end{aligned} \tag{26}
$$

where $\beta_1 = \beta_2\, \mathrm{e}^{-\frac{a}{\gamma_P \sigma_{PS_0}^2} - \frac{a\Delta_S}{2\gamma_S \sigma_{SS_0}^2}}$, $\beta_2 = \theta_1 e^{-\frac{\Delta_S}{2\gamma_S \sigma_{SS_0}^2}}$, $\beta_3 = \left(1-\theta_2\right)\mathrm{e}^{\frac{1}{\gamma_S \sigma_{SS_0}^2} - \frac{a}{\gamma_P \sigma_{PS_0}^2} - \frac{a}{\Delta_P \gamma_S \sigma_{SS_0}^2}}$, $\beta_4 = \theta_2\, \mathrm{e}^{-\frac{\Delta_P}{\gamma_P \sigma_{PS_0}^2} - \frac{\Delta_S}{2\gamma_S \sigma_{SS_0}^2} - \frac{\Delta_P\Delta_S}{2\gamma_P \sigma_{PS_0}^2}}$, $a = \frac{\Delta_P\left(2+\Delta_S\right)}{2-\Delta_P\Delta_S}$, $\theta_1 = \frac{2\gamma_S \sigma_{SS_0}^2}{2\gamma_S \sigma_{SS_0}^2 + \Delta_S \gamma_P \sigma_{PS_0}^2}$ and $\theta_2 = \frac{\gamma_P \sigma_{PS_0}^2}{\gamma_P \sigma_{PS_0}^2 + \Delta_P \gamma_S \sigma_{SS_0}^2}$.

On the other hand, when $\Xi = \Omega_n$ occurs, the achievable data rate between P and S_0 can be obtained from (10) as $C_{S_0}^2 = \log_2\left(1+\frac{z}{y+1}\right)$. In this case, the achievable data rate between S and S_0 has four possible scenarios as shown in **Table 1**.

Table 1. Secondary achievable rates under $\Xi = \Omega_n$

Scenarios	**Secondary achievable data rates**
IC fails in both t_0 and t_1	$C_{S_0,3} = \frac{1}{2}\log_2\left(1+\frac{x+y}{z+1}\right)$
IC succeeds in t_0 but fails in t_1	$C_{S_0,4} = \frac{1}{2}\log_2\left(1+x+\frac{y}{z+1}\right)$
IC fails in t_0 but succeeds in t_1	$C_{S_0,5} = \frac{1}{2}\log_2\left(1+y+\frac{x}{z+1}\right)$
IC succeeds in both t_0 and t_1	$C_{S_0,6} = \frac{1}{2}\log_2\left(1+x+y\right)$

Therefore, using the proposed IC-based best-relay transmission protocol, the secondary outage probability conditioned on that the case $\Xi = \Omega_n$ occurs can be calculated as

$$
\begin{aligned}
Pout_{\Omega_n} = &\Pr\left\{C_{S_0,3} < R_S, C_{S_0}^1 < R_P, C_{S_0}^2 < R_P\right\} \\
&+\Pr\left\{C_{S_0,4} < R_S, C_{S_0}^1 \geq R_P, C_{S_0}^2 < R_P\right\} \\
&+\Pr\left\{C_{S_0,5} < R_S, C_{S_0}^1 < R_P, C_{S_0}^2 \geq R_P\right\} \\
&+\Pr\left\{C_{S_0,6} < R_S, C_{S_0}^1 \geq R_P, C_{S_0}^2 \geq R_P\right\}
\end{aligned} \tag{27}
$$

Utilizing the results of Appendix B, $Pout_{\Omega_n}$ in (27) is obtained as

$$Pout_{\Omega_n} = Y_1 + Y_2 + Y_3 + Y_4 \tag{28}$$

Following the total probability law, the overall secondary outage probability of proposed protocol is derived as

$$Pout_{S_0}^{Pro} = Pout_{\Theta} P_{\Theta} + \sum_{n=1}^{2^N-1} Pout_{\Omega_n} P_{\Omega_n} \tag{29}$$

Simulation results will be presented in Section 4 to illuatrate the advantages of proposed protocol as compared to traditional underlay case [8].

4. Simulation Results

In this section, the performance of proposed protocol will be evaluated by simulation results, which is also compared with the traditional underlay case [8]. We let $Pout_{S_0}^{Tra}$ denote the secondary outage probability of traditional underlay protocol for simplicity.

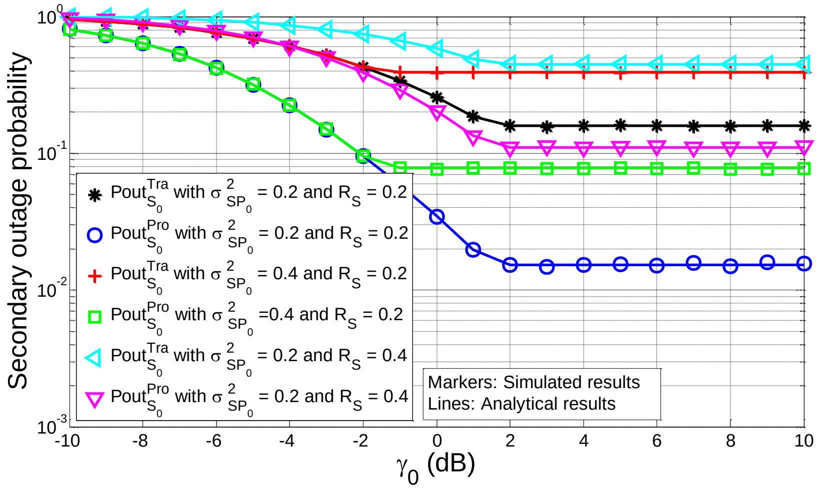

Fig. 3. Secondary outage probability versus γ_0 for the traditional and proposed underlay protocols with the PU QoS requirement $T_0 = 0.04$, relay number $N = 2$, P 's transmit SNR $\gamma_P = 10$ dB, priamry data rate $R_P = 0.4$ bits/s/Hz, and the channel variances $\sigma^2_{PP_0} = 1$, $\sigma^2_{PU_i} = \sigma^2_{PS_0} = 0.2$, $\sigma^2_{SS_0} = \sigma^2_{SU_i} = \sigma^2_{U_iS_0} = 1$ and $\sigma^2_{SP_0} = \sigma^2_{U_iP_0}$ [8]

First, **Fig. 3** depicts the secondary outage probability versus $\gamma_0 = E_0 / \sigma_0^2$ (i.e., the SNR of the maximum power E_0 allowed by the secondary system) under different settings for the traditional and proposed underlay protocols. Note that the simulation parameters are set according to [8] in this paper. As shown in **Fig. 3**, the proposed protocol significantly reduces the secondary outage probability compared with the traditional case under the stringent power constraints on SUs due to the use of IC. In low γ_0 regions, the SU power constraint imposed by the secondary system is the dominant factor to affect the secondary outage performance, thus the secondary outage probability will decrease as γ_0 increases in this case. On the other hand, in high γ_0 regions, since the SU transmit power limited by the PU QoS requirement T_0 becomes the dominant factor to induce a secondary outage, the secondary outage probability will keep at a constant value for a given T_0 when γ_0 is high. One also can observe from Fig. 3 that the secondary outage probability can be reduced when the interference links $S \to P_0$ and $U_i \to P_0$ become weak, which is due to the fact that more transmit power is allowed for SUs in this case. Clearly, the secondary outage probability will increase as the secondary data rate R_S is improved.

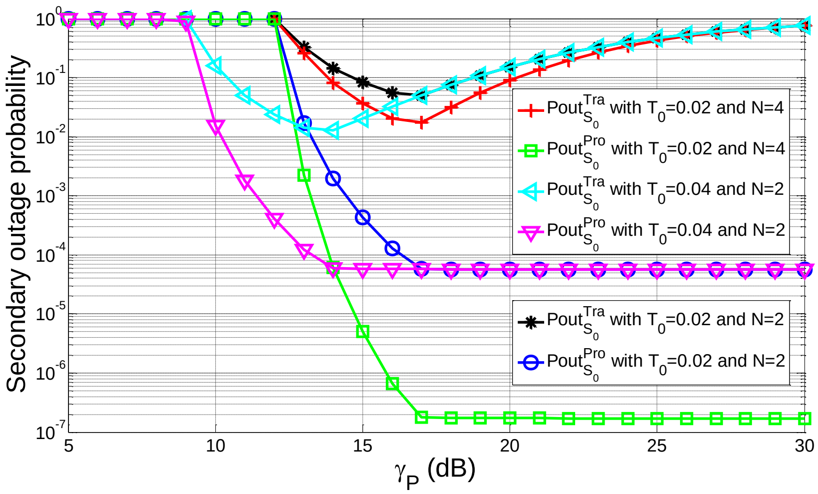

Fig. 4. Secondary outage probability versus γ_P for the traditional and proposed underlay protocols with $\gamma_0 = 10$ dB, $R_P = 0.4$ bits/s/Hz, $R_S = 0.2$ bits/s/Hz, $\sigma^2_{PP_0} = 1$, $\sigma^2_{PU_i} = \sigma^2_{PS_0} = 0.2$, $\sigma^2_{SS_0} = \sigma^2_{SU_i} = \sigma^2_{U_iS_0} = 1$ and $\sigma^2_{SP_0} = \sigma^2_{U_iP_0} = 0.2$

Second, **Fig. 4** illustrates the secondary outage probability versus γ_P under different settings for the traditional and proposed underlay protocols. It can be seen from **Fig. 4** that, under the strict power constraints on SUs, the secondary outage probability of traditional underlay protocol grows with γ_P increasing in high γ_P regions, which accounts for the fact that the interference from PUs is the dominant factor to induce a secondary outage in this case. However, owing to the use of IC, the secondary outage probability of proposed underlay protocol remains at a low level in high γ_P regions, where the SU power constraint imposed by the secondary system becomes the dominant factor to affect the secondary outage performance. This illustrates the advantages of proposed underlay protocol compared to the traditional case. In low γ_P regions, the secondary outage probability is equal to 1, which is because that the secondary transmissions are not allowed so as to ensure the PU QoS as much as possible when γ_P is low. Then, the secondary outage probability will decrease as γ_P grows since more available transmit power is allowed for SUs in this case. As expected, the secondary outage probability can be reduced by improving the number of relays. Besides, the secondary outage probability will decrease as the PU QoS requirement loosens.

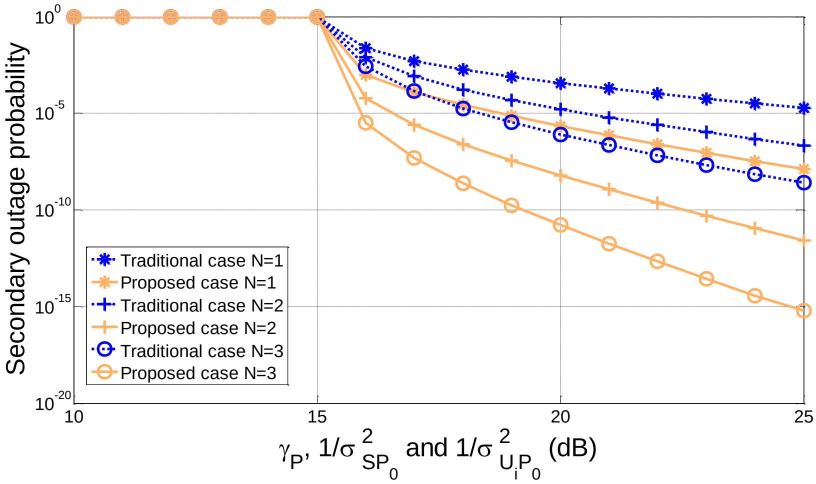

Fig. 5. Illustration of the generalized diversity gain with $T_0 = 0.01$, $R_P = 0.4$ bits/s/Hz, $R_S = 0.2$ bits/s/Hz, $\sigma^2_{PP_0} = 1$, $\sigma^2_{PU_i} = \sigma^2_{PS_0} = 0.1$, $\sigma^2_{SS_0} = \sigma^2_{SU_i} = \sigma^2_{U_iS_0} = 1$ and $\sigma^2_{SP_0} = \sigma^2_{U_iP_0} = 0.1$

Following [8], the generalized diversity gain of proposed protocol can be defined as

$$d^{Pro} = \lim_{\sigma^2_{SP_0} \to 0} \frac{\log\left(\lim\limits_{\gamma_P, 1/\sigma^2_{U_iP_0} \to \infty} Pout^{Pro}_{S_0} \right)}{\log\left(\sigma^2_{SP_0}\right)} \tag{30}$$

where the power constraint on SUs imposed by the secondary system should be removed to obtain d^{Pro}. From (29), we know that the closed-form expression of the secondary outage probability in proposed protocol is very complicated and thus it is impossible to derive d^{Pro} using (30) directly. The analysis of exact generalized diversity gain for the proposed underlay protocol is out of the scope of this paper, which will be considered in our future works. However, we still attempt to show the generalized diversity gain by simulations in **Fig. 5** for the proposed underlay protocol and then compare it with the traditional case [8]. One can observe from **Fig. 5** that the proposed underlay protocol achieves higher diversity order than the traditional case, which is due to that fact that, by using IC at SUs, additional diversity gain can be exploited by the interference links from the primary transmitters to the secondary receivers.

5. Conclusion

In this paper, we propose a two-phase IC-based cooperative transmission protocol with best-relay selection for underlay CRNs, where the IC technique is employed at both the secondary relays and the secondary destination. Then, the IC-based best-relay selection and cooperative relaying schemes are well developed. Our goal is to improve the secondary performance of underlay models under the stringent power constraints on SUs while satisfying a given PU QoS requirement. We evaluate the performance of proposed underlay protocol in terms of secondary outage probability and also derive the corresponding closed-form expression over Rayleigh fading channels. Finally, simulation results are presented to show that, under the stringent power constraints on SUs, the proposed protocol can achieve lower secondary outage probability as well as higher diversity order than the traditional case. Furthermore, the proposed protocol can be easily extended to other cases where different combining techniques are employed at the secondary destination. Proposed protocol also can reduce other interference in underlay CRNs provided that SUs are able to emulate the radio protocols of the interference users.

Appendix A: Calculation of (26)

In (15), the first term at the right-hand side can be rewritten as

$$\begin{aligned}&\Pr\left\{C_{S_0,1} < R_S, C_{S_0}^1 < R_P\right\}\\ &= \Pr\left\{\frac{1}{2}\log_2\left(1+\frac{2x}{z+1}\right) < R_S, \log_2\left(1+\frac{z}{x+1}\right) < R_P\right\}\\ &= \Pr\left\{\frac{2x}{z+1} < \Delta_S, \frac{z}{x+1} < \Delta_P\right\}\end{aligned} \tag{31}$$

When $\Delta_P\Delta_S < 2$, (31) is calculated as

$$\begin{aligned}&\Pr\left\{C_{S_0,1} < R_S, C_{S_0}^1 < R_P\right\}\\ &= \Pr\left\{x < \frac{\Delta_S}{2}(z+1), z < \Delta_P\right\} + \Pr\left\{\frac{z}{\Delta_P} - 1 < x < \frac{\Delta_S}{2}(z+1), \Delta_P < z < a\right\}\\ &= \int_0^{\Delta_P}\left[\int_0^{\frac{\Delta_S}{2}(z+1)} \frac{1}{\gamma_S\sigma_{SS_0}^2}\exp\left(-\frac{1}{\gamma_S\sigma_{SS_0}^2}x\right)dx\right]\frac{1}{\gamma_P\sigma_{PS_0}^2}\exp\left(-\frac{1}{\gamma_P\sigma_{PS_0}^2}z\right)dz\\ &+ \int_{\Delta_P}^{a}\left[\int_{\frac{z}{\Delta_P}-1}^{\frac{\Delta_S}{2}(z+1)} \frac{1}{\gamma_S\sigma_{SS_0}^2}\exp\left(-\frac{1}{\gamma_S\sigma_{SS_0}^2}x\right)dx\right]\frac{1}{\gamma_P\sigma_{PS_0}^2}\exp\left(-\frac{1}{\gamma_P\sigma_{PS_0}^2}z\right)dz\end{aligned} \tag{32}$$

where $a = \frac{\Delta_P\left(2+\Delta_S\right)}{2-\Delta_P\Delta_S}$. On the other hand, when $\Delta_P\Delta_S \geq 2$, (31) is derived as

$$\begin{aligned}
&\Pr\left\{C_{S_0,1} < R_S, C_{S_0}^1 < R_P\right\} \\
&= \Pr\left\{x < \frac{\Delta_S}{2}\left(z+1\right), z < \Delta_P\right\} + \Pr\left\{\frac{z}{\Delta_P} - 1 < x < \frac{\Delta_S}{2}\left(z+1\right), \Delta_P < z\right\}
\end{aligned} \tag{33}$$

The second term at the right-hand side of (26) can be rewritten as

$$\begin{aligned}
&\Pr\left\{C_{S_0,2} < R_S, C_{S_0}^1 \geq R_P\right\} \\
&= \Pr\left\{\frac{1}{2}\log_2\left(1+2x\right) < R_S, \log_2\left(1+\frac{z}{x+1}\right) \geq R_P\right\} \\
&= \Pr\left\{x < \frac{\Delta_S}{2}, z \geq \left(x+1\right)\Delta_P\right\} \\
&= \int_0^{\frac{\Delta_S}{2}} \left[\int_{(x+1)\Delta_P}^{\infty} \frac{1}{\gamma_P\sigma_{PS_0}^2}\exp\left(-\frac{1}{\gamma_P\sigma_{PS_0}^2}z\right)dz\right]\frac{1}{\gamma_S\sigma_{SS_0}^2}\exp\left(-\frac{1}{\gamma_S\sigma_{SS_0}^2}x\right)dx
\end{aligned} \tag{34}$$

By solving the integrations in (32)-(34) and then substituting them into (31), we have

$$Pout_{\Theta} = \begin{cases} 1+\beta_1-\beta_2-\beta_3-\beta_4, \Delta_P\Delta_S < 2 \\ 1-\beta_1+\beta_4, \Delta_P\Delta_S \geq 2 \end{cases} \tag{35}$$

Appendix B: Calculation of (27)

To simplify the notations, we define the parameters $\pi_1 = \frac{\Delta_P\left(2+\Delta_S\right)}{2-\Delta_P\Delta_S}$, $\pi_2 = \frac{-\mu+\sqrt{\mu^2+4\Delta_P\left(2+\Delta_S\right)}}{2}$, $\pi_3 = \frac{\Delta_P\left(1+\Delta_S\right)}{1-\Delta_P\Delta_S}$, $\pi_4 = \Delta_P\left(1+\frac{\Delta_S}{2}\right)$, $\pi_5 = \Delta_P\left(1+\Delta_S\right)$, $\mu = 2-\Delta_P-\Delta_P\Delta_S$, the function $f = \frac{1}{\gamma_P\sigma_{PS_0}^2}e^{-\frac{z}{\gamma_P\sigma_{PS_0}^2}}$ and the operator $T\left(A\right) = \sum_{k=1}^{2^{|\Omega_n|}-1}\left[\left(-1\right)^{|S_n(k)|}\left(A\right)\right]$, where $S_n\left(k\right)$ is the k th non-empty sub-collection of Ω_n. The four terms at the right-hand side of (17), respectively denoted as Y_1, Y_2, Y_3 and Y_4, can be calculated as follows. First,

$$Y_1 = \Pr\left\{ \frac{x+y}{z+1} < \Delta_S, \frac{z}{x+1} < \Delta_P, \frac{z}{y+1} < \Delta_P \right\} = \begin{cases} \int_{\Delta_P}^{\pi_1} \left(f_1 - f_2 \right) f dz + \int_0^{\Delta_P} f_3 f dz, \Delta_P \Delta_S < 2 \\ \int_{\Delta_P}^{\infty} \left(f_1 - f_2 \right) f dz + \int_0^{\Delta_P} f_3 f dz, \Delta_P \Delta_S \geq 2 \end{cases} \tag{36}$$

where $f_1 = \frac{T\left[\Phi_1(k)\right]}{\gamma_S \sigma_{SS_0}^2}$, $f_2 = \left(b_1 - \frac{b_2}{b_1} \right) T(c_1)$, $f_3 = 1 - b_2 + \frac{T\left[\Phi_2(k)\right]}{\gamma_S \sigma_{SS_0}^2}$, $b_1 = \mathrm{e}^{-\frac{1}{\gamma_S \sigma_{SS_0}^2}\left(\frac{z}{\Delta_P} - 1\right)}$, $b_2 = \mathrm{e}^{-\frac{\Delta_S (z+1)}{\gamma_S \sigma_{SS_0}^2}}$ and $c_1 = \mathrm{e}^{-\sum_{i \in S_n(k)} \frac{1}{\gamma_{U_i} \sigma_{U_i S_0}^2}\left(\frac{z}{\Delta_P} - 1\right)}$. Besides, $\Phi_1(k)$ and $\Phi_2(k)$ in (36) can be respectively written as

$$\Phi_1(k) = \begin{cases} \left[\Delta_S (z+1) - 2(z/\Delta_P - 1) \right] b_2, \eta_1 = 0 \\ c_2 \left(d_2 / d_1 - d_1 \right) / \eta_1, \eta_1 \neq 0 \end{cases} \tag{37}$$

$$\Phi_2(k) = \begin{cases} \Delta_S (z+1) b_2, \eta_1 = 0 \\ c_2 \left(d_2 - 1 \right) / \eta_1, \eta_1 \neq 0 \end{cases} \tag{38}$$

where $\eta_1 = \sum_{i \in S_n(k)} \frac{1}{\gamma_{U_i} \sigma_{U_i S_0}^2} - \frac{1}{\gamma_S \sigma_{SS_0}^2}$, $c_2 = \mathrm{e}^{-\sum_{i \in S_n(k)} \frac{\Delta_S (z+1)}{\gamma_{U_i} \sigma_{U_i S_0}^2}}$, $d_1 = e^{\eta_1 \left(\frac{z}{\Delta_P} - 1\right)}$ and $d_2 = \mathrm{e}^{\eta_1 \Delta_S (z+1)}$.

Second,

$$Y_2 = \Pr\left\{ x + \frac{y}{z+1} < \Delta_S, \frac{z}{x+1} \geq \Delta_P, \frac{z}{y+1} < \Delta_P \right\} = \begin{cases} \int_{\Delta_P}^{\pi_2} \left(f_4 - f_5 \right) f dz + \int_{\pi_2}^{\pi_3} \left(f_6 - f_7 \right) f dz, \Delta_P \Delta_S < 1 \\ \int_{\Delta_P}^{\pi_2} \left(f_4 - f_5 \right) f dz + \int_{\pi_2}^{\infty} \left(f_6 - f_7 \right) f dz, \Delta_P \Delta_S \geq 1 \end{cases} \tag{39}$$

where $f_4 = \frac{T\left[c_2 (e_1 - 1)/\eta_2\right]}{\gamma_S \sigma_{SS_0}^2}$, $f_5 = (1 - b_1) T(c_1)$, $f_6 = \frac{T\left(c_2 (e_2 - 1)/\eta_2\right)}{\gamma_S \sigma_{SS_0}^2}$, $f_7 = (1 - b_3) T(c_1)$, $b_3 = \mathrm{e}^{-\frac{1}{\gamma_S \sigma_{SS_0}^2}\left(\Delta_S - \frac{z - \Delta_P}{\Delta_P (z+1)}\right)}$, $\eta_2 = \sum_{i \in S_n(k)} \frac{z+1}{\gamma_{U_i} \sigma_{U_i S_0}^2} - \frac{1}{\gamma_S \sigma_{SS_0}^2}$, $e_1 = \mathrm{e}^{\eta_2 \left(\frac{z}{\Delta_P} - 1\right)}$ and $e_2 = \mathrm{e}^{\eta_2 \left(\Delta_S - \frac{z - \Delta_P}{\Delta_P (z+1)}\right)}$. Third,

$$Y_3 = \Pr\left\{ y + \frac{x}{z+1} < \Delta_S, \frac{z}{x+1} < \Delta_P, \frac{z}{y+1} \geq \Delta_P \right\}$$

$$= \begin{cases} \int_{\Delta_P}^{\pi_2} \left(f_8 + f_9 \right) f dz + \int_{\pi_2}^{\pi_3} f_{10} f dz, \Delta_P \Delta_S < 1 \\ \int_{\Delta_P}^{\pi_2} \left(f_8 + f_9 \right) f dz + \int_{\pi_2}^{\infty} f_{10} f dz, \Delta_P \Delta_S \geq 1 \end{cases} \tag{40}$$

where $f_8 = b_1 - b_2 + \left(b_1 - \frac{b_5}{b_4} \right) T\left(c_1\right)$, $f_9 = \frac{T\left[c_3 \left(g_1 - g_1^{(1+\Delta_S)/\Delta_S} / g_2 \right) / \eta_3 \right]}{\gamma_S \sigma_{SS_0}^2}$, $f_{10} = b_1 - b_2 + \frac{T\left[c_3 \left(g_1 - g_3 \right) / \eta_3 \right]}{\gamma_S \sigma_{SS_0}^2}$, $b_4 = \mathrm{e}^{-\frac{z(z+1)}{\Delta_P \gamma_S \sigma_{SS0}^2}}$, $b_5 = \mathrm{e}^{-\frac{(1+\Delta_S)(z+1)}{\gamma_S \sigma_{SS0}^2}}$, $c_3 = \mathrm{e}^{-\sum_{i \in S_n(k)} \frac{\Delta_S}{\gamma_{U_i} \sigma_{U_i S0}^2}}$, $\eta_3 = \sum_{i \in S_n(k)} \frac{1}{\gamma_{U_i} \sigma_{U_i S_0}^2 \left(z+1\right)} - \frac{1}{\gamma_S \sigma_{SS_0}^2}$, $g_1 = \mathrm{e}^{\eta_3 (1+z) \Delta_S}$, $g_2 = \mathrm{e}^{\frac{\eta_3 z(z+1)}{\Delta_P}}$ and $g_3 = \mathrm{e}^{\eta_3 \left(\frac{z}{\Delta_P} - 1 \right)}$.

Finally,

$$\begin{aligned} Y_4 &= \Pr\left\{ x + y < \Delta_S, \frac{z}{x+1} \geq \Delta_P, \frac{z}{y+1} \geq \Delta_P \right\} \\ &= \Pr\left\{ y < \frac{z}{\Delta_P} - 1, x < 1 + \Delta_S - \frac{z}{\Delta_P}, \pi_4 < z < \pi_5 \right\} \\ &\quad + \Pr\left\{ y < \frac{z}{\Delta_P} - 1, x < \frac{z}{\Delta_P} - 1, \Delta_P < z < \pi_4 \right\} \\ &\quad + \Pr\left\{ y < \Delta_S - x, 0 < x < \Delta_S, \pi_5 < z \right\} \\ &\quad + \Pr\left\{ y < \Delta_S - x, 1 + \Delta_S - \frac{z}{\Delta_P} < x < \frac{z}{\Delta_P} - 1, \pi_4 < z < \pi_5 \right\} \\ &= \int_{\Delta_P}^{\pi_4} f_{11} f dz + \int_{\pi_4}^{\pi_5} \left(f_{12} + f_{13} \right) f dz + \int_{\pi_5}^{\infty} f_{14} f dz \end{aligned} \tag{41}$$

where $f_{11} = \left(1 - b_1\right)\left[1 + T\left(c_1\right)\right]$, $f_{12} = 1 - b_1 + \left(1 - \frac{b_6}{b_1} \right) T\left(c_1\right)$, $f_{13} = \frac{T\left[\Phi_3\left(k\right)\right]}{\gamma_S \sigma_{SS_0}^2}$, $f_{14} = 1 - b_6 + \frac{T\left[\Phi_4\left(k\right)\right]}{\gamma_S \sigma_{SS_0}^2}$ and $b_6 = \mathrm{e}^{-\frac{\Delta_S}{\gamma_S \sigma_{SS0}^2}}$. Moreover, $\Phi_3\left(k\right)$ and $\Phi_4\left(k\right)$ can be respectively obtained as

$$\Phi_3\left(k\right)=\begin{cases} b_6\left(2z/\Delta_P-2-\Delta_S\right),\eta_1=0 \\ c_3\left(d_1-d_3/d_1\right)/\eta_1,\eta_1\neq 0 \end{cases} \tag{42}$$

$$\Phi_4\left(k\right)=\begin{cases} \Delta_S b_6,\eta_1=0 \\ c_3\left(d_3-1\right)/\eta_1,\eta_1\neq 0 \end{cases} \tag{43}$$

where $d_3=\exp\left(\eta_1\Delta_S\right)$.

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Zeyang Dai received the B.Eng. degree in information engineering from Anhui Normal University (AHNU), Wuhu, China, in 2007 and the M. Eng. degree in electrical engineering from Chengdu University of Information Technology (CUIT), Chengdu, China, in 2010. He is currently working towards his Ph.D. degree at the School of Communication & Information Engineering (SCIE), University of Electronic Science and Technology of China (UESTC), Chengdu, China. His research interests include cognitive radios, cooperative communications, and green radios.

Jian Liu received his B.S. degree in Automatic Control Theory and Applications from Shandong University, China, in 2000, and the Ph.D. degree in School of Information Science and Engineering from Shandong University in 2008. He is currently an associate professor of University of Science and Technology Beijing (USTB), Beijing, China. His research interests include cognitive radio networks, mobile mesh networks, and LTE-A. He is an IEEE member since 2009.

Prof. Keping Long received his M.S. and Ph.D. Degrees at UESTC in 1995 and 1998, respectively. From September 1998 to August 2000, he worked as a postdoctoral research fellow at National Laboratory of Switching technology and telecommunication networks in Beijing University of Posts and Telecommunications (BUPT). From September 2000 to June 2001, he worked as an associate professor at Beijing University of Posts and Telecommunications (BUPT). From July 2001 to November 2002, he was a research fellow in ARC Special Research Centre for Ultra Broadband Information Networks (CUBIN) at the University of Melbourne, Australia.

He is now a professor and dean at School of Computer & Communication Engineering (CCE), University of Science and Technology Beijing (USTB). He is the IEEE senior member, and the Member of Editorial Committee of Sciences in China Series F and China Communications. He is also the TPC and the ISC member for COIN2003/04/05/06/07/08/09/10, IEEE IWCN2010, ICON04/06, APOC2004/06/08, Co-chair of organization member for IWCMC2006, TPC chair of COIN2005/2008, TPC Co-chair of COIN2008/2010, He was awarded for the National Science Fund for Distinguished Young Scholars of China in 2007, selected as the Chang Jiang Scholars Program Professor of China in 2008. His research interests are Optical Internet Technology, New Generation Network Technology, Wireless Information Network, Value-added Service and Secure Technology of Network. He has published over 200 papers, 20 keynotes speaks and invited talks in the international conferences and local conferences.