Resource Allocation for Opportunistic Spectrum Sharing Based on Cooperative OFDM Relaying

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***Abstract*—In this paper, we consider opportunistic spectrum sharing when the primary system experiences unfavorable channel conditions. In the proposed spectrum sharing protocol, the secondary system tries to help the primary system to achieve its target rate by acting as an amplify-and-forward relay and allocating a fraction of its subcarriers to forward the primary signal. As a reward, the secondary system uses the remaining subcarriers to transmit its own signal, and thus gaining spectrum access. We study the joint optimization of the set of subcarriers used for cooperation, subcarrier pairing and secondary subcarrier power allocation such that the transmission rate of the secondary system is maximized, while helping the primary system, as a higher priority, to achieve its target rate. Simulation results demonstrate that both primary and secondary systems benefit from the proposed opportunistic spectrum sharing protocol.**

I. Introduction

Cognitive radio (CR) is a promising technology that has the potential to improve the frequency spectrum-utilization efficiency by allowing cognitive secondary systems to intelligently sense and opportunistically access the licensed spectrum of primary systems [1]. The role of cooperative transmission in cognitive radio for spectrum sharing has been studied in [2]. A spectrum leasing protocol is considered in [3], where the primary system leases a certain portion of its own transmission time to the secondary system and the secondary system uses a fraction of the leased time to help relay the primary signal. In [4], an opportunistic spectrum sharing protocol based on cooperative relaying is discussed, where the secondary system acts as a relay, using a fraction of the secondary power to forward the primary signal to ensure that the achievable rate of the primary system under spectrum sharing is no worse than that without spectrum sharing, and then uses its remaining power to transmit its own data. Recently, orthogonal frequency division multiplexing (OFDM) has been recognized as a potential transmission technology for CR systems due to its flexibility in allocating transmit resources [5]. In OFDM-based CR systems, the secondary system can transmit over the unused subcarriers left in the primary system [6] or flexibly share the subcarriers with the primary system on condition that the primary system is sufficiently protected [7].

Most existing work on spectrum sharing has concentrated on the scenario where the primary system is more than capable of supporting its target QoS and thereby is able to tolerate additional interference from the secondary system. This provides an opportunity for the secondary system to access the primary spectrum together with the primary system as long as the primary QoS is not affected. In this paper, we propose an opportunistic spectrum sharing protocol that exploits the situation when the primary system is incapable of supporting its target transmission rate (e.g., due to unfavorable channel conditions). As inspired by [4], the secondary system tries to help the primary system to achieve its target rate via two-phase cooperative OFDM relaying, where the secondary system acts as an amplify-and-forward (AF) relay for the primary system by allocating a fraction of its subcarriers to forward the primary signal. As a reward, the secondary system can use the remaining subcarriers to transmit its own signal, and thus gaining opportunistic spectrum access. In particular, the secondary system uses disjoint subsets of the subcarriers to transmit the primary and secondary signals, and thus no interference is experienced at the primary and secondary receivers. As a part of the protocol, if primary outage still occurs even when the secondary system serves as a pure relay for the primary transmission, the primary system will cease transmission and the secondary system will be granted access to the licensed primary spectrum. We study the joint optimization of the set of subcarriers used for cooperation, subcarrier pairing, and subcarrier power allocation, such that the transmission rate of the secondary system is maximized, while helping the primary system, as a higher priority, to achieve its target rate. This joint optimization problem is solved efficiently by using the dual decomposition method. Simulation results confirm the benefit of the proposed opportunistic spectrum sharing protocol to both primary and secondary systems.

II. System Model

We consider a cognitive radio system, where both the primary and secondary signals are OFDM modulated over K subcarriers. The primary OFDM system, comprising of a primary transmitter (PT) and primary receiver (PR), supports the relaying functionality. The secondary OFDM system, comprising of a secondary transmitter (ST) and secondary receiver (SR), can only opportunistically operate in the primary spectrum by exploiting the situation when the primary system is incapable of supporting its target rate. This situation provides an opportunity for the secondary system to access the spectrum of the primary system. We further assume that the secondary system is able to emulate the radio protocols and system parameters of the primary system.

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In this work, we consider a delay-limited primary system and its performance is evaluated by outage rate, while the secondary system attempts to gain opportunistic spectrum access and its performance is evaluated by ergodic rate. Both the primary and secondary systems experience independent and frequency-selective Rayleigh fading. The channel variances of PT→PR, PT→ST, ST→PR, ST→SR links are denoted as σ_1^2, σ_2^2, σ_3^2, and σ_4^2. With OFDM modulation, we assume that the channel seen at each subcarrier is modeled as frequency-flat Rayleigh fading. The channel coefficients of the PT→PR link and the PT→ST link over subcarrier k are denoted as $h_{1,k}$ and $h_{2,k}$, respectively. Likewise, the channel coefficients of the ST→PR link and the ST→SR link over subcarrier k' are denoted as $h_{3,k'}$ and $h_{4,k'}$, respectively. Furthermore, channel reciprocity is assumed for the ST→PR link. We consider slow fading where the channel coefficients remain constant over multiple OFDM symbols. Without loss of generality, we assume that all the noise terms are complex Gaussian random variables with zero mean and variance $\sigma^2 = 1$. The channel power gains are defined as $\gamma_{1,k} \triangleq |h_{1,k}|^2$, $\gamma_{2,k} \triangleq |h_{2,k}|^2$, $\gamma_{3,k'} \triangleq |h_{3,k'}|^2$, and $\gamma_{4,k'} \triangleq |h_{4,k'}|^2$, respectively. The transmit power of the signal sent by PT over subcarrier k is denoted as $p_{p,k}$, while the transmit power of the signal sent by ST over subcarrier k' is denoted as $p_{s,k'}$. The primary and secondary systems have a sum transmit power constraint over all subcarriers, denoted as P_p and P_s, respectively. In particular, the primary system adopts the water-filling algorithm to adaptively allocate power to each primary subcarrier.

III. Protocol Description and Achievable Rates

In this section, we describe the proposed protocol that both primary and secondary systems strictly comply with.

Firstly, the primary system predicts its achievable outage rate based on the current PT→PR link condition. Prior to any secondary cooperation, the instantaneous primary rate (in Nats/OFDM symbol) under direct transmission is given by

$$R_K = \sum_{k=1}^{K} \ln(1 + \gamma_{1,k} p_{p,k}) \tag{1}$$

where $p_{p,k} = (1/\lambda - 1/\gamma_{1,k})^+$, $(x)^+ \triangleq \max(0, x)$, $\ln$ denotes the natural logarithm, and the constant λ has to be chosen to satisfy the primary sum power constraint $\sum_{k=1}^{K} p_{p,k} = P_p$.

The primary outage probability in this case is given by $\mathcal{P}_{out}^d = \mathcal{P}(R_K < R_T)$, where $\mathcal{P}(\mathcal{A})$ denotes probability of $\mathcal{A}$ and R_T denotes the primary target rate. Note that given a channel delay profile of the PT→PR link, $\mathcal{P}_{out}^d$ only depends on its average SNR, given by $P_p\sigma_1^2$. On the other hand, the primary system can also predict its achievable outage rate C_ε (e.g., 10% outage rate $C_{10\%}$) based on the average SNR.

When C_ε falls below the target rate R_T, PR will seek cooperation from the neighboring nodes to improve its performance by sending out a request-to-cooperate (RTC) signal. This RTC is then responded by PT with an acknowledge-to-cooperate (ATC) signal. We presume that the information regarding P_p and R_T is embedded in RTC and the channel state information of PT→PR link is embedded in ATC. Upon receiving both RTC and ATC signals, ST estimates the channel gains of PT→ST, ST→PR and PT→PR links. Then ST is able to decide, under the current channel condition and power constraint, whether it is able to assist the instantaneous rate of the primary system to reach R_T by calculating the maximum instantaneous rate, R_{max}, when ST serves as a pure AF relay for the primary system by devoting all of its subcarriers and power to relay the primary signal. It thus follows that

$$R_{max} \triangleq \max \sum_{k=1}^{K} \sum_{k'=1}^{K} \rho_{k,k'} R_{k,k'}^p. \tag{2}$$

where $R_{k,k'}^p = \frac{1}{2} \ln\left(1 + p_{p,k}\gamma_{1,k} + \frac{p_{p,k}\gamma_{2,k}p_{sp,k'}\gamma_{3,k'}}{1+p_{p,k}\gamma_{2,k}+p_{sp,k'}\gamma_{3,k'}}\right)$; $p_{sp,k'}$ is the power allocated to subcarrier k' at ST for forwarding the primary signal; $\rho_{k,k'} \in \{0,1\}$ is the indicator for subcarrier pairing. If primary subcarrier k in the first phase is paired with secondary subcarrier k' in the second phase, $\rho_{k,k'} = 1$; otherwise $\rho_{k,k'} = 0$. It is shown in [8] that in this case the ordered subcarrier pairing $\{\tilde{\rho}_{k,k'}\}$ is optimal in achieving R_{max}. The optimal set of $\{p_{sp,k'}\}$ is thus given by

$$\{\tilde{p}_{sp,k'}\} = \arg \max_{\{p_{sp,k'}\}} \sum_{k=1}^{K} \sum_{k'=1}^{K} \tilde{\rho}_{k,k'} R_{k,k'}^p \tag{3}$$

subject to $\sum_{k'=1}^{K} p_{sp,k'} \le P_s$ and $p_{sp,k'} \ge 0, \forall k'$.

It is easy to verify that the problem in (3) is a convex optimization problem. By applying the Karush-Kuhn-Tucker (KKT) conditions [9], we can obtain the optimal solution as

$$\tilde{p}_{sp,k'} = A(\sqrt{A^2 + \gamma_{3,k'}B/\nu} + A - B)/(\gamma_{3,k'}B) \tag{4}$$

where $A = p_{p,k}\gamma_{2,k}$, $B = 2(1 + p_{p,k}\gamma_{1,k} + p_{p,k}\gamma_{2,k})$, and ν has to be chosen to satisfy the sum power constraint at ST.

A. Access Mode

If $R_{max} < R_T$, which suggests that the primary system cannot reach its target rate, even when ST serves a pure AF relay contributing all of its resources to assist the primary transmission, as a part of the protocol, the primary system will stop transmission and the secondary system will be granted full spectrum access to the primary spectrum. This operation mode is referred to as Access mode in this paper.

In this mode, the instantaneous secondary rate can be written as

$$R_s^d = \sum_{k'=1}^{K} \ln(1 + p_{s,k'}^d \gamma_{4,k'}) \tag{5}$$

where $p_{s,k'}^d = \left(1/\eta - 1/\gamma_{4,k'}\right)^+$. The constant η has to be chosen to satisfy the sum power constraint $\sum_{k'=1}^{K} p_{s,k'}^d = P_s$.

B. Cooperation Mode

If $R_{max} \ge R_T$, ST will broadcast a confirm-to-cooperate (CTC) signal to indicate that it can cooperate with the primary system and the primary system correspondingly switches into a two-phase AF relaying mode, with ST being the relay node. As a reward, ST can also transmit its own data and thus achieving secondary spectrum access. This operation mode is referred to as Cooperation mode. We discuss the two-phase AF relaying involved in this mode as follows.

In the first phase, PT uses all the K subcarriers to transmit its signal while PR and ST listen. We denote the set of K subcarriers for primary and secondary systems as Ω_p and Ω_s, respectively, i.e., $\Omega_p = \{1, 2, ..., K\}$ and $\Omega_s = \{1, 2, ..., K\}$.

In the second phase, PT remains silent while ST pairs a subset of its K subcarriers, $\mathcal{G}_s \subseteq \Omega_s$, with a subset of the K primary subcarriers, $\mathcal{G}_p \subseteq \Omega_p$, for cooperative AF relaying, where $|\mathcal{G}_s| = |\mathcal{G}_p| = N$. Note that both $\mathcal{G}_p$ and $\mathcal{G}_s$ are embedded in the CTC signal and thus are known to PR and SR. In general, ST receives a primary signal over subcarrier $k \in \mathcal{G}_p$, amplifies it, and then forwards it over subcarrier $k' \in \mathcal{G}_s$ to PR. Note that the subcarrier index k' may not be the same as k and thus they form a subcarrier pair (k, k'). In this work, we assume that each subcarrier from $\mathcal{G}_p$ is paired with one and only one subcarrier from $\mathcal{G}_s$.

With PR performing MRC for the received signals over the two phases, the instantaneous rate of the primary system with secondary cooperation can be shown as

$$R_p = \sum_{k\in\mathcal{G}_p}\sum_{k'=1}^{K} \rho_{k,k'} R^p_{k,k'} + \frac{1}{2}\sum_{k\in\overline{\mathcal{G}}_p} \ln(1 + p_{p,k}\gamma_{1,k}). \quad (6)$$

In the second phase, ST also uses its remaining $K - N$ subcarriers to transmit its own signal. The instantaneous rate of the secondary system (in Nats/OFDM symbol) is given by

$$R^c_s = \frac{1}{2}\sum_{k'\in\overline{\mathcal{G}}_s} \ln(1 + p_{ss,k'}\gamma_{4,k'}) \quad (7)$$

where $p_{ss,k'}$ is the power allocated to subcarrier k' ($k' \in \overline{\mathcal{G}}_s$) at ST for transmitting its own signal.

IV. Resource Allocation in Cooperation mode

In this section, we seek joint optimization of the primary subcarrier set $\mathcal{G}_p$, subcarrier pairing set $\boldsymbol{\rho} = \{\rho_{k,k'}\}$ and power allocation set $\boldsymbol{p} = \{p_{sp,k'}|k' \in \mathcal{G}_s,\ p_{ss,k'}|k' \in \overline{\mathcal{G}}_s\}$ to maximize the instantaneous secondary rate R^c_s when cooperation takes place. Note that the optimal $\mathcal{G}_s$ can be obtained immediately after obtaining the optimal $\mathcal{G}_p$ and subcarrier pairing. The joint optimization problem can be formulated as

$$\max_{\mathcal{G}_p,\boldsymbol{\rho},\boldsymbol{p}} R^c_s \quad (8)$$

subject to $R_p \geq R_T$, $\sum_{k'\in\mathcal{G}_s} p_{sp,k'} + \sum_{k'\in\overline{\mathcal{G}}_s} p_{ss,k'} \leq P_s$, and $p_{sp,k'} > 0, \forall k' \in \mathcal{G}_s$.

Obtaining the joint optimal $\mathcal{G}^*_p$, $\boldsymbol{\rho}^*$ and $\boldsymbol{p}^*$ requires solving a mixed integer programming problem. However, this is computationally prohibitive. Also, it is clear that the problem in (8) is non-convex. It has been shown in [11] that the duality gap of a non-convex resource optimization problem satisfying the time-sharing condition in multi-carrier systems is nearly zero if the number of subcarriers is large (e.g., $K \geq 32$). The proof of time-sharing condition and zero duality gap is given in Appendix A. In the following, we show that by using the dual decomposition method, the problem in (8) can be solved in two computationally efficient steps.

A. Optimizing Dual Variables

The Lagrange dual function for (8) can be written as

$$g(\boldsymbol{\beta}) = \max_{\{\mathcal{G}_p,\boldsymbol{\rho},\boldsymbol{p}\}} L(\mathcal{G}_p, \boldsymbol{\rho}, \boldsymbol{p}) \quad (9)$$

where the Lagrangian is given by (11) at the top of the next page. $\boldsymbol{\beta} \triangleq (\beta_t, \beta_s)$ in (11) is the vector of the dual variables associated with the rate and power constraints. As shown in our full paper [10], the optimal $\boldsymbol{\beta}$ can be obtained by using subgradient-based methods with guaranteed convergence.

B. Optimizing $\mathcal{G}_p$, $\boldsymbol{\rho}$ and $\boldsymbol{p}$ with Given Dual Variables

Computing the dual function $g(\boldsymbol{\beta})$ involves determining the optimal $\mathcal{G}_p$, $\boldsymbol{\rho}$ and $\boldsymbol{p}$ at a given dual point $\boldsymbol{\beta}$. This is implemented in the following three steps. In the first step, we find the optimal $\boldsymbol{p}$ conditioned on fixed $\boldsymbol{\rho}$ and $\mathcal{G}_p$; in the second step, we find the optimal $\boldsymbol{\rho}$ given a fixed $\mathcal{G}_p$; in the third step, we find the optimal $\mathcal{G}_p$.

1) Finding the optimal $\boldsymbol{p}$ for fixed $\boldsymbol{\rho}$ and $\mathcal{G}_p$: Applying the KKT conditions, the optimal $\boldsymbol{p}$, $\boldsymbol{p}^* = \{p^*_{sp,k'}|k' \in \mathcal{G}_s,\ p^*_{ss,k'}|k' \in \overline{\mathcal{G}}_s\}$, that maximizes (11) for a given dual point $\boldsymbol{\beta}$ can be obtained as

$$p^*_{sp,k'} = \frac{A(\sqrt{A^2 + \gamma_{3,k'}B\beta_t/\beta_s} + A - B)}{\gamma_{3,k'}B} \quad (12)$$

$$p^*_{ss,k'} = \left(\frac{1}{2\beta_s} - \frac{1}{\gamma_{4,k'}}\right)^+. \quad (13)$$

2) Finding the optimal $\boldsymbol{\rho}$ for a fixed $\mathcal{G}_p$: As shown in [10], (11) can be rewritten as

$$L(\mathcal{G}_p, \boldsymbol{\rho}, \boldsymbol{p}) = \sum_{k\in\mathcal{G}_p}\sum_{k'=1}^{K} \rho_{k,k'}F_{k,k'} + \frac{\beta_t}{2}\sum_{k\in\overline{\mathcal{G}}_p} \ln(1 + p_{p,k}\gamma_{1,k}) + \sum_{k'=1}^{K}\left(\frac{1}{2}\ln\left(1+p^*_{ss,k'}\gamma_{4,k'}\right) - \beta_s p^*_{ss,k'}\right) + \beta_s P_s - \beta_t R_T \quad (14)$$

where for $k \in \mathcal{G}_p$ and $k' \in \{1, 2, ..., K\}$,

$$F_{k,k'} = \frac{\beta_t}{2}\ln\left(1 + p_{p,k}\gamma_{1,k} + C_{k,k'}\right) - \frac{1}{2}\ln\left(1 + p^*_{ss,k'}\gamma_{4,k'}\right) - \beta_s\left(p^*_{sp,k'} - p^*_{ss,k'}\right)$$

with $C_{k,k'} = p_{p,k}\gamma_{2,k}p^*_{sp,k'}\gamma_{3,k'}/(p_{p,k}\gamma_{2,k} + p^*_{sp,k'}\gamma_{3,k'})$.

We only need to work on the first term on the right-hand side (RHS) of (14) to find the optimal subcarrier pairing that maximizes the Lagrangian, as it is the only term involving $\rho_{k,k'}$ in (14). As a result, for each $k \in \mathcal{G}_p$, the index of the secondary subcarrier that should be paired with it is given by

$$k'^* = \arg\max_{k'} F_{k,k'}. \quad (15)$$

Now, for each $k \in \mathcal{G}_p$, k and k'^* form a pair (k, k'^*). The optimal $\rho_{k,k'}$ are then given by

$$\rho^*_{k,k'^*} = 1 \quad (16a)$$

$$\rho^*_{k,k'} = 0,\ \forall k' \neq k'^*. \quad (16b)$$

$$L(\mathcal{G}_p, \boldsymbol{\rho}, \boldsymbol{p}) = \frac{1}{2} \sum_{k' \in \overline{\mathcal{G}}_s} \ln(1 + p_{ss,k'}\gamma_{4,k'}) + \beta_t \Bigg(\frac{1}{2} \sum_{k \in \mathcal{G}_p} \sum_{k'=1}^{K} \rho_{k,k'} \ln\left(1 + p_{p,k}\gamma_{1,k} + \frac{p_{p,k}\gamma_{2,k} p_{sp,k'}\gamma_{3,k'}}{p_{p,k}\gamma_{2,k} + p_{sp,k'}\gamma_{3,k'}}\right)$$
$$+ \frac{1}{2} \sum_{k \in \overline{\mathcal{G}}_p} \ln(1 + p_{p,k}\gamma_{1,k}) - R_T \Bigg) + \beta_s \Bigg(P_s - \sum_{k' \in \overline{\mathcal{G}}_s} p_{ss,k'} - \sum_{k' \in \mathcal{G}_s} p_{sp,k'} \Bigg), \quad \beta_t, \beta_s \geq 0. \tag{11}$$

3) Finding the optimal $\mathcal{G}_p$: With (16), (14) can be further written as

$$L(\mathcal{G}_p, \boldsymbol{\rho}, \boldsymbol{p}) = \sum_{k \in \mathcal{G}_p} G_{k,k'^*} + \frac{\beta_t}{2} \sum_{k=1}^{K} \ln(1 + p_{p,k}\gamma_{1,k}) + \beta_s P_s$$
$$+ \sum_{k'=1}^{K} \left(\frac{1}{2} \ln\left(1 + p^*_{ss,k'}\gamma_{4,k'}\right) - \beta_s p^*_{ss,k'} \right) - \beta_t R_T \tag{17}$$

where $G_{k,k'^*} = F_{k,k'^*} - \beta_t \ln(1 + p_{p,k}\gamma_{1,k})/2$.

Since only the first term on the RHS of (17) involves $\mathcal{G}_p$, the optimal $\mathcal{G}_p$ can be found as

$$\mathcal{G}_p^* = \arg\max_{\mathcal{G}_p} \sum_{k \in \mathcal{G}_p} G_{k,k'^*}. \tag{18}$$

Solving (18) is simple as we only need to find all $k \in \Omega_p$ that have a positive G_{k,k'^*}, and all these k's form $\mathcal{G}_p^*$.

So far, we have obtained the optimal primal variables $\{\mathcal{G}_p^*, \boldsymbol{\rho}^*, \boldsymbol{p}^*\}$ for given dual variables. By updating the dual variables as shown in our full paper [10], the joint optimization problem stated in (8) can be finally solved.

V. Simulation Results

In the simulations, we aim to evaluate the proposed opportunistic spectrum access protocol, which is designed to exploit the potentially weak PT→PR link. We consider quasi-static frequency-selective Rayleigh fading channels with a 6-tap equal-gain equally-spaced delay profile, where the delay interval between adjacent taps is equal to the inverse of the OFDM system bandwidth. We set $\sigma_2^2 = \sigma_3^2 = \sigma_4^2 = 0$ dB. We also set $K = 32$, $P_p = 10$ dB, $P_s = 20$ dB, and $R_T = 3$ bps/Hz, unless otherwise specified. The 10% outage rate of the primary system, $C_{10\%}$, is considered in the simulations.

The probabilities of operating in the Cooperation and Access modes at $\sigma_1^2 = -8$ dB are shown in Fig. 1 where we can see that when P_s increases, the secondary system will have more chances to help the primary system to reach R_T via the Cooperation mode. Fig. 1 also shows that at the same P_s, a lower R_T gives a higher probability of operating in the Cooperation mode as it is easier for the primary system to reach a lower R_T with the secondary cooperation.

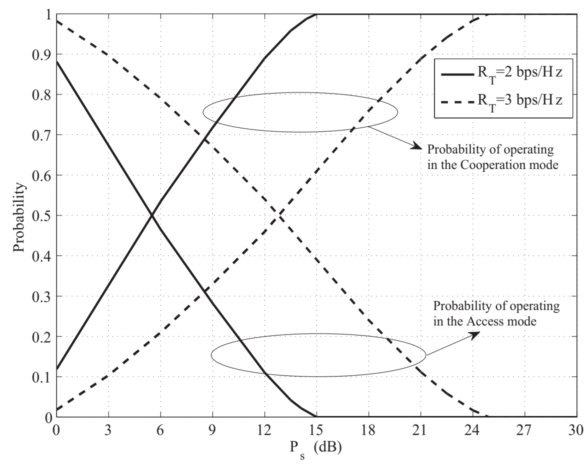

Fig. 1. Probability of operating in the Cooperation and Access modes.

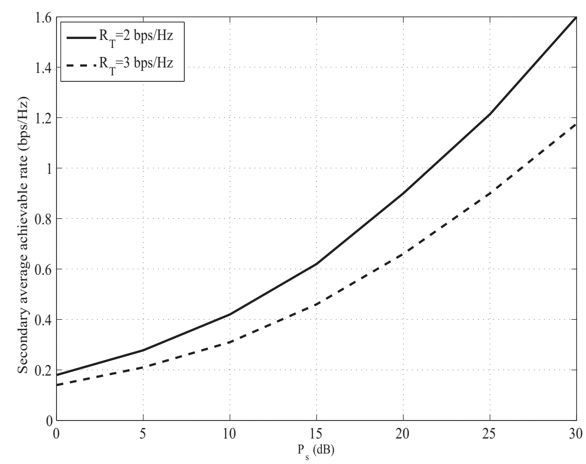

Fig. 2. Average achievable rate of the secondary system. $\sigma_1^2 = -8$ dB.

The average achievable rate of the secondary system is shown in Fig. 2. The average secondary rate is calculated as $E[R_s^c] \cdot \mathcal{P}(R_{max} > R_T) + E[R_s^d] \cdot \mathcal{P}(R_{max} \leq R_T)$, where $\mathcal{P}(R_{max} > R_T)$, denoting the probability of operating in the Cooperation mode, and $\mathcal{P}(R_{max} \leq R_T)$, denoting the probability of operating in the Access mode, have been investigated in Fig. 1. As shown in Fig. 1, when P_s increases, the Cooperation mode is getting more dominant. Therefore, a lower R_T allows the secondary system to allocate more resources to transmit its own signal, leading to a higher average rate, as shown in Fig. 2.

The outage rate of the primary system is shown in Fig. 3. The case of direct primary transmission is also plotted for comparison. Fig. 3 clearly shows the improvement of the primary outage rate with the proposed spectrum access protocol. We observe from the figure that a weaker primary channel (i.e., a lower σ_1^2) requires a higher P_s to boost the outage rate

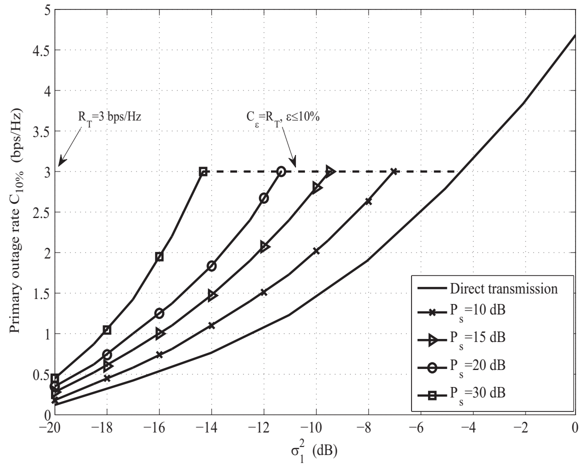

Fig. 3. Outage rate of the primary system.

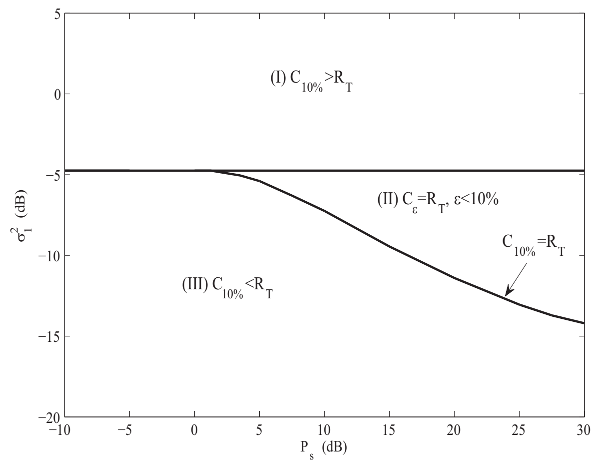

Fig. 4. Critical rate regions under the proposed protocol.

to R_T. On the other hand, if the primary link is good, e.g., $\sigma_1^2 > -4.6$ dB in Fig. 3, the primary outage rate is already greater than R_T, and thus no secondary access is possible.

Finally, the critical (outage) rate regions for the proposed spectrum sharing protocol is illustrated in Fig. 4. When σ_1^2 is greater than -4.6 dB, no secondary access is possible and this region is denoted as Zone I in Fig. 4. However, when σ_1^2 is below a critical value (-4.6 dB in this case), the achievable outage rate under direct transmission is less than R_T. This is the region that we aim to exploit with the proposed spectrum access protocol and bring benefit to both primary and secondary systems, as shown in Fig. 4. When σ_1^2 is below the critical value, the primary system will request secondary cooperation and thus secondary access becomes possible (through Cooperation mode or Access mode). Based on the outage rate requirement, this region can be divided into two zones: Zone II and Zone III, as shown in Fig. 4. In Zone II, the primary system is able to achieve the target outage rate with assistance from the secondary cooperation; in the meanwhile, the secondary system also gains secondary access to the primary spectrum during the cooperation. It should be noted that even after operating in the Cooperation mode, the achievable outage rate may still fall below R_T, if P_s is not large enough. This area is denoted as Zone III in Fig. 4. Fig. 4 clearly shows that both primary and secondary systems benefit from the proposed opportunistic spectrum access protocol.

Appendix A

Let $\boldsymbol{x}$ and $\boldsymbol{y}$ be the optimal solutions to the joint optimization problem with rate constraints R_{Tx} and R_{Ty}, respectively. For any $0 \le \nu \le 1$, there always exists a feasible solution $\boldsymbol{z}$, such that $R_{Tz} \ge \nu R_{Tx} + (1-\nu)R_{Ty}$ and $f(\boldsymbol{z}) \ge \nu f(\boldsymbol{x}) + (1-\nu) f(\boldsymbol{y})$, where $f(.)$ is the objective function of the joint optimization problem in (8). Thus our joint optimization problem satisfies the time-sharing condition.

To prove the time-sharing property implies zero duality gap, we first need to prove that the objective function of our joint optimization problem is a concave function of R_T. Let R_{Tx}, R_{Ty} and R_{Tz} be the rate constraints with $R_{Tz} \ge \nu R_{Tx} + (1-\nu)R_{Ty}$ for some $0 \le \nu \le 1$. Let $\boldsymbol{x}$, $\boldsymbol{y}$ and $\boldsymbol{z}$ be the optimal solutions to the joint optimization problem with rate constraints R_{Tx}, R_{Ty} and R_{Tz}, respectively. Since $R_{Tz} \ge \nu R_{Tx} + (1-\nu)R_{Ty}$, the time-sharing property implies that there exists a $\boldsymbol{z'}$ such that $R_{Tz'} \ge \nu R_{Tx} + (1-\nu)R_{Ty}$ and $f(\boldsymbol{z'}) \ge \nu f(\boldsymbol{x}) + (1-\nu) f(\boldsymbol{y})$. Since $\boldsymbol{z'}$ is a feasible solution for the optimization problem, this means that $f(\boldsymbol{z}) \ge f(\boldsymbol{z'}) \ge \nu R_{Tx} + (1-\nu)R_{Ty}$, thus proving that our joint optimization problem is a concave function of R_T. Then we can prove that duality gap is zero by using the similar methods in [11].

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