Secondary Spectrum Access Based on Cooperative OFDM Relaying

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***Abstract*—In this paper, we propose an opportunistic spectrum sharing protocol that exploits the situation when the primary system experiences weak channel conditions. Specifically, when the outage rate of the primary systeme falls below the target rate, the secondary system tries to help the primary system achieve its target rate by acting as a decode-and-forward relay for the primary system, and allocating a fraction of its subcarriers to forward the primary signal. As a reward, the secondary system gains spectrum access by using the remaining subcarriers to transmit its own signal. We study the joint optimization of the set of subcarriers used for cooperation and the secondary subcarrier power allocation such that the transmission rate of the secondary system is maximized, while guaranteeing the primary system to achieve its target rate. Simulation results demonstrate that both primary and secondary systems can benefit from the proposed secondary spectrum access scheme.**

***Index Terms*—Secondary spectrum access, cooperative relaying, OFDM, power allocation.**

I. Introduction

In traditional frequency spectrum regulation, almost all the frequency bands are exclusively allocated to specific systems in a predetermined way. However, FCC studies have found that this static frequency allocation results in inefficient spectrum usage [1]. On the other hand, many emerging wireless networks might not be able to find available frequency spectrum to use. Cognitive radio (CR) is a promising technology to improve the network spectrum-utilization efficiency by allowing cognitive secondary systems to intelligently sense and opportunistically access the spectrum of license-holding primary systems [2], [3].

The role of cooperative transmission in cognitive radio for spectrum sharing has been studied in [4]-[5]. A spectrum leasing protocol is considered in [4], 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 [5], distributed spectrum sharing protocols based on cooperative relaying are discussed. The secondary system is designed to act as a relay, where a fraction of the secondary system's power is used 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 the secondary system 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 [6]. In OFDM-based CR systems, secondary system can transmit over the unused subcarriers left in the primary system [7] or flexibly share the subcarriers with primary system on condition that the primary system is sufficiently protected [8].

In this paper, we propose an opportunistic spectrum sharing protocol that exploits the situation when the primary system experiences a poor link quality. Specifically, 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 a decode-and-forward (DF) 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 the primary system still cannot achieve its target rate even when the secondary system acts a pure relay for the primary transmission, the primary system will stop transmission and the secondary system will then be granted full spectrum access to the licensed primary spectrum. We show that when the achievable rate of the primary system falls below its target rate, the secondary system can opportunistically assist the primary system to achieve its target rate with a proper resource allocation strategy. Simulation results confirm the benefit of the proposed spectrum access scheme to both primary and secondary systems.

II. System Model

We consider a cooperative spectrum access system, as shown in Fig. 1, 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 and has the license to operate in a certain spectrum. The secondary OFDM system, which can act as a DF relay for the primary system [5], comprising of a secondary transmitter (ST) and secondary receiver (SR), can only opportunistically operate in this spectrum by exploiting the situation when the PT→PR link is weak. 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

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to emulate the radio protocols and system parameters of the primary system.

We consider that the primary system is a delay-limited system and its performance is evaluated by outage rate and outage probability, while the secondary system attempts to gain opportunistic spectrum access and its performance is evaluated by average (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_0^2, σ_1^2, σ_2^2, and σ_3^2. 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 PT→ST link over subcarrier k ($1 \le k \le K$) are denoted as $h_{0,k}$, and $h_{1,k}$, respectively. Likewise, the channel coefficients of the ST→PR link and the ST→SR link over subcarrier k' ($1 \le k' \le K$) are denoted as $h_{2,k'}$ and $h_{3,k'}$, respectively. 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 $\gamma_{0,k} \triangleq |h_{0,k}|^2$, $\gamma_{1,k} \triangleq |h_{1,k}|^2$, $\gamma_{2,k'} \triangleq |h_{2,k'}|^2$, and $\gamma_{3,k'} \triangleq |h_{3,k'}|^2$, 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 system and the secondary system 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 approach to adaptively allocate power to each primary subcarrier.

III. Protocol Description and Achievable Rates of Primary/Secondary Systems

The primary system needs to predict its achievable outage rate based on the current average SNR of the PT→PR link. Without any relay cooperation from the secondary system, the instantaneous rate (in Nats/OFDM symbol) of the primary system with direct transmission is given by

$$R_K = \sum_{k=1}^{K} \ln(1 + \gamma_{0,k} p_{p,k}) \tag{1}$$

where $\ln$ denotes the natural logarithm, and $p_{p,k}$ follows the water-filling approach.

The primary outage probability in this case is given by

$$\mathcal{P}_{out}^d = \mathcal{P}(R_K < R_T) \tag{2}$$

where $\mathcal{P}(\mathcal{A})$ denotes probability of event $\mathcal{A}$ and R_T denotes the target rate of the primary system. Note that with a fixed channel delay profile of the PT→PR link, $\mathcal{P}_{out}^d$ only depends on its average SNR, given by $\rho = P_p \sigma_0^2$. 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 underlying ρ.

When the achievable outage rate 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 ragarding P_p and R_T is embedded in RTC and the channel state information of PT→PR link in embedded in ATC.

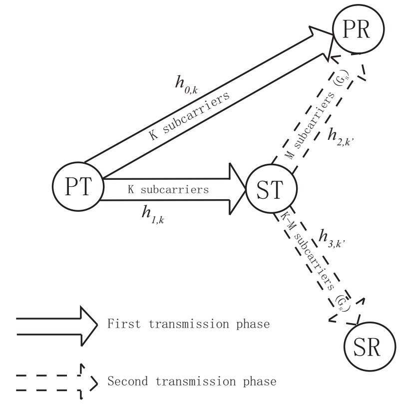

Fig. 1. System model of spectrum sharing based on cooperative OFDM relaying.

Upon receiving both RTC and ATC signals, ST is able to estimate the channel gains of PT→ST, ST→PR and PT→PR links. Then ST decides, under the current channel condition and power, 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 DF relay for the primary system by devoting all of its subcarriers and power to relay the primary signal.

Thus, R_{max} can be written as

$$R_{max} = \min\{R_1^{max}, R_2^{max}\} \tag{3}$$

where $R_1^{max} = \frac{1}{2}\sum_{k=1}^{K} \ln(1 + \gamma_{1,k} p_{p,k})$ and $R_2^{max} = \frac{1}{2}\sum_{k'=1}^{K} \ln(1 + \gamma_{2,k'} p_{sp,k'} + \gamma_{0,k'} p_{p,k'})$ are the maximum achievable rates at ST and PR over two phases, respectively. $p_{sp,k'}$ in R_2^{max} is the power allocated to subcarrier k' at ST which is used to relay the date of the primary system. The optimal power allocation of $p_{sp,k'}$ follows the water-filling approach, $p_{sp,k'} = (1/\tau - (1 + \gamma_{0,k'} p_{p,k'})/\gamma_{2,k'})^+$, where the constant τ has to be chosen to satisfy the secondary sum power constraint $\sum_{k'=1}^{K} p_{sp,k'} = P_s$. In this work, we do not consider optimizing the primary subcarrier power allocation when secondary cooperation takes place, which implies that $p_{p,k'}$ in R_2^{max} is the same as $p_{p,k}$.

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

In the first phase, PT uses all the K subcarriers to transmit its data to ST and PR. The achievable rate of the PT→ST link can be written as

$$R_1 = \frac{1}{2}\sum_{k=1}^{K} \ln(1+\gamma_{1,k}p_{p,k}). \tag{4}$$

We denote the set of K subcarriers available in the second phase as Ω_s, i.e., $\Omega_s = \{1,2,...,K\}$.

In the second phase, ST tries to decode the primary data and uses a subset of the K subcarriers, $\mathcal{G}_s \subseteq \Omega_s$, where $|\mathcal{G}_s| = M$, to help forward the decoded primary data to PR. The indices of these M secondary subcarriers used for relaying are embedded in the CTC signal and thus are known to both PR and SR. Thus, the achievable primary rate at PR conditioned on successful decoding at ST can be written as

$$\begin{aligned} R_2 = &\frac{1}{2}\sum_{k'\in\mathcal{G}_s} \ln(1+\gamma_{2,k'}p_{sp,k'}+\gamma_{0,k'}p_{p,k'}) \\ &+\frac{1}{2}\sum_{k'\in\overline{\mathcal{G}}_s} \ln(1+\gamma_{0,k'}p_{p,k'}) \end{aligned} \tag{5}$$

where $p_{sp,k'}$ is the power allocated to subcarrier k' at ST which is used to relay the data of the primary system. In the meantime, ST uses the remaining $K-M$ subcarriers in $\overline{\mathcal{G}}_s$ to transmit its own data to SR. The instantaneous rate of the secondary system (in the Cooperation mode) can thus be written as

$$R_s^c = \frac{1}{2}\sum_{k'\in\overline{\mathcal{G}}_s} \ln(1+\gamma_{3,k'}p_{ss,k'}) \tag{6}$$

where $p_{ss,k'}$ is the power allocated to subcarrier k' at ST for transmitting its own data.

Thus the instantaneous rate of the primary system at PR over two phases can be written as

$$R_p = \min\{R_1, R_2\}. \tag{7}$$

Since $\mathcal{G}_s$ is embedded in the CTC, by overhearing the CTC, PR only decodes the subcarriers indicated in $\mathcal{G}_s$ in the second phase, and SR only decodes the subcarriers indicated in $\overline{\mathcal{G}}_s$. We will proceed to jointly optimize the subcarrier set $\mathcal{G}_s$ and subcarrier power allocation in Section IV.

However, if $R_{max} < R_T$, which suggests that the primary system still cannot reach its target rate, even when ST serves a pure DF 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 then be granted full spectrum access to the licensed primary spectrum. This operation mode is referred to as Full Access mode throughout this paper.

In this mode the instantaneous rate of the secondary system can be written as

$$R_s^d = \sum_{k'=1}^{K} \ln(1+p_{s,k'}^d\gamma_{3,k'}) \tag{8}$$

where $p_{s,k'}^d = \left(\frac{1}{\eta} - \frac{1}{\gamma_{3,k'}}\right)^+$, follows the water-filling approach. The constant η has to be chosen to satisfy the sum power constraint $\sum_{k'=1}^{K} p_{s,k'}^d = P_s$.

IV. Problem Formulation and Optimal Resource Allocation in Cooperation mode

In this section, we seek the joint optimization of subcarrier set $\mathcal{G}_s$ and power allocation set $\boldsymbol{p} = \{p_{sp,k'}, p_{ss,k'}\}$ to maximize the instantaneous achievable rate of secondary system, R_s^c, while guaranteeing the primary system to achieve its target rate.

This joint optimization problem can be formulated as

$$\max_{\{\mathcal{G}_s,\boldsymbol{p}\}} R_s \tag{9}$$

subject to

$$R_1 \geq R_T \tag{10a}$$
$$R_2 \geq R_T \tag{10b}$$
$$\sum_{k'\in\mathcal{G}_s} p_{sp,k'} + \sum_{k'\in\overline{\mathcal{G}}_s} p_{ss,k'} \leq P_s \tag{10c}$$

where (10a) and (10b) are the primary target rate constraint, i.e., $R_p = \min\{R_1, R_2\} \geq R_T$. It is obvious that the problem in (9) is a convex optimization problem. The Lagrange dual function of the problem in (9) can be written as

$$g(\boldsymbol{\beta}) = \max_{\{\mathcal{G}_s,\boldsymbol{p}\}} L(\mathcal{G}_s, \boldsymbol{p}) \tag{11}$$

where the Lagrangian $L(\mathcal{G}_s, \boldsymbol{p})$ is given by (16) at the top of the next page and $\boldsymbol{\beta} = (\beta_{R_1}, \beta_{R_2}, \beta_P)$ is the Lagrange multipliers. The optimal $\boldsymbol{\beta}$ can be obtained by using the subgradient-based methods [10].

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

1) Finding the optimal $\boldsymbol{p}$ *for a fixed* $\mathcal{G}_s$*:* For a fixed $\mathcal{G}_s$, the partial derivatives of the Lagrangian in (16) with respective to the optimization variables $p_{sp,k'}$ and $p_{ss,k'}$ are given by

$$\frac{\partial L(\mathcal{G}_s,\boldsymbol{p})}{\partial p_{sp,k'}} = \frac{\beta_{R_2}\gamma_{2,k'}}{2(1+\gamma_{2,k'}p_{sp,k'}+\gamma_{0,k'}p_{p,k'})} - \beta_P \tag{17a}$$
$$\frac{\partial L(\mathcal{G}_s,\boldsymbol{p})}{\partial p_{ss,k'}} = \frac{\gamma_{3,k'}}{2(1+\gamma_{3,k'}p_{ss,k'})} - \beta_P. \tag{17b}$$

By the Karush-Kuhn-Tucker conditions [11], the partial derivative of the Lagrangian is equal to zero at the optimal solution. Hence, the optimal solution to $p_{sp,k'}$ and $p_{ss,k'}$ can be obtained as

$$p_{sp,k'}^* = \left(\frac{\beta_{R_2}}{2\beta_P} - \frac{1+\gamma_{0,k'}p_{p,k'}}{\gamma_{2,k'}}\right)^+ \tag{18a}$$
$$p_{ss,k'}^* = \left(\frac{1}{2\beta_P} - \frac{1}{\gamma_{3,k'}}\right)^+. \tag{18b}$$

2) Finding the optimal $\mathcal{G}_s$*:* Substituting (18) into (16), we can obtain the Lagrangian as shown in (19).

$$L(\mathcal{G}_s, \boldsymbol{p}) = \frac{1}{2} \sum_{k' \in \overline{\mathcal{G}}_s} \ln(1 + \gamma_{3,k'} p_{ss,k'}) + \beta_{R_1} \left(\frac{1}{2} \sum_{k=1}^{K} \ln(1 + \gamma_{1,k} p_{p,k}) - R_T \right) + \beta_P \left(P_s - \sum_{k' \in \mathcal{G}_s} p_{sp,k'} - \sum_{k' \in \overline{\mathcal{G}}_s} p_{ss,k'} \right)$$
$$+ \beta_{R_2} \left(\frac{1}{2} \sum_{k' \in \mathcal{G}_s} \ln(1 + \gamma_{2,k'} p_{sp,k'} + \gamma_{0,k'} p_{p,k'}) + \frac{1}{2} \sum_{k' \in \overline{\mathcal{G}}_s} \ln(1 + \gamma_{0,k'} p_{p,k'}) - R_T \right) \tag{16}$$

$$L(\mathcal{G}_s, \boldsymbol{p}) = \frac{1}{2} \sum_{k' \in \overline{\mathcal{G}}_s} \ln(1 + \gamma_{3,k'} p^*_{ss,k'}) + \beta_{R_1} \left(\frac{1}{2} \sum_{k=1}^{K} \ln(1 + \gamma_{1,k} p_{p,k}) - R_T \right) + \beta_P \left(P_s - \sum_{k' \in \mathcal{G}_s} p_{sp,k'} - \sum_{k' \in \overline{\mathcal{G}}_s} p_{ss,k'} \right)$$
$$+ \beta_{R_2} \left(\frac{1}{2} \sum_{k' \in \mathcal{G}_s} \ln(1 + \gamma_{2,k'} p^*_{sp,k'} + \gamma_{0,k'} p_{p,k'}) + \frac{1}{2} \sum_{k' \in \overline{\mathcal{G}}_s} \ln(1 + \gamma_{0,k'} p_{p,k'}) - R_T \right) \tag{19}$$

Through some mathematical manipulation, (19) can be rewritten as

$$\begin{aligned} L(\mathcal{G}_s, \boldsymbol{p}) = &\sum_{k \in \mathcal{G}_s} F_{k'} + \sum_{k'=1}^{K} \left(\frac{1}{2} \ln(1 + \gamma_{3,k'} p^*_{ss,k'}) \right. \\ &\left. + \frac{\beta_{R_2}}{2} \ln(1 + \gamma_{0,k'} p_{p,k'}) - \beta_P p^*_{ss,k'} \right) \\ &+ \sum_{k=1}^{K} \left(\frac{\beta_{R_1}}{2} \ln(1 + \gamma_{1,k} p_{p,k}) \right) + \beta_P P_s \\ &- (\beta_{R_1} + \beta_{R_2}) R_T \end{aligned} \tag{20}$$

where

$$\begin{aligned} F_{k'} = &\frac{\beta_{R_2}}{2} \ln(1 + \gamma_{2,k'} p^*_{sp,k'} + \gamma_{0,k'} p_{p,k'}) \\ &- \frac{\beta_{R_2}}{2} \ln(1 + \gamma_{0,k'} p_{p,k'}) - \frac{1}{2} \ln(1 + \gamma_{3,k'} p^*_{ss,k'}) \\ &+ \beta_P p^*_{ss,k'} - \beta_P p^*_{sp,k'}. \end{aligned} \tag{21}$$

We only need to work on the first term on the right-hand side of (20) to find the optimal subcarrier set $\mathcal{G}_s$ that maximizes the Lagrangian, since it is the only term involving $\mathcal{G}_s$ in (20). Thus, the optimal $\mathcal{G}_s$ can be found as

$$\mathcal{G}_s^* = \arg \max_{\mathcal{G}_s} \sum_{k' \in \mathcal{G}_s} F_{k'}. \tag{22}$$

Solving (22) is simple as we only need to find all the k' ($k' \in \Omega_s$) that make $F_{k'}$ positive. Then, all these k' form $\mathcal{G}_s^*$.

V. Simulation Results

In this section, simulation results are presented to demonstrate the performance of the proposed spectrum sharing protocol in terms of primary outage rate/probability and secondary average rate.

We let the number of subcarriers $K = 32$. 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 $\sigma_1^2 = \sigma_2^2 = \sigma_3^2 = 0$ dB for all the simulations, while various values of σ_0^2 are tested. We aim to evaluate the proposed opportunistic spectrum sharing protocol, which is designed to exploit the potentially weak PT→PR link. We also set $P_p = 10$ dB, $P_s = 20$ dB, and $R_T = 3$ bps/Hz, unless otherwise specified. 10% outage rate of the primary system, $C_{10\%}$, is considered in the simulations.

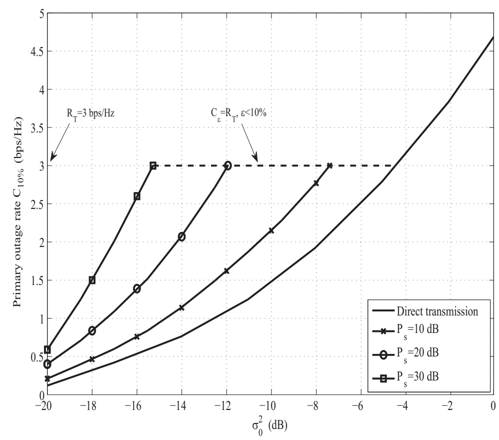

Fig. 2. Outage rate of the primary system.

The outage rate of the primary system is shown in Fig. 2. The case of direct primary transmission is also plotted for comparison. Fig. 2 clearly shows the improvement of the primary outage rate with the proposed spectrum sharing protocol. We can observe from the figure that a weaker primary channel (i.e., a lower σ_0^2) requires a higher P_s to boost the outage rate to R_T. Moreover, once the outage rate meets R_T, the outage rate will not be further increased beyond R_T. This is not unexpected based on the proposed protocol. On the other hand, if the primary link is good, e.g., $\sigma_0^2 > -4.6$ dB in Fig. 2, the primary outage rate is already greater than R_T, and thus no secondary access is possible.

The probabilities of operating in the Cooperation mode and in the Full Access mode are shown in Fig. 3. It is easy to see that when P_s increases, the secondary system will have more chances to help the primary system to reach R_T via

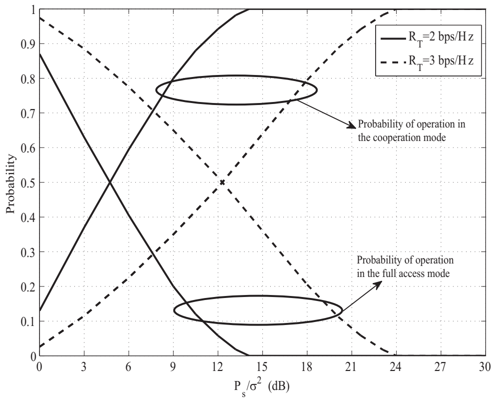

Fig. 3. Average probabilities of operating in the cooperation mode and the full access mode. $\sigma_0^2 = -8$ dB.

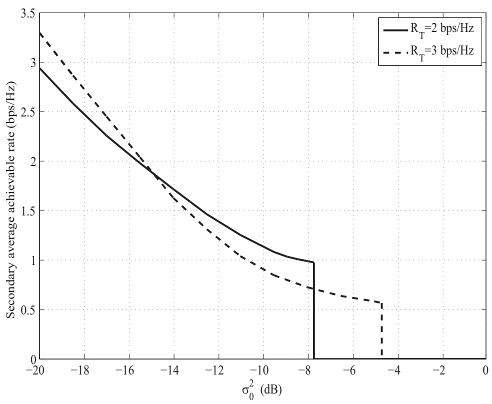

Fig. 4. Average secondary achievable rate versus σ_0^2.

the Cooperation mode. Fig. 3 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.

The average achievable rate of the secondary system versus σ_0^2 is shown in Fig. 4. The average rate of the secondary system is calculated as

$$\bar{R}_s = E[R_s^c] \cdot \mathcal{P}_c + E[R_s^d] \cdot \mathcal{P}_d \tag{23}$$

where $\mathcal{P}_c \triangleq \mathcal{P}(R_{max} > R_T)$ denotes the probability of operating in the cooperation mode and $\mathcal{P}_d \triangleq \mathcal{P}(R_{max} \leq R_T)$ denotes the probability of operating in the full access mode have been shown in Fig. 3. We can observe from Fig. 4 that a lower σ_0^2 always leads to a higher $\bar{R}_s$. This is because that a lower σ_0^2 suggests a weaker primary channel, and thus it is more often for the secondary system to work in the Full Access mode as in this case it is more difficult to achieve the primary target rate, resulting in a higher probability of operating in the Full Access mode. Fig. 4 also shows that a lower R_T requires a weaker primary link to enable secondary access. We also notice in Fig. 4 that at a relatively small σ_0^2, e.g., -10 dB, a lower R_T (i.e., $R_T = 2$ bps/Hz) brings a higher $\bar{R}_s$ as compared to $R_T = 3$ bps/Hz; while at a much smaller σ_0^2, e.g., -20 dB, a higher R_T actually brings a higher $\bar{R}_s$. The reason is that when σ_0^2 is very small, a higher R_T brings a higher probability of working in the Full Access mode and thus a higher $\bar{R}_s$. For some σ_0^2, the behavior of $\bar{R}_s$ can be very complicated, due to the joint effect of the Cooperation mode and the Full Access mode.

VI. Conclusion

In this paper, we propose an opportunistic spectrum sharing protocol that exploits the situation when the primary system experiences weak channel conditions. The secondary system, which can act as a DF relay for the primary system, tries to help the primary system achieve its target rate by allocating a fraction of its subcarriers to decode and forward the primary signal. At the same time, the secondary system can use the remaining subcarriers to transmit its own signal, and thus gaining opportunistic spectrum access. We study the joint optimization of the set of subcarriers used for cooperation and the secondary subcarrier power allocation such that the transmission rate of the secondary system is maximized while ensuring the primary system to achieve its target rate. Simulation results were presented to show that the proposed secondary spectrum access scheme can benefit both the primary and secondary systems.

VII. Acknowledgment

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