Copyright ⓒ 2013 KSII

Hybrid Spectrum Sharing with Cooperative Secondary User Selection in Cognitive Radio Networks

Md Fazlul Kader [1], Asaduzzaman[2] and Md. Moshiul Hoque[2]
[1]Department of Applied Physics, Electronics and Communication Engineering, University of Chittagong
Chittagong, Bangladesh
[e-mail: f.kader@cu.ac.bd]
[2]Department of Computer Science & Engineering, Chittagong University of Engineering & Technology
Chittagong, Bangladesh
[e-mail: asad@cuet.ac.bd,moshiulh@yahoo.com]
*Corresponding author: Md Fazlul Kader

Received July 4, 2013; revised August 26, 2013; accepted September 21, 2013; published September 30, 2013

Abstract

In this paper, we propose a cooperative hybrid spectrum sharing protocol by jointly considering interweave (opportunistic) and underlay schemes. In the proposed protocol, secondary users can access the licensed spectrum along with the primary system. Our network scenario comprises a single primary transmitter-receiver (PTx-PRx) pair and a group of M secondary transmitter-receiver (STx-SRx) pairs within the transmission range of the primary system. Secondary transmitters are divided into two groups: active and inactive. A secondary transmitter that gets an opportunity to access the secondary spectrum is called “active”. One of the idle or inactive secondary transmitters that achieves the primary request target rate R_{PT} will be selected as a best decode-and-forward (DF) relay (Re) to forward the primary information when the data rate of the direct link between PTx and PRx falls below R_{PT}. We investigate the ergodic capacity and outage probability of the primary system with cooperative relaying and outage probability of the secondary system. Our theoretical and simulation results show that both the primary and secondary systems are able to achieve performance improvement in terms of outage probability. It is also shown that ergodic capacity and outage probability improve when the active secondary transmitter is located farther away from the PRx.

Keywords: Outage probability, ergodic capacity, cooperative relaying, decode-and-forward

http://dx.doi.org/10.3837/tiis.2013.09.001

1. Introduction

As a solution for the spectrum inefficiency problem, cognitive radio (CR) is an exciting and emerging technology that has attracted a great deal of attention in recent years for enhancing the utilization of limited resources [1]. In cognitive radio networks (CRNs), primary (licensed) users (PUs) coexist with secondary (unlicensed) users (SUs) in the same frequency band to achieve better spectrum utilization.

1.1 Related Work

Generally, in CRNs, three models have been considered in the literature for spectrum sharing: the interweave, underlay and overlay. In the opportunistic spectrum access (OSA) or interweave model [2-3], CRs (SUs) opportunistically access the unused licensed band, commonly referred to as "spectrum hole" only when it is detected idle. However, the main problems of the interweave models are: high sensitivity to the detection error and PU traffic pattern [3-4]. In underlay model [5-6], SUs are allowed to transmit simultaneously with the PUs as long as the interference generated by SUs to PUs below some accepted threshold. Because of the strict power constraints imposed on SUs and the interference from PUs [7] , the SUs may have a bad transmission performance which is a major problem in underlay approaches. In the overlay model, the SUs simultaneously transmit with the PUs over the same spectrum provided that the SUs may help the PUs such that PUs can transmit by cooperative communication techniques, such as advanced coding or cooperating relaying techniques [8]. However, due to the mutual interference between PUs and SUs, the overlay approach may still experience a secondary transmission performance degradation.

A spectrum sharing protocol by jointly considering interweave and overlay models was proposed in [9]. To facilitate the spectrum sharing protocols, dirty paper coding and perfect spectrum sensing are used in [9]. Hybrid spectrum sharing protocols by jointly considering overlay and underlay models have been proposed in [10-12]. In [13], under hybrid spectrum sharing protocol, an optimal transmission allocation scheme to achieve maximum energy-efficiency is investigated. In this work, the authors considered one PU pair and one SU pair, in which they interfere with each other. Moreover, a proper spectrum sharing model is selected by SUs based on the state of the PUs.

Because of the adversity of the common channel between PTx and PRx pair, it is impossible to establish a direct link (DL) between them. In order to solve this problem, cooperative relay has been introduced into CRNs as in [14] and various relay selection strategies have been proposed such as [15-16]. The relay nodes assist the primary system so that the PTx-PRx pair can transmit more data via this relay link while transmitting to the DL. In addition, using a relay node between source and destination gives an extra benefit of reducing the overall path loss [17]. By this way, it is possible to increase system throughput and spectrum efficiency.

Spectrum sharing protocols considering amplify-and-forward (AF) relaying have been proposed in [18-19] and decode-and-forward (DF) relaying were investigated in [20-21]. In [18], a cooperative relaying spectrum sharing CR system considering constraints on the average received-interference at the PRx is investigated where AF relays are employed to help in the SUs communication process. There is no DL between source and associated destination nodes and the communication is established in a dual hop fashion with the help of a relay. In [20], a single STx partially acts as a DF relay for the primary system consisted of a simple transmitter-receiver pair. The DF based spectrum sharing protocol was generalized to a

Copyright ⓒ 2013 KSII

multi-user scenario where multiple secondary transmitters compete for opportunistic access of the primary user's spectrum by assisting them [21]. In [22], the authors extended the work in [21] by considering a more general scenario where the primary system is a dual hop selective relaying network and secondary nodes may act either as relays for the primary system or serve as secondary access transmitters. But in their work, they did not consider any DL between PTx and PRx as well as extra relays are used to assist the primary.

1.2 Our Main Contributions

In this paper, our main contributions can be summarized as follows:

1) A novel cooperative hybrid spectrum sharing model by jointly considering interweave and underlay schemes so that the SUs can access the licensed spectrum along with the PU.
2) We investigate the ergodic capacity and outage probability of the primary system with cooperative relaying.
3) We evaluate the outage probability of the SUs by considering the following three cases based on PU activity.
   - If the data rate of PTx to PRx achieves R_{PT}.
   - If the data rate of PTx to PRx falls below R_{PT} over the DL but achieves R_{PT} on the relaying link.
   - If the PTx-PRx pair is idle or primary system is in outage.

   The above three cases are mutually exclusive. So, the outage probability of the each case is calculated separately. Then, the total outage probability is calculated to establish the relationship among the above cases.
4) It is shown that, both the PU and SUs are able to achieve performance improvement in terms of outage probability when the active secondary transmitter is located farther away from the PRx. It is also shown that the ergodic capacity of the PU with cooperative relaying degrades when the active secondary transmitter becomes closer to the PRx.
5) Closed-form expressions of the outage probabilities are derived and validated by the simulation results. Moreover, interference limited environment is considered.

The main advantage of our proposed spectrum sharing model is that our scheme provides better spectrum utilization compared to the individual consideration of either interweave or underlay scheme.

The cooperative relaying scheme proposed in [23] has been incorporated in this research paper for the clarity of the presentation of our current work. But the notable differences between this work and [23] are as follows. In [23], we only proposed a cooperative SU selection scheme for an underlay CRN. But in this work, we have proposed a hybrid spectrum sharing model with joint consideration of underlay and interweave schemes. The main contributions of the current work have been summarized above.

1.3 Organization of the Paper

The rest of this paper is organized as follows. In section 2, we introduce the system model. In section 3, SU selection schemes are illustrated. Section 4 describes the outage probability analysis. Analytical results validated by simulation results are given in section 5. Finally, we conclude this paper in section 6.

2. System Model

2.1 System Description

We consider a hybrid spectrum sharing model by jointly considering interweave and underlay schemes for CRNs consisting of a primary transmitter (PTx) and a primary receiver (PRx) as well as a group of M STx-SRx pairs. The proposed system model is shown in **Fig. 1**.

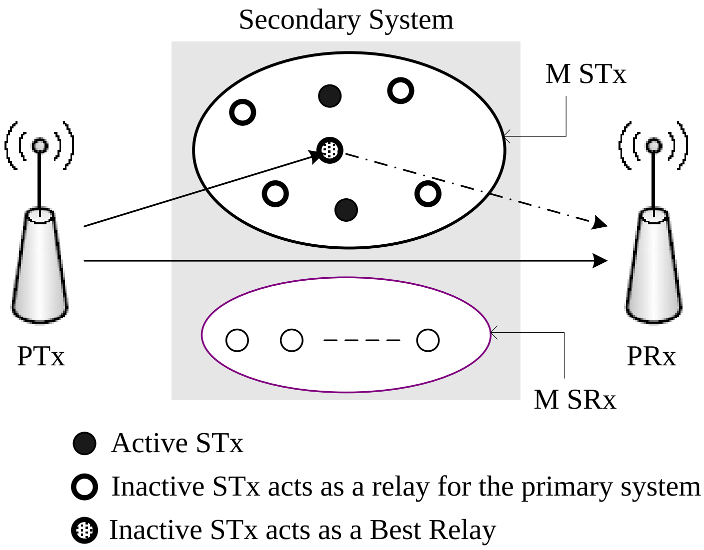

Fig. 1. System Model under consideration. The dashed dotted line indicates that best relay transmits only when the cooperation is required. The link between each STx to its corresponding SRx and the interference links are not shown in the **Fig. 1** for simplicity.

Secondary transmitters are divided into two groups. In the first group, K $(K \in M)$ active secondary transmitters ST_i, $i \in \{1, 2, \ldots, K\}$ which may opportunistically use the PU spectrum or may transmit data with the coexistence of PTx below a certain interference threshold to the PRx. In the second group, $N=M-K$ inactive secondary transmitters ST_j, $j \in \{1, 2, \ldots, N)\}$ which are in idle state, act as relays to assist the primary system. In [22], a group of secondary transmitters as well as relays participate in the cooperation procedure to assist the primary system and one of the nodes is selected as a best relay node to forward the primary information. During the best relay selection procedure, no secondary spectrum access is allowed. The secondary transmitters may compete for the secondary spectrum access in the second transmission phase after the successful selection of the best relay for the primary system when the primary system is not in outage. But in our proposed method, only the inactive secondary transmitters will participate in the relay selection procedure to cooperate the PU. At the same time, an active secondary transmitter may transmit its data to the corresponding receiver causing interference below the certain threshold to the PRx. The active secondary transmitter causes interference to the PRx when the DL between PTx and PRx exists or to the ST_j as well as the PRx during cooperation. Similarly, the PTx causes interference to the SRx when an active secondary transmitter transmits data to its corresponding receiver. Moreover, SUs or CRs interfere with each other when more than one SUs transmit simultaneously. When the data rate between the PTx and PRx over the DL falls below R_{PT} then the primary transmission

Copyright ⓒ 2013 KSII

from PTx to PRx is performed over two transmission phases via the help of the best inactive secondary transmitter which acts as a DF relay to the primary system. Moreover, we consider signal to noise plus interference ratio (SNIR) over links PTx-PRx, PTx-ST_j (Re_j), ST_j-PRx and ST_i-SR_i.

2.2 Channel Model

Assume that the channels over all links are subject to Rayleigh flat fading plus additive white Gaussian noise (AWGN) because large-scale fading is almost constant and can be mitigated by the power control over a long period of time whereas small-scale fading can not. Each node is a single antenna system and a half duplex radio. Also assume that the channel coefficients remain static during the both transmission phases. Let, link gain $\alpha_{i,j}$ between nodes *i* and *j* is an exponentially distributed random variable with a mean value $\lambda_{i,j}$ [24]. To get the desired effect of the position of the active secondary transmitter with respect to the PRx, we consider $\lambda_{i,j} = (1/d_{i,j})^n$ where $d_{i,j}$ denotes the distance between node *i* and *j* and *n* is the path loss exponent. The transmit power at PTx, ST_i and ST_j is denoted as P_{PT}, P_{ST_i} and P_{ST_j} respectively. We assume that PTx and each STx adopt adaptive power allocation scheme as follows:

- The PTx may increase its transmit power to the peak .
- When a STx acts as a relay to forward the primary information, it uses the same transmit power as the PTx.
- If the PU is in idle state or primary system is in outage, a STx can increase its transmit power to reach the maximum.
- In addition, if the PU is present, only a STx limits its transmit power to satisfy a predefined interference threshold to the PRx.

2.3. Secondary Transmission Scheme with State Transition

The state transition scenario of the secondary transmitters is shown in **Fig. 2**. Assume that at most one STx-SRx pair may change its state from inactive to active at any time instant. The state $S_{STi} = 1$ denotes active while $S_{STi} = 0$ denotes inactive where S_{STi} represents the state of the i^{th} STx among *M* secondary transmitters. From **Fig. 2**, it is clear that the STx may be in any of the following state scenarios:

1) The first level of the state diagram in **Fig. 2** shows that if none of the secondary transmitters is able to achieve the secondary target date rate R_{ST} then all the secondary transmitters are in inactive states. In such scenario, no secondary transmission is allowed. So, all the secondary transmitters participate in the relay selection procedure to forward the primary information if the data rate of the DL between PTx and PRx falls below R_{PT} .
2) The second level in **Fig. 2** shows that only one STx may be active at a time. This happens when the PU is present. So, all the remaining secondary transmitters are inactive. In this scenario, an active secondary transmitter may transmit in parallel with the PTx satisfying a predefined interference threshold to the PRx. If the active secondary transmitter fails to achieve R_{ST} then it goes to the initial state i.e., first level in the state diagram.
3) When the PU is absent or the PU fails to achieve R_{PT} over the DL as well as relaying link then there is no primary transmission in the channel. In such scenario, at most two

among M secondary transmitters may be active at a time which is shown in the third level of the state diagram in **Fig. 2**. One of the active secondary transmitters may become opportunistic secondary i.e., it transmits as like as the PU and another active secondary transmitter may transmit satisfying certain interference threshold to the opportunistic SRx. If only one STx achieves R_{ST} then the state goes to the second level in **Fig. 2**. If no secondary transmitter achieves R_{ST} then all the secondary transmitters go to the initial state i.e., first or fourth level of the state diagram. Although the first and fourth levels of the state diagram are same but we have drawn them as separate level for the simplicity of our drawing.

Moreover, the secondary spectrum access policy is described in details in section 3.2. It is also assumed that primary and secondary systems use the link layer control signals like RTS and CTS to access the channel as in [15].

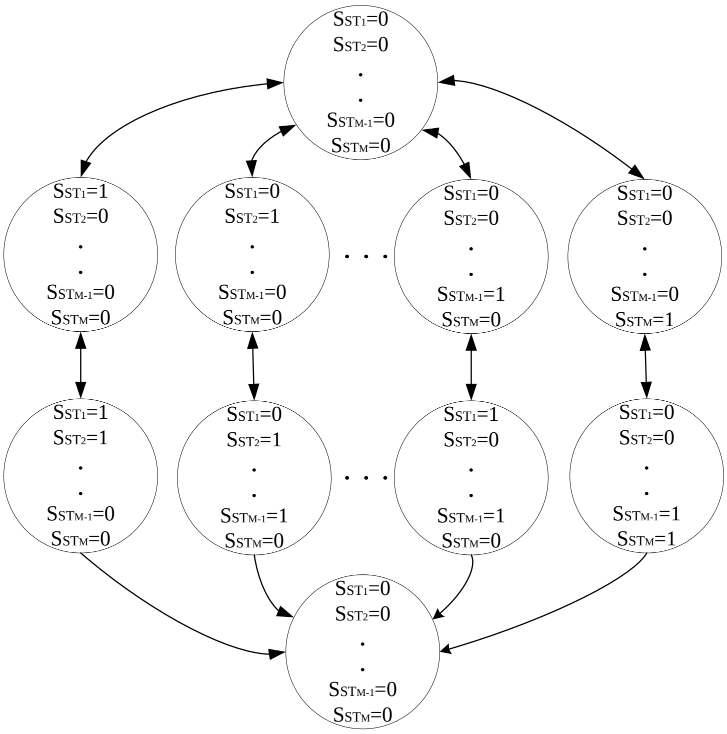

Fig. 2. General state transition scenario of the CR Transmitter (STx) of our proposed spectrum sharing model.

3. Secondary User Selection Scheme: Description and Implementation

3.1 Cooperative Secondary User Selection

When the data rate of the PU over the DL falls below R_{PT} then one of the inactive secondary transmitters acts as a cooperative relay to forward the primary information. The detailed explanation of our cooperative secondary selection as a relay for the primary system is given in [23]. In this section, we will summarize the scheme for the sake of clarity of our spectrum sharing model. The achievable rate of the links PTx-PRx, PTx-to-Re$_j$ and Re$_j$-to-PRx are given by

Copyright ⓒ 2013 KSII

$$R_{PTx-PRx} = \log_2(1+SNIR_{PTx-PRx}) \tag{1}$$

$$R_{PTx-\mathrm{Re}_j} = \frac{1}{2}\log_2(1+SNIR_{PTx-\mathrm{Re}_j}) \tag{2}$$

$$R_{\mathrm{Re}_j-PRx} = \frac{1}{2}\log_2(1+SNIR_{\mathrm{Re}_j-PRx}) \tag{3}$$

where the scaling factor ½ in (2) and (3) is due to the fact that the overall transmission is divided into two phases. The SNIR of the corresponding links can be represented as

$$SNIR_{PTx-PRx} = \frac{\alpha_{PTx-PRx}P_{PT}}{\sum_{i=1}^{K}\alpha_{ST_i-PRx}P_{ST_i} + \eta_1} \tag{4}$$

$$SNIR_{PTx-\mathrm{Re}_j} = \frac{\alpha_{PTx-\mathrm{Re}_j}P_{PT}}{\sum_{i=1}^{K}\alpha_{ST_i-\mathrm{Re}_j}P_{ST_i} + \eta_2} \tag{5}$$

$$SNIR_{\mathrm{Re}_j-PRx} = \frac{\alpha_{\mathrm{Re}_j-PRx}P_{ST_j}}{\sum_{i=1}^{K}\alpha_{ST_i-PRx}P_{ST_i} + \eta_3} \tag{6}$$

where $\eta_1 \sim CN(0,\sigma_1^2)$, $\eta_2 \sim CN(0, \sigma_2^2)$, $\eta_3 \sim CN(0, \sigma_3^2)$ denote AWGN. We assume that only one active secondary transmitter (i.e., $K=1$) may transmit data with the coexistence of PTx-PRx pair below a certain interference threshold to the PRx at a time when PTx-PRx pair is active. Moreover, noise powers are negligible in the interference limited environment [25]. Therefore, (4), (5) and (6) are respectively approximated as follows:

$$SNIR_{PTx-PRx} \cong \frac{\alpha_{PTx-PRx}P_{PT}}{\alpha_{ST_i-PRx}P_{ST_i}} \tag{7}$$

$$SNIR_{PTx-\mathrm{Re}_j} \cong \frac{\alpha_{PTx-\mathrm{Re}_j}P_{PT}}{\alpha_{ST_i-\mathrm{Re}_j}P_{ST_i}} \tag{8}$$

$$SNIR_{\mathrm{Re}_j-PRx} \cong \frac{\alpha_{\mathrm{Re}_j-PRx}P_{ST_j}}{\alpha_{ST_i-PRx}P_{ST_i}} \tag{9}$$

The equivalent end-to-end data rate of the two hop cooperative link is the minimum one of the two hops [26]. We denote S, the set of relays that can be considered for relay selection as

$$S = \{ j \mid j \in N, \min\{R_{PTx-\mathrm{Re}_j}, R_{\mathrm{Re}\,j-PRx}\} > R_{PT}\} \tag{10}$$

We consider a similar relay selection procedure as in [23]. So, our proposed protocol selects the best relay Re_{best} if it satisfies the following condition

$$\mathrm{Re}_{best} = \arg\max_{m\in\{S\}}(\min\{R_{PTx-\mathrm{Re}_m}, R_{\mathrm{Re}_m-PRx}\}) \tag{11}$$

After the selection of the best inactive secondary (best relay), the PTx transmits the message to the best relay in the first time slot. If the best relay is able to decode the message successfully then it will forward this message to the PRx in the second time slot. Otherwise, the best relay remains silent and the system declares an outage. Therefore, the ergodic capacity which is defined as the maximum achievable long term rate without considering any delay constraint, of the primary system with the considered relay selection of (11) can be expressed as

$$C_P^{RS} = \mathbf{E}[\min\{R_{PTx-\mathrm{Re}_{best}}, R_{\mathrm{Re}_{best}-PRx}\}] \tag{12}$$

In our relay selection procedure, we have considered all N links. Hence, from (10), (11) and (12), it is clear that the ergodic capacity of the PU through the relaying link is the long term best relay rate among N relays without any delay constraint consideration.

3.2 Active Secondary User Selection for Secondary Spectrum Access

In this paper, we show that if all the active secondary nodes have an equal power scheme then the position of the active secondary transmitter with respect to the PRx affects the outage performance and ergodic capacity. Selection of active SU for spectrum access is described in three different possible scenarios. The proposed scenarios are:

- Scenario I (SI): A secondary node selection when the data rate of the PTx to PRx over the DL achieves R_{PT}.
- Scenario II (SII): A secondary node selection when the data rate of the PTx to PRx falls below R_{PT} over the DL but achieves R_{PT} on the relaying link PTx-Re_m-PRx.
- Scenario III (SIII): Two secondary nodes selection for spectrum access when PTx-PRx pair is idle or primary system is in outage.

3.2.1 Secondary Node Selection in SI

Only one secondary node can access the channel in this scenario. All secondary nodes compete for spectrum access considering CSMA/CA like random access protocol [27]. Let, a secondary node ST_p gets opportunity to access the channel causing interference to the PRx below a certain interference threshold. Then, ST_p becomes a member of active secondary nodes i.e., $p \in K$. Now, the data rate over the links ST_p to SR_p is given by

$$R_{STp-SRp} = \log_2\left(1 + SNIR_{STp-SRp}\right) \tag{13}$$

According to (7), (8) and (9), the received SNIR at the SR_p can be expressed as

$$SNIR_{STp-SRp} = \frac{\alpha_{STp-SRp} P_{ST_i}}{\sigma^2_{PInt}} \tag{14}$$

Assume, $\sigma^2_{PInt} = P_{PInt} + \eta_{SR} \approx P_{PInt}$ where P_{PInt} and η_{SR} denote interference caused by PTx at SR_p and AWGN respectively. In CR spectrum sharing system, it is allowed to share the PU's spectrum by SU as long as the amount of interference caused by STx at the PRx is below a predefined threshold I_{th} , which is the maximum tolerable interference level at the PRx [5]. So, the transmission power of the SU is constrained to allow this spectrum sharing and is given as follows:

$$\alpha_{STp-PRx} P_{ST_i} \le I_{th} \text{ Or, } P_{STi} = \frac{I_{th}}{\alpha_{STp-PRx}} \tag{15}$$

By putting (15) into (14), we get

$$SNIR_{STp-SRp} = \frac{\alpha_{STp-SRp} I_{th}}{\alpha_{STp-PRx} \sigma^2_{PInt}} \tag{16}$$

3.2.2 Secondary Node Selection in SII

To select the secondary node for spectrum access, the following situations are considered:

Copyright ⓒ 2013 KSII

- Suppose SI is happening. Afterwards, if the primary rate falls below R_{PT} then the secondary transmitter ST_p which is using the channel satisfying I_{th} will use the channel as usual as in SI. All other inactive secondary transmitters will participate in the relay selection procedure according to section 3.1. Assume that the active secondary node will ignore the primary cooperation control messages i.e., it will not respond to the PU request message for cooperation.
- Among the inactive secondary transmitters, only the nodes which satisfy (10), start their countdown timers to cooperate the primary system. So, other inactive secondary transmitters are free to compete for secondary spectrum access.
- If PTx→Re_{best}→PRx link is established, then all other inactive secondary transmitters except Re_{best} will compete for secondary spectrum access as in [27].

The data rate of the active secondary is calculated as in SI.

3.2.3 Secondary Node Selection in SIII

We assume that if the PTx-PRx pair is idle then they will be considered as in outage. Hence, when the primary system is in outage, two secondary nodes get the opportunity to access the primary spectrum. One of the secondary transmitters will opportunistically use the PU's spectrum i.e., it acts as like as the PU and at the same time another STx coexist satisfying I_{th} to the opportunistic SRx at the same spectrum band. It is assumed that all the secondary nodes keep information about the Re_{best} of the immediate previous cooperating transmission phase. So, the Re_{best} (ST_{oppr}) will be the opportunistic secondary during the outage of the primary system. Remaining secondary transmitters will compete for spectrum access as in [27] satisfying I_{th} to the opportunistic SRx and let ST_q, $q \in M \setminus \{ST_{oppr}\}$ succeeds to access the spectrum. Then, ST_{oppr} and ST_q become members of active secondary groups K i.e., $K=2$. Now, the data rate over the links ST_q to SR_q and ST_{oppr} to SR_{oppr} are given by

$$R_{STq-SRq} = \log_2\left(1 + SNIR_{STq-SRq}\right) \tag{17}$$

$$R_{SToppr-SRoppr} = \log_2\left(1 + SNIR_{SToppr-SRoppr}\right) \tag{18}$$

The opportunistic STx acts like a PU when the primary system is in outage. So, the transmission power P_{SToppr} of the ST_{oppr} does not need to consider interference constraint. But ST_q must satisfy I_{th} to the SR_{oppr}. So, the transmission power of the ST_q needs to constrain i.e., $\alpha_{STq-SRoppr} P_{ST_i} \le I_{th}$. Therefore, according to (7), (8) and (9), the received SNIR at the SR_{oppr} and SR_q can be expressed as

$$SNIR_{SToppr-SRoppr} = \frac{\alpha_{SToppr-SRoppr} P_{SToppr}}{\alpha_{STq-SRoppr} P_{ST_i}} \tag{19}$$

$$SNIR_{STq-SRq} = \frac{\alpha_{STq-SRq} P_{STi}}{\sigma_q^2} = \frac{\alpha_{STq-SRq} I_{th}}{\alpha_{STq-SRoppr} \sigma_q^2} \tag{20}$$

Assume $\sigma_q^2 = P_{Intoppr} + \eta_q \approx P_{Intoppr}$ where $P_{Intoppr}$ and η_q denote interference caused by ST_{oppr} at the SR_q and AWGN respectively.

4. Outage Analysis

4.1 Outage Probability of the Primary System

The primary system is in outage if the following two conditions occur: (i) The data rate of the DL between PTx and PRx falls below R_{PT} and (ii) None of the inactive secondary nodes achieves R_{PT} i.e., $|S|=0$. So, the outage probability of the primary system is expressed as

$$P_{OUT}^{P} = P_r\{R_{PTx-PRx} < \mathrm{R}_{\mathrm{PT}}\} \times P_r\{|S|=0\}$$
$$= P_r\{R_{PTx-PRx} < \mathrm{R}_{\mathrm{PT}}\} \times P_r\{\max_{m\in N}(\min\{R_{PTx-\mathrm{Re}_m}, R_{\mathrm{Re}_m-PRx}\}) < \mathrm{R}_{\mathrm{PT}}\}$$
$$= P_r\{R_{PTx-PRx} < \mathrm{R}_{\mathrm{PT}}\} \times \prod_{m=1}^{N}\{P_r\{(\min\{R_{PTx-\mathrm{Re}_m}, R_{\mathrm{Re}_m-PRx}\}) < \mathrm{R}_{\mathrm{PT}}\}\}$$
$$= P_r\{R_{PTx-PRx} < \mathrm{R}_{\mathrm{PT}}\} \times \prod_{m=1}^{N}\left[1-\left(1-P_r\{R_{PTx-\mathrm{Re}_m} < \mathrm{R}_{\mathrm{PT}}\}\right)\left(1-P_r\{R_{\mathrm{Re}_m-PRx} < \mathrm{R}_{\mathrm{PT}}\}\right)\right] \quad (21)$$

In (21), the outage probability for the links PTx-PRx, PTx-to-Re_m and Re_m-to-PRx are given by

$$P_r\{R_{PTx-PRx} < \mathrm{R}_{\mathrm{PT}}\} = P_r\left\{\frac{\alpha_{PTx-PRx}}{\alpha_{ST_i-PRx}} < \rho_{\mathrm{PTx\text{-}PRx}}\right\} \quad (22)$$

$$P_r\{R_{PTx-\mathrm{Re}_m} < \mathrm{R}_{\mathrm{PT}}\} = P_r\left\{\frac{\alpha_{PTx-\mathrm{Re}_m}}{\alpha_{ST_i-\mathrm{Re}_m}} < \rho_{\mathrm{PTx\text{-}Re}_m}\right\} \quad (23)$$

$$P_r\{R_{\mathrm{Re}_m-PRx} < \mathrm{R}_{\mathrm{PT}}\} = P_r\left\{\frac{\alpha_{\mathrm{Re}_m-PRx}}{\alpha_{ST_i-PRx}} < \rho_{\mathrm{Re}_m-PRx}\right\} \quad (24)$$

where $\rho_{\mathrm{PTx\text{-}PRx}} = (2^{R_{PT}}-1)\times(1/\frac{P_{PT}}{P_{ST_i}})$, $\rho_{\mathrm{PTx\text{-}Re_m}} = (2^{2R_{PT}}-1)\times(1/\frac{P_{PT}}{P_{ST_i}})$ and

$$\rho_{\mathrm{Re_m}-PRx} = (2^{2R_{PT}}-1)\times(1/\frac{P_{ST_m}}{P_{ST_i}})$$

Let, g_o and g_1 are exponential random variables with means λ_0 and λ_1 respectively. Then, the probability density function (PDF) of $X = g_0/g_1$ is expressed as [28].

$$f_X(x) = \frac{\lambda_0\lambda_1}{(\lambda_0+\lambda_1 x)^2}$$

Similarly, all the link gains assumed in this paper are exponentially distributed random variables with their corresponding mean values which are defined in section 2. Thus, the outage probability for the links PTx-PRx can be derived as

$$P_r\{R_{PTx-PRx} < \mathrm{R}_{\mathrm{PT}}\} = \int_0^{\rho_{PTx-PRx}} \frac{\lambda_{PTx-PRx}\lambda_{STi-PRx}}{(\lambda_{PTx-PRx}+\lambda_{STi-PRx}x)^2}dx$$
$$= \frac{\rho_{PTx-PRx}\lambda_{STi-PRx}}{\lambda_{PTx-PRx}+\rho_{PTx-PRx}\lambda_{STi-PRx}} \quad (25)$$

Copyright ⓒ 2013 KSII

Similarly, the outage probability for the links PTx-to-Re_m and Re_m-to-PRx can be derived as

$$P_r\{R_{PTx-Re_m} < R_{PT}\} = \frac{\rho_{PTx\text{-}Re_m}\lambda_{STi-Re_m}}{\lambda_{PTx-Re_m} + \rho_{PTx\text{-}Re_m}\lambda_{STi-Re_m}} \quad (26)$$

$$P_r\{R_{Re_m-PRx} < R_{PT}\} = \frac{\rho_{Re_m-PRx}\lambda_{STi-PRx}}{\lambda_{Re_m-PRx} + \rho_{Re_m-PRx}\lambda_{STi-PRx}} \quad (27)$$

By substituting (25), (26) and (27) in (21), we get the total outage probability of the primary system.

4.2 Outage Probability of the Secondary System

In this section, we will derive the outage probability of the secondary system with request target rate R_{ST} by considering three scenarios of the secondary spectrum access.

4.2.1 Outage Probability of SI

The secondary system is in outage if the data rate of the DL between PTx and PRx achieves R_{PT} but secondary data rate falls below R_{ST}. The outage probability is therefore given by

$$P_{OUT}^{S,(SI)} = P_r\{R_{PTx-PRx} > R_{PT}\} \times P_r\{R_{STp-SRp} < R_{ST}\}$$
$$= \{1 - P_r\{R_{PTx-PRx} < R_{PT}\}\} \times P_r\{R_{STp-SRp} < R_{ST}\} \quad (28)$$

In (28), the outage probability for the link ST_p to SR_p can be written as

$$P_r\{R_{STp-SRp} < R_{ST}\} = P_r\left\{\frac{\alpha_{STp-SRp}}{\alpha_{STp-PRx}} < \rho_{STp\text{-}SRp}\right\} = \frac{\rho_{STp\text{-}SRp}\lambda_{STp-PRx}}{\lambda_{STp-SRp} + \rho_{STp\text{-}SRp}\lambda_{STp-PRx}} \quad (29)$$

where $\rho_{STp\text{-}SRp} = (2^{R_{ST}} - 1) \times (1/\frac{I_{th}}{\sigma_{PInt}^2})$

Now, substituting (25) and (29) in (28), we can get the outage probability of the secondary system of SI.

4.2.2 Outage Probability of SII

The secondary system is in outage if the following situations occur simultaneously:

i) The data rate of the DL between PTx and PRx falls below R_{PT} .
ii) The data rate of the link PTx-Re_m-PRx achieves R_{PT} , and
iii) The secondary data rate falls below R_{ST}.

In the case of simplicity of our derivation, we assume that same STx i.e., STp transmits in SI and SII. So, the outage probability can be expressed as

$$P_{OUT}^{S,(SII)} = P_r\{R_{PTx-PRx} < R_{PT}\} \times \left\{\prod_{m=1}^{N}\{P_r\{(\min\{R_{PTx-Re_m}, R_{Re_m-PRx}\}) > R_{PT}\}\}\right\} \times P_r\{R_{STp-SRp} < R_{ST}\}$$

$$= P_r\{R_{PTx-PRx} < \mathrm{R}_{\mathrm{PT}}\} \times \left\{1 - \prod_{m=1}^{N} \{P_r\{(\min\{R_{PTx-\mathrm{Re}_m}, R_{\mathrm{Re}_m-PRx}\}) < \mathrm{R}_{\mathrm{PT}}\}\}\right\} \times P_r\{R_{STp-SRp} < \mathrm{R}_{\mathrm{ST}}\} \quad (30)$$

Substituting (25), (26), (27) and (29) in (30), we get the outage probability of the secondary system of SII.

4.2.3 Outage Probability of SIII

The outage of the SUs occur when the following three conditions occur simultaneously:

i) The PTx and PRx pair is idle or primary system is in outage.
ii) The data rate of the opportunistic secondary node falls below R_{ST}.
iii) The data rate of the secondary node satisfying I_{th} falls below R_{ST}.

The outage probability of the secondary system is therefore expressed as

$$P_{OUT}^{S,(SIII)} = P_r\{R_{STq-SRq} < \mathrm{R}_{\mathrm{ST}}\} \times P_r\{R_{SToppr-SRoppr} < \mathrm{R}_{\mathrm{ST}}\} \times P_{OUT}^{P} \quad (31)$$

In (31), the outage probability for the link $\mathrm{ST_q}$-$\mathrm{SR_q}$ and $\mathrm{SR_{oppr}}$-$\mathrm{SR_{oppr}}$ are written as

$$P_r\{R_{SToppr-SRoppr} < \mathrm{R}_{\mathrm{ST}}\} = P_r\left\{\frac{\alpha_{SToppr-SRoppr}}{\alpha_{STq-SRoppr}} < \rho_{\mathrm{SToppr\text{-}SRoppr}}\right\}$$

$$= \frac{\rho_{\mathrm{SToppr\text{-}SRoppr}}\lambda_{STq-SRoppr}}{\lambda_{SToppr-SRoppr} + \rho_{\mathrm{SToppr\text{-}SRoppr}}\lambda_{STq-SRoppr}} \quad (32)$$

$$P_r\{R_{STq-SRq} < \mathrm{R}_{\mathrm{ST}}\} = P_r\left\{\frac{\alpha_{STq-SRq}}{\alpha_{STq-SRoppr}} < \rho_{\mathrm{STq\text{-}SRq}}\right\} = \frac{\rho_{\mathrm{STq\text{-}SRq}}\lambda_{STq-SRoppr}}{\lambda_{STq-SRq} + \rho_{\mathrm{STq\text{-}SRq}}\lambda_{STq-SRoppr}} \quad (33)$$

where $\rho_{\mathrm{SToppr\text{-}SRoppr}} = (2^{R_{ST}} - 1) \times (1/\frac{P_{SToppr}}{P_{STi}})$ and $\rho_{\mathrm{STq\text{-}SRq}} = (2^{R_{ST}} - 1) \times (1/\frac{I_{th}}{\sigma_q^2})$

Now, substituting (21), (32) and (33) in (31), we get the outage probability of the secondary system of SIII.

The three scenarios described in section 3.2 in the selection of active secondary transmitter for spectrum access are mutually exclusive. So, the outage probability of the each scenario is calculated separately. However, by summing (28), (30) and (31), we can get the total outage probability of the secondary system as follows:

$$P_{OUT}^{S} = P_{OUT}^{S,(SI)} + P_{OUT}^{S,(SII)} + P_{OUT}^{S,(SIII)} \quad (34)$$

5. Simulation Results and Discussions

In this section, we present the simulation and theoretical results to study the performance of our proposed spectrum sharing model. PTx and PRx are located at (0, 40) and (100, 40) respectively. To reduce the number of model parameters, we assume that all the inactive secondary transmitters which act as relays are located at approximately the same distance between PTx and PRx as in [29-30] and variable location of active secondary transmitter is considered to show that the ergodic capacity and outage probability are affected by the

Copyright ⓒ 2013 KSII

position of the active secondary transmitter with respect to the PRx. Moreover, slow fading is considered in this paper. So, to get the effect of all relays, fading co-efficient of each relay is independent to each other. Assume, path loss exponent n=2 and meter is the unit of distance here.

In **Fig. 3** and **Fig. 4**, we show the simulation result of the ergodic capacity of the primary system with a cooperative SU selection as a function of SNIR. Here, we assume $SNIR = P_{PT} /(P_{ST_i} + Noise) = P_{ST_j} /(P_{ST_i} + Noise)$ and SNIR varies from 0 dB to 18 dB. It can be observed from **Fig. 3** that the ergodic capacity of the primary system monotonically increases with SNIR for both direct transmission (DT) and with the considered relay selection of (11) as expected. In addition, it is clear from **Fig. 3** that the better ergodic capacity can be achieved with increasing *N*. **Fig. 4** shows the impact of the position of the active secondary transmitter with respect to the PRx. Ergodic capacity decreases as the active secondary transmitter becomes closer to the PRx. If two active secondary transmitters have same transmit power then closer one to the PRx causes more interference to the PRx because of shorter distance.

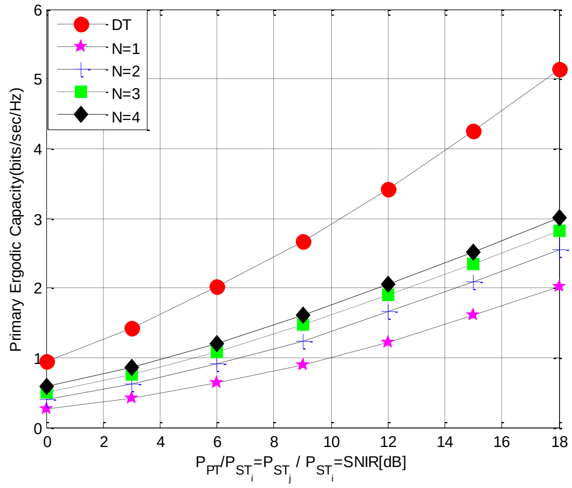

Fig. 3. Primary ergodic capacity with cooperative secondary user selection when the active secondary transmitter is located at (30, 30) and inactive secondary transmitters (relay sets) are located at (50, 50).

In **Fig. 5** and **Fig. 6**, we show the outage probability of the primary system as a function of SNIR in dB. Simulation results are verified by theoretical results developed in section 4 and they match with each other in all cases. **Fig. 5** shows the outage probability decreases with increasing SNIR as well as *N*. It can be observed that the proposed spectrum sharing model with cooperative relays shows better outage performance than non-cooperative network. In **Fig. 6**, we show the outage probability of the primary network with the varying position of the active secondary transmitter. It can be observed that primary outage increases as the active secondary transmitter becomes closer to the PRx. If two active secondary transmitters have the same transmit power, the closer one with respect to PRx causes more interference to the PRx which is clear from **Fig 6**. On the contrary, we can say that if each active secondary transmitter satisfy a fixed interference threshold i.e., I_{th} then their position with respect to the PRx as well as relay nodes do not impact on the performance of the primary outage probability which is clear from (7), (8) and (9).

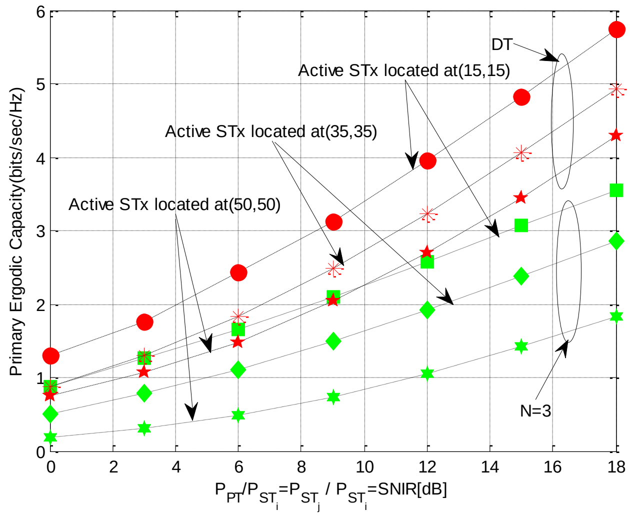

Fig. 4. Impact of the position of active secondary transmitter with respect to PRx. Inactive secondary transmitters (relay sets) are located at (60, 60).

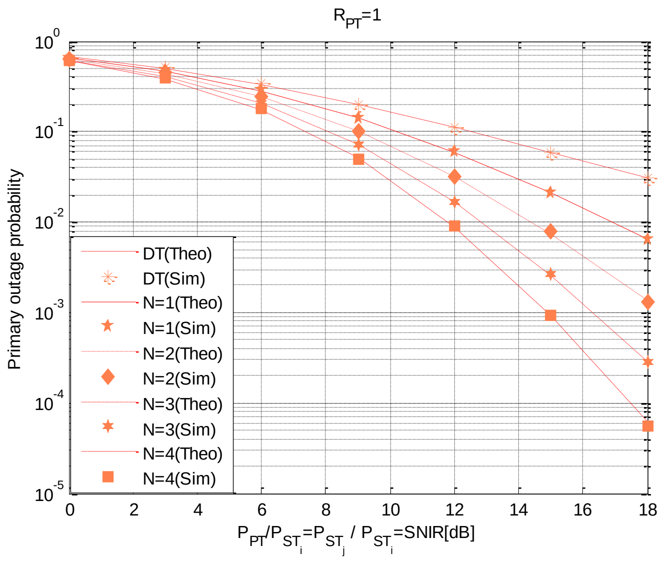

Fig. 5. Outage probability of the primary network. Active secondary transmitter is located at (30, 30) and inactive secondary transmitters (relay sets) are located at (50, 40).

In **Fig. 7** and **Fig. 8**, we show the outage probability of the secondary system in SI and SII respectively. We assume I_{th} / σ^2_{PInt} varies from 0 dB to 18 dB and inactive secondary transmitters (relay sets) are located at (60, 40). To clarify the comparison, we assume the distance between STx and SRx is 100 meters in all cases. We also verified the theoretical results with simulation results and they are well matched with each other. It can be observed from **Fig. 7** and **Fig. 8** that the outage probability of the secondary network decreases with increasing I_{th}. In addition, the outage performance improves when the active secondary transmitter is located farther away from the PRx. It is also obvious that secondary outage increases with an increasing R_{ST}.

Copyright ⓒ 2013 KSII

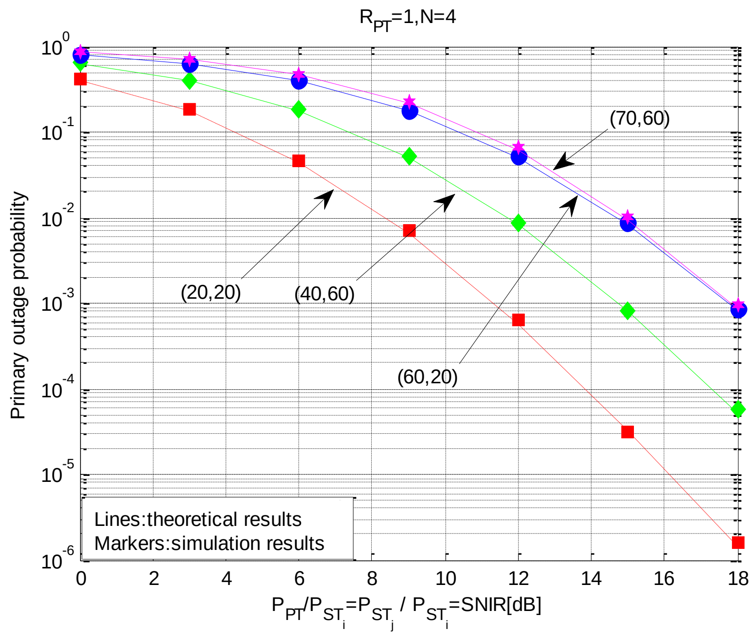

Fig. 6. Outage probability of the primary network with the varying position of the active secondary transmitter. Inactive secondary transmitters (relay sets) are located at (60, 40).

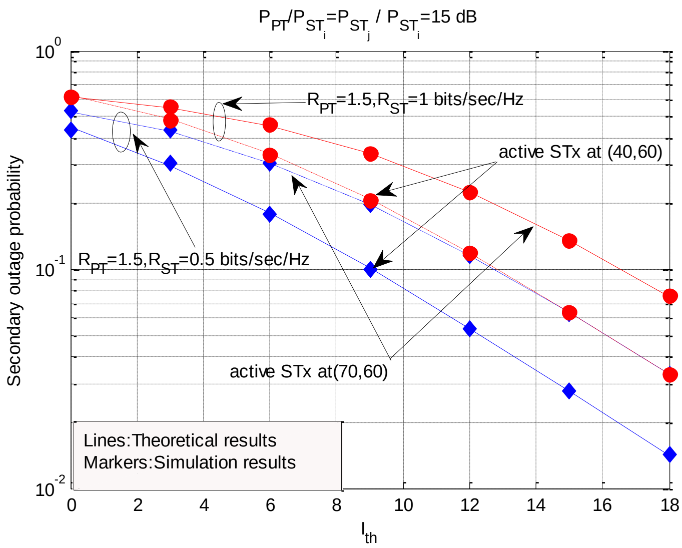

Fig. 7. Outage probability of the secondary network in SI.

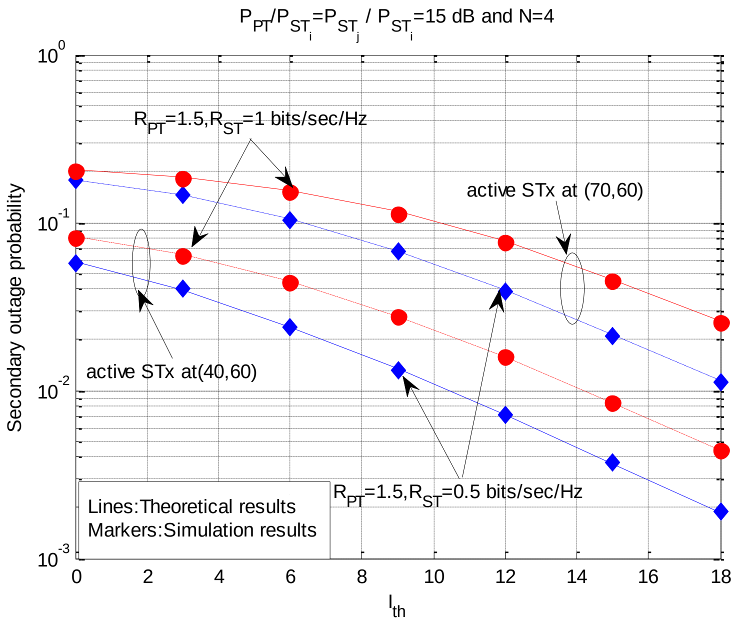

Fig. 8. Outage probability of the secondary network in SII.

In **Fig. 9**, we show the outage probability of secondary network in SIII with different values of R_{ST} and I_{th}. We consider two cases of R_{ST} where $R_{ST}=0.5$ bits/sec/Hz and $R_{ST}=1$ bits/sec/Hz respectively. Two cases of I_{th} where $I_{th}=5$ dB and $I_{th}=10$ dB are considered. Inactive secondary transmitters (relay sets) are located at (60, 40) and the distance between STx and SRx is 100 meters in all cases as in SI and SII. Theoretical results are also verified by simulation results. Here, we assume SNIR= $P_{SToppr}/P_{STi} = P_{PT}/P_{ST_i}$ and SNIR varies from 0 dB to 18 dB. During computation of the secondary outage probability, we assume same primary outage probability P_{OUT}^{P} i.e., fixed P_{OUT}^{P} for all four cases described above. We can observe from **Fig. 9** that secondary outage increases with a decreasing I_{th}. It is also observed that secondary outage increases with an increasing R_{ST}. Distance between two active secondary transmitters (i.e., opportunistic STx and STx satisfying I_{th} with respect to SRoppr) is same for all four cases.

If we compare **Fig. 7**, **Fig. 8** and **Fig. 9** then it is obvious that better secondary outage performance is found for SIII because of the increasing number of secondary transmission as well as primary system is in outage. It is also noted that in SI and SII the primary system is not in outage.

In **Fig. 10**, we show the total outage probability of the SU with different values of R_{ST}. Here, we assume SNIR= $P_{PT}/P_{ST_i} = P_{ST_j}/P_{ST_i} = P_{SToppr}/P_{STi}$ =15 dB and $I_{th}/\sigma_{PInt}^2 = I_{th}/\sigma_q^2$ varies from 0 dB to 18 dB. Three cases of R_{ST} where $R_{ST}=0.5$ bits/sec/Hz, $R_{ST}=0.75$ bits/sec/Hz and $R_{ST}=1$ bits/sec/Hz are considered. Inactive secondary transmitters (relay sets) are located at (60, 40) and the distance between STx and SRx is 100 meters in all cases as in SI, SII and SIII. For above three cases of R_{ST}, we considered same P_{OUT}^{P} as well as same distance between two active secondary transmitters (i.e., opportunistic STx and STx satisfying I_{th} with respect to SRoppr). Theoretical results are validated by the simulation results. It can be observed from **Fig. 10** that P_{OUT}^{S} increases with increasing R_{ST}. It is also observed that P_{OUT}^{S} decreases with

Copyright ⓒ 2013 KSII

increasing values of I_{th}.

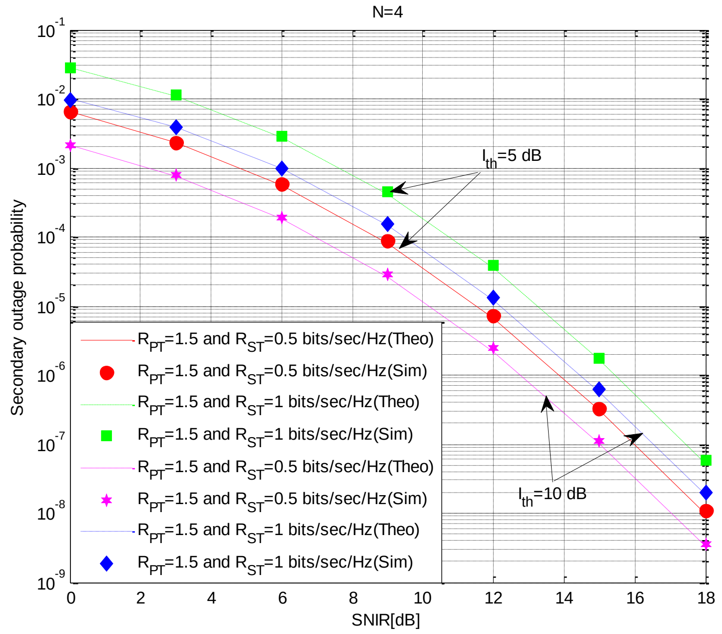

Fig. 9. Outage probability of the secondary network in SIII.

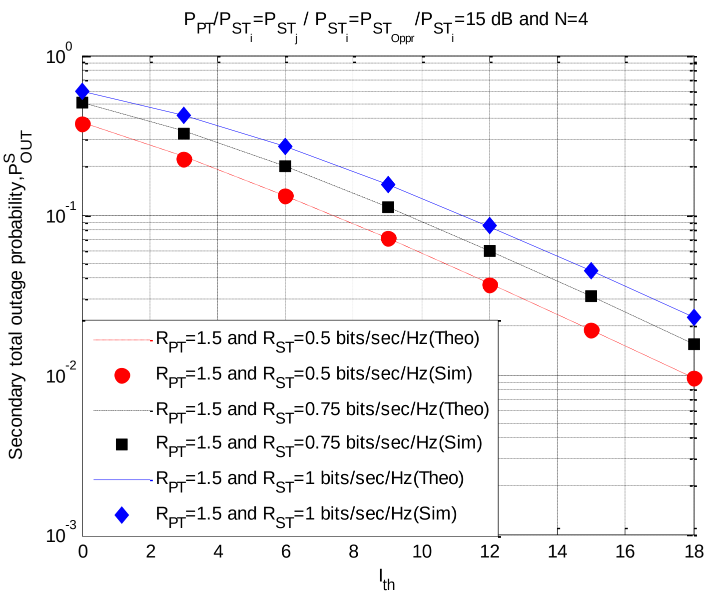

Fig. 10. Total outage probability of the secondary network.

However, in this paper, we have proposed a hybrid spectrum sharing model with joint consideration of the interweave and underlay schemes. We have considered interference limited environments in our proposed model. In addition, our proposed system model differs than others. In our model, inactive secondary transmitters act as cooperative nodes for the PU and active secondary transmitter coexist with the PU satisfying I_{th}. It is also shown that ergodic capacity and outage probably improve when the active secondary transmitter is located farther away from the PRx. Therefore, it is too difficult to compare our model with other spectrum sharing models (e.g., [22]). Furthermore, it will be considered as a future work.

Most of the modern communication systems are coded system. In this paper, we have considered DF relaying because it shows the following advantages over AF relaying: (i) DF relaying is better for coded systems as well as (ii) in [31], it is shown that single antenna multi-hop Rayleigh-fading relay channels under the DF protocol achieve higher ergodic capacity than under the AF one.

6. Conclusion

In this paper, we have proposed a hybrid spectrum sharing protocol with cooperative SU selection. Best cooperative secondary node is selected based on SNIR between the links PTx-to-ST_j and ST_j-to-PRx i.e., the ST_j which achieves best primary request target rate on the relaying link. We have investigated the ergodic capacity, outage probability of the primary network with cooperative relaying as well as the outage probability of the secondary network and these are affected by the position of the active secondary transmitter with respect to PRx. The ergodic capacity and outage probability of the primary system improve when more number of inactive secondary transmitters i.e., relays participate in the cooperation procedure. Moreover, the outage probability of the secondary network improves as the number of active secondary transmitter increases as well as the primary system is in outage. We also derived closed-form expressions for the outage probability of both the primary and secondary systems. In addition, analyzing the impact of the access delay on the capacity in the two cooperative relay phases will be considered in future work.

References

[1] S. Haykin, “Cognitive radio: brain-empowered wireless communications,” *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, pp. 201–220, February, 2005. Article (CrossRef Link).

[2] Q. Zhao and A. Swami, “A decision-theoretic framework for opportunistic spectrum access,” *IEEE Wireless Commun. Mag.,* vol. 14, no. 4, pp. 14–22, August, 2007. Article (CrossRef Link).

[3] Y. Zou, Y. Yao and B. Zheng, “A cooperative sensing based cognitive relay transmission scheme without a dedicated sensing relay channel in cognitive radio networks,” *IEEE Transactions on Signal Processing*, vol. 59, no. 2, pp.854–858, February, 2011. Article (CrossRef Link).

[4] K. Letaief and W. Zhang, “Cooperative communications for cognitive radio networks,” *Proceedings of the IEEE,* vol. 97, no. 5, pp. 878-893, May, 2009. Article (CrossRef Link).

[5] A. Ghasemi and E. S. Sousa, “Fundamental limits of spectrum-sharing in fading environments,” *IEEE Trans. Wireless Commun.,* vol. 6, no. 2, pp. 649–658, February, 2007. Article (CrossRef Link).

[6] Z. Dai, J. Liu, C. Wang and K. Long, “An adaptive cooperation communication strategy for enhanced opportunistic spectrum access in cognitive radios,” *IEEE Communications Letters,* vol. 16, no. 1, pp. 40-43, January, 2012. Article (CrossRef Link).

Copyright ⓒ 2013 KSII

[7] R. Manna, RHY. Louie, Li Yonghui and B. Vucetic, "Cooperative spectrum sharing in cognitive radio networks with multiple antennas," *IEEE Transactions on Signal Processing,* vol. 59, no.11, pp. 5509–5522, November, 2011. Article (CrossRef Link).

[8] A. Goldsmith, S. Jafar, I. Maric and S. Srinivasa, "Breaking spectrum gridlock with cognitive radios: an information theoretic perspective," *Proceedings of the IEEE,* vol. 97, no. 5, pp. 894-914, May, 2009. Article (CrossRef Link).

[9] I. Krikidis, J. N. Laneman, J. S. Thompson and S. McLaughlin, "Protocol design and throughput analysis for multi-user cognitive cooperative systems," *IEEE Trans. on Wireless Commun.*, vol. 8, no. 9, pp. 4740–4751, September, 2009. Article (CrossRef Link).

[10] G. Bansal , O. Duval and F. Gagnon., "Joint overlay and underlay power allocation scheme for ofdm-based cognitive radio systems," in *Proc.of IEEE VTC* 2010-Spring, pp. 1-5, May 16-19, 2010. Article (CrossRef Link).

[11] V. Chakravarthy, L. Xue, Z. Ruolin, W. Zhiqiang and M. Temple, "A novel hybrid overlay/underlay cognitive radio waveform in frequency selective fading channels," in *Proc. of Cognitive Radio Oriented Wireless Networks and Communications,* pp. 1-6, June 22-24, 2009. Article (CrossRef Link).

[12] Z. Dai, J. Liu and K. Long, "Cooperative transmissions for secondary spectrum access in cognitive radios," *Int. J. Commun. Syst.,* January, 2013. Article (CrossRef Link).

[13] T.Qiu, W.Xu, T.Sonf, Z. He and B.Tian, "Energy-efficient transmission for hybrid spectrum sharing in cognitive radio networks," in *Proc. of IEEE VTC* Spring, pp. 1-5, May 15-18, 2011. Article (CrossRef Link).

[14] Q. Zhang, J. Jia and J. Zhang, "Cooperative relay to improve diversity in cognitive radio Networks," *IEEE Communications Magazine,* vol. 47, no. 2, pp. 111-117, February, 2009. Article (CrossRef Link).

[15] A. Bletsas, A. Khisti, D. P. Reed and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE Journal on Select Areas in Communications,* vol. 24, no. 3, pp. 659–672, March, 2006. Article (CrossRef Link).

[16] Asaduzzaman, H. Y. Kong and I. Koo, "Opportunistic relaying based spectrum leasing for cognitive radio networks," *Journal of Communications and Networking,* vol.13, no. 1, pp. 50-55, February, 2011. Article (CrossRef Link).

[17] J. Cho and Z. J. Haas, "On the throughput enhancement of the downstream channel in cellular radio networks through multihop relaying," *IEEE J. Sel. Areas Commun.*, vol. 22, no. 7, pp. 1206–1219, September, 2004. Article (CrossRef Link).

[18] V. Asghari and S. Aissa, "Performance of cooperative spectrum-sharing systems with amplify-and-forward relaying," *IEEE Trans. Wireless Commun.*, vol. 11, no. 4 pp. 1295–1300, April, 2012. Article (CrossRef Link).

[19] Y. Han, A. Pandharipande and S. H. Ting, "Cooperative spectrum sharing via controlled amplify-and-forward relaying," in *Proc. of IEEE PIMRC'08*, pp. 1–5, September 15-18, 2008. Article (CrossRef Link).

[20] Y. Han, A. Pandharipande and S. H. Ting, "Cooperative decode-and forward relaying for secondary spectrum access," *IEEE Trans. Wireless Commun.*, vol. 8, no. 10, pp. 4945–4950, October, 2009. Article (CrossRef Link).

[21] Y. Han, S. H. Ting and A. Pandharipande, "Cooperative spectrum sharing protocol with secondary user selection," *IEEE Trans. Wireless Commun.*, vol. 9, no. 9, pp. 2914–2923, September, 2010. Article (CrossRef Link).

[22] Y. Han, S. H. Ting and A. Pandharipande, "Cooperative spectrum sharing protocol with selective relaying System," *IEEE Trans. on Commun.*, vol. 60, no. 1, pp. 62-67, January, 2012. Article (CrossRef Link).

[23] M. F. Kader, Asaduzzaman and M. Chowdhury, "Cooperative secondary user selection as a relay for the primary system in underlay cognitive radio networks," in *Proc. of IEEE 15th International Conference on Computer and Information Technology (ICCIT'12)*, pp. 275-278, December 22-24, 2012. Article (CrossRef Link).

[24] A. Papoulis, *Probability, Random Variables, and Stochastic Processes*. McGraw-Hill, 1991.

[25] H.Kim, S.Lim, H.Wang and D.Hong, “Optimal power allocation and outage analysis for cognitive full duplex relay systems,” *IEEE Trans. Wireless Commun.*, vol. 11, no.10, pp. 3754–3765, October, 2012. Article (CrossRef Link).
[26] A. Bletsas, H. Shin and M. Z. Win, “Cooperative communications with outage-optimal opportunistic relaying,” *IEEE Transactions on Wireless Communications*, vol. 6, no. 9, pp. 3450–3460, September, 2007. Article (CrossRef Link).
[27] S.-Y. Lien, C.-C. Tseng and K.-C. Chen, “Carrier sensing based multiple access protocols for cognitive radio networks,” in *Proc. of IEEE International Conference on Communications (ICC)*, pp. 3208–3214, May 19-23, 2008. Article (CrossRef Link).
[28] H. Wang, J. Lee, S. Kim and D. Hong, “Capacity enhancement of secondary links through spatial diversity in spectrum sharing,” *IEEE Trans. Wireless Commun.*, vol. 9, no. 2, pp. 494–499, February, 2010. Article (CrossRef Link).
[29] O. Simeone, I. Stanojev, S. Savazzi, Y. Bar-Ness, U. Spagnolini and R. Pickholtz, “Spectrum leasing to cooperating secondary ad hoc networks,” *IEEE JSAC,* vol. 26, no. 1, pp. 203 –213, January, 2008. Article (CrossRef Link).
[30] J. Zhang and Q. Zhang, “Stackelberg game for utility-based cooperative cognitive radio networks,” in *Proc. of ACM MOBIHOC*, pp. 23-32, May 18-21, 2009. Article (CrossRef Link).
[31] G. Farhadi and N. Beaulieu, “On the ergodic capacity of multi-hop wireless relaying Systems,” *IEEE Trans. Wireless Comm.*, vol. 8, no. 5, pp. 2286-2291, May, 2009. Article (CrossRef Link).

Md Fazlul Kader received the B. Sc. Engineering degree in computer Science and engineering (CSE) from Chittagong University of Engineering and Technology (CUET), Bangladesh in 2005. From 2007 onwards he is a faculty member of the Dept. of Applied Physics, Electronics and Communication Engineering, University of Chittagong, Bangladesh. He is currently working toward the M.Sc. Engineering degree in the Department of CSE, CUET, Bangladesh. His major research interests include cognitive radio networks, cooperative communications, computer network, pattern recognition etc.

Asaduzzaman received the B. Sc. Engineering degree in electrical and electronics engineering from Chittagong University of Engineering and Technology, Bangladesh, in 2001. From 2001 onwards he has been serving as a faculty member in the Department of Computer Science and Engg., Chittagong University of Engineering and Technology (CUET), Chittagong, Bangladesh. He received his Ph.D. from the Department of Electrical Engineering, University of Ulsan, Korea in 2010. His major research interests include wireless communication systems with emphasis on cooperative communications and MIMO systems, wireless sensor networks, modulation and coding techniques, cognitive radio, etc.

Md. Moshiul Hoque received his B. Sc. in electrical and electronics engineering from Chittagong University of Engineering and Technology (CUET), Bangladesh and MSc in Computer Science and Engineering from Bangladesh University of Engg. & Tech. (BUET), in 2001 and 2005 respectively. Hoque received his Ph.D in science & engg. in 2012 from Saitama University, Japan. In 2001, he joined as a lecturer in CUET and became an associate professor in 2012. His major research interests include sensor network, wireless network security, human robot interaction and computer vision. He is a student member of IEEE, Robotics Society of Japan.