An Anti-Interference Cooperative Spectrum Sharing Strategy with Joint Optimization of Time and Bandwidth

Weidang Lu, Jing Wang, Weidong Ge, Feng Li, Jingyu Hua, and Limin Meng

Abstract: **In this paper, we propose an anti-interference cooperative spectrum sharing strategy for cognitive system, in which a secondary system can operate on the same spectrum of a primary system. Specifically, the primary system leases a fraction of its transmission time to the secondary system in exchange for cooperation to achieve the target rate. To gain access to the spectrum of the primary system, the secondary system needs to allocate a fraction of bandwidth to help forward the primary signal. As a reward, the secondary system can use the remaining bandwidth to transmit its own signal. The secondary system uses different bandwidth to transmit the primary and its own signal. Thus, there will be no interference felt at primary and secondary systems. We study the joint optimization of time and bandwidth allocation such that the transmission rate of the secondary system is maximized, while guaranteeing the primary system, as a higher priority, to achieve its target transmission rate. Numerical results show that the secondary system can gain significant improvement with the proposed strategy.**

Index Terms: **Cognitive system, cooperative relaying, resource allocation, spectrum sharing.**

I. INTRODUCTION

The current utilization of the spectrum is quite inefficient because of the fixed spectrum allocation. A recent survey of spectrum utilization made by the Federal Communications Commission (FCC) has indicated significant temporal and geographical variations in the utilization of the licensed spectrum, ranging from as low as 15% to 85% [1]. Cognitive radio (CR) is a promising technology to improve the spectrum utilization efficiency by allowing unlicensed (secondary) systems to operate in licensed frequency bands of the licensed (primary) systems while adhering to the interference limitations of the primary systems [2]–[4].

Spectrum sharing for secondary system access has been studied extensively [5]–[8]. A dynamic spectrum sharing problem for the centralized uplink cognitive radio networks using orthogonal frequency division multiple access is investigated in [5]. The secondary system can gain access to the spectrum if it detects the spectrum hole through spectrum sensing [6]. With detect-and-avoid mechanism, the harmful interference to primary systems caused by the secondary system can be effectively prevented. The secondary system may also be allowed to share the primary spectrum through simultaneous transmission under the condition that the resultant interference at the primary system is below a prescribed threshold in order to protect the primary transmission, as a higher priority [7], [8].

Most existing work on spectrum sharing concentrated on the case where the direct transmission link of primary system is good enough to support its target QoS, which makes it possible to tolerate additional interference from the secondary system. This provides an opportunity for the secondary system to access the primary spectrum by working simultaneously with the primary system, as long as the primary quality of service (QoS) is not affected by the secondary system. [7] and [9] study the optimal power allocation which maximizes the secondary achievable rate subject to the interference power constraint at the primary receiver, in order to protect the transmission of the primary system. While in [8] the rate loss constraint is considered. The optimal power allocation strategy to maximize the secondary rate with individual interference power constraint imposed on each subcarrier is considered in [10], where the secondary and primary systems coexist in the same spectrum, and both of them are orthogonal frequency division multiplexing (OFDM)-modulated.

Cooperative diversity has been proposed as an important technique to enlarge system coverage and increase link reliability [11], [12], since it can combat the effects of path loss in wireless links. The role of cooperative diversity in cognitive radio for spectrum sensing and sharing has been studied in [13]. A centralized spectrum leasing protocol with time allocation based on Stackelberg games is considered in [14], where the secondary system uses a fraction of the time leased by the primary system to transmit its own signal in gaining spectrum access, and uses another part of the time to forward the primary signal. Distributed spectrum sharing protocols with power allocation based on cooperative amplify-and-forward (AF) and decode-and-forward (DF) relaying are discussed in [15] and [16], where the secondary system uses a fraction 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 sharing, and then uses the remaining power to transmit its own signal. A cooperative spectrum sharing protocol with joint time and power allocation is proposed in [17] where the performance of the secondary system can be improved. However, in this spectrum sharing protocol, the secondary system still broadcasts a superimposed signal which is a linear weighted combination of primary and secondary signal. It will cause interference to both primary and secondary systems. We proposed

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a frequency domain anti-interference spectrum sharing protocol with joint subcarrier and power allocation in [18]–[20], where the secondary system helps the primary system achieve the target rate by acting as an AF or DF relay for the primary system, which uses a fraction of accessed subcarriers to forward the primary signal in achieving the target rate, while using the remaining subcarriers to transmit its own signal.

In this paper, we propose an anti-interference cooperative spectrum sharing strategy with joint time and bandwidth allocation, which aims to maximize the transmission rate of secondary system, while guaranteeing the primary system achieve its target rate. The primary and secondary systems will not experience interference as the secondary system uses disjoint bandwidth to transmit primary and secondary signal. Specifically, the primary system leases a fraction of its transmission time to the secondary system in exchange for cooperation to achieve its target rate. In order to access to the spectrum of the primary system, the secondary system needs to help the primary system achieve the target rate by acting as a DF relay to forward the primary signal with a fraction of bandwidth. As a reward, the secondary system can use the remaining accessed bandwidth to transmit its own signal.

The main contributions of this paper are described as follows. First, unlike the previous spectrum sharing protocol, we proposed an anti-interference spectrum sharing protocol, there will be no interference felt at primary and secondary systems. Second, joint time and bandwidth allocation is derived, such that the transmission rate of the secondary system is maximized, while helping the primary system, as a higher priority, to achieve its target transmission rate. Finally, computer simulations are performed to demonstrate the presented analytical results.

The remainder of this paper is organized as follows. In Section II, we introduce the system model. The achievable rates of the primary and secondary systems are analyzed in Section III. The optimal time and bandwidth allocation is presented in Section IV. Simulation results are provided in Section V to illustrate the performance of the proposed spectrum sharing protocol and resource allocation algorithm. Finally we conclude this paper in Section VI.

II. SYSTEM MODEL

The proposed cognitive system is shown in Fig. 1. The primary system, comprising of a primary transmitter (PT) and a primary receiver (PR), supports the relaying functionality and has the license to operate in a certain spectrum of bandwidth. The secondary system, comprising of a secondary transmitter (ST) and a secondary receiver (SR), is seeking to exploit possible transmission opportunities. We assume that the secondary system is able to emulate the radio protocols and system parameters of the primary system [16], [18].

The channels over links PT→PR, PT→ST, ST→PR, ST→SR are modeled on Rayleigh flat fading with channel coefficients denoted by h_1, h_2, h_3, and h_4, respectively. We have $h_i \sim CN(0, d_i^v)$, $i = 1, 2, 3$, and 4, where v is the path loss exponent and d_i is the normalized distance between the respective transmitters and receivers. This normalization is done with respect to the distance between PT and PR, i.e., $d_1 = 1$. We denote the instantaneous channel gain as $\gamma_i = |h_i|^2$. We assume all channel coefficients remain static within a duration of two transmission slots.

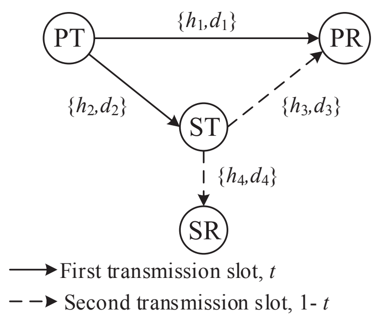

Fig. 1. System model.

III. ACHIEVABLE RATES OF PRIMARY AND SECONDARY SYSTEMS

We first consider the situation where only the primary system is operating. The primary signal is transmitted from PT to PR over channel h_1, with transmit power P_p. Thus, the achievable rate of the primary system is given as

$$R_d = W \log_2 \left(1 + \frac{P_p \gamma_1}{N_0}\right) \tag{1}$$

where N_0 is the additive white Gaussian noise power spectral density.

Spectrum sharing with a secondary system is allowed under the condition that the secondary system can help the primary system achieve the target rate R_t. The secondary system decides whether it is able to assist the primary system to achieve the target rate by the following two-slot DF cooperative transmission.

In the first slot which occupies time $t (0 < t < 1)$, as shown by the solid arrows in Fig. 1, PT transmits the primary signal to PR and ST. The achievable rate of PT→PR and PT→ST links can be written as

$$R_d^t = tW \log_2 \left(1 + \frac{P_p \gamma_1}{N_0}\right), \tag{2}$$

$$R_p^1 = tW \log_2 \left(1 + \frac{P_p \gamma_2}{N_0}\right). \tag{3}$$

In the second slot which occupies time $1 - t$, ST tries to decode the primary signal and allocates $b (0 < b < 1)$ fraction of the bandwidth which is granted by the primary system to help forward the signal of PT to PR by using its half power. The achievable primary rate at PR conditioned on successful decoding at ST can be written by (4) at the top of next page, where P_s is the transmit power of the secondary system.

Thus, the achievable rate of the primary system at PR over two slots can be written as

$$R_p = \min\{R_p^1, R_p^2\}. \tag{5}$$

$$R_p^2 = \begin{cases} tW\log_2\left(1+\frac{P_s\gamma_3}{2N_0}+\frac{P_p\gamma_1}{N_0}\right)+[(1-t)b-t]W\log_2\left(1+\frac{P_s\gamma_3}{2N_0}\right), & (1-t)b>t, \\ (1-t)bW\log_2\left(1+\frac{P_s\gamma_3}{2N_0}+\frac{P_p\gamma_1}{N_0}\right)+[t-(1-t)b]W\log_2\left(1+\frac{P_p\gamma_1}{N_0}\right), & (1-t)b\le t. \end{cases} \tag{4}$$

In the mean time, ST uses the remaining $(1-b)$ fraction of the bandwidth and its half power to transmit its own signal to SR. Thus, the achievable rate of the secondary system can be written as

$$R_s = (1-t)(1-b)W\log_2\left(1+\frac{P_s\gamma_4}{2N_0}\right). \tag{6}$$

If the achievable rate of the primary system helped by ST can achieve the target rate, i.e., $R_p \ge R_t$, then ST will be granted by the primary system to access the spectrum of the primary system.

IV. OPTIMAL TIME AND BANDWIDTH ALLOCATION

In this section, we seek joint optimization of time t and bandwidth b to maximize the secondary system's transmission rate R_s while guaranteeing the primary system to achieve the target rate R_t. This joint optimization problem can be formulated as

$$\max_{t,b} R_s \tag{7}$$

subject to

$$R_p \ge R_t, \tag{8a}$$
$$0 < t < 1, \tag{8b}$$
$$0 < b < 1. \tag{8c}$$

For the sake of simplicity, we let

$$R_2 = W\log_2\left(1+P_p\frac{\gamma_2}{N_0}\right), \tag{9a}$$
$$R_3 = W\log_2\left(1+P_s\frac{\gamma_3}{2N_0}\right), \tag{9b}$$
$$R_4 = W\log_2\left(1+P_s\frac{\gamma_4}{2N_0}\right), \tag{9c}$$
$$R_5 = W\log_2\left(1+P_s\frac{\gamma_3}{2N_0}+P_p\frac{\gamma_1}{N_0}\right). \tag{9d}$$

Substituting R_2, R_3, R_4, and R_5 into (7) and (8), we can obtain

$$\max_{t,b}(1-t)(1-b)R_4 \tag{10}$$

subject to

$$tR_2 \ge R_t, \tag{11a}$$
$$R_p^2 \ge R_t, \tag{11b}$$
$$0 < t < 1, \tag{11c}$$
$$0 < b < 1 \tag{11d}$$

where

$$R_p^2 = \begin{cases} tR_5 + [(1-t)b-t]R_3, & (1-t)b > t, \\ (1-t)bR_5 + [t-(1-t)b]R_1, & (1-t)b \le t. \end{cases} \tag{12}$$

To satisfy the first condition of (11), we can obtain $t \ge R_t/R_2$. To satisfy the third condition, R_2 should be larger than R_t. It is easy to understand that if $R_2/R_t < 1$, it means that the secondary system can not help PT achieve the target rate even when it uses all the time and bandwidth to help forward the primary signal.

From (10), we can find that the secondary transmission rate R_s monotonically decreases with t. Thus, the optimal time allocation of our joint optimization problem is

$$t^* = \frac{R_t}{R_2}. \tag{13}$$

From (12), we can observe that there are two different cases for the second condition.

Case 1: When $(1-t)b > t$, $R_p^2 = tR_5 + [(1-t)b-t]R_3$. To satisfy the second condition of (11), we can obtain

$$b \ge \frac{\big(R_t + t(R_3 - R_5)\big)}{\big((1-t)R_3\big)}. \tag{14}$$

Substituting the optimal t^* in, we can obtain

$$b \ge \frac{\big(R_t(R_2 + R_3 - R_5)\big)}{\big((R_2 - R_t)R_3\big)}. \tag{15}$$

To satisfy the fourth condition of (11), as we have already obtained $R_2 > R_t$, thus we can obtain

$$R_2 + R_3 - R_5 > 0, \tag{16a}$$
$$\frac{R_2R_3}{(R_2 + 2R_3 - R_5)} > R_t. \tag{16b}$$

From (10), we can find that the secondary transmission rate R_s monotonically decreases with b. Thus, the optimal bandwidth allocation of our joint optimization problem is

$$b^* = \frac{R_t(R_2 + R_3 - R_5)}{(R_2 - R_t)R_3}. \tag{17}$$

Case 2: When $(1-t)b \le t$, $R_p^2 = (1-t)bR_5 + [t-(1-t)b]R_1$. To satisfy the second condition of (11), we can obtain

$$b \ge \frac{\big(R_t - tR_1\big)}{\big((1-t)(R_5 - R_1)\big)}. \tag{18}$$

Substituting the optimal t^* in, we can obtain

$$b \ge \frac{\big(R_t(R_2 - R_1)\big)}{\big((R_2 - R_t)(R_5 - R_1)\big)}. \tag{19}$$

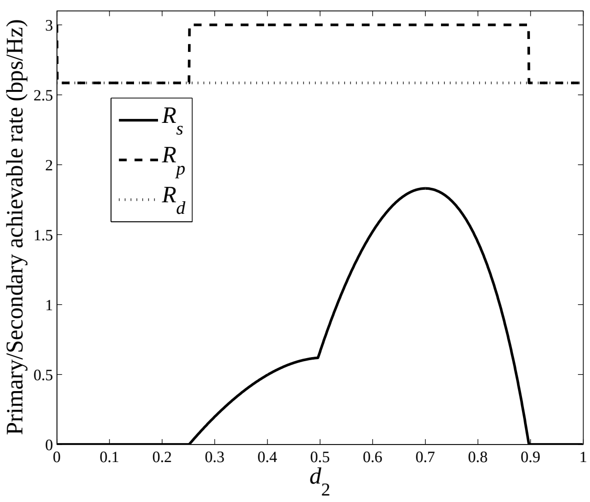

Fig. 2. Value of R_s and R_p versus different locations of ST.

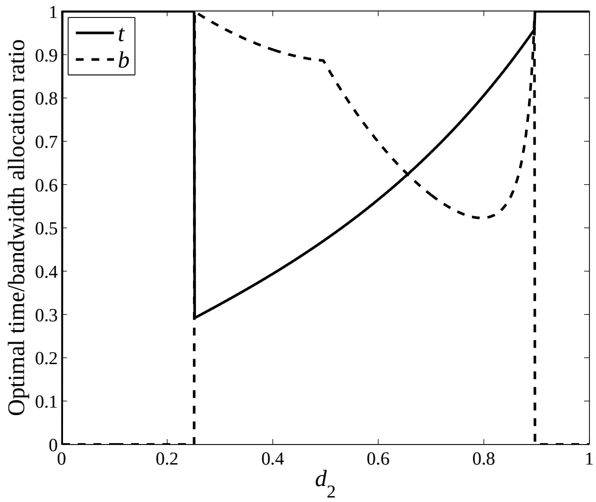

Fig. 3. Fraction of time and bandwidth versus different locations of ST.

To satisfy the fourth condition of (11), as we have already obtained $R_2 > R_t$, thus we can obtain

$$R_2 - R_1 > 0, \tag{20a}$$

$$R_5 - R_1 > 0, \tag{20b}$$

$$\frac{R_2(R_5 - R_1)}{(R_2 - 2R_1 + R_5)} > R_t. \tag{20c}$$

As the secondary transmission rate R_s monotonically decreases with b, the optimal bandwidth allocation of our joint optimization problem is

$$b^* = \frac{R_t(R_2 - R_1)}{(R_2 - R_t)(R_5 - R_1)}. \tag{21}$$

Substituting t^* and b^* into (10), we can obtain

$$R_s^* = \begin{cases} \dfrac{AR_3 - R_t(R_2 + R_3 - R_5)}{R_3} \dfrac{R_4}{R_2}, & (1-t)b > t, \\ \dfrac{AB - R_t(R_2 - R_1)}{B} \dfrac{R_4}{R_2}, & (1-t)b \leq t \end{cases} \tag{22}$$

where $A = R_2 - R_t$ and $B = R_5 - R_1$.

V. SIMULATION RESULTS

We considered a system topology where PT, PR, ST, and SR are collinear. In a two-dimensional X-Y plane, PT and PR are located at points (0, 0) and (1, 0), respectively, thus $d_1 = 1$. ST moves on the positive X axis, whereas SR is located in the middle of PR and ST. Therefore, $d_3 = 1 - d_2$ and $d_4 = 1/2d_3$. The path loss exponent remains at $v = 4$, and $P_p/N_0 = 3$ dB, $P_s/N_0 = 10$ dB, $R_t = 3$ bps/Hz, unless otherwise specified. The other parameters used in the simulations include $W = 1$. In Fig. 2, the Y-axis represents the achievable rate of primary and secondary systems, while the X-axis represents d_2. We can observe from Fig. 2 that when $d_2 \leq 0.25$, $R_s = 0$, and $R_p = R_d$, which indicates that when ST located far away from PR, the SNR of ST→PR link is not good enough to help the primary system achieve the target rate. With the movement of ST from the left (near PT) to the right (far away from PT), the SNR of ST→PR link becomes good enough to help the primary system to achieve the target rate. Then, the secondary system will be granted by the primary system to access its spectrum. Thus, R_s becomes positive, and R_p achieves to R_t. However, when ST moves far away from PT, i.e., $d_2 \geq 0.89$, R_s becomes to 0 and R_p turns to R_d again. It is because the SNR of PT→ST link becomes worse, the secondary system can not help the primary system to achieve the target rate. Thus, the secondary system will not be granted to access to the spectrum of primary system.

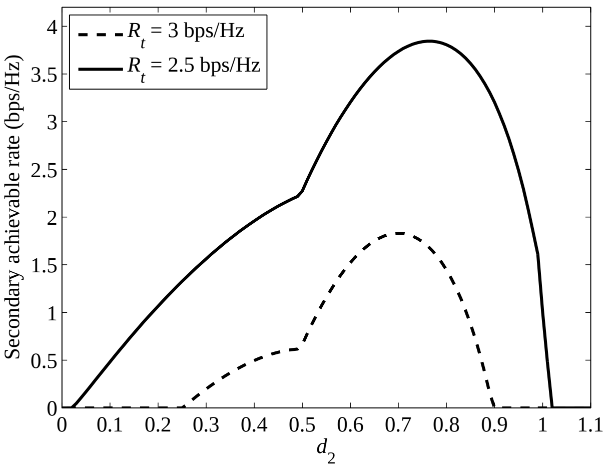

Fig. 4. Value of R_s versus different locations of ST with different R_t.

Fig. 3 shows the optimal time and bandwidth allocation of the proposed strategy. With ST moves farther away from PT, the SNR of PT→ST link becomes worse, thus the primary system needs to allocate more time to guarantee its first slot transmission achieve its target rate. At the same time, the SNR of ST→PR link becomes better, thus, the secondary system will al-

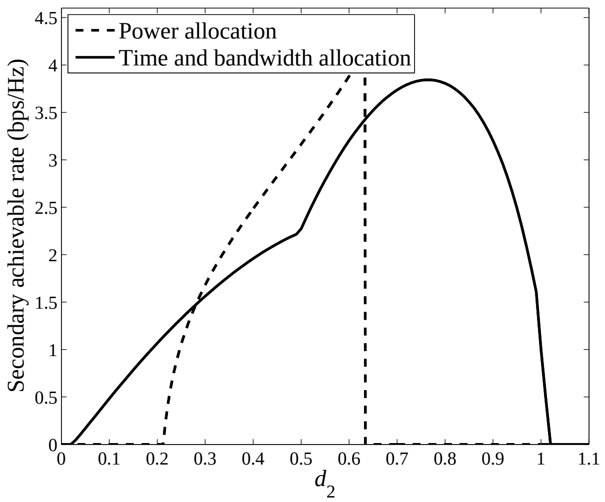

Fig. 5. Value of R_s versus different locations of ST when $R_t = 2.5$ bps/Hz.

locate less bandwidth in the second transmission slot to help the primary system achieve the target rate. However, with ST moves further away from PT, the primary system allocates less time to the secondary system. To gain spectrum access, the secondary system needs to allocate more bandwidth to help the primary system achieve the rate.

Fig. 4 shows the achievable rate of secondary system with different target rate R_t. We can observe from Fig. 4 that with smaller target rate, the achievable rate of secondary system will be larger. And the secondary system can access to the primary spectrum with larger d_2. This is because when the target rate becomes smaller, it is easier for the secondary to achieve, the secondary system will use less time and bandwidth to forward the primary signal. Then, more time and bandwidth can be left to the secondary system to transmit its own signal, thus makes the achievable rate of the secondary system larger.

Fig. 5 compares the achievable rate of the secondary system with our proposed strategy and the strategy in [17] where $t^* = 1/2$ and power allocation is optimized. We can observe from Fig. 5 that the access range of our proposed strategy, which is from 0.02 to 1.02, is much larger than the access range of the strategy in [17], which is from 0.21 to 0.62. This is because, the primary and secondary systems will experience interference in the strategy of [17], while there will be no interference felt in our proposed strategy. Moreover, the time allocation in strategy of [17] is fixed to $1/2$, while in our strategy the time can be adaptively allocated according to the channel of PT$\rightarrow$ST and ST$\rightarrow$PR links. Thus, the secondary system with our proposed strategy can access to the primary spectrum with larger range.

VI. CONCLUSION

In this paper, we propose a cooperative spectrum sharing strategy. In the proposed strategy, the secondary system gains spectrum access by assisting the primary system to meet its target rate. Specifically, the secondary system helps to decode and forward the primary signal through a faction of bandwidth, and gains spectrum access by using the remaining bandwidth to transmit its own signal. The primary and secondary systems will not experience interference as the secondary system uses disjoint bandwidth to transmit primary and secondary signal. We studied the joint optimization of time and bandwidth allocation such that the transmission rate of the secondary system is maximized, while guaranteeing the primary system, as a higher priority, to achieve its target transmission rate. Simulation results confirmed the efficiency of the proposed spectrum sharing strategy as well as its benefit to both the primary and secondary systems.

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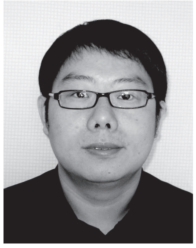

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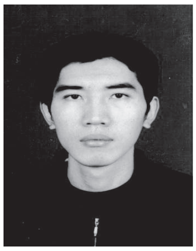

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