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Research Article

Opportunistic Cognitive Relaying: A Win-Win Spectrum Sharing Scheme

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A cost-effective spectrum sharing architecture is proposed to enable the legacy noncognitive secondary system to coexist with the primary system. Specifically, we suggest to install a few intermediate nodes, namely, the cognitive relays, to conduct the spectrum sensing and coordinate the spectrum access. To achieve the goal of win-win between primary and secondary systems, the cognitive relay may act as a cooperator for both of them, and an *Opportunistic Cognitive Relaying* (OCR) scheme is specially devised. In this scheme, the cognitive relay opportunistically switches among three different working modes, that is, *Relay for Primary Link* (RPL), *Relay for Secondary Link* (RSL), or *Relay for Neither of the Links* (RNL), respectively, based on the channel-dependent observation of both systems. In addition, the transmit power for cognitive relay and secondary transmitter in each mode are optimally determined by maximizing the transmission rate of secondary system while keeping or even reducing the outage probability of primary system. Simulation results validate the efficiency of the proposed spectrum sharing scheme.

1. Introduction

With the increasing demands of radio spectrum ascribing to the speed-up deployment of wireless communication systems recently, dynamic spectrum sharing [1] seems to be promising and desirable for wireless systems with heterogeneous priorities to coexist and operate. For licensed (primary) wireless systems, there is no problem that they have exclusive access to licensed spectrum. In contrast, the unlicensed (secondary) wireless systems usually need to equip cognitive radios [2] to conduct the corresponding spectrum sensing and spectrum decision before spectrum access [3]. Unfortunately, the existing legacy wireless devices generally have no cognitive functionalities and thus do not have the capabilities of sensing and decision. To make things even worse, in some cases it might be too costly to upgrade the whole secondary system and also impossible to re-configure each secondary device with plug-in or add-on cognitive radio. Thus, it remains challenging for spectrum sharing among legacy wireless systems.

Recently, the technology of cooperative relay [4] has emerged as a powerful approach to guarantee transmission reliability and achieve throughput enhancement in wireless systems. Some wireless network service providers (NSPs) are planning or even have started to deploy relay nodes into their systems to enhance the hot-spot or hot-zone coverage and performance [5]. Besides the well-known benefits brought by the intermediate relay, it may also provide us with an opportunity to enable spectrum sharing among the licensed system running by NSP and the unlicensed system, that is, if the intermediate relay nodes could be equipped with cognitive radios, they may play the roles of both spectrum activity monitor and spectrum access coordinator, thus enable current noncognitive secondary system to coexist with the primary system in a cost effective way.

Motivated by the above consideration, in this paper, we propose to add cognitive functionalities to the intermediate relay nodes, so as to assist the transmission over either the primary link or the secondary link. Such relay nodes are therefore termed as “cognitive relays” in the rest of the paper. In the literature, several cognitive relay schemes have been proposed w.r.t. different assisted objects. For example, the secondary user may act as cognitive relay for one another to improve the throughput of secondary system [6], decrease the outage probability of secondary link [7], or reduce the interference caused to the primary system [8, 9]. More specially, the secondary user may even use parts of its power to forward the primary user's signal [10], which achieves the largest rate of secondary link without bringing down the channel capacity of primary link. In consideration of packet burstiness in the primary system, the secondary user can relay packets for the primary link [11] so as to drain the primary queue more rapidly and exploit more transmission opportunities for itself. For all of them, the cognitive relay works dedicated for one system and thus is designed to optimize only one system's performance. In the proposed architecture, the cognitive relay is a coordinator of the two systems and may act as transmission cooperator for both of them. Thus, it now has the goal of achieving win-win performance gain for both systems. In this paper, we consider a conceptual simple scenario with one pair of primary users, one pair of secondary users, and a cognitive relay. Similar model with two homogeneous sources is considered in [12] from information theoretic perspective, which assumes either "message cognitive" or "signal cognitive" at the relay, together with source cooperation and interference cancelation at the receivers to investigate the capacity region. While [13] suggests interference forwarding to enable the receiver with weak interference to carry out interference cancelation. However, these assumptions are difficult to be satisfied in practice.

So far, we have introduced a cost-effective infrastructure of enabling the current noncognitive secondary systems to coexist with the primary systems. Based on that, we propose an *Opportunistic Cognitive Relaying* (OCR) scheme, in which the cognitive relay employs regenerative decode-and-forward (DF) cooperation protocol and may work in either *Relay for Neither of the Links* (RNL), *Relay for Secondary Link* (RSL), or *Relay for Primary Link* (RPL) mode. The selection of modes depends on channel measurements and a unified mode selection criterion is given. For each mode, we find the optimal transmit power for both the secondary Tx and the cognitive relay that maximizes the transmission rate of secondary link while keeping or even reducing the outage probability of primary link. Since both systems may get benefits from the OCR scheme, it is a spectrum-sharing scheme with win-win performance gains. Finally, the performance improvements achieved by OCR scheme in terms of the outage probability of primary link, and the transmission rate of secondary link are validated by simulations.

The rest of the paper is organized as follows. Section 2 describes the network architecture and communication scenario. The win-win OCR scheme and three transmission modes for the cognitive relay are elaborated in Section 3. Then, in Section 4, several simulations are given to evaluate the performance of the proposed OCR scheme. Finally, Section 5 discusses some aspects worthy of further investigation, and Section 6 concludes the paper.

2. Network Architecture and Communication Scenario

2.1. Network Architecture. As seen from Figure 1, there are three components in the coexistent wireless systems, that is, primary system, secondary system, and cognitive relay. Being aware of the fact that the secondary users lack cognitive functionalities here, the tasks of sensing the environment, analyzing the channel information, and making decisions on operating parameters, are all transferred to the cognitive relays. In this way, other than forwarding message for primary or secondary users, the cognitive relay also plays the roles of spectrum monitor and access coordinator, to distribute the information sensed and coordinate the transmissions of a group of secondary users through an out-of-band channel. While the details of medium access control (MAC) protocol is not the main concern of this paper, which is left for further investigation. The evident advantage of the proposed spectrum sharing architecture is to exempt the necessity of deploying cognitive radio for each legacy wireless device at a small infrastructure cost.

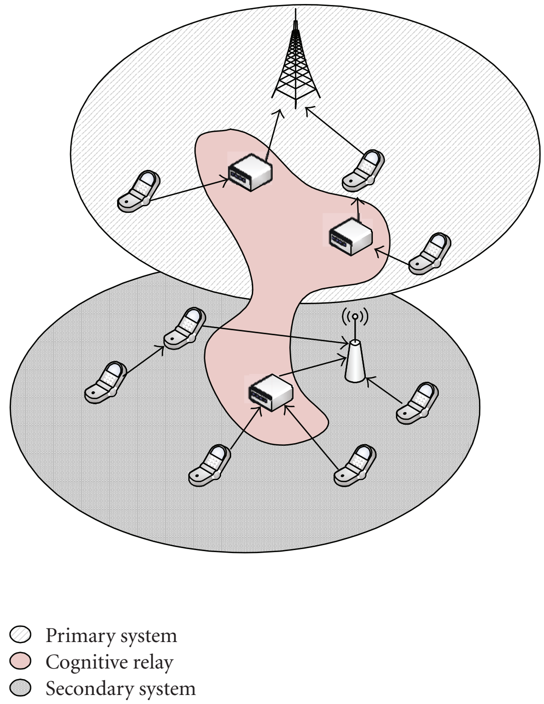


Figure 1: A cost-effective spectrum sharing architecture.

2.2. Communication Scenario. Consider that both primary and secondary systems operate in a time division multiple access (TDMA) manner, that is, at any time block, there is only one primary (secondary) Tx communicates with its intended Rx. Besides, transmission synchronization is assumed between primary and secondary systems. In this way, the basic communication scenario is shown in Figure 2(a), which consists of a primary pair, a secondary pair, and the cognitive relay, denoted as P_{Tx}, P_{Rx}, S_{Tx}, S_{Rx}, and C_{R}, accordingly. Note that the solid arrowed lines represent the signal links, while the dashed ones denote the interference links. The channel fading coefficient between Tx i and Rx j is denoted by h_{ij}, where i, j reads "p" for the primary user, "s" for the secondary user, and "r" for the

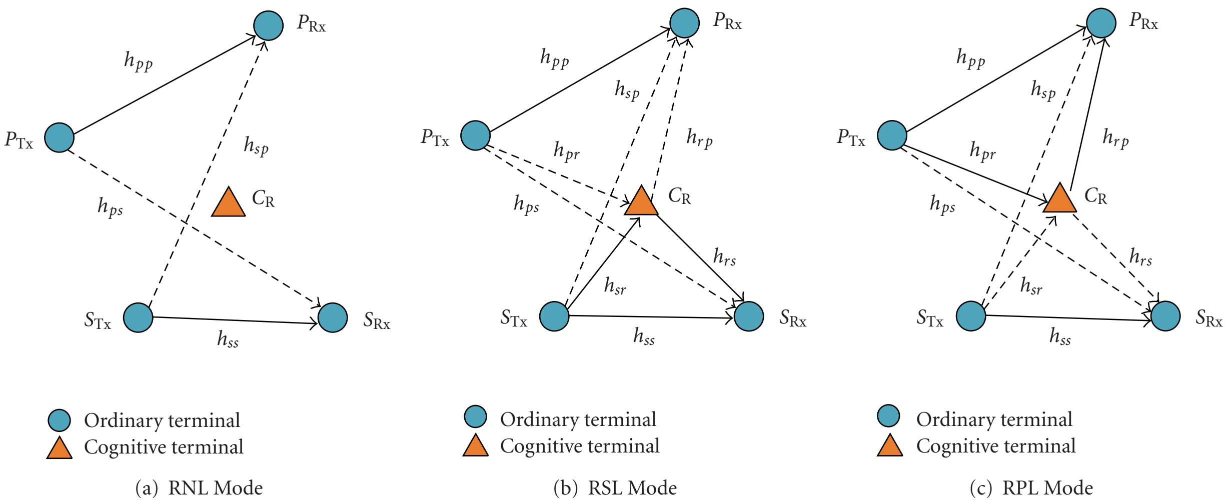


Figure 2: The three modes in OCR scheme.

cognitive relay. We assume that, h_{ij} is a zero-mean circularly symmetric complex Gaussian random variable, that is, $h_{ij} \sim \mathcal{CN}(0, \sigma_{ij}^2)$. In this regard, the power gain on link ij, that is, $|h_{ij}|^2$, is exponentially distributed with parameter σ_{ij}^2. Besides, additive white Gaussian noise (AWGN) are assumed at all receivers with equal variances σ_n^2. The cognitive relay is assumed to know instantaneous channel state information (CSI) of all links through channel estimation and information exchange (The channel gains h_{pr} and h_{sr} can be obtained by estimating the pilot signal of the primary and secondary Txs, respectively. Besides, the cognitive relay acquires h_{pp} and h_{sp} from the feedbacks. The acquisition of other channel gains are somewhat difficult, and a minor modification of the protocol proposed in [10] is suggested.) . Assume that the primary Tx has zero CSI or does not exploit the CSI even if it is obtained, and it simply transmits with constant power P_P. Specifically, an error-free transmission rate R_{req} is desired. Besides, the maximum allowable transmit powers of the secondary Tx and the cognitive relay are $P_S^{\max}$ and $P_R^{\max}$, respectively.

Specially, the regenerated DF cooperation model [4] is adopted, and the whole time block is divided equally into two slots. Define T as the time duration of one slot, and therefore one time block lasts $2T$. In addition to direct transmission, the primary link may also perform indirect transmission with the help of cognitive relay. In response, there are two encoding schemes for the primary Tx. In the case of direct transmission, the primary Tx transmits at rate R_{req} bit/s, and therefore $2R_{\text{req}}T$ bits of message are sent in two slots. It is equivalent to ask the primary Tx to transmit at $2R_{\text{req}}$ bit/s instead when indirect transmission is carried out. That is, it has to send $2R_{\text{req}}T$ bits in total to the cognitive relay in the first slot, then the latter forwards the received messages to the primary Rx in the second slot. According to Shannon's theorem [14], as long as the channel capacity is larger than the transmission rate, the transmitted symbols can be decoded with arbitrary small error probability, that is, error-free transmission is achieved. On the contrary, the transmitted symbols will undergo nonzero error probability. The transmission outage is defined as the event that a target error-free transmission rate can not achieved. In this paper, we are interested in the error-free transmission rate.

Three transmission modes in the scenario are mainly considered.

(i) *Relay for Primary Link (RPL)*: by sending a relay notification to the primary Tx, the cognitive relay cooperates with it to send messages to the primary Rx. It is obvious that, cooperative transmission via the cognitive relay is capable of avoiding transmission outages of primary link, which results in reduced outage probability. In Section 3.4, we will see that, if there is large interference margin (which is defined later) presented by the primary link, the cognitive relay may decide to work in RPL mode in favor of improving the transmission rate of secondary link.

(ii) *Relay for Secondary Link (RSL)*: as the name implies, the cognitive relay helps forwarding messages for the secondary pair in this mode. Due to the cooperative diversity gain exploited by the cognitive relay, the transmission rate of secondary link may be increased comparing to that of the direction transmission.

(iii) *Relay for Neither of the Links (RNL)*: in this mode, the cognitive relay is not involved in the transmission of either primary or secondary system. However, it has to inform the secondary Tx of the acquired link CSIs to enable spectrum sharing.

3. Win-Win OCR Scheme

The OCR scheme is proposed with the aim of maximizing the transmission rate of secondary link while minimizing the outage probability of primary link. The mode selection criterion of cognitive relay is thereby designed as follows: when the channel capacity of the primary link is smaller than the target transmission rate R_{req}, it first checks if RPL mode works, that is, if the transmission outage can be avoided by cooperation. Provided that RPL mode works, the cognitive relay will send a relay notification to the primary Tx. If not, the cognitive relay chooses from the other two modes according to the achievable transmission rate of secondary link. When the primary link is not going to be in outage, the cognitive relay should compare three modes in terms of secondary throughput and selects the best one.

In what follows, we are going to reveal the details of the three modes, mainly focusing on the power control of both secondary Tx and cognitive relay.

3.1. RNL Mode. In this mode, both primary and secondary pairs perform direct transmission, and the cognitive relay does not forward messages for any of them. In order to realize simultaneous transmission with the primary link, the secondary Tx must make sure that the primary link can still transmit at R_{req} with P_P successfully, that is,

$$\frac{\left|h_{pp}\right|^2 P_P}{\left|h_{sp}\right|^2 P_s + \sigma_n^2} \geq \gamma_{\text{req}}, \tag{1}$$

where P_s is the transmit power of secondary Tx, and γ_{req} is defined as the signal-to-interference plus noise ratio (SINR) requirement w.r.t. transmission rate R_{req}, that is, $(1/2)\log_2(1 + \gamma_{\text{req}}) = R_{\text{req}}$. Let us define $Q_{pp}(R_{\text{req}})$ as the interference margin introduced by the primary link with rate requirement of R_{req}

$$Q_{pp}\left(R_{\text{req}}\right) = \frac{\left|h_{pp}\right|^2 P_P}{\gamma_{\text{req}}} - \sigma_n^2, \tag{2}$$

which is derived from (1). Intuitively, $Q_{ij}(x)$ specifies how much interference ij link can endure while an error-free transmission rate x can still be achieved. As a result of deep channel fading, the channel capacity of primary link may fall short of the target transmission rate, which leads to $Q_{pp}(R_{\text{req}}) < 0$. If this happens, it will not introduce any new outage events no matter how much power the secondary Tx uses, as if the primary link sets no constraint on external interference, that is, $Q_{pp}(R_{\text{req}}) = +\infty$. In summary, if the primary link carries out direct transmission, then the interference margin of it can be redefined as follows:

$$\widetilde{Q}_{pp}\left(R_{\text{req}}\right) = \begin{cases} Q_{pp}\left(R_{\text{req}}\right), & Q_{pp}\left(R_{\text{req}}\right) \geq 0, \\ +\infty, & Q_{pp}\left(R_{\text{req}}\right) < 0. \end{cases} \tag{3}$$

Furthermore, considering the maximum transmit power constraint, the secondary Tx should adjust its transmit power to

$$P_s = \min\left(\frac{\widetilde{Q}_{pp}\left(R_{\text{req}}\right)}{\left|h_{sp}\right|^2}, P_S^{\max}\right). \tag{4}$$

Then the received SINR of secondary Rx suffering from the primary transmission [15] is

$$\gamma_{ss} = \frac{|h_{ss}|^2 P_s}{\left|h_{ps}\right|^2 P_P + \sigma_n^2}. \tag{5}$$

Specifically, block fading channel is considered here, that is, the channel gains remain constant during one block but vary independently across different blocks. In this regard, the link CSIs remains constant during two successive slots of one block. Then the transmission rate of secondary link is $R_s^{\text{RNL}} = C(\gamma_{ss})$, where $C(x) = (1/2)\log_2(1 + x)$.

3.2. RSL Mode. In RSL mode, the primary Tx behaves the same as in RNL mode, that is, transmits with power P_P at rate R_{req} in both two slots. Meanwhile, the secondary Tx transmits in the first slot, and then the cognitive relay cooperatively forwards the regenerated messages to the secondary Rx in the following slot. In the first slot, considering the interference margin $\widetilde{Q}_{pp}(R_{\text{req}})$ and the maximum transmit power constraint $P_S^{\max}$, the transmit power of secondary Tx P_s should be set as (4). Then the SINR of *sr* and *ss* links are

$$\gamma_{sr} = \frac{|h_{sr}|^2 P_s}{\left|h_{pr}\right|^2 P_P + \sigma_n^2}, \qquad \gamma_{ss} = \frac{|h_{ss}|^2 P_s}{\left|h_{ps}\right|^2 P_P + \sigma_n^2}. \tag{6}$$

As the secondary Tx transmits concurrently with the primary one, the cognitive relay receives the composite signal, and simply regards the power emitted from primary Tx as interference when decoding the message sent from secondary Tx. After that, the cognitive relay forwards the regenerated message to the secondary Rx in the second slot. In an analogous manner, the transmit power of cognitive relay should be set to

$$P_r = \min\left(\frac{\widetilde{Q}_{pp}\left(R_{\text{req}}\right)}{\left|h_{rp}\right|^2}, P_R^{\max}\right). \tag{7}$$

By doing so, the primary link can still achieve the error-free transmission rate R_{req} as long as $Q_{pp}(R_{\text{req}}) > 0$. Then the SINR of *rs* link is

$$\gamma_{rs} = \frac{|h_{rs}|^2 P_r}{\left|h_{ps}\right|^2 P_P + \sigma_n^2}. \tag{8}$$

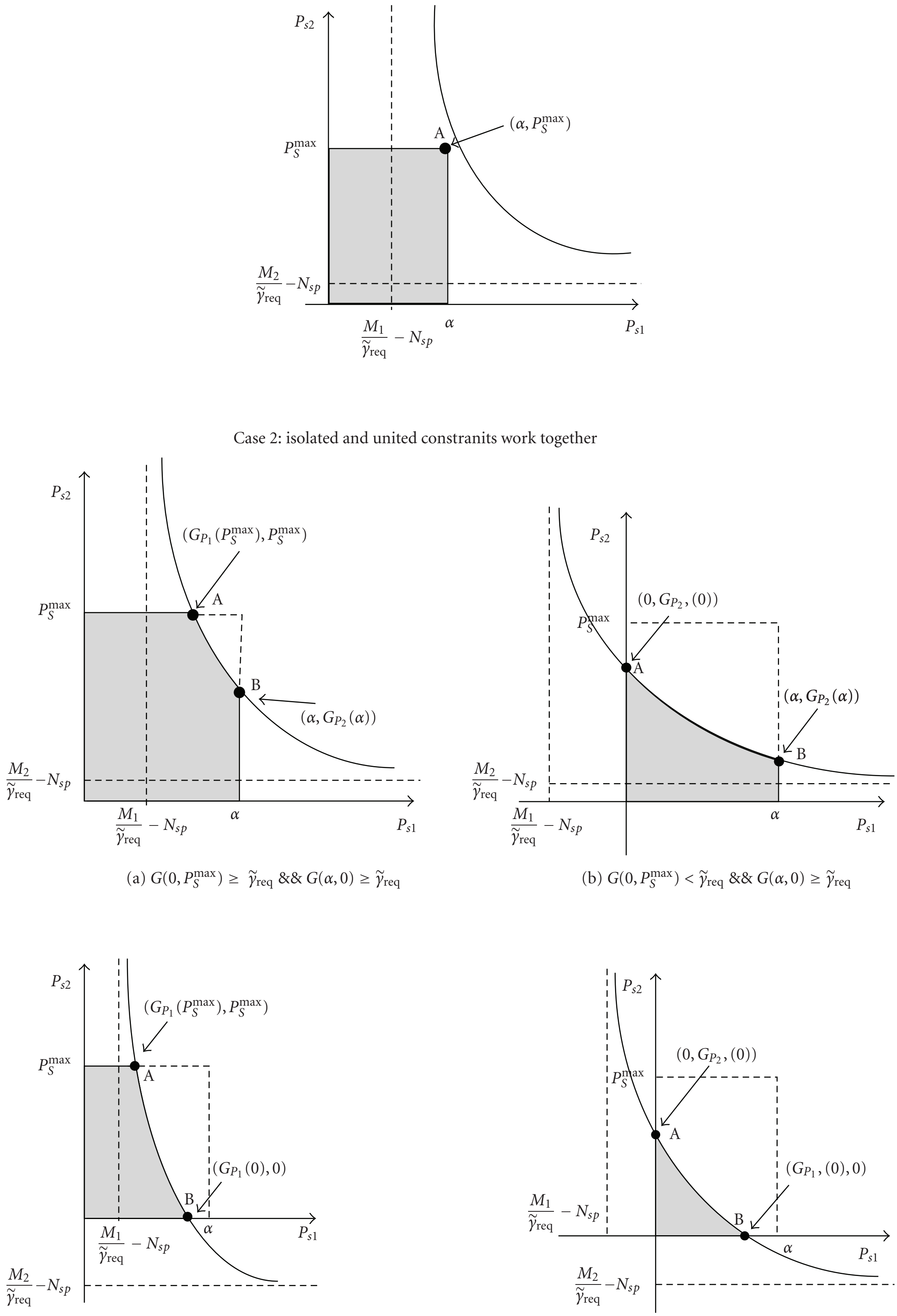
According to the DF cooperation protocol, the achievable transmission rate of secondary link can be represented as follows:

$$R_s^{\text{RSL}} = \frac{1}{2} C(\min(\gamma_{sr}, \gamma_{ss} + \gamma_{rs})), \tag{9}$$

where 1/2 is due to the fact that transmission rate has to be averaged over two slots.

3.3. RPL Mode. As long as RPL mode is selected, the primary Tx sends messages to the corresponding Rx via the cognitive relay. As mentioned before, the primary Tx should transmit

Case 1: isolated constraint dominates



(a) $G(0, P_S^{\max}) \geq \tilde{\gamma}_{\text{req}}$ && $G(\alpha, 0) \geq \tilde{\gamma}_{\text{req}}$

(b) $G(0, P_S^{\max}) < \tilde{\gamma}_{\text{req}}$ && $G(\alpha, 0) \geq \tilde{\gamma}_{\text{req}}$

(c) $G(0, P_S^{\max}) \geq \tilde{\gamma}_{\text{req}}$ && $G(\alpha, 0) < \tilde{\gamma}_{\text{req}}$

(d) $G(0, P_S^{\max}) < \tilde{\gamma}_{\text{req}}$ && $G(\alpha, 0) < \tilde{\gamma}_{\text{req}}$

Figure 3: The feasible region for P_{s1} and P_{s2}. Given fixed P_r, the best transmit power pair (P_{s1}, P_{s2}) is shown by point A in the case of $G(\alpha, P_S^{\max}) \geq \tilde{\gamma}_{\text{req}}$. Otherwise, the best transmit power pair is either achieved on point A or point B for each subcase.

at $2R_{\text{req}}$ bit/s in this mode, in order to send $2R_{\text{req}}T$ bits of messages in total to the cognitive relay in the first slot. Let $\widetilde{\gamma}_{\text{req}}$ be the SINR requirement w.r.t. transmission rate $2R_{\text{req}}$ bit/s, that is, $(1/2)\log_2(1+\widetilde{\gamma}_{\text{req}}) = 2R_{\text{req}}$. It is easy to prove that, $\widetilde{\gamma}_{\text{req}} = (1+\gamma_{\text{req}})^2 - 1$. Generally, the interference margins presented in pr and rp links are not equal. In this regard, the secondary Tx is motivated to transmit at different power levels in two slots, namely, P_{s1} and P_{s2}, so as to fully exploit the transmission opportunities. Besides, assume that the cognitive relay transmits with power P_r.

Let γ_{pp}, γ_{rp}, and γ_{pr} denote the received SINR of pp, rp and pr link in this mode, respectively. Similar to (9), the achievable transmission rate of primary link can be represented as $R_p^{\text{RPL}} = (1/2)\min(C(\gamma_{pr}), C(\gamma_{pp}+\gamma_{rp}))$, the two items of which are both required to be larger than $2R_{\text{req}}$, for the purpose of guaranteeing reliable transmission over the primary link. By taking the transmission rate of secondary link as optimization goal, and the target SINR of primary link as constraint, the optimization problem in RPL mode can be modelled as

$$\max_{P_r,P_{s1},P_{s2}} \quad C\left(\frac{|h_{ss}|^2 P_{s1}}{\left|h_{ps}\right|^2 P_P + \sigma_n^2}\right) + C\left(\frac{|h_{ss}|^2 P_{s2}}{|h_{rs}|^2 P_r + \sigma_n^2}\right) \tag{10a}$$

$$\text{s.t.} \quad \frac{\left|h_{pr}\right|^2 P_P}{|h_{sr}|^2 P_{s1} + \sigma_n^2} \geq \widetilde{\gamma}_{\text{req}}, \tag{10b}$$

$$\frac{\left|h_{pp}\right|^2 P_P}{\left|h_{sp}\right|^2 P_{s1} + \sigma_n^2} + \frac{\left|h_{rp}\right|^2 P_r}{\left|h_{sp}\right|^2 P_{s2} + \sigma_n^2} \geq \widetilde{\gamma}_{\text{req}}, \tag{10c}$$

$$0 \leq P_r \leq P_R^{\max}, \quad 0 \leq P_{s1}, \quad P_{s2} \leq P_S^{\max}, \tag{10d}$$

which is optimized over power triple (P_r, P_{s1}, P_{s2}). It is obvious that, constraint (10b) and (10c) are exactly the same as $C(\gamma_{pr}) \geq 2R_{\text{req}}$ and $C(\gamma_{pp}+\gamma_{rp}) \geq 2R_{\text{req}}$. Besides, the final transmission rate of secondary link should be averaged over two slots, that is, $R_s^{\text{RPL}} = 1/2$ (10a). Observing from problem (10a) that, the transmit power of cognitive relay, that is, P_r, is not the greater the better in RPL mode. As P_r grows, P_{s2} can be enlarged accordingly as (10c) indicates. However, larger P_r introduces more interference to the simultaneously active secondary link in the second slot as (10a) shows. As a result, P_r should be traded off between the two opposite effects.

Being aware of this fact, we tried to solve problem (10a) with fixed P_r first. To start with, constraints (10b)–(10d) are classified into two types, where (10b) and (10d) are isolated constraints and (10c) is united constraint. On one hand, according to the isolated constraint (10b) and (10d), P_{s1} should be set not larger than

$$\alpha = \min\left(\frac{Q_{pr}\left(2R_{\text{req}}\right)}{|h_{sr}|^2}, P_S^{\max}\right), \tag{11}$$

where $Q_{pr}(2R_{\text{req}})$ is the interference margin presented by pr link w.r.t. rate $2R_{\text{req}}$, which is calculated in a similar way as $Q_{pp}(R_{\text{req}})$ in (2). On the other hand, P_{s1} and P_{s2} should lie in the area restricted by a locus function $G(P_{s1}, P_{s2}) \geq \widetilde{\gamma}_{\text{req}}$ as Figure 3 shows, and

$$G(x,y) = \frac{M_1}{x+N_{sp}} + \frac{M_2}{y+N_{sp}}, \tag{12}$$

which is directly derived from the united constraint (10c). In addition, the symbols used in locus function $G(x,y)$ are defined as follows:

$$M_1 = \frac{\left|h_{pp}\right|^2 P_P}{\left|h_{sp}\right|^2}, \quad M_2 = \frac{\left|h_{rp}\right|^2 P_r}{\left|h_{sp}\right|^2}, \quad N_{sp} = \frac{\sigma_n^2}{\left|h_{sp}\right|^2}, \tag{13}$$

where M_1 and M_2 are perceived as normalized received power, and N_{sp} is regarded as the normalized noise. By setting $G(P_{s1}, x) = \widetilde{\gamma}_{\text{req}}$, P_{s1} can be presented as a function of x, that is,

$$G_{P_{s1}}(x) = \frac{M_1}{\widetilde{\gamma}_{\text{req}} - \left(M_2/\left(x+N_{sp}\right)\right)} - N_{sp}, \tag{14}$$

Given $P_{s2} = x$, $G_{P_{s1}}(x)$ specifies how large P_{s1} could be under the united constraint (10c). In an analogous manner, $G_{P_{s2}}(x)$ is defined by setting $G(x, P_{s2}) = \widetilde{\gamma}_{\text{req}}$.

In the case of $P_r = P_R^{\max}$, as long as $\alpha \geq 0$ and $G(0,0) \geq \widetilde{\gamma}_{\text{req}}$ are both satisfied, the error-free transmission rate $2R_{\text{req}}$ bit/s can be achieved without considering the interference from secondary link, that is, RPL mode is feasible. In this regard, define $\alpha \geq 0$ && $G(0,0)|_{P_r=P_R^{\max}} \geq \widetilde{\gamma}_{\text{req}}$ as the *effective relay condition*, which is used to check the feasibility of RPL mode. Suppose that the *effective relay condition* is satisfied, then the following theorem summarizes the solution to problem (10a) with fixed P_r.

Theorem 1. *Given fixed P_r, the best transmit power pair of secondary link is $(P_{s1}^*, P_{s2}^*) = (\alpha, P_S^{\max})$ in the case of $G(\alpha, P_S^{\max}) \geq \widetilde{\gamma}_{req}$. Otherwise, it leads to four subcases, and the best transmit power pair is either achieved on point A or point B shown in Figure 3, whose coordinates are listed in Table 1. Then the transmission rate of the secondary link with fixed P_r is*

$$R_s(P_r) = \frac{1}{2}\left(C\left(H_{s1}P_{s1}^*\right) + C\left(H_{s2}P_{s2}^*\right)\right), \tag{15}$$

where H_{s1} and H_{s2} are defined as the normalized channel power gains of secondary link in the 1st and 2nd slot respectively, that is

$$H_{s1} = \frac{|h_{ss}|^2}{\left|h_{ps}\right|^2 P_P + \sigma_n^2}, \qquad H_{s2} = \frac{|h_{ss}|^2}{|h_{rs}|^2 P_r + \sigma_n^2}. \tag{16}$$

Proof. See the appendix. □

As shown in Theorem 1, the best transmit power pair (P_{s1}, P_{s2}) can be jointly determined through a simple comparison, provided that P_r is fixed. In this regard, the best power triple (P_r^*, P_{s1}^*, and P_{s2}^*) in terms of the performance of secondary link, can be found numerically by increasing P_r from 0 to $P_R^{\max}$. To be more specific, the procedure of searching the optimal solution of optimization problem

Table 1: Four subcases for the solution candidates.

Condition	Coordinates of Point A	Coordinates of Point B
$G(0, P_S^{\max}) \geq \widetilde{\gamma}_{\text{req}}$ && $G(\alpha, 0) \geq \widetilde{\gamma}_{\text{req}}$	$(G_{P_{s1}}(P_S^{\max}), P_S^{\max})$	$(\alpha, G_{P_{s2}}(\alpha))$
$G(0, P_S^{\max}) < \widetilde{\gamma}_{\text{req}}$ && $G(\alpha, 0) \geq \widetilde{\gamma}_{\text{req}}$	$(0, G_{P_{s2}}(0))$	$(\alpha, G_{P_{s2}}(\alpha))$
$G(0, P_S^{\max}) \geq \widetilde{\gamma}_{\text{req}}$ && $G(\alpha, 0) < \widetilde{\gamma}_{req}$	$(G_{P_{s1}}(P_S^{\max}), P_S^{\max})$	$(G_{P_{s1}}(0), 0)$
$G(0, P_S^{\max}) < \widetilde{\gamma}_{\text{req}}$ && $G(\alpha, 0) < \widetilde{\gamma}_{\text{req}}$	$(0, G_{P_{s2}}(0))$	$(G_{P_{s1}}(0), 0)$

(10a) can be summarized as follows:

(1) Initialize power $P_r = 0$, $R_s^{\text{RPL}} = 0$ and $\Delta P_r = \varepsilon$, where ε is a small positive constant.

(2) Solve problem (10a) with given P_r by Theorem 1. Compare the resulting transmission rate of secondary link $R_s(P_r)$ with R_s^{RPL}. If $R_s(P_r) > R_s^{\text{RPL}}$, then set $R_s^{\text{RPL}} = R_s(P_r)$ and record the associated power triple $(P_r, P_{s1}, \text{and } P_{s2})$.

(3) $P_r = P_r + \Delta P_r$, go back to step 2 until P_r can not be increased.

(4) R_s^{RPL} is the final solution, and $(P_r, P_{s1}, \text{and } P_{s2})$ is the optimal power triple.

3.4. Summary of OCR Scheme. Due to the time varying fading channel, the channel capacity of primary link may fall short of the target transmission rate ($Q_{pp}(R_{\text{req}}) < 0$), or have a surplus of that ($Q_{pp}(R_{\text{req}}) \geq 0$). According to the value of $Q_{pp}(R_{\text{req}})$, the win-win OCR scheme can be summarized into two cases, and some insights are also obtained.

Case 1 ($Q_{pp}(R_{\text{req}}) < 0$). As a result of deep fading, the primary link may be in potential outage, that is, $Q_{pp}(R_{\text{req}}) < 0$. If the *effective relay condition* is not met, then the cognitive relay can not use RPL mode to help the primary link prevent transmission outage, which implies that RPL mode fails. Consequently, it seems as if the primary link sets no constraint on external interference, that is, $\widetilde{Q}_{pp}(R_{\text{req}}) = +\infty$. In this case, either RNL or RSL mode is adopted, depending on which one achieves larger transmission rate of secondary link. Otherwise, if the *effective relay condition* is satisfied, then RPL mode works. In this regard, the primary link will not experience a transmission outage through the assistance of cognitive relay, and therefore the outage probability of primary link can be minimized when considering erogdic channel fading.

Case 2 ($Q_{pp}(R_{\text{req}}) \geq 0$). In this case, the primary link is not in outage. It seems as if RPL mode is not necessary here, however, it is not true. When $Q_{pp}(2R_{\text{req}}) > 0$, that is, the primary link is far away from outage, the cognitive relay may decide to work in RPL mode in favor of improving the transmission rate of secondary link. To elaborate, in the first slot, the primary Tx transmits at rate $2R_{\text{req}}$ bit/s. Considering that $Q_{pp}(2R_{\text{req}}) > 0$, the primary Rx could receive $2R_{\text{req}}T$ bits of message correctly in that slot. In other words, the target transmission rate of primary link has already been achieved during the first slot, that is, $R_p^{\text{RPL}} = 2R_{\text{req}}T/2T = R_{\text{req}}$. While in the second slot, the cognitive relay does not transmit at all as promised, that is, $P_r = 0$. By doing so, the secondary user could transmit with full power in the second slot, and therefore may achieve higher transmission rate. In view of this fact, the cognitive relay has to choose from the three modes by comparing the achievable transmission rates of secondary link.

As stated above, RPL mode is not only useful in Case 1 for the purpose of avoiding potential outage. More than that, it will be selected in Case 2 under certain conditions. In summary, in addition to avoiding transmission outages of primary link, RPL mode is beneficial to improving the transmission rate of secondary link as well.

4. Simulation Results

In this section, we will give some numerical results of the achievable transmission rate of secondary link and the outage probability of primary link by analyzing the impacts of different parameters. Specifically, assume that $\sigma_{ij}^2 = 1$, for all i, j for all the transmission and interference links, that is, power gain $|h_{ij}|^2$ is exponentially distributed with parameter 1. Besides, assume that the SINR requirement of primary link is 6 dB here, that is, $\gamma_{\text{req}} = 6$ dB. Define $\gamma_P = P_P/\sigma_n^2$ as the normalized power of primary Tx. Similarly, γ_S and γ_R are defined in the same way. In particular, each data point represents a simulation over 20, 0000 realizations. For performance comparison, three transmission schemes are listed below.

(1) *Relay-Disabled System (RDS)*. the cognitive relay does not participate in the transmission of either primary or secondary system, but informs the secondary link the necessary CSI information to enable simultaneous spectrum sharing. In other words, the cognitive relay always works in RNL mode.

(2) *Relay-Aided Secondary System (RSS)*. the cognitive relay helps improving the throughput of secondary system. As a result, RNL and RSL are alternately performed here. Provided that $Q_{pp}(R_{\text{req}}) < 0$, the secondary Tx will transmit with full power in RSS scheme. While in OCR scheme, the transmit power of secondary Tx has to be restricted if RPL mode works. Given a large probability of $Q_{pp}(R_{\text{req}}) < 0$, the secondary link may therefore achieve higher transmission rate in RSS scheme than in OCR scheme, that is, $R_s^{\text{RSS}} > R_s^{\text{OCR}}$.

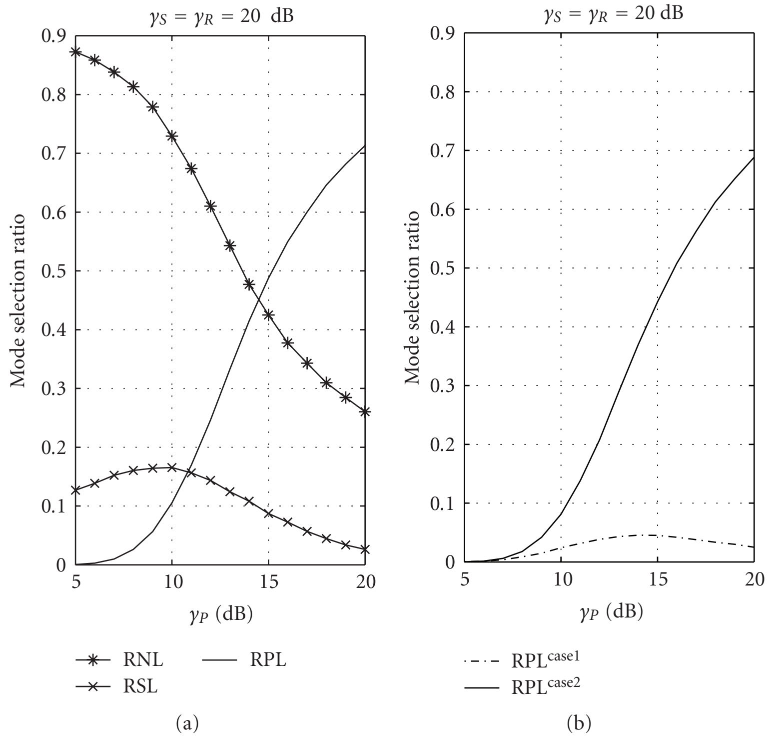


Figure 4: Transmission mode selection ratio.

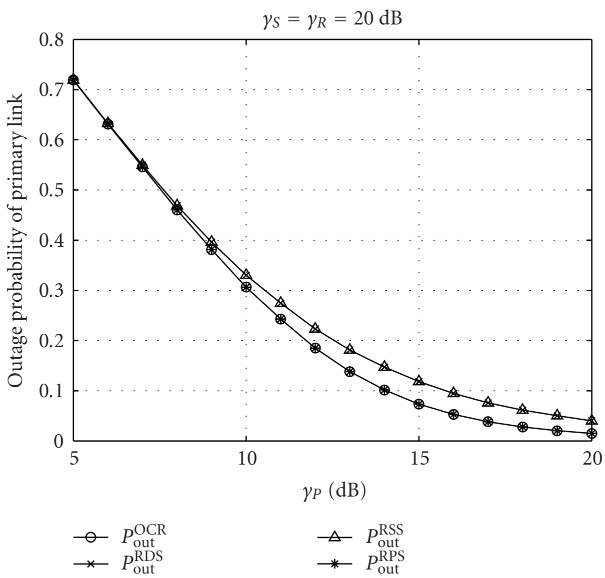


Figure 5: Outage probability of primary link.

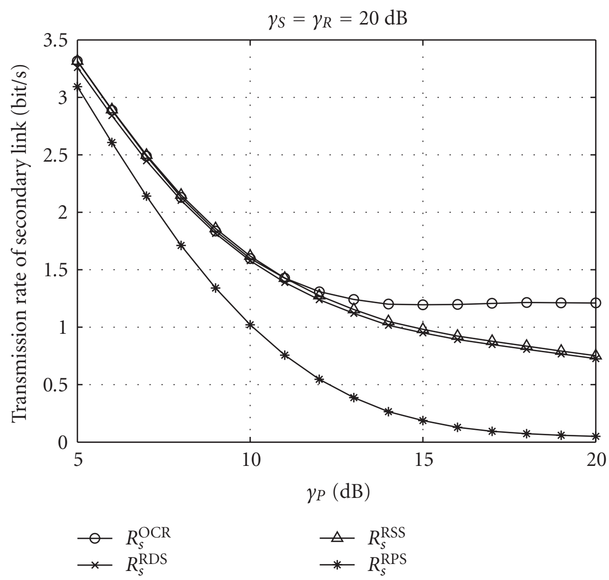


Figure 6: Transmission rate of secondary user.

(3) *Relay-Aided Primary System (RPS)*. the cognitive relay merely aims to avoid transmission outages of primary link. Similar to OCR scheme, only if the *effective relay condition* is satisfied, the transmission outage of primary link can be avoided. Different from RPL mode, the cognitive relay here transmits with the power that satisfies $G(0,0) = \widetilde{\gamma}_{\text{req}}$ without considering the secondary link. As a result, when $Q_{PP}(R_{\text{req}}) < 0$ and the *effective relay condition* is met, the secondary link has to keep silence in the second slot then.

4.1. Mode Selection Ratio. Figure 4(a) shows mode selection ratios of OCR scheme versus γ_P, where $\gamma_S = \gamma_R = 20$ dB. We can see that, RNL mode is selected less often as γ_P increases, while RPL mode shows the opposite trend. The basic reason is that, the *effective relay condition* is satisfied with larger probability as γ_P grows, which results in higher selection ratio of RPL mode. Comparing with RNL and RPL mode, RSL mode behaves more stably when γ_P varies. As summarized in Section 3.4, RPL mode may be employed in both two cases, and the ratios are depicted in Figure 4(b). In Case 1, the cognitive relay tries its best to lower down the outage probability of primary link. While in Case 2, the cognitive relay may choose RPL mode in favor of improving the transmission rate of secondary user. As the outage probability of primary link is diminishing when γ_P increases as shown in Figure 5, the selection ratio of RPL mode in Case 1 is not increasing accordingly. Conversely, $Q_{pp}(2R_{\text{req}}) > 0$ happens more often when γ_P becomes larger, and then RPL mode is more likely to be beneficial to increasing the transmission rate of secondary link. As a result, the selection ratio of RPL mode in Case 2 increases as γ_P grows.

4.2. Outage Probability of Primary Link. Figure 5 shows the performance in terms of outage probability of primary link, where $\gamma_S = \gamma_R = 20$ dB and γ_P grows from 0 dB to 20 dB. In OCR and RPS schemes, when the primary link is in potential outage, that is, $Q_{pp}(R_{\text{req}}) < 0$, the transmission outage may be avoided by the cooperation of cognitive relay. In this regard, the outage probabilities of primary link in OCR and RPS schemes are of course smaller than that of RDS and RSS ones, in which the cognitive relay is not designated to assist the transmission over primary link. In addition to the above observation, we can also see that, the performance gain gradually appears as γ_P grows larger than 7 dB. Similarly, it is due to the fact that the *effective relay condition* is satisfied more often, which in turn leads to much smaller outage probability of primary link.

4.3. Transmission Rate of Secondary Link. In Figure 6, the average transmission rate of secondary link under four schemes are presented, where γ_S and γ_R are both set to 20 dB. In RPS mode, if the *effective relay condition* is satisfied, the secondary Tx can not transmit at all in the second slot as stated before. That is why the secondary link achieves smallest transmission rate in RPS scheme. Besides, the transmission rate of secondary link achieved in RSS scheme is slightly larger than that of RDS scheme, that is, $R_s^{\text{RSS}} > R_s^{\text{RDS}}$, basically due to the diversity gain acquired by the cognitive relay. Generally, the four schemes can be arranged w.r.t. the transmission rate in ascending way, that is, $R_s^{\text{RPS}} < R_s^{\text{RDS}} < R_s^{\text{RSS}} < R_s^{\text{OCR}}$. That is, the more attention the cognitive relay pays to the secondary link, the larger transmission rate the latter achieves. However, there is exception. When γ_P is smaller than 12 dB, the transmission rate of secondary link in OCR scheme is slightly less than that in RSS scheme. The reason has already been explained before, that is, when $Q_{pp}(R_{\text{req}}) < 0$, the secondary Tx could transmit with full power in RSS scheme. However, the cognitive relay tries to prevent transmission outage of primary link in OCR scheme, which leads to smaller transmit power of secondary Tx. When γ_P grows larger than 12 dB, the probability that $Q_{pp}(R_{\text{req}}) < 0$ is greatly diminished, which makes OCR scheme superior than RSS because of the flexible mode selection. In practical systems, too large outage probability is not tolerable by the primary link. So γ_P must be set appropriately to yield a much smaller outage probability, for example, 1% or even smaller. Accordingly, we can see that the average transmission rate of secondary link under OCR scheme grows much larger than the other three.

Figure 7 shows the impacts of varying γ_S and γ_R on the transmission rate of secondary link. It is obvious that, the transmission rates of secondary link under all schemes become lager as γ_S grows. However, there are slight performance gains as γ_R grows. The reason is two-fold. On one hand, the probability that $Q_{pp}(R_{\text{req}}) < 0$ is quite small when $\gamma_P = 20$ dB, and the mode selection ratios are therefore highly stable. On the other hand, as γ_S is larger than γ_R, it dominates in determining the achievable transmission rate of secondary link.

5. Discussion

Our paper focuses on proposing a cost-effective spectrum sharing architecture for legacy noncognitive wireless systems. To admit, the proposed OCR scheme is far from from practical, however, it can be regarded as a feasibility study on this possible settings. This section lists some issues that can be further investigated or improved.

(i) How to determine the location of cognitive relay in the initialization of network deployment is not involved in this paper. Intuitively, the best location for the cognitive relay can be determined in the average sense given the statistical channel gains of all links.

(ii) Besides, some practical issues are not considered, such as the code design for cognitive relay, the corresponding MAC protocol, which points out a future direction for us.

(iii) In this paper, the cognitive relay helps none, one, or the other link, which do not exploit all the possibilities. In fact, our work could be further explored by letting the cognitive relay assist both primary and secondary links simultaneously. However, the consideration of such possibility might require other assumptions which are even more difficult to be satisfied in practice, thus is left for further investigation.

6. Conclusion

In this paper, we propose a win-win spectrum sharing scheme for the legacy wireless systems to coexist. The cognitive relay, which is installed by NSP, plays the roles of monitor, coordinator and cooperator simultaneously, thus enables the secondary user to access the licensed spectrum without cognitive functionalities. The proposed OCR scheme aims to maximize the transmission rate of secondary link given the precondition that the outage probability of primary link is minimized. Three modes adopted by the cognitive relay are introduced, together with mode

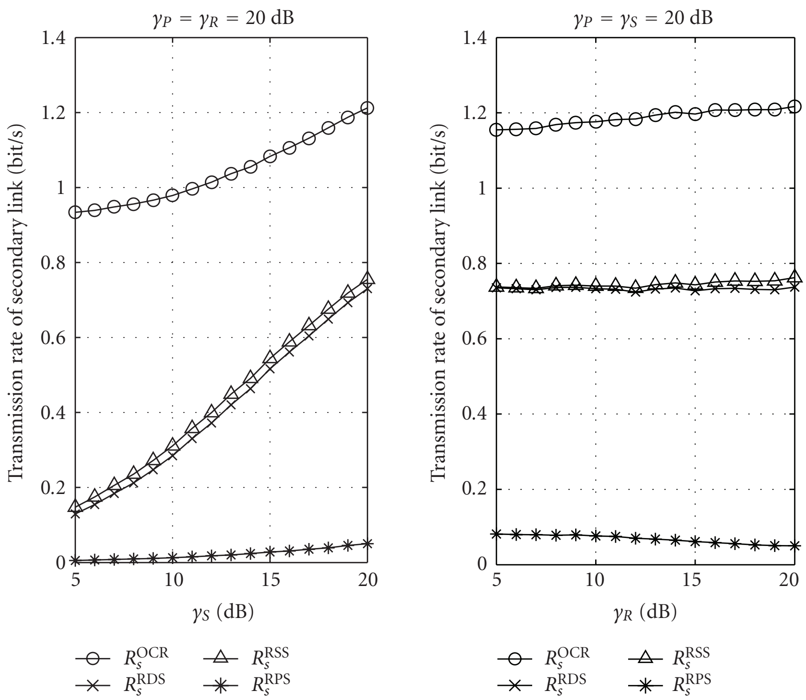


FIGURE 7: RPL mode selection ratio in two cases.

selection criterion. Simulation results validate the advantages of OCR scheme on decreasing outage probability of primary link and increasing the transmission rate of secondary user.

Appendix

Proof of Theorem 1. According to constraints of problem (10a) in Section 3, we can draw the feasible region of variables P_{s1} and P_{s2} in Figure 3. As transmit power P_{s1} and P_{s2} are both required to be nonnegative, only the first quadrant is considered here in the sequel. Specifically, isolated constraints (10b) and (10d) confine P_{s1} and P_{s2} to be in a rectangle, whose four vertexes are $(0,0)$, $(\alpha,0)$, $(0,P_S^{\max})$, and $(\alpha,P_S^{\max})$, respectively. Moreover, the feasible region of P_{s1} and P_{s2} restricted by the united constraint (10c) is an open area, which is framed by line $P_{s1}=0$, $P_{s2}=0$ and the curve of $G(P_{s1},P_{s2})=\widetilde{\gamma}_{\text{req}}$ for $P_{s1},P_{s2}\geq 0$. According to the relationship of the isolated and the united constraints, there are two cases.

Case 1 (isolated constraint dominates). In the case of $G(\alpha,P_S^{\max})\geq\widetilde{\gamma}_{\text{req}}$, the feasible region of variable P_{s1} and P_{s2} in this case can be shown by the shadowed rectangle in Figure 3, that is, the rectangle restricted by the isolated constraints does not intersect with the curve of $G(P_{s1},P_{s2})=\widetilde{\gamma}_{\text{req}}$ for $P_{s1},P_{s2}\geq 0$. In other words, the isolated constraint dominates the feasible region of P_{s1} and P_{s2}. Discarding the log function, the objective function (10a) can be expressed as

$$f(P_{s1},P_{s2})=(1+H_{s1}P_{s1})(1+H_{s2}P_{s2}). \tag{A.1}$$

We can see that $f(P_{s1},P_{s2})$ is monotonically increasing with either P_{s1} or P_{s2}, respectively. Therefore, the best power pair must be obtained at the top right corner of the feasible region, that is, $(P_{s1}^*,P_{s2}^*)=(\alpha,P_S^{\max})$.

Case 2 (isolated and united constraints work together). Contrarily, if $G(\alpha,P_S^{\max})<\widetilde{\gamma}_{\text{req}}$, then the rectangle restricted by the isolated constraints intersects with the curve of $G(P_{s1},P_{s2})=\widetilde{\gamma}_{\text{req}}$ for $P_{s1},P_{s2}\geq 0$, which makes the feasible region smaller than the rectangle. As Figure 3 shows that, this case can further be divided into four subcases from the graphical point of view. The corresponding conditions and the coordinates of point A and B are already summarized in Table 1.

It is easy to prove that the best power pair of (P_{s1},P_{s2}) must be achieved in the curve of which connects point A and B, that is, $G(P_{s1},P_{s2})$ for $P_{l1}\leq P_{s1}\leq P_{u1}$ and $P_{l2}\leq P_{s2}\leq P_{u2}$, where there are four possibilities for the values of them according to the four subcases. The values of both (P_{l1},P_{u1}) and (P_{l2},P_{u2}) can be readily read from Figure 3, and we will not dwell on them then. Accordingly, the optimization problem (A.1) can be rewritten as

$$\max_{P_{s1},P_{s2}} \quad H_{s1}P_{s1}+H_{s2}P_{s2}+H_{s1}H_{s2}P_{s1}P_{s2}, \tag{A.2a}$$

$$\text{s.t.} \quad \frac{M_1}{P_{s1}+N_{sp}}+\frac{M_2}{P_{s2}+N_{sp}}=\widetilde{\gamma}_{\text{req}}, \tag{A.2b}$$

$$P_{l1}\leq P_{s1}\leq P_{u1}, \quad P_{l2}\leq P_{s2}\leq P_{u2}. \tag{A.2c}$$

Based on (A.2b), the product of $P_{s1}P_{s2}$ can be expressed as linear function of P_{s1} and P_{s2}, that is,

$$P_{s1}P_{s2} = \frac{(M_1 + M_2)N_{sp}}{\widetilde{\gamma}_{\text{req}}} - N_{sp}^2 + \left(M_1 - N_{sp}\right)P_{s2} + \left(M_2 - N_{sp}\right)P_{s1}. \tag{A.3}$$

Plugging (A.3) into the objective function (A.2a), the object turns out to be a linear function of P_{s1} and P_{s2},

$$\max_{P_{s1},P_{s2}} \quad MP_{s1} + NP_{s2} \qquad \text{s.t.} \quad \text{(A.2b)(A.2c)}, \tag{A.4}$$

where

$$M = H_{s1} + H_{s1}H_{s2}M_2 - H_{s1}H_{s2}N_{sp}, \qquad N = H_{s2} + H_{s1}H_{s2}M_1 - H_{s1}H_{s2}N_{sp}. \tag{A.5}$$

Let $F(x, y) = Mx + Ny$, then the value of $F(x, y)$ is proportional to the y-intercept. Generally, M and N are both positive, which makes the slope of line $F(x, y)$ positive too. Therefore, the righter the curve $F(x, y)$ moves towards, the greater the intercept will be, which results in greater transmission rate of secondary user. Besides, it is easy to verify that $G(x, y)$ for $x, y > 0$ is a convex function. In this way, either point A or B achieves the best transmit rate of the secondary user, which depends on the scope of line $F(x, y)$ and that of the line connecting point A and B. □

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