Spectrum Hole Utilization in Cognitive Two-way Relaying Networks

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Abstract

This paper investigates the spectrum hole utilization of cooperative schemes for the two-way relaying model in order to improve the utilization efficiency of limited spectrum holes in cognitive radio networks with imperfect spectrum sensing. We propose two specific bidirectional secondary data transmission (BSDT) schemes with two-step and three-step two-way relaying models, i.e., two-BSDT and three-BSDT schemes, where the spectrum sensing and the secondary data transmission are jointly designed. In the proposed cooperative schemes, the best two-way relay channel between two secondary users is selected from a group of secondary users serving as cognitive relays and assists the bi-directional communication between the two secondary users without a direct link. The closed-form asymptotic expressions for outage probabilities of the two schemes are derived with a primary user protection constraint over Rayleigh fading channels. Based on the derived outage probabilities, the spectrum hole utilization is calculated to evaluate the percentage of spectrum holes used by the two secondary users for their successful information exchange without channel outage. Numerical results show that the spectrum hole utilization depends on the spectrum sensing overhead and the channel gain from a primary user to secondary users. Additionally, we compare the spectrum hole utilization of the two schemes as the varying of secondary signal to noise ratio, the number of cognitive relays, and symmetric and asymmetric channels.

Keywords: Cognitive radio networks, spectrum hole utilization, multiple two-way relays, outage probability, secondary data transmission

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1. Introduction

Cognitive radio is emerging as a promising solution to the problem of low efficient spectrum utilization that has appeared as a result of stringent spectrum allocations [1-3]. For the full use of a spectrum hole unoccupied by its primary network at a particular time and specific geographic location, cognitive radio can find the spectrum hole by spectrum sensing and allows unlicensed users, i.e., secondary users or cognitive users, to communicate over the detected spectrum hole. It is clear that the efficient utilization of limited spectrum holes can improve the quality of communication among secondary users, such as spectrum hole detection, transmission outage, and channel capacity.

One-way cooperative relaying, which assists one source to transmit information to one destination, has been considered as an effective means to improve the performance of spectrum sensing and secondary user transmissions in cognitive radio networks (CRNs) [4]. The detection time and detection probabilities for the presence of primary users are improved as one-way cooperative relays are applied in spectrum sensing [5-8]. The chances of secodary users to access the primary users' spectrum can also increase with the utilization of one-way cooperative relaying [9]. When multiple secondary users serve as one-way cooperative relays to help data transmissions from one secondary user to the other, paper [10] has studied the spectrum hole utilization efficiency which is the percentage of spectrum holes utilized by the secondary user source for its successful data transmissions without channel outage. However, one-way relaying techniques have low spectral efficiency due to the half-duplex operation mode [11]. Specifically, when two terminals T_1 and T_2 intend to exchange information, one-way relaying protocols need four sequential steps, i.e., T_1 transmits information to the relay and T_2 in the first step; in the second step, the relay forwards its information to T_2; in the third step, T_2 in turn transmits information to the relay and T_1; and in the fourth step, the relay forwards its information to T_1, whereas two-way relaying protocols generally need two steps or three steps. For the three-step two-way relaying protocols, T_1 and T_2 transmit their own information in the first and second steps, respectively. In the third step, the relay broadcasts its information to the two terminals. For the two-step two-way relaying protocols, T_1 and T_2 simultaneously transmit information to the relay in the first step. Then, the relay broadcasts its information in the second step. It was shown that the two-way relaying protocols, which exploit the shared broadcast channel nature of the wireless medium, have higher spectral efficiency than one-way relaying protocols [11][12][1].

Since two-way relaying protocols can achieve high spectral efficiency, they also have great potential to further improve the CRNs performance. Most of the current studies consider the scenario where secondary users share the spectrum of the primary user as long as they do not interfere with primary user operations and thus spectrum sensing is not required. In [13-15], two-way relays acted by secondary users are applied to assist two primary users' bi-directional traffic. In exchange for secondary users relaying services, secondary users either broadcast

[1] This paper mainly takes advantage of high spectral efficiency of two-way relaying protocols. However, for achieving the high spectral efficiency, two-way relaying protocols need some sacrifices at some other aspects, such as hardware implementation and communication complexity. For example, two-way relaying protocols require more critical synchronization than one-way relaying protocols including source to source node synchronization, and handshaking between the sources and relay nodes. Another example is that for the successful self-interference cancellation in two-way relaying protocols, the appropriate channel estimation schemes are needed to estimate both source to relay channels and relay to source channels.

secondary information in the last step of the two-way relaying protocols [13], or achieve their own communication in the primary user's sub-channels for a fraction of time [14][15]. It was demonstrated that the performance of both the primary and secondary systems can be enhanced by cooperation between the primary and secondary users [16].

In the other scenario which is also considered in this paper, secondary users achieve their own communication only in the spectrum holes and thus spectrum sensing is required. For this scenario, the two-step two-way relaying protocol is discussed for the spectrum sensing improvement in [17], where secondary users serve as two-way relays to assist the bi-directional traffic between two primary users and in the second step of the protocol, the secondary users broadcast their information to the cognitive base station (i.e., fusion center) which determines whether the primary users are present or not. However, when the bidirectional traffic between two secondary users is performed through the help of the two-way relays, the performance of secondary data transmissions has not been fully studied. This has motivated our work.

In non-cognitive radio networks, the performance of two-way relaying assisted information exchange between two end-sources has been extensively analyzed. Paper [18] compares the outage probability of two-step and three-step two-way protocols based on decode-and-forward (DF) relaying, where the three-step protocol is better than the two-step protocol at the high signal-to-noise ratio (SNR) region. The amplify-and-forward (AF) and DF relaying of two-step two-way relaying protocols are investigated in [19], where outage probability performance of DF outperforms that of AF as all nodes have a single antenna and the target rates of two end-sources are equal. For the networks including multiple two-way relays, the optimal relaying selection among a group of relays usually achieves full diversity and high spectral efficiency through saving the used channels. Paper [20] discusses a relay selection scheme for two-step AF relaying networks, which is to maximize the worse received signal-to-noise ratio (SNR) of the two end-sources. Then, paper [21] investigates the relay selection for three-step DF relaying channels, which is to minimize the average sum bit-error-rate (BER) of the two end-sources. Considering the imperfect channel state information (CSI) with a high feedback rate and a sufficiently high maximum Doppler Shift, paper [22] discusses the partial relay selection for AF relays.

Compared with the above performance analysis of two-way relaying protocols in non-cognitive radio networks, CRNs face two challenges. The first is that the mutual interference between the primary and the secondary users has to be considered [23][24] due to the coexisting of the primary and secondary users in the same spectrum and due to the existing of the false alarm of spectrum holes, which means imperfect spectrum sensing. The second is that spectrum sensing and secondary data transmissions must be jointly designed, since they are closely connected [25][26].

In this paper, we focus on two-way relaying assisted secondary data transmissions with multiple relays and jointly consider spectrum sensing and bidirectional data transmissions. The main contributions of this paper are summarized as follows. First, we extend the idea of the one-way relaying assisted SFSS-BRDT (selective fusion spectrum sensing and best relay data transmission) scheme [10] to the two-way relaying scenario, i.e., the SFSS is used for achieving spectrum sensing results and then the best relay is selected from a group of two-way cognitive relays to help the bidirectional traffic between two secondary users. Second, two-step and three-step bidirectional secondary data transmission (BSDT) schemes (i.e., two-BSDT and three-BSDT schemes) are proposed, where the typical two-step and three-step two-way relaying protocols based on DF relaying are applied in bidirectional secondary data transmissions. Finally, the closed-form asymptotic expressions of outage probabilities are derived for the two proposed schemes, where the interference from the primary user to secondary users is considered due to the existence of the false alarm of spectrum holes. Meanwhile, under a primary user protection constraint, we calculate and evaluate the spectrum hole utilization which is the percentage of spectrum holes utilized by two secondary users for their successful information exchange without channel outage.

The remainder of the paper is organized as follows. In Section 2, we describe the system model and propose two-BSDT and three-BSDT schemes. Section 3 derives outage probabilities of the proposed schemes. Next, in Section 4, we conduct the computer simulations and numerical evaluations. Finally, Section 5 gives some concluding remarks.

2. System Model

In a primary network, a primary user works on a slotted structure. In each time slot, either the spectrum is occupied by the primary user, or it is idle. On the other hand, a cognitive relay network coexists with the primary network, where a set of M secondary users as cognitive relays (CRs) denoted by $\psi = \{\mathrm{CR}_i | \, i = 1,2, \ldots, M\}$ assists a secondary user $\mathrm{SU_s}$ for both sensing the spectrum hole unoccupied by the primary user in a fraction of time and exchanging information with another secondary user $\mathrm{SU_d}$. The direct link between $\mathrm{SU_s}$ and $\mathrm{SU_d}$ does not exist due to the poor quality of the channel. A time slotted structure of cognitive transmissions is illustrated in **Fig. 1** which includes the spectrum sensing slot α and the secondary data transmission slot $1-\alpha$. The parameter α is also referred to as spectrum sensing overhead.

To be practically feasible, all nodes operate in half-duplex mode. Each wireless link between two terminals is modeled as a Rayleigh fading channel where the fading process is considered as constant during one time slot. The independent channel coefficients from two different terminals a to b (or a$\rightarrow$b) is denoted as h_{ab}. Notice that random variables (RVs) $|h_{ab}|^2$ follow exponential distributions with mean σ_{ab}^2. In addition, we denote the terminals $\mathrm{SU_s}$, $\mathrm{SU_d}$, CR_i and the primary user as the subscripts s, d, i, and p. The transmitting power at each terminal is P_l, where $l \in \{s, d, i, p\}$. The additive white Gaussian noise (AWGN) at all receivers is modeled as a complex Gaussian random variable with zero mean and variance N_0. Thus, the SNR at each terminal can be given by $\gamma_l = P_l/N_0$. R_s and R_d are the data rate at $\mathrm{SU_s}$ and $\mathrm{SU_d}$, respectively.

2.1 Spectrum Sensing

We refer to [10] for designing the spectrum sensing protocol. In the first sub-phase of spectrum sensing as shown in **Fig. 1**, i.e., the first sub-phase of the time slot k, $\mathrm{SU_s}$ and CRs independently detect a spectrum hole and each secondary user applies an energy detection method[2].

In the second sub-phase, i.e., the second sub-phase of the time slot k, the detection results of all CRs are forwarded to $\mathrm{SU_s}$ for fusion with an "AND" rule. In order to avoid interfering with the primary user in this sub-phase, a common control channel (CCC) is applied to forward the CRs' detection results [27]. Here, we consider only the selective fusion spectrum sensing

[2] To simplify the analysis of spectrum sensing, we assume that $\mathrm{SU_d}$ does not assist in sensing the spectrum hole. In fact, if $\mathrm{SU_d}$ joins in detecting the primary user, it only means that the number of secondary users to sensing the spectrum hole adds one and becomes M + 2. Therefore, we can discuss the different value of M to know the performance diversity as $\mathrm{SU_d}$ participates in the spectrum sensing.

(SFSS) scheme in [10], where only the successfully decoded outcomes in SU_s are selected for fusion.

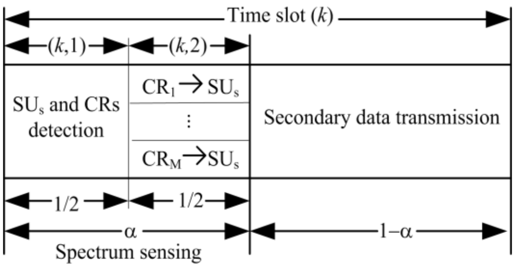

Fig. 1. Time slotted structure of cognitive transmissions

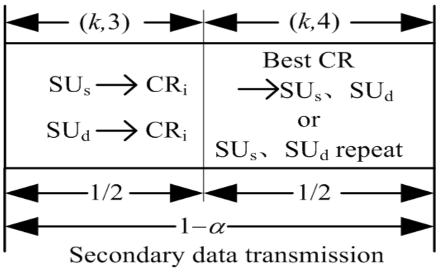

Fig. 2. Time slotted structure of two-BSDT scheme

Notice that the above spectrum sensing protocol belongs to the parallel sensing strategy [28][29] where the secondary users simultaneously sense a primary user's channel in a time slot and update the channel selections in the next slot. In the scenario with existing multiple primary users, a secondary user can simultaneously utilize the method of wideband spectrum sensing [30] to detect multiple users.

For notational convenience, we denote $H_p(k)$ to represent whether there is a spectrum hole unoccupied by the primary user for the time slot k. Let $H_p(k) = H_0$ if there is a spectrum hole for the time slot k. Otherwise, we set $H_p(k) = H_1$. Meanwhile, $H_p(k)$ can be modeled as a Bernoulli random variable with parameter P_a, i.e., $\Pr\{H_p(k) = H_0\} = P_a$ and $\Pr\{H_p(k) = H_1\} = 1 - P_a$. For a clear representation of the detection of spectrum holes, we denote $H_s(k)$ as the final fusion sensing result at SU_s for the time slot k. Then, the detection probability of spectrum holes is represented as $P_{ds} = \Pr\{H_s(k) = H_0|H_p(k) = H_0\}$. Similarly, the false alarm probability of spectrum holes is given by $P_{fs} = \Pr\{H_s(k) = H_0|H_p(k) = H_1\}$.

2.2 Secondary Data Transmission

After a spectrum hole is detected by spectrum sensing, the related information of the SU_d node (e.g. the code of SU_d receiver) is broadcast to the CRs by SU_s over the CCC. Then, SU_s, CRs and SU_d are switched to the channel of the detected hole to build a communication link. In **Section 2.2.1** and **2.2.2**, the received signals and the signal-to-interference-and-noise ratios (SINR) at terminals SU_s, SU_d and CR_i are given when the interference from the primary user is considered[3], which means the false alarm of spectrum holes occurs. For the case that no false alarm of spectrum holes exists, the received signals and SNRs at these terminals are not given, since they can be easily obtained by deleting *the primary user interference terms* of those corresponding expressions with the interference from the primary user. Additionally, for

[3] We assume that secondary users know the channel state information (CSI) of the primary user and the estimation of channels between diferent secondary users is perfect. Such assumption has also been widely adopted in existing literature such as [9][10][16][17]. Additionally, a method to estimate the channels of the primary user by referring to [34] is to utilize the pilot symbols transmitted from the primary transmitter to its receiver for the estimation of the channels between the two primary transceivers. Specifically, when the primary user transmits a pilot symbol at the beginning of its transmission frame, the secondary users observe pilot signals during the spectrum sensing and then each secondary user estimates the CSI of the primary user using the pilot signals. A method to estimate secondary users channel information is the pilot-assisted channel estimation using compressing sensing techniques for the OFDM-based cognitive radio networks [35]. To be specific, secondary transmitters send pilot symbols to other secondary receivers using some idle subcarriers detected by spectrum sensing. Then, the secondary receivers perform the sparse channel estimation using the pilot symbols. Note that for the sparse channel estimation using compressing sensing techniques, the pilot design is necessary at the secondary transmitters and the results of the pilot design need to be sent to the secondary receivers through a common control channel.

protecting the primary user from the secondary signals' interference, the false alarm probability P_{fs} of spectrum holes should be guaranteed to a target value. Hence, through the paper, we consider $P_{fs} = 0.001$ to protect the primary user's quality-of-service (QoS)[4].

2.2.1 Two-BSDT Scheme

The two-BSDT scheme needs two sub-phases to complete the bidirectional data exchange between SU_s and SU_d as shown in **Fig. 2**. In the first sub-phase, SU_s and SU_d simultaneously send their data to CRs. Thus, the received signal at CR_i is expressed as

$$y_i(k,3) = h_{si}\sqrt{P_s}x_s(k,3) + h_{di}\sqrt{P_d}x_d(k,3) + h_{pi}\sqrt{P_p}x_p(k,3) + n_i(k,3) \tag{1}$$

where $x_s(k,3)$, $x_d(k,3)$ and $x_p(k,3)$ are the transmitting signals for the third sub-phase of the time slot k at terminals SU_s, SU_d and the primary user, respectively. $n_i(k,3)$ is AWGN at CR_i. *The primary user interference term* $h_{pi}\sqrt{P_p}x_p(k,3)$ expresses the interference from the primary user.

In the second sub-phase, i.e., the fourth sub-phase of the time slot k, all CRs decode their received signals. We define a decoding set D which includes a non-empty subcollection D_m of all CRs and an empty set $\varnothing$.

• Case 1: $D = D_m$. Those CR_i which have successfully decoded both $x_s(k,3)$ and $x_d(k,3)$ form D_m. First, we define events

$$E_{s\to i} = \left\{ \frac{1-\alpha}{2}\log_2\left(1+\frac{|h_{si}|^2\gamma_s}{|h_{di}|^2\gamma_d + |h_{pi}|^2\gamma_p + 1}\right) > R_s \right\} \tag{2}$$

and

$$E_{d\to i} = \left\{ \frac{1-\alpha}{2}\log_2\left(1+\frac{|h_{di}|^2\gamma_d}{|h_{si}|^2\gamma_s + |h_{pi}|^2\gamma_p + 1}\right) > R_d \right\} \tag{3}$$

from Eq.(1) with considering the primary user interference term. Then, the event $E(i)$ of successfully decoding at CR_i includes three events $E_1(i)$, $E_2(i)$ and $E_3(i)$. Specifically, $E_1(i)$ is that $E_{s\to i}$ and $E_{d\to i}$ are both satisfied, i.e., $E_1(i) = E_{s\to i} \cap E_{d\to i}$. The events $E_2(i)$ and $E_3(i)$ happen when only $E_{s\to i}$ or $E_{d\to i}$ is satisfied and the corresponding event

$$E_{d\to i}^{\text{SIC}} = \left\{ \frac{1-\alpha}{2}\log_2\left(1+\frac{|h_{di}|^2\gamma_d}{|h_{pi}|^2\gamma_p + 1}\right) > R_d \right\}$$

or

$$E_{s\to i}^{\text{SIC}} = \left\{ \frac{1-\alpha}{2}\log_2\left(1+\frac{|h_{si}|^2\gamma_s}{|h_{pi}|^2\gamma_p + 1}\right) > R_s \right\}$$

is satisfied. That means $E_2(i) = E_{s\to i} \cap \overline{E_{d\to i}} \cap E_{d\to i}^{\text{SIC}}$ and $E_3(i) = \overline{E_{s\to i}} \cap E_{d\to i} \cap E_{s\to i}^{\text{SIC}}$, where CR_i

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[4] According to IEEE 802.22 requirement, the detection probability P_d of the presence of primary user should be guaranteed to a target value, i.e., $P_d = \Pr\{H_s(k) = H_1 | H_p(k) = H_1\} \geq 0.9$. Therefore, the false alarm probability P_{fs} of spectrum holes equals $1 - P_d$ and needs to be below 0.1, i.e., $P_{fs} \leq 0.1$.

will attempt successive interference cancellation (SIC) to decode the remaining data stream [31]. Thus, the event E(i) can be given by[5]

$$\mathrm{E}(i)=\mathrm{E}_1(i)\cup\mathrm{E}_2(i)\cup\mathrm{E}_3(i)=(\mathrm{E}_{s\to i}\cap\mathrm{E}^{\mathrm{SIC}}_{d\to i})\cup(\mathrm{E}^{\mathrm{SIC}}_{s\to i}\cap\mathrm{E}_{d\to i}),\quad i\in D_m \tag{4}$$

Meanwhile, CR$_j$ in the complementary set of D_m (i.e., $\bar{D}_m=\psi-D_m$) fails to decode its received signals, which satisfies

$$\bar{\mathrm{E}}(j)=\overline{(\mathrm{E}_{s\to j}\cap\mathrm{E}^{\mathrm{SIC}}_{d\to j})\cup(\mathrm{E}^{\mathrm{SIC}}_{s\to j}\cap\mathrm{E}_{d\to j})},\quad j\in\bar{D}_m \tag{5}$$

where the expressions of $\mathrm{E}_{s\to j}$, $\mathrm{E}^{\mathrm{SIC}}_{d\to j}$, $\mathrm{E}^{\mathrm{SIC}}_{s\to j}$ and $\mathrm{E}_{d\to j}$ are obtained from those of $\mathrm{E}_{s\to i}$, $\mathrm{E}^{\mathrm{SIC}}_{d\to i}$, $\mathrm{E}^{\mathrm{SIC}}_{s\to i}$ and $\mathrm{E}_{d\to i}$, respectively, by changing their subscript i to j. Similarly, as the primary user interference does not exist, the event $\tilde{\mathrm{E}}(i)$ of CR$_i$ successful decoding in the set D_m and the event $\bar{\tilde{\mathrm{E}}}(j)$ of CR$_j$ decoding failure in the set $\bar{D}_m$ can be respectively given by

$$\tilde{\mathrm{E}}(i)=(\tilde{\mathrm{E}}_{s\to i}\cap\tilde{\mathrm{E}}^{\mathrm{SIC}}_{d\to i})\cup(\tilde{\mathrm{E}}^{\mathrm{SIC}}_{s\to i}\cap\tilde{\mathrm{E}}_{d\to i}),\quad i\in D_m \tag{6}$$

$$\bar{\tilde{\mathrm{E}}}(j)=\overline{(\tilde{\mathrm{E}}_{s\to j}\cap\tilde{\mathrm{E}}^{\mathrm{SIC}}_{d\to j})\cup(\tilde{\mathrm{E}}^{\mathrm{SIC}}_{s\to j}\cap\tilde{\mathrm{E}}_{d\to j})},\quad j\in\bar{D}_m \tag{7}$$

where

$$\tilde{\mathrm{E}}_{s\to t}=\left\{\frac{1-\alpha}{2}\log_2\left(1+\frac{|h_{st}|^2\gamma_s}{|h_{dt}|^2\gamma_d+1}\right)>R_s\right\},\tilde{\mathrm{E}}_{d\to t}=\left\{\frac{1-\alpha}{2}\log_2\left(1+\frac{|h_{dt}|^2\gamma_d}{|h_{st}|^2\gamma_s+1}\right)>R_d\right\},$$
$$\tilde{\mathrm{E}}^{\mathrm{SIC}}_{s\to t}=\left\{\frac{1-\alpha}{2}\log_2\left(1+|h_{st}|^2\gamma_s\right)>R_s\right\},\tilde{\mathrm{E}}^{\mathrm{SIC}}_{d\to t}=\left\{\frac{1-\alpha}{2}\log_2\left(1+|h_{dt}|^2\gamma_d\right)>R_d\right\},t\in\{i,j\}.$$

In the set D_m, only the best relay is selected to broadcast its signal through network coding (bitwise XOR between SU$_\mathrm{s}$'s and SU$_\mathrm{d}$'s decoded data streams [32]). Then, the respective received signals at the two end-sources are expressed as

$$y_s(k,4\,|\,D=D_m)=h_{is}\sqrt{P_i}x_i(k,4)+h_{ps}\sqrt{P_p}x_p(k,4)+n_s(k,4) \tag{8}$$
$$y_d(k,4\,|\,D=D_m)=h_{id}\sqrt{P_i}x_i(k,4)+h_{pd}\sqrt{P_p}x_p(k,4)+n_d(k,4) \tag{9}$$

where $x_i(k,4)$ and $x_p(k,4)$ are the transmitting signals for the fourth sub-phase of the time slot k at CR$_i$ and the primary user, respectively. $n_s(k,4)$ and $n_d(k,4)$ are AWGN at SU$_\mathrm{s}$ and SU$_\mathrm{d}$, respectively. *The primary user interference terms* are $h_{ps}\sqrt{P_p}x_p(k,4)$ and $h_{pd}\sqrt{P_p}x_p(k,4)$. Hence, the corresponding received SINR are given by

[5] Here, we refer to [31] for defining the event E(i) of successfully decoding at CR$_i$. Considering the practical scenario where SU$_\mathrm{s}$ and SU$_\mathrm{d}$ lack mutual cooperation and coordination, and each of them selects a fixed data rate to simultaneously transmit their signals to CR$_i$, we eliminate the event that both $\mathrm{E}^{\mathrm{SIC}}_{s\to i}$ and $\mathrm{E}^{\mathrm{SIC}}_{d\to i}$ are satisfied as events $\mathrm{E}_{s\to i}$ and $\mathrm{E}_{d\to i}$ are both unsatisfied. If both $\mathrm{E}^{\mathrm{SIC}}_{s\to i}$ and $\mathrm{E}^{\mathrm{SIC}}_{d\to i}$ are satisfied, SU$_\mathrm{s}$ and SU$_\mathrm{d}$ will transmit signals to CR$_i$, respectively, without the interference from each other.

$$\mathrm{SINR_s}(\mathrm{CR}_i) = \frac{|h_{is}|^2 \gamma_i}{|h_{ps}|^2 \gamma_p + 1}, \quad i \in D_m \tag{10}$$

$$\mathrm{SINR_d}(\mathrm{CR}_i) = \frac{|h_{id}|^2 \gamma_i}{|h_{pd}|^2 \gamma_p + 1}, \quad i \in D_m \tag{11}$$

In general, the "best" relay is defined as achieving the maximum of the worse SINR of the two-way links from CR_i to $\mathrm{SU_s}$ and $\mathrm{SU_d}$. The selection criterion can be expressed as[6]

$$\text{Best relay} = \arg\max_{i \in D_m} \min(\mathrm{SINR_s}(\mathrm{CR}_i), \mathrm{SINR_d}(\mathrm{CR}_i)) \tag{12}$$

Then, the received SINR at the selected best link is given by

$$\mathrm{SINR_{best}}(\mathrm{CR}_i)(D = D_m) = (\mathrm{SINR_s}(\mathrm{CR_{bestrelay}}), \mathrm{SINR_d}(\mathrm{CR_{bestrelay}})) \tag{13}$$

• Case 2: $D = \varnothing$, i.e., D is empty. All CRs in the set ψ fail to decode the received signals. That means the event $\overline{\mathrm{E}}(i)$ or $\overline{\tilde{\mathrm{E}}}(i)$ with no interference from the primary user is satisfied as

$$\overline{\mathrm{E}}(i) = \overline{(\mathrm{E}_{s\to i} \cap \mathrm{E}^{\mathrm{SIC}}_{d\to i}) \cup (\mathrm{E}^{\mathrm{SIC}}_{s\to i} \cap \mathrm{E}_{d\to i})}, \quad i \in \psi \tag{14}$$

$$\overline{\tilde{\mathrm{E}}}(i) = \overline{(\tilde{\mathrm{E}}_{s\to i} \cap \tilde{\mathrm{E}}^{\mathrm{SIC}}_{d\to i}) \cup (\tilde{\mathrm{E}}^{\mathrm{SIC}}_{s\to i} \cap \tilde{\mathrm{E}}_{d\to i})}, \quad i \in \psi \tag{15}$$

Thus, an outage of data transmission occurs and then $\mathrm{SU_s}$ and $\mathrm{SU_d}$ will start a new transmitting process.

2.2.2 Three-BSDT Scheme

The three-BSDT scheme which includes three sub-phases is displayed in **Fig. 3**. The two end-sources $\mathrm{SU_s}$ and $\mathrm{SU_d}$ broadcast each data to CRs in the first and second sub-phases (i.e. the third and fourth sub-phases of the time slot k), respectively. The corresponding signals received at CR_i are expressed as

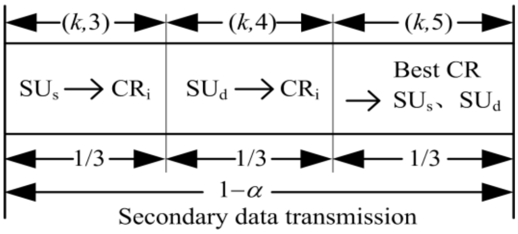

Fig. 3. Time slotted structure of three-BSDT scheme

[6] Here, the best-relay selection criterion takes into account the condition of the interference links from the primary user to the two end-sources, different from [20] where it is in non-cognitive radio two-way relaying networks that there is no primary user. Additionally, for using the best-relay selection criterion, a centralized algorithm can be developed by referring to [9][33]. Specifically, a table including the related channel information (i.e., $|h_{is}|^2$, $|h_{id}|^2$, $|h_{ps}|^2$, $|h_{pd}|^2$) should be maintained at $\mathrm{SU_s}$. Note that $|h_{is}|^2$ and $|h_{id}|^2$ may be estimated by CRs, while $|h_{ps}|^2$ and $|h_{pd}|^2$ could be estimated by $\mathrm{SU_s}$ and $\mathrm{SU_d}$, respectively. Then, such channel information is transmitted to $\mathrm{SU_s}$ over CCC. Finally, using the proposed criterion (i.e., Eq. (12)), the best relay can be determined by looking up the table.

$$y_i(k,3) = h_{si}\sqrt{P_s}x_s(k,3) + h_{pi}\sqrt{P_p}x_p(k,3) + n_i(k,3) \quad (16)$$

$$y_i(k,4) = h_{di}\sqrt{P_d}x_d(k,4) + h_{pi}\sqrt{P_p}x_p(k,4) + n_i(k,4) \quad (17)$$

where $x_d(k,4)$ is the transmitting signal at SU_d for the fourth sub-phase of the time slot k. $n_i(k,4)$ is AWGN at CR_i. $h_{pi}\sqrt{P_p}x_p(k,3)$ and $h_{pi}\sqrt{P_p}x_p(k,4)$ are *the primary user interference terms*.

In the third sub-phase, i.e. the fifth sub-phase of time slot k, all CRs decode their received signals. Being similar to two-BSDT scheme, we define a decoding set D.

• Case 1: $D = D_m$. Those CR_i which have successfully decoded both $x_s(k,3)$ and $x_d(k,4)$ form D_m. Considering the primary user interference terms, we define events

$$\mathrm{F}_{s\to i} = \left\{ \frac{1-\alpha}{3}\log_2\left(1+\frac{|h_{si}|^2\gamma_s}{|h_{pi}|^2\gamma_p+1}\right) > R_s \right\} \quad (18)$$

and

$$\mathrm{F}_{d\to i} = \left\{ \frac{1-\alpha}{3}\log_2\left(1+\frac{|h_{di}|^2\gamma_d}{|h_{pi}|^2\gamma_p+1}\right) > R_d \right\} \quad (19)$$

from Eqs.(16) and (17). In the set D_m, the event $\mathrm{F}(i)$ of CR_i successful decoding is expressed as

$$\mathrm{F}(i) = \mathrm{F}_{s\to i} \cap \mathrm{F}_{d\to i}, \;\; i \in D_m . \quad (20)$$

Due to the lack of a direct link between the two end-sources, the case that only one of the signals $x_s(k,3)$ and $x_d(k,4)$ is successfully decoded at CR_i can not achieve the successful bidirectional data exchange between the two end-sources and thus is not included in the set D_m. Then, the event $\bar{\mathrm{F}}(j)$ of CR_j decoding failure in the set $\bar{D}_m$ is given by

$$\bar{\mathrm{F}}(j) = \overline{\mathrm{F}_{s\to j} \cap \mathrm{F}_{d\to j}}, \;\; j \in \bar{D}_m \quad (21)$$

where the expressions of $\mathrm{F}_{s\to j}$ and $\mathrm{F}_{d\to j}$ are obtained from those of Eqs. (18) and (19), respectively, whose subscript is are converted into js. Similarly, as the primary user interference does not exist, the event $\tilde{\mathrm{F}}(i)$ of CR_i successful decoding in the set D_m and the event $\tilde{\bar{\mathrm{F}}}(j)$ of CR_j decoding failure in the set $\bar{D}_m$ are respectively expressed as

$$\tilde{\mathrm{F}}(i) = \tilde{\mathrm{F}}_{s\to i} \cap \tilde{\mathrm{F}}_{d\to i}, \;\; i \in D_m \quad (22)$$

$$\tilde{\bar{\mathrm{F}}}(j) = \overline{\tilde{\mathrm{F}}_{s\to j} \cap \tilde{\mathrm{F}}_{d\to j}}, \;\; j \in \bar{D}_m \quad (23)$$

where

$$\tilde{\mathrm{F}}_{s\to t} = \left\{ \frac{1-\alpha}{3}\log_2\left(1+|h_{st}|^2\gamma_s\right) > R_s \right\}, \; \tilde{\mathrm{F}}_{d\to t} = \left\{ \frac{1-\alpha}{3}\log_2\left(1+|h_{dt}|^2\gamma_d\right) > R_d \right\}, \; t \in \{i, j\} .$$

In the set D_m, only the best relay is selected to broadcast its signal through network coding. Thus, the respective received signals at the two end-sources are expressed as

$$y_s(k,5\,|\,D=D_m)=h_{is}\sqrt{P_i}x_i(k,5)+h_{ps}\sqrt{P_p}x_p(k,5)+n_s(k,5) \tag{24}$$

$$y_d(k,5\,|\,D=D_m)=h_{id}\sqrt{P_i}x_i(k,5)+h_{pd}\sqrt{P_p}x_p(k,5)+n_d(k,5) \tag{25}$$

where $x_i(k,5)$ and $x_p(k,5)$ are the transmitting signals for the fifth sub-phase of the time slot k at CR_i and the primary user, respectively. $n_s(k,5)$ and $n_d(k,5)$ are AWGN at SU_s and SU_d, respectively. *The primary user interference terms* are $h_{ps}\sqrt{P_p}x_p(k,5)$ and $h_{pd}\sqrt{P_p}x_p(k,5)$. From Eqs.(24) and (25), we obtain the corresponding SINR at the two end-sources just as Eqs.(10) and (11). Besides, the selection criterion of the best relay is also the same as Eqs.(12) and (13) in the two-BSDT scheme.

- Case 2: $D=\varnothing$, i.e., D is empty and all CRs in the set ψ fail to decode the received signals.

Then, the event $\bar{\mathrm{F}}(i)$ (or $\bar{\tilde{\mathrm{F}}}(i)$ as no interference from the primary user) is satisfied, i.e.,

$$\bar{\mathrm{F}}(i)=\overline{\mathrm{F}_{s\to i}\cap \mathrm{F}_{d\to i}},\quad i\in\psi \tag{26}$$

$$\bar{\tilde{\mathrm{F}}}(i)=\overline{\tilde{\mathrm{F}}_{s\to i}\cap \tilde{\mathrm{F}}_{d\to i}},\quad i\in\psi \tag{27}$$

Thus, the data transmission outage happens.

3. Outage Probability

3.1 Two-BSDT Scheme

Since the aim of the two-way relaying network is to exchange information between two end-sources, an outage event is declared when the channel capacity of either $SU_s\to SU_d$ or $SU_d\to SU_s$ falls below the data rate. Thus, the outage probability of two-BSDT scheme can be calculated as

$$\begin{aligned}\mathrm{P_{out}}&=\Pr\left\{\frac{1-\alpha}{2}\log_2(1+\mathrm{SINR})<R\right\}\\&=\Pr\{\mathrm{SINR}(D=\varnothing)<\gamma\Delta,D=\varnothing\}+\sum_{m=1}^{2^M-1}\Pr\{\min\left(\mathrm{SINR_{best}}(D=D_m)\right)<\gamma\Delta,D=D_m\}\end{aligned} \tag{28}$$

where $R=R_s=R_d$ and $\Delta=[2^{2R/(1-\alpha)}-1]/\gamma_s$. Assuming that $\gamma_p=a\gamma_s$ where a is a constant. The transmitting power of all secondary users is assumed to be equal, which means $\gamma_s=\gamma_d=\gamma_i=\gamma$. According to Eq.(13) and the definition of $D=D_m$ in **Section 2.2.1**, and considering the spectrum hole sensing results P_{ds} and P_{fs}, we write the term $\Pr\{\min(\mathrm{SINR_{best}}(D=D_m))<\gamma\Delta, D=D_m\}$ in Eq.(28) as

$$\begin{aligned}&\Pr\{\min\left(\mathrm{SINR_{best}}(D=D_m)\right)<\gamma\Delta,D=D_m\}\\&=\mathrm{P_a P_{ds}}\Pr\{\max_{i\in D_m}\min(|h_{is}|^2,|h_{id}|^2)<\Delta\}\times\prod_{i\in D_m}\Pr\{\tilde{\mathrm{E}}(i)\}\times\prod_{j\in\bar{D}_m}\Pr\left\{\bar{\tilde{\mathrm{E}}}(j)\right\}\\&+(1-\mathrm{P_a})\mathrm{P_{fs}}\Pr\left\{\max_{i\in D_m}\min\left(\frac{|h_{is}|^2}{|h_{ps}|^2\gamma_p+1},\frac{|h_{id}|^2}{|h_{pd}|^2\gamma_p+1}\right)<\Delta\right\}\times\prod_{i\in D_m}\Pr\{\mathrm{E}(i)\}\times\prod_{j\in\bar{D}_m}\Pr\{\bar{\mathrm{E}}(j)\}\end{aligned} \tag{29}$$

From Eqs.(6) and (4), we obtain the probabilities

$$\begin{aligned}\Pr\{\tilde{\mathrm{E}}(i)\} &= \Pr(|h_{si}|^2 > \Delta |h_{di}|^2 \gamma + \Delta, |h_{di}|^2 > \Delta) + \Pr(|h_{di}|^2 > \Delta |h_{si}|^2 \gamma + \Delta, |h_{si}|^2 > \Delta) \\ &\quad - \Pr(|h_{si}|^2 > \Delta |h_{di}|^2 \gamma + \Delta,\ |h_{di}|^2 > \Delta |h_{si}|^2 \gamma + \Delta) \\ &= A(i)\exp(-\Gamma_1(i)\Delta) + B(i)\exp(-\Gamma_2(i)\Delta)\end{aligned} \tag{30}$$

$$\begin{aligned}\Pr\{\mathrm{E}(i)\} &= \Pr(|h_{si}|^2 > \Delta |h_{di}|^2 \gamma + \Delta |h_{pi}|^2 \gamma_p + \Delta,\ |h_{di}|^2 > \Delta |h_{pi}|^2 \gamma_p + \Delta) \\ &\quad + \Pr(|h_{di}|^2 > \Delta |h_{si}|^2 \gamma + \Delta |h_{pi}|^2 \gamma_p + \Delta,\ |h_{si}|^2 > \Delta |h_{pi}|^2 \gamma_p + \Delta) \\ &\quad - \Pr(|h_{si}|^2 > \Delta |h_{di}|^2 \gamma + \Delta |h_{pi}|^2 \gamma_p + \Delta,\ |h_{di}|^2 > \Delta |h_{si}|^2 \gamma + \Delta |h_{pi}|^2 \gamma_p + \Delta) \\ &= \frac{A(i)\exp(-\Gamma_1(i)\Delta)}{1+\Delta\gamma_p\sigma_{pi}^2\Gamma_1(i)} + \frac{B(i)\exp(-\Gamma_2(i)\Delta)}{1+\Delta\gamma_p\sigma_{pi}^2\Gamma_2(i)}\end{aligned} \tag{31}$$

where $A(i) = \sigma_{si}^2 / (\Delta\gamma\sigma_{di}^2 + \sigma_{si}^2)$, $B(i) = \sigma_{di}^2 / (\Delta\gamma\sigma_{si}^2 + \sigma_{di}^2)$, $\Gamma_1(i) = 1/\sigma_{di}^2 + (1+\Delta\gamma)/\sigma_{si}^2$ and $\Gamma_2(i) = 1/\sigma_{si}^2 + (1+\Delta\gamma)/\sigma_{di}^2$. According to Eqs.(7) and (30), $\Pr\{\bar{\tilde{\mathrm{E}}}(j)\}$ in Eq.(29) equals $1-\left[A(j)\exp(-\Gamma_1(j)\Delta) + B(j)\exp(-\Gamma_2(j)\Delta)\right]$. Similarly, $\Pr\{\bar{\mathrm{E}}(j)\} = 1 - A(j)\exp(-\Gamma_1(j)\Delta) \Big/ \left(1+\Delta\gamma_p\sigma_{pj}^2\Gamma_1(j)\right) - B(j)\exp(-\Gamma_2(j)\Delta) \Big/ \left(1+\Delta\gamma_p\sigma_{pj}^2\Gamma_2(j)\right)$ from Eqs.(5) and (31). The other terms in Eq.(29) are calculated as

$$\Pr\{\max_{i\in D_m} \min(|h_{is}|^2, |h_{id}|^2) < \Delta\} = \prod_{i\in D_m} \left\{1 - \exp[-(1/\sigma_{is}^2 + 1/\sigma_{id}^2)\Delta]\right\} \tag{32}$$

$$\begin{aligned}&\Pr\left\{\max_{i\in D_m} \min\left(\frac{|h_{is}|^2}{|h_{ps}|^2\gamma_p+1}, \frac{|h_{id}|^2}{|h_{pd}|^2\gamma_p+1}\right) < \Delta\right\} \\ &\quad = \Pr\{\max_{i\in D_m} X_i < \Delta\} = \Pr\{X_1 < \Delta, X_2 < \Delta, \ldots, X_{|D_m|} < \Delta\}\end{aligned} \tag{33}$$

In Eq.(33), X_i equals $\min\left(|h_{is}|^2 \big/ (|h_{ps}|^2\gamma_p + 1),\ |h_{id}|^2 \big/ (|h_{pd}|^2\gamma_p + 1)\right)$. We have proved in Appendix A that the event $X_i < \Delta$ is independent with other events $X_j < \Delta$ ($i, j \in D_\mathrm{m}$ and $i \neq j$) under the conditions of $\sigma_{ps}^4\gamma_p^2\Delta^2/(\sigma_{is}^2\sigma_{js}^2) \to 0$ and $\sigma_{pd}^4\gamma_p^2\Delta^2/(\sigma_{id}^2\sigma_{jd}^2) \to 0$. Thus, the closed-form asymptotic expression of Eq.(33) is given as

$$\begin{aligned}\Pr\{\max_{i\in D_m} X_i < \Delta\} &= \Pr\{X_i < \Delta\} \\ &= \prod_{i\in D_m}\left[1 - \Pr\left(\frac{|h_{is}|^2}{|h_{ps}|^2\gamma_p+1} > \Delta\right)\Pr\left(\frac{|h_{id}|^2}{|h_{pd}|^2\gamma_p+1} > \Delta\right)\right] \\ &= \prod_{i\in D_m}\left(1 - \frac{\exp\left[-(1/\sigma_{is}^2 + 1/\sigma_{id}^2)\Delta\right]}{(1+\Delta\gamma_p\sigma_{ps}^2/\sigma_{is}^2)(1+\Delta\gamma_p\sigma_{pd}^2/\sigma_{id}^2)}\right)\end{aligned} \tag{34}$$

Eq.(34) can be derived by Eq.(A.2) in Appendix A.

In addition, from Eqs.(14) and (15), the term $\Pr\{\mathrm{SINR}(D = \varnothing) < \gamma\Delta, D = \varnothing\}$ in Eq.(28) is found to be

$$\begin{aligned}&\Pr\{\mathrm{SINR}(D=\varnothing)<\gamma\Delta, D=\varnothing\}\\&=\mathrm{P_a P_{ds}}\prod_{i=1}^{M}\Pr\left\{\bar{\tilde{\mathrm{E}}}(i)\right\}+(1-\mathrm{P_a})\mathrm{P_{fs}}\prod_{i=1}^{M}\Pr\{\bar{\mathrm{E}}(i)\}+\mathrm{P_a}(1-\mathrm{P_{ds}})+(1-\mathrm{P_a})(1-\mathrm{P_{fs}})\end{aligned} \tag{35}$$

where $\Pr\left\{\bar{\tilde{\mathrm{E}}}(i)\right\}=1-\Pr\left\{\tilde{\mathrm{E}}(i)\right\}$ and $\Pr\{\bar{\mathrm{E}}(i)\}=1-\Pr\{\mathrm{E}(i)\}$, whose closed-form expressions can be obtained from Eqs.(30) and (31).

At this point, we have obtained the closed-form asymptotic expressions of the outage probability for two-BSDT scheme.

3.2 Three-BSDT Scheme

Being similar to Eq.(28), the outage probability of three-BSDT scheme can be expressed as

$$\begin{aligned}\mathrm{P_{out}}&=\Pr\left\{\frac{1-\alpha}{3}\log_2(1+\mathrm{SINR})<R\right\}\\&=\Pr\{\mathrm{SINR}(D=\varnothing)<\gamma\Lambda, D=\varnothing\}+\sum_{m=1}^{2^M-1}\Pr\{\min\left(\mathrm{SINR_{best}}(D=D_m)\right)<\gamma\Lambda, D=D_m\}\end{aligned} \tag{36}$$

where $\Lambda = [2^{3R/(1-\alpha)} - 1]/\gamma_s$. According to Eq.(13) and the definition of $D = D_{\mathrm{m}}$ in **Section 2.2.2**, and considering the spectrum hole sensing results $\mathrm{P_{ds}}$ and $\mathrm{P_{fs}}$, we write the term $\Pr\{\min(\mathrm{SINR_{best}}(D = D_{\mathrm{m}})) < \gamma\Lambda, D = D_{\mathrm{m}}\}$ in Eq.(36) as

$$\begin{aligned}&\Pr\{\min\left(\mathrm{SINR_{best}}(D=D_m)\right)<\gamma\Lambda, D=D_m\}\\&=\mathrm{P_a P_{ds}}\Pr\{\max_{i\in D_m}\min(|h_{is}|^2,|h_{id}|^2)<\Lambda\}\times\prod_{i\in D_m}\Pr\{\tilde{\mathrm{F}}(i)\}\times\prod_{j\in\bar{D}_m}\Pr\left\{\bar{\tilde{\mathrm{F}}}(j)\right\}\\&+(1-\mathrm{P_a})\mathrm{P_{fs}}\Pr\left\{\max_{i\in D_m}\min\left(\frac{|h_{is}|^2}{|h_{ps}|^2\gamma_p+1},\frac{|h_{id}|^2}{|h_{pd}|^2\gamma_p+1}\right)<\Lambda\right\}\times\prod_{i\in D_m}\Pr\{\mathrm{F}(i)\}\times\prod_{j\in\bar{D}_m}\Pr\{\bar{\mathrm{F}}(j)\}\end{aligned} \tag{37}$$

From Eqs.(22) and (20), we obtain the probabilities

$$\Pr\{\tilde{\mathrm{F}}(i)\}=\Pr(|h_{si}|^2>\Lambda,\ |h_{di}|^2>\Lambda)=\exp[-(1/\sigma_{si}^2+1/\sigma_{di}^2)\Lambda] \tag{38}$$

$$\begin{aligned}\Pr\{\mathrm{F}(i)\}&=\Pr(|h_{si}|^2>\Lambda|h_{pi}|^2\gamma_p+\Lambda,\ |h_{di}|^2>\Lambda|h_{pi}|^2\gamma_p+\Lambda)\\&=\frac{\exp\left[-(1/\sigma_{si}^2+1/\sigma_{di}^2)\Lambda\right]}{1+(\sigma_{pi}^2/\sigma_{si}^2+\sigma_{pi}^2/\sigma_{di}^2)\Lambda\gamma_p}\end{aligned} \tag{39}$$

where the closed-form expression of Eq.(39) is derived from Eq.(A.1) in Appendix A. According to Eqs.(23) and (38), $\Pr\left\{\bar{\tilde{\mathrm{F}}}(j)\right\}$ in Eq.(37) equals $1-\exp[-(1/\sigma_{sj}^2+1/\sigma_{dj}^2)\Lambda]$. Similarly, $\Pr\{\bar{\mathrm{F}}(j)\}$ is equal to $1-\exp\left[-(1/\sigma_{sj}^2+1/\sigma_{dj}^2)\Lambda\right]/\left[1+(\sigma_{pj}^2/\sigma_{sj}^2+\sigma_{pj}^2/\sigma_{dj}^2)\Lambda\gamma_p\right]$ from Eqs. (21) and (39). The other terms in Eq.(37) are expressed as

$$\Pr\{\max_{i\in D_m}\min(|h_{is}|^2,|h_{id}|^2)<\Lambda\}=\prod_{i\in D_m}\left\{1-\exp[-(1/\sigma_{is}^2+1/\sigma_{id}^2)\Lambda]\right\} \tag{40}$$

$$\Pr\left\{\max_{i\in D_m}\min\left(\frac{|h_{is}|^2}{|h_{ps}|^2\gamma_p+1},\frac{|h_{id}|^2}{|h_{pd}|^2\gamma_p+1}\right)<\Lambda\right\}=\prod_{i\in D_m}\left(1-\frac{\exp\left[-(1/\sigma_{is}^2+1/\sigma_{id}^2)\Lambda\right]}{(1+\Lambda\gamma_p\sigma_{ps}^2/\sigma_{is}^2)(1+\Lambda\gamma_p\sigma_{pd}^2/\sigma_{id}^2)}\right) \quad (41)$$

The closed-form expression of Eq. (40) is obtained by referring to Eq.(32). The closed-form asymptotic expression of Eq.(41) is similar to Eq.(34) and satisfies the conditions of $\sigma_{ps}^4\gamma_p^2\Lambda^2/(\sigma_{is}^2\sigma_{js}^2)\to 0$ and $\sigma_{pd}^4\gamma_p^2\Lambda^2/(\sigma_{id}^2\sigma_{jd}^2)\to 0$.

In addition, from Eqs.(26) and (27), we write the term $\Pr\{\mathrm{SINR}(D=\varnothing)<\gamma\Lambda, D=\varnothing\}$ in Eq.(36) as

$$\begin{aligned}&\Pr\{\mathrm{SINR}(D=\varnothing)<\gamma\Lambda, D=\varnothing\}\\&=\mathrm{P_a}\mathrm{P_{ds}}\prod_{i=1}^{M}\Pr\left\{\bar{\tilde{\mathrm{F}}}(i)\right\}+(1-\mathrm{P_a})\mathrm{P_{fs}}\prod_{i=1}^{M}\Pr\{\bar{\mathrm{F}}(i)\}+\mathrm{P_a}(1-\mathrm{P_{ds}})+(1-\mathrm{P_a})(1-\mathrm{P_{fs}})\end{aligned} \quad (42)$$

where $\Pr\left\{\bar{\tilde{\mathrm{F}}}(i)\right\}=1-\Pr\left\{\tilde{\mathrm{F}}(i)\right\}$ and $\Pr\{\bar{\mathrm{F}}(i)\}=1-\Pr\{\mathrm{F}(i)\}$, whose closed-form expressions can be obtained from Eqs.(38) and (39), respectively.

Now, we have derived the closed-formed asymptotic expressions of the outage probabilities for two-BSDT and three-BSDT schemes. According to [10], the definition of the spectrum hole utilization η is based on the derived outage probability, i.e.,

$$\eta=(1-\mathrm{P_{out}})/\mathrm{P_a}. \quad (43)$$

The spectrum hole utilization can be considered as a measure to quantify the percentage of spectrum holes utilized by $\mathrm{SU_s}$ and $\mathrm{SU_d}$ for their successful data exchange. In the next section, we give the numerical evaluation of η for the two BSDT schemes.

4. Simulation Results

In this section, we will evaluate the spectrum hole utilization for two-BSDT and three-BSDT schemes according to Eq.(43). For a primary user's QoS requirement, the false alarm probability $\mathrm{P_{fs}}$ of spectrum holes needs to be below a required target value. Here, we set $\mathrm{P_{fs}}$ = 0.001. In the spectrum sensing protocol, Eq.(29) in [10] can be applied to calculate the detection probability $\mathrm{P_{ds}}$ of spectrum holes under the given target value of $\mathrm{P_{fs}}$.

Considering the effect of the spectrum sensing on secondary data transmissions, we discuss the performance of the spectrum sensing first. **Fig. 4** shows that the detection probability $\mathrm{P_{ds}}$ of spectrum holes varies with the secondary SNR (γ_s), the channel gain σ_{pi}^2 and the number (M) of CRs. It is obvious that $\mathrm{P_{ds}}$ becomes larger with the rise of γ_s, the reason of which is that the higher γ_s results in the lower outage probability to transmit sensing results from CRs to $\mathrm{SU_s}$. As the gain σ_{pi}^2 of channels from the primary user to CR_i increases from 0.1 to 1, the energy of the primary user is more easily detected by CR_i, which leads to the rise of $\mathrm{P_{ds}}$. On the other hand, an increased number of CRs from M = 4 to 8 achieves higher $\mathrm{P_{ds}}$ due to the merit of the spectrum sensing protocol SFSS, i.e., although the rise of M and the limited CCC resources bring the transmission failure of initial sensing results received at $\mathrm{SU_s}$, the SFSS protocol is able to identify and discard such transmission failure, and thus the performance of the spectrum sensing is not affected.

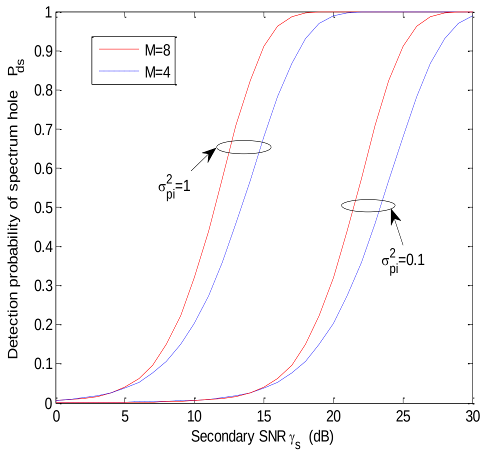

Fig. 4. Detection probability of spectrum holes versus secondary SNR with $P_a = 0.6$, $\alpha = 0.5$, $a = \sqrt{2}$, $\sigma_{si}^2 = \sigma_{is}^2 = \sigma_{di}^2 = \sigma_{id}^2 = 1$ and $\sigma_{pi}^2 =$

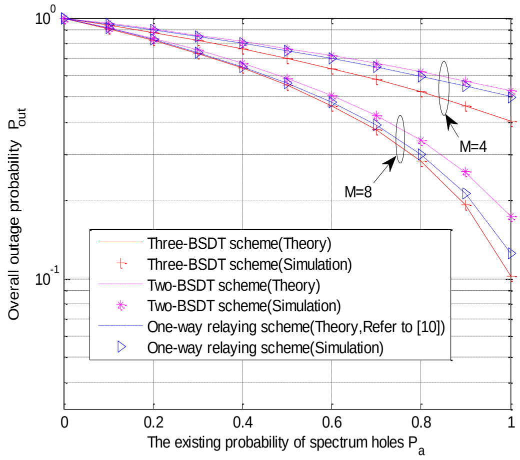

Fig. 5. Overall outage probability versus the existing probability of spetrum holes with $\alpha = 0.5$, $a = \sqrt{2}$, $R = 0.5$ bit/s/Hz, $\sigma_{si}^2 = \sigma_{is}^2 = \sigma_{di}^2 = \sigma_{id}^2 = 1$ and $\sigma_{pi}^2 = \sigma_{ps}^2 = \sigma_{pd}^2 = 1$.

Fig. 5 shows the overall outage probability versus the existing probability (P_a) of spectrum holes for two-BSDT scheme, three-BSDT scheme and one-way relaying scheme[7]. As observ--ed from **Fig. 5**, the overall outage probability decreases with the incremental existing probability of spectrum holes. The reason is that with the increasing P_a, cognitive users can transmit information through choosing more available spectrum holes in order to keep communicating without interruption. Moreover, the overall outage probability is further low as the number of cognitive relays increases from M = 4 to 8. It can be also seen that the two-BSDT scheme performs worse than both the three-BSDT and one-way relaying schemes, since the performance of the two-BSDT scheme is interference-limited, which is indicated by Eqs.(2) and (3). In addition, the simulations match the theoretical results very well.

Next, we give the spectrum hole utilization versus the secondary SNR (γ_s) for two-BSDT, three-BSDT and one-way relaying schemes as shown in **Fig. 6**. It is clear that the theoretical results fit well with the simulation and the three-BSDT scheme (in terms of spectrum hole utilization) outperforms both two-BSDT and one-way relaying schemes for both σ_{pi}^2=1 and 0.1. Additionally, the two-BSDT scheme appears a performance floor and thus performs worse than one-way relaying scheme in the high SNR region. This results indicates that for the best spectrum hole utilization, the two-BSDT scheme with network coding is not suitable for all SNR values. Therefore, compared with two-BSDT scheme, the three-BSDT scheme is the best choice across the whole SNR region. Considering the simple hardware implementation and low communication complexity, however, one-way relaying scheme is also attractive in high SNR, since its spectrum hole utilization is similar to that of the three-BSDT scheme in the high SNR region according to **Fig. 6**.

[7] One-way relaying scheme is obtained by referring to [10] where the cognitive relay CR_i acts as one-way relaying to assist the information transmission from SU_s to SU_d through two sub-phases. Being different from [10], one-way relaying scheme achieves the information exchange between SU_s and SU_d assisted by one-way relaying CR_i through four sub-phases. In addition, the direct link between SU_s and SU_d is not considered due to the poor quality of the channel.

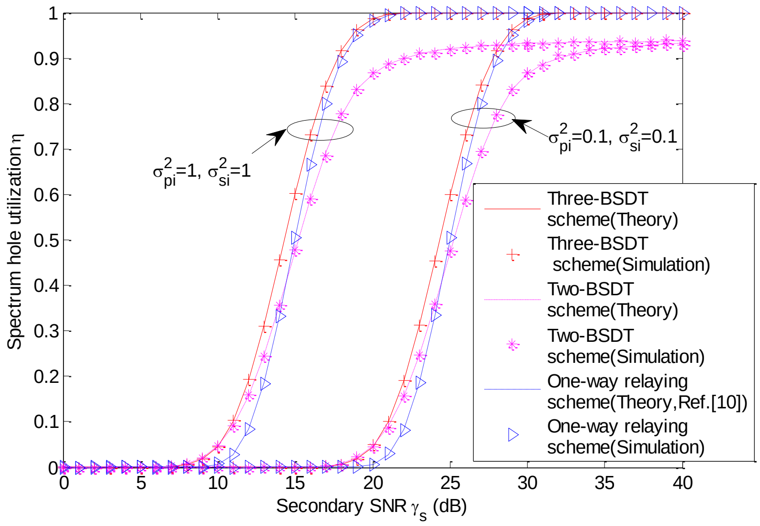

Fig. 6. Spectrum hole utilization versus secondary SNR with P_a = 0.6, α = 0.5, $a = \sqrt{2}$, R = 0.5 bit/s/Hz, M = 4, $\sigma^2_{si} = \sigma^2_{is} = \sigma^2_{di} = \sigma^2_{id}$ and $\sigma^2_{pi} = \sigma^2_{ps} = \sigma^2_{pd}$

For the comparison between $\sigma^2_{pi} = \sigma^2_{si}$ = 1 and 0.1 in **Fig. 6**, we can see that the spectrum hole utilizations of the three schemes are better for $\sigma^2_{pi} = \sigma^2_{si}$ = 1 than those for $\sigma^2_{pi} = \sigma^2_{si}$ = 0.1 which means that the channels from the primary user to CR_i and those among cognitive users have higher attenuation. This phenomenon shows that the decrease of P_{ds} with σ^2_{pi} from 1 to 0.1 as shown in **Fig. 4** becomes the dominant factor adversely resulting in the poor overall outage performance of secondary data transmissions, although the decrease of σ^2_{pi} from 1 to 0.1 degrades the interference from the primary user to CR_i and improves the partial outage performance. It also demonstrates that the spectrum sensing performance directly affects the spectrum hole utilization of secondary users.

In addition, we also investigate the spectrum hole utilization versus the number (M) of CRs in **Fig. 7** for symmetric channels where $\sigma^2_{si} = \sigma^2_{di}$ = 100 and asymmetric channels where σ^2_{si} =1, σ^2_{di} = 100. It is straightforward that the three-BSDT scheme and the two-BSDT scheme increase with the rise of M for both symmetric and asymmetric channels. The reason is that the spectrum hole detection performance of SFSS protocol is unaffected by many error initial sensing results which occur with an increased number of CRs, and thus the spectrum hole utilization is not diminished. Furthermore, we can find that when the number of CRs is smaller than a critical value, the spectrum hole utilization of the three-BSDT scheme for symmetric channels is better than that for asymmetric channels. The reason is that the asymmetric channel from SU_s to CR_i has larger attenuation (σ^2_{si} = 1) and thus the probability of successfully decoding at CR_i is lessened by this poor channel. However, the spectrum hole utilization of the two-BSDT scheme for asymmetric channels is better than that of symmetric channels before a critical value due to the interference-limited characteristic of the two-BSDT scheme. Specifically, for the poor channel in asymmetric channels, CR_i can use SIC to decode the data stream and thus the probability of successfully decoding at CR_i is higher for asymmetric channels. **Fig. 7** also demonstrates that, no matter which scheme (two-BSDT or three-BSDT) is used, the performance gap between symmetric channels and asymmetric

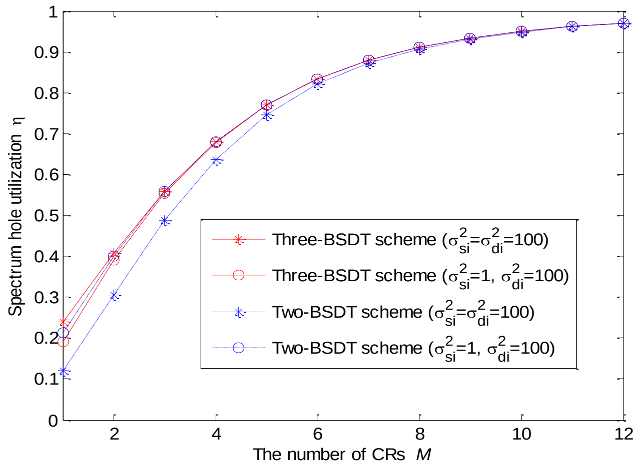

Fig. 7. Spectrum hole utilization versus the number of CRs with $P_a = 0.6$, $\alpha = 0.5$, $a = \sqrt{2}$, $R = 0.5$ bit/s/Hz, $\gamma_s = 15$ dB, $\sigma_{is}^2 = \sigma_{id}^2 = 100$ and $\sigma_{pi}^2 = \sigma_{ps}^2 = \sigma_{pd}^2 = 1$.

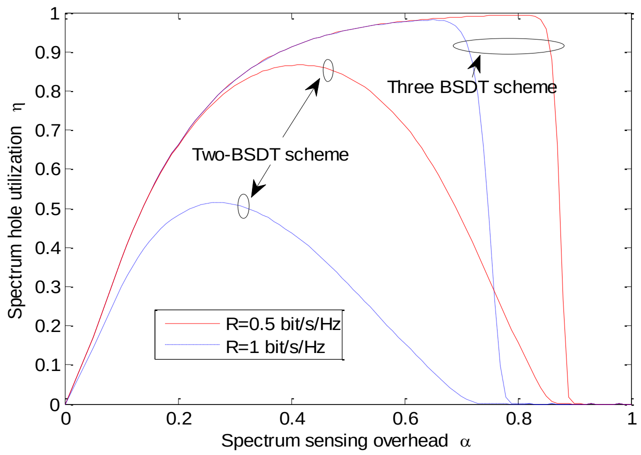

Fig. 8. Spectrum hole utilization versus spectrum sensing overhead with $P_a = 0.6$, $a = \sqrt{2}$, $M = 3$, $\gamma_s = 20$ dB, $\sigma_{si}^2 = \sigma_{is}^2 = \sigma_{di}^2 = \sigma_{id}^2 = 1$ and $\sigma_{pi}^2 = \sigma_{ps}^2 = \sigma_{pd}^2 = 1$.

channels decreases and even disappears with the increasing of M. The reason is that the increased number of CRs reduces the possibility for all relays to fail to decode the data streams, which makes the successfully decoding probability at CRs grown and further improves the overall outage performance and spectrum hole utilization performance. The same reason leads to the lessening of the perform disparity between the three-BSDT scheme and the two-BSDT scheme as M increases regardless of the specific channels used.

Lastly, we illustrate the spectrum hole utilization versus the spectrum sensing overhead α for $R = 0.5$ bit/s/Hz and $R = 1$ bit/s/Hz. In **Fig. 8**, the spectrum hole utilization corresponding to $R = 0.5$ bit/s/Hz is larger than that to $R = 1$ bit/s/Hz regardless of the specific scheme used. This shows that due to the decrease in R, the probabilities of decoding failure at cognitive users drop and so do the communication outages occurring between the two end-sources. Also the lower R requires less time duration allocated for secondary data transmissions, which induces the longer spectrum sensing time duration left for $R = 0.5$ bit/s/Hz as shown in **Fig. 8**. It is clear that an optimal sensing overhead corresponding to the maximum of spectrum hole utilization exists for the two schemes. Moreover, no matter which data rate (R = 0.5 bit/s/Hz or R = 1 bit/s/Hz) is used, the three-BSDT scheme has larger optimal sensing overhead than the two-BSDT scheme and achieves higher spectrum hole utilization. The reason is that the larger sensing overhead obtains the higher detection probability of spectrum holes, which brings on the lower outage probability of the three-BSDT scheme, whereas outage probability of the two -BSDT scheme can not always reduce with the increase of detection probability of spectrum holes due to the interference-limited feature of it. Since the three-BSDT scheme has higher spectrum hole utilization than the two-BSDT scheme regardless of the specific data rate used, it is better for high data rate applications to choose the three-BSDT scheme.

5. Conclusion

In this paper, we studied the spectrum hole utilization of secondary bidirectional data transmissions between two secondary end-sources in CRNs with imperfect spectrum sensing. We derived closed-form asymptotic expressions of outage probabilities for two-BSDT and three-BSDT schemes over Rayleigh fading channels. Due to the interference-limited characteristic of two-BSDT scheme, three-BSDT scheme has better spectrum hole utilization than two-BSDT scheme in symmetric channels, whereas the spectrum hole utilization of two-BSDT scheme is greatly improved in asymmetric channels and thus two-BSDT scheme is more appropriate for applications with asymmetric channels. Furthermore, the performance gap between symmetric channels and asymmetric channels diminishes as the number of CRs rises. On the other hand, when the influence of channel gain from the primary user to secondary users on spectrum hole utilization is considered, the spectrum hole utilization becomes poor as the decrease of the channel gain induces the decline of detection probability of spectrum holes. Finally, the optimal spectrum sensing overhead is investigated in order to maximize the spectrum hole utilization, which indicates the necessity of joint optimization of spectrum sensing and secondary data transmissions.

Appendix A

Theorem: Given i, $j \in D_{\mathrm{m}}$ and $i \neq j$, $X_t = \min(x_{ts}, x_{td})$, where $x_{ts} = |h_{ts}|^2 / (|h_{ps}|^2 \gamma_p + 1)$ and $x_{td} = |h_{td}|^2 / (|h_{pd}|^2 \gamma_p + 1)$, $t \in (i, j)$. If $\sigma_{ps}^4 \gamma_p^2 \Delta^2 / (\sigma_{is}^2 \sigma_{js}^2) \to 0$ and $\sigma_{pd}^4 \gamma_p^2 \Delta^2 / (\sigma_{id}^2 \sigma_{jd}^2) \to 0$, all the events in $\Pr\{X_1 < \Delta, X_2 < \Delta, \ldots, X_{|D_m|} < \Delta\}$ are mutually independent.

Proof: According to the expression of X_t, it is obvious that if only RVs x_{is}, x_{id}, x_{js} and x_{jd} are mutually independent, X_i and X_j also do. We have assumed that the channels between different nodes are independent, which means RVs $|h_{is}|^2$, $|h_{js}|^2$, $|h_{id}|^2$, $|h_{jd}|^2$, $|h_{ps}|^2$ and $|h_{pd}|^2$ are mutually independent. Therefore, x_{is} and x_{id} satisfy the independence. Likewise, x_{is} and x_{jd}, x_{id} and x_{js}, x_{js} and x_{jd} also do. The following discusses the independence of x_{is} and x_{js}, the result of which is applicable to x_{id} and x_{jd}. First, we derive the probabilities of both $x_{is} < v$ and $x_{js} < w$, where $v,w > 0$. Assuming that $r = |h_{is}|^2$, $s = |h_{ps}|^2$ and $u = |h_{js}|^2$. The joint probability density function of r, s and u is expressed as

$$g(r,s,u) = \begin{cases} \lambda_{is}\lambda_{ps}\lambda_{js}\exp(-\lambda_{is}r - \lambda_{ps}s - \lambda_{js}u) & r,s,u \geq 0 \\ 0 & r,s,u < 0 \end{cases}$$

where. $\lambda_{is} = 1/\sigma_{is}^2$, $\lambda_{ps} = 1/\sigma_{ps}^2$ and $\lambda_{js} = 1/\sigma_{js}^2$. Thus,

$$\begin{aligned}&\Pr(x_{is} < v, x_{js} < w)\\ &= \Pr\left(\frac{r}{s\gamma_p + 1} < v, \frac{u}{s\gamma_p + 1} < w\right) = \int_0^{\infty} ds \int_0^{sw\gamma_p + w} du \int_0^{sv\gamma_p + v} g(r,s,u) dr \\ &= 1 - \frac{\lambda_{ps}\exp(-\lambda_{is}v)}{\lambda_{ps} + \lambda_{is}v\gamma_p} - \frac{\lambda_{ps}\exp(-\lambda_{js}w)}{\lambda_{ps} + \lambda_{js}w\gamma_p} + \frac{\lambda_{ps}\exp(-\lambda_{is}v - \lambda_{js}w)}{\lambda_{ps} + \lambda_{is}v\gamma_p + \lambda_{js}w\gamma_p}\end{aligned} \tag{A.1}$$

Second, we calculate the probability of $x_{is} < v$.

$$\Pr(x_{is} < v) = \Pr\left(\frac{r}{s\gamma_p + 1} < v\right) = \int_0^{\infty} ds \int_0^{sv\gamma_p + v} h(r,s) dr = 1 - \frac{\lambda_{ps}\exp(-\lambda_{is}v)}{\lambda_{ps} + \lambda_{is}v\gamma_p} \tag{A.2}$$

where

$$h(r,s) = \begin{cases} \lambda_{is}\lambda_{ps}\exp(-\lambda_{is}r - \lambda_{ps}s) & r,s \geq 0 \\ 0 & r,s < 0 \end{cases}$$

Similarly, the probability of $x_{js} < w$ is given by

$$\Pr(x_{js} < w) = 1 - \frac{\lambda_{ps}\exp(-\lambda_{js}w)}{\lambda_{ps} + \lambda_{js}w\gamma_p} \tag{A.3}$$

Therefore,

$$\begin{aligned}&\Pr(x_{is} < v)\Pr(x_{js} < w)\\ &= 1 - \frac{\lambda_{ps}\exp(-\lambda_{is}v)}{\lambda_{ps} + \lambda_{is}v\gamma_p} - \frac{\lambda_{ps}\exp(-\lambda_{js}w)}{\lambda_{ps} + \lambda_{js}w\gamma_p} + \frac{\lambda_{ps}\exp(-\lambda_{is}v - \lambda_{js}w)}{\lambda_{ps} + \lambda_{is}v\gamma_p + \lambda_{js}w\gamma_p + \lambda_{is}\lambda_{js}vw\gamma_p^2 / \lambda_{ps}^2}\end{aligned} \tag{A.4}$$

Comparing Eqs. (A.1) with (A.4), we can obtain if $\lambda_{is}\lambda_{js}vw\gamma_p^2 / \lambda_{ps}^2 \to 0$, Eq.(A.1) equals Eq.(A.4), which means $x_{is} < v$ and $x_{js} < w$ are independent. Likewise, we can get $x_{id} < v$ and $x_{jd} < w$ independent if $\lambda_{id}\lambda_{jd}vw\gamma_p^2 / \lambda_{pd}^2 \to 0$ where $\lambda_{id} = 1/\sigma_{id}^2$, $\lambda_{jd} = 1/\sigma_{jd}^2$ and $\lambda_{pd} = 1/\sigma_{pd}^2$. When $v = w = \Delta$, we obtain $\lambda_{is}\lambda_{js}vw\gamma_p^2 / \lambda_{ps}^2 = \sigma_{ps}^4\gamma_p^2\Delta^2 / (\sigma_{is}^2\sigma_{js}^2)$ and $\lambda_{id}\lambda_{jd}vw\gamma_p^2 / \lambda_{pd}^2 = \sigma_{pd}^4\gamma_p^2\Delta^2 / (\sigma_{id}^2\sigma_{jd}^2)$. Accordingly, If $\sigma_{ps}^4\gamma_p^2\Delta^2 / (\sigma_{is}^2\sigma_{js}^2) \to 0$ and $\sigma_{pd}^4\gamma_p^2\Delta^2 / (\sigma_{id}^2\sigma_{jd}^2) \to 0$, the events in $\Pr\{X_1 < \Delta, X_2 < \Delta, \ldots, X_{|D_m|} < \Delta\}$ are all mutually independent.

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