A Spectrum Access Scheme for MIMO Cognitive Networks with Beamforming Design

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Abstract. This paper studies a spectrum access scheme to increase the spectral utilization for the multi-antenna cognitive radio (CR) network. The network comprises of one transmitter-receiver pair for primary users (PUs) and another pair for secondary users (SUs) with secondary transmitter equipped with multi-antenna. We divide the transmission time into two equal time phases, the first for PUs to transmit signals and the second for SUs to relay and transmit self-information. We aim to maximize the data rate of the secondary system through designing the beamforming vectors and power scaling factors with zero-force beamforming (ZFBF) to eliminate the co-channel interference, under the condition that PUs can achieve the target rate. The simulation results demonstrate a higher spectral utilization and a performance gain with the proposed scheme.

Keywords: Cognitive network · MIMO · Beamforming · Multi-antenna

1 Introduction

With the booming of the wireless radio, spectrum resources are getting more and more scarce. As the conception of cognitive radio (CR) first proposed by Joseph Mitola in 1999 [1], there emerged a new model to improve the utilization of spectrum resources as cognitive radios have a good performance in increasing spectral efficiency [2]. In the common wireless network, once users with licensed spectrum have connection interruptions, there is a waste of spectrum. While in a cooperative cognitive network, the situation is quite different. Users are generally divided into two parts in a cooperative cognitive network, PUs with licensed spectrum and SUs without license. Then SUs sense the spectrum whether it is spare or not. Once it's spare, SUs can access the spectrum after bargaining with PUs.

In a cooperative cognitive network, generally PUs lease the spectrum to SUs and SUs separate part of the power to assist PUs to achieve win-win results [3–5]. In [6], the authors proposed a two-phase transmission protocol aimed to achieve spectrum access in a cooperative cognitive network. In the first phase, only the primary transmitter is allowed to broadcast and in the second phase it turns to secondary system. The

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power of the secondary transmitter is designed to ensure the primary system quality-of-service (QoS). While in [7], in both two phases, PUs and SUs were designed to transmit information at same time with the SUs transmission power limited to satisfy the QoS of PUs. Both of [6, 7] show that two-phase cognitive transmission protocol can significantly decrease the outage probability of the secondary system while ensuring the PUs QoS and improve the spectral utilization at same time.

Multiple-input multiple-output (MIMO) technology was originally conceived in 1970s when Bell Labs engineers tried to break through the bandwidth limitations caused by signal interferences. MIMO uses antenna arrays at the transmitter and receiver [8]. Thus MIMO cognitive networks contain at least one user with multi-antenna. As the MIMO channels can obviously increase the channel capacity [9], cooperative MIMO becomes a hot issue.

There are generally two main aims in cooperative MIMO cognitive networks, larger capacity and lower bit error rate (BER). Recently, a scheme for optimal power allocation to maximize the secondary throughput in a MIMO cognitive network was proposed in [10]. Furthermore, in [11], the paper has studied both bandwidth and power allocation to maximize the sum rate of an overlay CR system assisted with multiple antennas two-way relays in which PUs cooperate with SUs for mutual benefits [11]. Antenna selection is also a popular research area in MIMO cognitive networks. In [12], antenna selection is used to maximize the CR data rate, while it is designed to decrease the BER in [7, 8].

In this paper, we aim at proposing a cooperative spectrum access scheme for MIMO cognitive network to improve the spectral utilization. We apply the two-phase transmission protocol to our scheme. The design object is to maximize the transmission rate of the secondary system on the condition that the primary system can satisfy the rate constraint. On purpose of eliminating the co-channel interference, we apply ZFBF to construct the beamforming vector and power scaling factors. At last, we compare the transmission rate of secondary system with various parameters and estimate the performance with simulation results.

2 System Model

The system model of the MIMO cognitive network we considered is shown in Fig. 1. The whole system consists of two transmitter and receiver pairs which are PUs (PT and PR) and SUs (ST and SR). The PUs and the SUs share with the same spectrum and we assume the bandwidth is W. We assume that the secondary transmitter ST equipped with M ($M \geq 2$) antennas and other users equipped with a single antenna. The channels are flat Rayleigh fading channels and the Channel State Information (CSI) is perfectly obtained. In this model, let $\mathbf{h}_1$, $\mathbf{h}_2$, $\mathbf{h}_3$, h_d ($\mathbf{h_1}, \mathbf{h_2} \in \mathbb{C}^{1\times M}, \mathbf{h}_3 \in \mathbb{C}^{1\times M}$) represent the channel coefficients of ST $\rightarrow$ PR, ST $\rightarrow$ SR, PT $\rightarrow$ ST, PT $\rightarrow$ PR, respectively.

When there are no SUs, PT sends information directly to PR, the signal received by PR can be written as

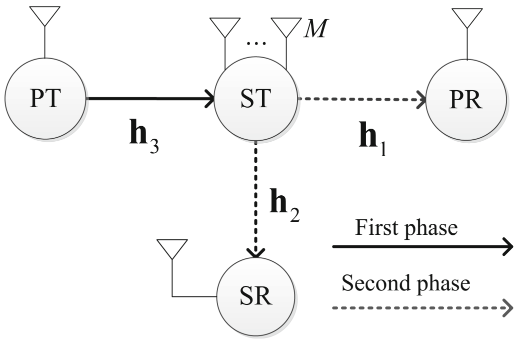

Fig. 1. The system model

$$r_d = \sqrt{P_p} h_d x_1 + n_d \tag{1}$$

where P_P is the transmission power of PT, x_1 is the transmitted symbol from PT, n_d is the complex addictive white Gaussian noise (AWGN) whose means is zero and variance is σ_d^2. Then the transmission rate of PT $\rightarrow$ PR can be written as

$$R_d = W \log_2(1 + \frac{P_P h_d^2}{\sigma_d^2}) \tag{2}$$

We assume that the secondary system gets a chance to access the spectrum when the transmission rate of primary system cannot reach the target rate R_T. But only when the secondary system can assist primary system to reach the target rate, it can really have access to the spectrum. In this paper, we divide the transmission time into two equal time phases. In the first phase, PT transmits signals to ST, the signal received by ST can be written as

$$\mathbf{r_3} = \sqrt{P_P} \mathbf{h}_3 x_1 + \mathbf{n}_3 \tag{3}$$

where $\mathbf{n}_3$ is the complex addictive white Gaussian noise and $E(\mathbf{n}_3, \mathbf{n}_3^{\mathrm{H}}) = \sigma_3^2 \mathbf{I}_{\mathrm{M}}$. Then the transmission rate becomes

$$R_3 = \frac{1}{2} W \log_2(1 + \frac{||\mathbf{h}_3||^2 P_p}{\sigma_3^2}) \tag{4}$$

There is a coefficient of 1/2 because the first phase only possesses half of the transmission time.

In the second phase, as the dotted lines showed in Fig. 1, ST makes use of multi-antenna, on the one hand, forward signals to PR (assume that the received signal is perfectly decoded) and on the other hand, send self-information to ST at same time. Let $x_1, x_2, \mathbf{f}_1, \mathbf{f}_2$ ($\mathbf{f}_1, \mathbf{f}_2 \in \mathbb{C}^{M \times 1}$), and P_1, P_2 be the data symbols, beamforming weight vectors, and transmission power scaling factors respectively (ST $\rightarrow$ PR, ST $\rightarrow$ SR).

Define $\mathbf{x} = [x_1\ x_2]^{\mathrm{T}}$, $\mathbf{F} = [\mathbf{f}_1\ \ \mathbf{f}_2]$, $\mathbf{P} = diag\{p_1, p_2\}$, so that the transmitted signal $\mathbf{s}$ can be written as $\mathbf{s} = \mathbf{F}\mathbf{x}$, as a result, the received signals of PR and SR can be written respectively as

$$\mathbf{r}_{sp} = (\sqrt{P_1}\mathbf{h_1}\mathbf{f_1})x_1 + (\sqrt{P_2}\mathbf{h_1}\mathbf{f_2})x_2 + \mathbf{n_1} \tag{5}$$

$$\mathbf{r}_{ss} = (\sqrt{P_2}\mathbf{h_2}\mathbf{f_2})x_2 + (\sqrt{P_1}\mathbf{h_2}\mathbf{f}_1)x_1 + \mathbf{n_2} \tag{6}$$

where $\mathbf{n}_i$ is the complex addictive white Gaussian noise and $E(\mathbf{n}_i, \mathbf{n}_i^{\mathrm{H}}) = \sigma_i^2\mathbf{I}_M$. Hence the transmission rate of ST → PR and ST → SR can be written respectively as

$$R_1 = \frac{1}{2}W\log_2(1 + \frac{P_1|\mathbf{h_1}\mathbf{f_1}|^2}{P_2|\mathbf{h_1}\mathbf{f_2}|^2 + \sigma_1^2}) \tag{7}$$

$$R_S = R_2 = \frac{1}{2}W\log_2(1 + \frac{P_2|\mathbf{h_2}\mathbf{f_2}|^2}{P_1|\mathbf{h_2}\mathbf{f}_1|^2 + \sigma_2^2}) \tag{8}$$

subject to the power constraint $P_1||\mathbf{f_1}||^2 + P_2||\mathbf{f_2}||^2 \le P_S$. Where R_S is the transmission rate of secondary system, after the two phases, the transmission rate of primary system can be written as

$$R_P = \min\{R_1, R_3\} \tag{9}$$

The reason of taking the minimum is that the capacity of the primary system is limited to the worse link between PT → ST and ST → PR.

Finally, the problem can be concluded that design the beamforming vector $\mathbf{F}$ and the transmission power scaling factors P_1 and P_2 to maximize the transmission rate of secondary system after ST assists the primary system to reach the target rate.

3 Parameters Design Based on ZFBF

We make the beamforming weight vector of one user i be orthogonal to the channel vector of any other user k according to the design of ZFBF to eliminate the interference of other users in the same channels, that is, we select the beamforming weight vector satisfied the condition $\mathbf{h}_i\mathbf{j}_k = 0,\ \forall i \ne k$ [15]. Then we let $\mathbf{H} = [\mathbf{h_1^{\mathrm{H}}}\ \ \mathbf{h_2^{\mathrm{H}}}]^{\mathrm{H}}$, one easy choice of the beamforming weight matrix $\mathbf{F}$ is the pseudoinverse of the $\mathbf{H}$

$$\mathbf{F} = \mathbf{H}^{\dagger} = \mathbf{H}^{\mathrm{H}}(\mathbf{H}\mathbf{H}^{\mathrm{H}})^{-1} \tag{10}$$

where $\mathbf{F} = [\mathbf{f}_1\ \ \mathbf{f}_2]$. Bring $\mathbf{f}_1$, $\mathbf{f}_2$ into (7), (8) respectively, we have

$$R_1 = \frac{1}{2}W\log_2(1 + \frac{P_1}{\sigma_1^2}) \tag{11}$$

$$R_S = R_2 = \frac{1}{2} W \log_2(1 + \frac{P_2}{\sigma_2^2}) \tag{12}$$

subject to $P_1||\mathbf{f}_1||^2 + P_2||\mathbf{f}_2||^2 \leq P_S$.

Next we just design the power scaling factors to maximize the transmission rate of secondary system satisfied the condition that the transmission rate of primary system reach the target. That is, we have

$$\max_{P_1} R_S \tag{13}$$

subject to

$$\begin{cases} R_1 \geq R_T \\ R_3 \geq R_T \\ P_1||\mathbf{f}_1||^2 + P_2||\mathbf{f}_2||^2 = P_S \end{cases} \tag{14}$$

Bring $P_1 = \frac{P_S - P_2||\mathbf{f}_2||^2}{||\mathbf{f}_1||^2}$ into R_1, we can get

$$\frac{1}{2} W \log_2(1 + \frac{P_S - P_2||\mathbf{f}_2||^2}{||\mathbf{f}_1||^2 \sigma_1^2}) \geq R_T \tag{15}$$

$$P_2 \leq \frac{P_S - (2^{\frac{2R_T}{W}} - 1)||\mathbf{f}_1||^2 \sigma_1^2}{||\mathbf{f}_2||^2} \tag{16}$$

It's obvious that R_S monotonically increases with the increase of P_2 according to (14). Thus we choose the maximum value of P_2 as the optimal solution which can be written as

$$P_2^* = \frac{P_S - (2^{\frac{2R_T}{W}} - 1)||\mathbf{f}_1||^2 \sigma_1^2}{||\mathbf{f}_2||^2} \tag{17}$$

Finally, we can get the maximum rate of R_S which can be written as

$$R_{s\max} = \frac{1}{2} W \log_2(1 + \frac{P_s - \left(2^{\frac{2R_T}{W}} - 1\right)||\mathbf{f}_1||^2 \sigma_1^2}{||\mathbf{f}_2||^2 \sigma_2^2}) \tag{18}$$

4 Simulation Result

In this section, we analyze the result of the proposed scheme with different parameters. For simplicity, we assume that PT, PR, ST and SR are on a same 2-D coordinate diagram. We let PT, PR, SR lie on the same line. PT and PR are located on (0, 0) and

(1, 0) respectively, ST moved between PT and PR. Define that the distance PT → ST on the coordinate diagram is d, that is, the coordinate of ST is (d, 0). Thus the distance ST → PR is $1 - d$. Assume that the distance between ST and SR is half of that between ST and PR. So we set the coordinate of SR to be (d, 0.5(1 − d)). In our simulation, we assume that the path-loss exponent ν is −3, the licensed spectrum bandwidth W is 1, all noise variance σ^2 are 1, the power of PT P_T is 8 dB and the power of ST P_S is 10 dB.

Figure 2 shows the transmission rate of the secondary system with various R_T versus the different position of ST when ST equipped with 4 antennas. As is shown, $R_s = 0$ when $R_T = 3$bps/Hz and $d < 0.14$. It indicates that when ST is far away from PR, the SNR of the link ST → PR is bad and R_1 cannot reach the target rate R_T. So the secondary system cannot access the spectrum and have no rate. With ST getting close to PR, the SNR of the link ST → PR is getting better and both R_1 and R_3 can achieve the target rate, then the secondary system can access to the spectrum. And the rate of secondary system is increasing for the SNR of the link ST → SR is getting better. When $d > 0.74$, $R_S = 0$ again since the SNR of the link PR → ST is bad and R_3 cannot achieve target rate R_T. The Fig. 2 also indicates that the access range is smaller when R_T increases to 3.5bps/Hz. That's because it makes high demands of the SNR for both of the link PT → ST and ST → PR. Also the power scaling factor of P_1 increases with the increase of R_T. Obviously, another power scaling factor P_2 will decrease which makes the rate of secondary system decrease correspondingly.

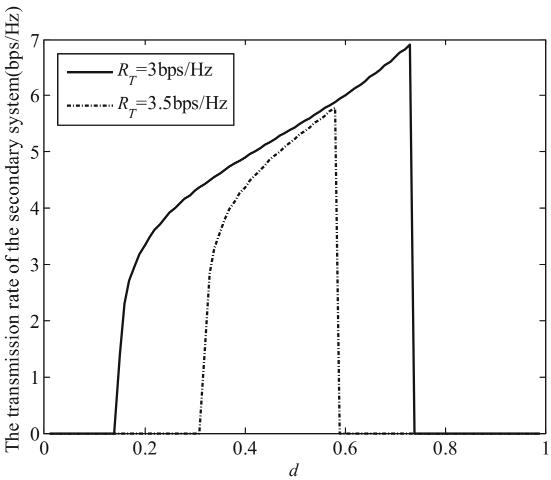

Fig. 2. The rate of secondary system with various R_T versus different position of ST

Figure 3 describes the transmission rate of the secondary system with various M versus different position of ST when $R_T = 3$ bps/Hz. As we can observe from the figure, both of the rate and the access range of the secondary system are increasing with the increase number of ST's antennas. It's because increasing the number of antennas can improve the channel capacity while keeping the SNR and the bandwidth unchanged. That is, the secondary system can reach the R_T with large number of antennas even when the SNR is worse. Then the access range increases to $0.14 < d < 0.74$ and $0 < d < 0.94$ with $M = 4$ and $M = 8$ respectively. Obviously, the rate of the secondary system increases with the capacity of the whole system when the R_T is unchanged.

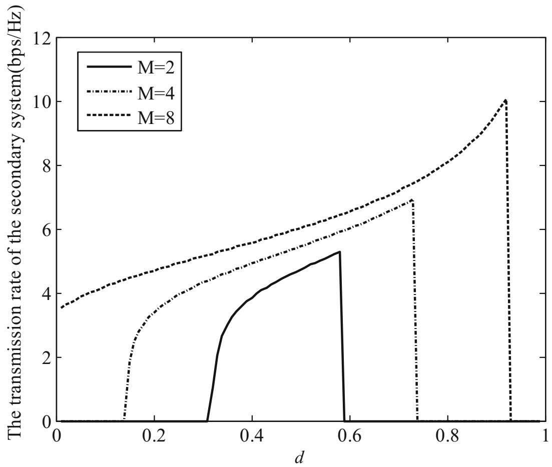

Fig. 3. The rate of secondary system with various M versus different position of ST

In Fig. 4, we set $R_T = 3$bps/Hz and fix ST in the middle of PT and PR, i.e. $d = 0.5$. Figure 4 shows the transmission rate of the secondary system versus the P_S increasing from 5 dB to 25 dB, respectively, with various M. As we can observe, the rate

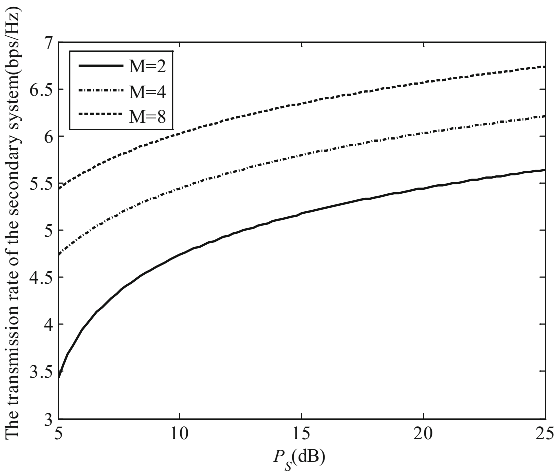

Fig. 4. The rate of secondary system with various M versus different P_S

increases with the increase of P_S. For the position of ST and the value of R_T are fixed, the channel coefficient matrix is considered to be unchanged in our model. Thus the power scaling factor P_1 is unchanged and P_2 increases with the P_S relatively. Also the curve trend corresponds to the relationship between SNR and the channel capacity. Obviously, the rate increase with the M same as Fig. 3 shows.

5 Conclusion

To enhance the spectral utilization, we proposed a cooperative spectrum access scheme in flat fading channel for MIMO cognitive networks where the secondary transmitter ST equipped with multi-antenna. We derived the two-phase transmission protocol in our model to guarantee the service of PUs and the ZFBF to eliminate the co-channel interference between ST $\rightarrow$ PR and ST $\rightarrow$ SR. The results show that the scheme evidently improves the spectral utilization and achieves a win-win result. Note that increasing the antennas can obtain more gain.

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