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SINR-balancing based cooperative spectrum sharing scheme for MIMO cognitive radio systems①

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Abstract

In order to improve the system capacity of the primary user (PU) and secondary user (SU) of multiple-input-multiple-output (MIMO) cognitive radio (CR) system, a signal to interference plus noise ratio balancing (SINR-balancing) based cooperative spectrum sharing (CSS) scheme is proposed, in which PU leases a fraction of its transmission time to SU in exchange for the SU relaying the PU's data cooperatively. The SINR-balancing based corresponding beamforming vectors are designed and time-division is also optimized for the proposed scheme. Simulation results show that compared to conventional opportunistic spectrum sharing (OSS) scheme, the proposed CSS scheme can effectively enhance the system performance of both PU and SU and provide an effective cooperation mechanism for PU and SU to determine whether to request cooperation.

Key words: cognitive radio(CR), multiple-input-multiple-output(MIMO), beamforming, cooperative relay, balance

0 Introduction

Due to the explosive growth in wireless services and applications in the last decade, the available spectrum resources become more and more scarce. Recently, cognitive radio (CR) in Ref. [1] has gained significant attention as a promising technology for the future wireless networks due to its potential ability to provide highly efficient spectrum utilization while allowing secondary users (SUs) to coexist with primary users (PUs). The idea of CR was first proposed for the scenario in which SU can opportunistically access the PU's licensed bands only when the spectrum holes are detected, which mainly focus on time and/or frequency domains. However, when service load of PU is high and spectrum holes are quite limited, SU can hardly get opportunity to transmit. Wireless transmissions via multiple transmit antennas and multiple receive antennas, or the so-called multiple-input multiple-output (MIMO) transmissions, have received considerable attention during the past decade. Naturally, the potential of (MIMO CR) was anticipated in Ref. [2] for its additional spatial degrees of freedom (DOF), which brings more flexibility and performance gain. Generally speaking, multi-antennas can be used to allocate transmit dimensions in space and hence provide the secondary transmitter in a CR network more degrees of freedom in addition to time and frequency so as to balance between maximizing its own transmit rate and minimizing the interference powers at the primary receivers, which have gained explosive studies[3-7].

In the early pioneer work[3], MIMO was introduced into the CR system, and the algorithm is based on the singular-value decomposition (SVD) of the secondary MIMO channel after the projection into the null space of the channel from the secondary transmitter to the primary receivers (thereby removing completely the interference at all primary receivers). Based on the idea of opportunistic interference alignment (OIA) in Ref. [4], the SU can further fully explore the spatial DOF without interfering the PU's transmission. For the MIMO CR downlink multiuser system, the linear precoding designs are given in Ref. [5]. However, the above schemes are essentially exploring the spatial spectrum holes, which are to transmit in the dimension orthogonal to the interfering channel of the PU, thus limited to the spatial dimension. Some work relaxes the restricted condition and design transmission schemes under the condition of interference less than a certain threshold. The SU's performance is optimized based on the PU's rate constraint in Ref. [6]. However, it is assumed that the SU transmitter knows channel state

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information (CSI) of all links, that is not true due to the fact that the PU is not compulsory to share its related CSI.

In this paper, the cooperative spectrum sharing (CSS) scheme is studied based on the following observation: when the PU's link is relatively weak, it needs longer time to finish its load transmission; at the same time, the SU's performance is rather limited due to the limited spatial DOF and time/frequency spectrum holes. Under this condition, PU may have the motivation to lease its partial spectrum resource to exchange for SU's collaboration, and SU can also gain more transmission opportunities by collaboratively relaying the PU's information. There have been some works on the cooperative spectrum sharing schemes[7-10], in which the frequency and power resource allocation problem under the single-antenna scenario is mainly considered. In this paper, a beamforming based cooperative spectrum sharing scheme for MIMO cognitive radio systems is proposed, in which PU leases partial transmission time to SU, and SU can have an opportunity to transmit its information while relaying the PU's information at the same time. In the scheme, PU can optimize the slot allocation to maximize its performance, while SU will give the beamforming vectors design based on signal to interference plus noise ratio balancing (SINR-Balancing) to guarantee the performance of PU and SU at the same time. The simulation results show that compared to the conventional opportunistic spectrum sharing (OSS) schemes, the proposed cooperative spectrum sharing scheme effectively enhances the overall system performance.

The paper is organized as follows. The system model and the transmission scheme are introduced in Section 1. In Section 2, the conventional scheme is first given, then the proposed cooperative spectrum sharing scheme is described. In Section 3, simulation results are presented to illustrate the proposed algorithm. Section 4 concludes the paper.

1 System model

This paper considers a MIMO cognitive radio network consisting of a primary transmitter - receiver pair and a secondary base station- receiver pair, in which ST has the cognitive capability. This paper considers the scenario where multiple antennas are equipped at the PU transmitter (PT) and SU transmitter (ST), with M_P and M_S antennas respectively, while the PU receiver (PR) and SU receiver (SR) are configured with single antenna (for practical communication system, the counterpart of the transmitter can be the base-station, while the receiver can be the user equipment). For comparison, the conventional spectrum sharing model is presented first, as shown in Fig. 1(a), where the PT and ST transmit at the same time. For the proposed cooperative spectrum sharing scheme, a half-duplex division frame structure with decode-and-forward (DF) relay mode is considered, in which the transmission period of each frame is divided into two slots and the fraction of time used in the first and second slots are accordingly denoted as α and $1-\alpha(0<\alpha<1)$, respectively, as shown in Fig. 1(b). During the first slot α, PT transmits signal to PR, and the signal is received and decoded at the ST as well. In the second slot $1-\alpha$, PT keeps silent, while ST transmits its own signal to SR and forwards the PT's signal to PR.

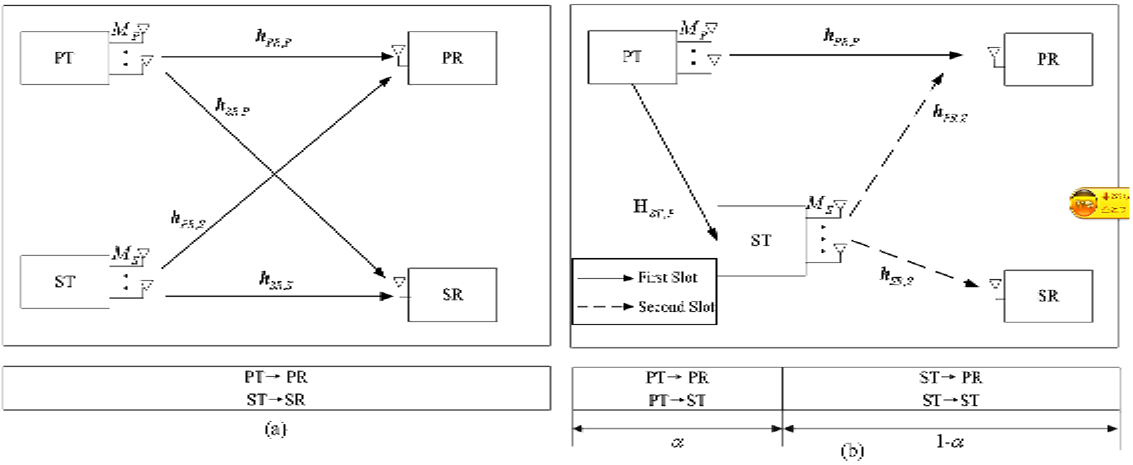

Fig. 1 System model

In the first slot, PT transmits signal x_P multiplied by the beamforming vector $\boldsymbol{w}_P$, in which $E[x_P x_P^H]=1$ and $\mathrm{Tr}\{\boldsymbol{w}_P^H \boldsymbol{w}_P\}=1$ are to be satisfied for total power normalization. The received signal at PR, ST in the first slot can be expressed as

$$\begin{aligned} y_{PR} &= \sqrt{\frac{P_{PU}}{\alpha}}\mathbf{h}_{PR,P}\mathbf{w}_P x_P + n_{PR} \\ \mathbf{y}_{ST} &= \sqrt{\frac{P_{PU}}{\alpha}}\mathbf{H}_{ST,P}\mathbf{w}_P x_P + \mathbf{n}_{ST} \end{aligned} \qquad (1)$$

where $\sqrt{\frac{P_{PU}}{\alpha}}$ denotes the transmit power resulting in equal power consumption in one transmission period compared to conventional model and $\mathbf{h}_{PR,P} \in \mathbb{C}^{1\times M_P}$ denotes the channel from the PT to PR with each element being i. i. d. complex Gaussian variable and follows the distribution as $\mathbf{h}_{PR,P} \sim CN(0, d_{PR,PT}^{-n_0}\mathbf{I})$. Accordingly, the channel from PT to ST is denoted as $\mathbf{H}_{ST,P} \sim CN(0, d_{ST,PT}^{-n_0}\mathbf{I})$. n_0 denotes the path-loss factor, $d_{PR,PT}$ denotes the distance between PT and PR, while $d_{ST,PT}$ denotes the distance between PT and ST. n_{PR}, $\mathbf{n}_{ST}$ denotes the noise vector at the receiver PR and ST respectively, which follows the distribution as $CN(0,\mathbf{I})$. Then the achievable rate of the relay linking from PT to ST in the first slot can be expressed as

$$R_{S,P} = \alpha \log_2\left|\mathbf{I} + \frac{P_{PU}}{\alpha}\mathbf{H}_{ST,P}\mathbf{w}_P\mathbf{w}_P^H\mathbf{H}_{ST,P}^H\right| \qquad (2)$$

Signal x_P for PU is first decoded at ST, then ST designs the beamforming vectors of $\mathbf{w}_{PR,S}$, $\mathbf{w}_{SR,S}$ and allocates the power $P_{SU,P}$, $P_{SU,S}$ for the PU's signal x_P and SU's signal x_S respectively, in which $E[x_S x_S^H] = 1$ and total power constraint is given as

$$\begin{aligned} &\mathrm{Tr}\{\mathbf{w}_{PR,S}^H\mathbf{w}_{PR,S}\} = 1,\ \mathrm{Tr}\{\mathbf{w}_{SR,S}^H\mathbf{w}_{SR,S}\} = 1 \\ &P_{SU,P} + P_{SU,S} \leqslant P_{SU}/(1-\alpha) \end{aligned} \qquad (3)$$

In the second slot, the received signal at PR and SR can be expressed as

$$\begin{aligned} y_{PR} &= \mathbf{h}_{PR,S}(\sqrt{P_{SU,P}}\mathbf{w}_{PR,S}x_P + \sqrt{P_{SU,S}}\mathbf{w}_{SR,S}x_S) + n_{PR} \\ y_{SR} &= \mathbf{h}_{SR,S}(\sqrt{P_{SU,P}}\mathbf{w}_{PR,S}x_P + \sqrt{P_{SU,S}}\mathbf{w}_{SR,S}x_S) + n_{SR} \end{aligned} \qquad (4)$$

where $\mathbf{h}_{PR,S} \sim CN(0, d_{PR,ST}^{-n_0}\mathbf{I})$ and $\mathbf{h}_{SR,S} \sim CN(0, d_{SR,ST}^{-n_0}\mathbf{I})$ denote the channel from ST to PR and SR, respectively. Similarly, $d_{PR,ST}$ denotes the distance between ST and PR, while $d_{SR,ST}$ denotes the distance between ST and SR, n_{SR} denotes the noise vector at the receiver SR with $n_{SR} \sim CN(0,1)$. Since cooperative spectrum sharing is considered in this paper, the default precondition is that the PT-PR link is weak or the PT-ST link is relatively more reliable, thus $d_{ST,PT} < d_{PR,PT}$ is reasonably assumed. The SINR at the PR in the second slot is calculated as

$$\gamma_{PU,CSS} = \frac{P_{SU,P}|\mathbf{h}_{PR,S}\mathbf{w}_{PR,S}|^2}{1 + P_{SU,S}|\mathbf{h}_{PR,S}\mathbf{w}_{SR,S}|^2} \qquad (5)$$

Then the achievable rate of the ST-PR link in the second slot is given by

$$R_{P,S} = (1-\alpha)\log_2(1 + \gamma_{PU,CSS}) \qquad (6)$$

Then PU's achievable rate is given by $R_{PU,CSS} = \min\{R_{S,P}, R_{P,S}\}$. The SINR at the SR is denoted as

$$\gamma_{SU,CSS} = \frac{P_{SU,S}|\mathbf{h}_{SR,S}\mathbf{w}_{SR,S}|^2}{1 + P_{SU,P}|\mathbf{h}_{SR,S}\mathbf{w}_{PR,S}|^2} \qquad (7)$$

Correspondingly, the SU's achievable rate is given by

$$R_{SU,CSS} = (1-\alpha)\log_2(1 + \gamma_{SU,CSS}) \qquad (8)$$

In this paper, it is assumed that PT knows $\mathbf{h}_{PR,P}$, and ST knows $\mathbf{h}_{SR,S}$ due to the nature of channel reciprocity[3-6]. Further, PT and ST can share partial channel information under the mode of cooperative spectrum sharing, and thus PT knows $\mathbf{H}_{ST,P}$ while ST gets the rate requirement information of PU, based on which the beamforming vectors $\mathbf{w}_P$, $\mathbf{w}_{PR,S}$, $\mathbf{w}_{SR,S}$ are designed as the following section.

2 Cooperative spectrum sharing scheme design

2.1 Conventional opportunistic spectrum sharing

For comparison, in this subsection we first give the beamforming design for the scheme of conventional opportunistic spectrum sharing[3-5], in which the PU neglects the existence of SU and maximizes the achievable rate of the direct PT-PR link, while SU should generate zero-interference to PR. Apparently, the PU will take the maximum ratio transmission (MRT) scheme to maximize its own data rate, accordingly the beamforming vector is denoted as

$$\mathbf{w}_{P,OSS} = \frac{\mathbf{h}_{PR,P}^H}{\|\mathbf{h}_{PR,P}\|} \qquad (9)$$

Thus the PU's achievable rate is given as

$$\begin{aligned} R_{PU,OSS} &= \log_2(1 + P_{PU}\|\mathbf{h}_{PR,P}\mathbf{w}_{P,OSS}\|_F^2) \\ &= \log_2(1 + P_{PU}\|\mathbf{h}_{PR,P}\|_F^2) \end{aligned} \qquad (10)$$

The beamforming design criterion of SU is to maximize its own data rate while generating no interference to PR. According to the matrix projection theory[3,11], the beamforming vector of SU is expressed as

$$\mathbf{w}_{S,OSS} = \frac{\mathbf{P}_{SU}^{\perp}\mathbf{h}_{SR,S}^H}{\|\mathbf{P}_{SU}^{\perp}\mathbf{h}_{SR,S}^H\|} \qquad (11)$$

where $\mathbf{P}_{SU}^{\perp} = (\mathbf{I} - \mathbf{h}_{PR,S}^H(\mathbf{h}_{PR,S}\mathbf{h}_{PR,S}^H)^{-1}\mathbf{h}_{PR,S})$. Then the SU's achievable rate is given as

$$R_{SU,OSS} = \log_2\left(1 + \frac{P_{SU}\|\mathbf{h}_{SR,S}\mathbf{w}_{S,OSS}\|_F^2}{P_{PU}\|\mathbf{h}_{SR,P}\mathbf{w}_{P,OSS}\|_F^2}\right) \qquad (12)$$

2.2 Cooperative spectrum sharing

Since the direct PT-PR link is relatively weak, and the optimization of time division may result in unequal duration of two slots, it is not practical for PR to take the maximum ratio combining (MRC) algorithm. Thus for simplicity, receiver PR will only decode the signal from ST in the second slot. Accordingly, in the first slot the PT will take the transmission scheme of maximizing the achievable rate of relay link of PT-ST. Let $\boldsymbol{H}_{ST,P} = \boldsymbol{U}_{ST,P}\boldsymbol{\Lambda}_{ST,P}\boldsymbol{V}_{ST,P}^{H}$ be the SVD of the relay link, where $\boldsymbol{\Lambda}_{ST,P} = \mathrm{diag}(\lambda_1, \cdots, \lambda_{M_P})$ is a diagonal matrix with descending ordered singular value. Then the beamforming vector at the PT is denoted as $\boldsymbol{w}_{P,OSS} = \boldsymbol{v}_{\max}$, where $\boldsymbol{v}_{\max}$ is the right singular vector corresponding to the maximum singular value. The achievable rate of the relay link PT-ST is given as

$$R_{S,P} = \alpha \log_2 \left| \boldsymbol{I} + \frac{P_{PU}}{\alpha} \boldsymbol{H}_{ST,P} \boldsymbol{w}_{P,OSS} \boldsymbol{w}_{P,OSS}^{H} \boldsymbol{H}_{ST,P}^{H} \right|$$
$$\overset{det(I+AB)=det(I+BA)}{=} \alpha \log_2 \left(1 + \frac{P_{PU}\lambda_1^2}{\alpha} \right) \qquad (13)$$

In the second slot, it's a typical multiuser MIMO downlink system for ST according to Eqs (6) and (8), for which the available precoding schemes such as dirty-paper coding (DPC) and zero-forcing (ZF) can be used to solve the problem. However, although the sum-rate can be maximized through DPC, it is complexity prohibitive for practical implementation, while ZF cannot fully explore the spatial DOF and is prone to be limited by the number of antennas. In this paper, we will still consider linear beamforming vector design and guarantee that the cooperation will not degenerate the performance of PU and SU compared to OSS scheme.

According to Eqs (6) (10) and the constraint of $R_{P,S} \geqslant R_{PU,OSS}$, we have

$$(1-\alpha)\log_2(1+\gamma_{PU,CSS}) \geqslant \log_2(1+P_{PU}\,\|\boldsymbol{h}_{PR,P}\|_F^2)$$
$$\Rightarrow \gamma_{PU,CSS} \geqslant \gamma_{PU,\,tar} = (1+P_{PU}\,\|\boldsymbol{h}_{PR,P}\|_F^2)^{\frac{1}{1-\alpha}} - 1 \qquad (14)$$

Considering the sufficiency of cooperation condition, the cooperation should not degenerate the SU's performance, thus $R_{SU,CSS} \geqslant R_{SU,OSS}$ should be satisfied. According to equation and , we have

$$(1-\alpha)\log_2(1+\gamma_{SU,CSS})$$
$$\geqslant \log_2\left(1 + \frac{P_{SU}\,\|\boldsymbol{h}_{SR,S}\boldsymbol{w}_{S,OSS}\|_F^2}{P_{PU}\,\|\boldsymbol{h}_{SR,P}\boldsymbol{w}_{P,OSS}\|_F^2}\right)$$
$$\Rightarrow \gamma_{SU,CSS} \geqslant \gamma_{SU,\,tar} = \left(1 + \frac{P_{SU}\,\|\boldsymbol{h}_{SR,S}\boldsymbol{w}_{S,OSS}\|_F^2}{P_{PU}\,\|\boldsymbol{h}_{SR,P}\boldsymbol{w}_{P,OSS}\|_F^2}\right)^{\frac{1}{1-\alpha}} - 1 \qquad (15)$$

Based on Eqs (14) and (15), the system can be regarded as a typical downlink scenario, where users must achieve individual target SINRs for successful communication and fairness guaranteed. Thus the problem of beamforming vectors design and power allocation can be transformed into SINR balancing problem as

$$\max_{P_{SU,P},P_{SU,S},\boldsymbol{w}_{SR,S},\boldsymbol{w}_{PR,S}} \min\left(\frac{\gamma_{PU,CSS}}{\gamma_{PU,\,tar}}, \frac{\gamma_{SU,CSS}}{\gamma_{SU,\,tar}}\right) \qquad (16)$$
$$\text{s. t.} \quad P_{SU,P} + P_{SU,S} \leqslant P_{SU}/(1-\alpha)$$

Note that the problem can be solved by using uplink-downlink duality iteratively[12], which is omitted here for simplification. According to *Lemma* 1 in Ref. [12], the optimal solution of problem satisfies

$$\frac{\gamma_{PU,CSS}}{\gamma_{PU,\,tar}} = \frac{\gamma_{SU,CSS}}{\gamma_{SU,\,tar}} = \lambda \qquad (17)$$
$$P_{SU,P} + P_{SU,S} = P_{SU}/(1-\alpha)$$

From Eq. (17), we can see that when $\lambda > 1$ the PU's performance and SU's performance in the CSS mode will outperform the corresponding performance in the OSS mode. While when $\lambda < 1$ both the performance of PU and SU are degenerated, certainly neither PU nor SU will request cooperation. Thus, the proposed SINR-balancing based beamforming design provides an effective cooperation mechanism or guideline for PU and SU to determine whether to request cooperation.

As for PU, there also exists a time-division optimization problem to optimize its own performance, which is expressed as

$$\max_{\alpha}\left\{\alpha\log_2\left(1+\frac{P_{PU}\lambda_1^2}{\alpha}\right), (1-\alpha)\log_2(1+\gamma_{PU,CSS})\right\} \qquad (18)$$

Since α is a real value between 0 and 1, it can be easily found through one-dimension linear search. The proposed scheme can be summarized as follows: Step 1, PU or SU request cooperation, and then partial CSI can be exchanged. Step 2, for a given value of α, the PU's and SU's achievable rate can be obtained based on equation and. Step 3, PU can search the optimal time division value to maximize its own rate by iteratively calculating the achievable rate based on Step 2.

3 Simulation results

We now present numerical results for the PU and SU for the proposed CSS scheme and conventional OSS scheme as well for comparison. Since cooperative spectrum sharing is considered in this paper where $d_{ST,PT} < d_{PR,PT}$ is reasonably assumed, without loss of generality, we assume that ST is located between PT and PR, and define $SNR = P_{PU} = P_{SU}$ as the signal to noise ratio at the PT and ST. We first give the cooperative performance of PU and SU versus SNR with different antenna configuration and other parameters fixed as $d_{PR,PT} = 3$, $d_{ST,PT} = 1$, $d_{PR,ST} = 2$, $d_{SR,PT} = 1$, $d_{SR,ST} = 2$, simple time division $\alpha = 0.5$[11] and path-loss factor n_0

= 4. The achievable rate of PU and SU versus SNR is presented in Fig. 2 and Fig. 3 respectively with M_P = 1. As shown in Fig. 2 and Fig. 3, compared to the conventional OSS mode, in which the PU's performance is limited by the weak direct link while the SU's performance is limited by the interference from PU, the proposed CSS scheme can effectively enhance the performance of both PU and SU, and the performance gain increases as M_S increases. As SNR increases, to guarantee that the PU's performance in the CSS mode is always better than in the OSS mode, ST will allocate more power to PU's data, thus the SU's performance gaining in the CSS mode will drop, as shown in Fig. 3.

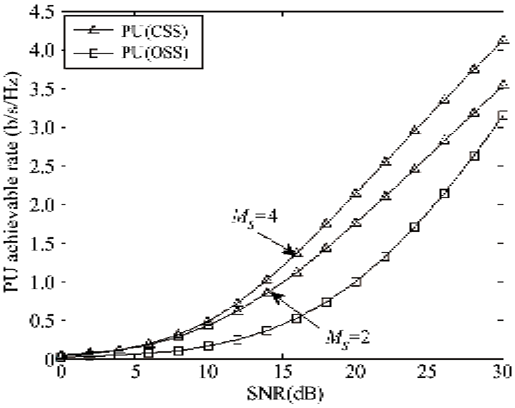

Fig. 2 Achievable rate vs. SNR, M_P = 1

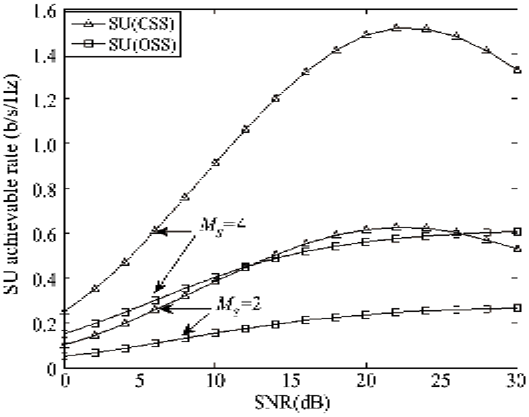

Fig. 3 Achievable rate vs. SNR, M_P = 1

The cooperative performance with $M_P > 1$ is further presented in Fig. 4. It is seen that when SNR is relatively low, the CSS scheme can still bring obvious performance gain. However, as SNR increases, limited by the spatial DOF of ST and loss of duty cycle due to time division, the cooperative performance of PU is worse than in the OSS mode, that is $\gamma_{PU,CSS} < \gamma_{PU,tar}$. Based on the SINR balancing in equation , the SU's cooperative performance is also worse than in the OSS mode, as shown in Fig. 4. As a result, when SNR is relatively high, neither PU nor SU will consider cooperation. As was expected, the proposed CCS scheme provides an effective cooperation mechanism for PU and SU to determine whether to request cooperation, which can also be referred as mode switch.

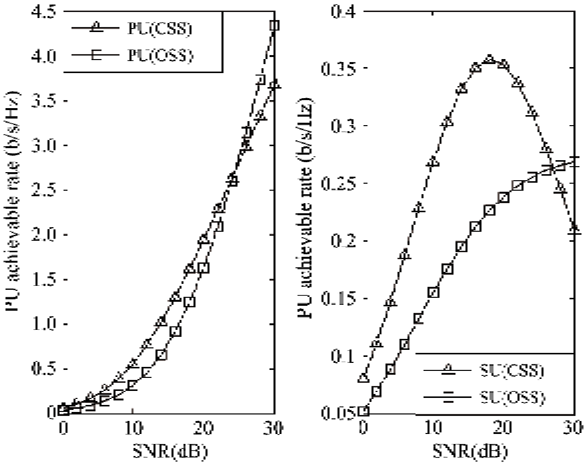

Fig. 4 Achievable rate vs. SNR, $M_P = M_S = 2$

Fig. 5 shows the cooperative performance versus $d_{ST,PT}$ with optimal time division α under a linear system topology as in Ref. [11], where ST is located between PT and PR while PT is located between ST and SR. Thus we have $d_{PR,PT} = d_{ST,PT} + d_{PR,ST}$ and $d_{SR,ST} = d_{PT,ST} + d_{SR,PT}$ with other parameters as $M_P = 2$, $M_S = 3$, $d_{PR,PT} = 3$, $d_{SR,PT} = 1$, $d_{SR,ST} = 2$, SNR = 14dB. Since the PU's performance is limited by the minimum achievable rate of PT-ST relay link and ST-PR cooperative link, according to the equation, there always exist an optimal $d_{ST,PT}$ to maximize PU's performance for each time division value α, as can be seen from Fig. 6, and vice versa. Apparently, compared to conventional OSS scheme, the proposed CSS scheme can effectively enhance the performance of both PU and SU. The performance with fixed time division α = 0.5 for

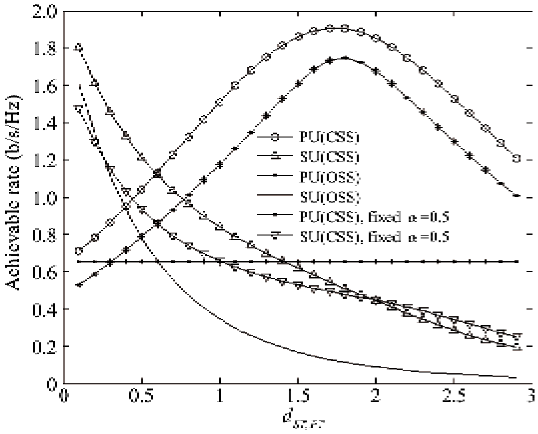

Fig. 5 Achievable rate vs. $d_{ST,PT}$

comparison in Fig. 6 is also given, from which we can see that with optimal α the PU's performance is further enhanced, while the SU's performance with optimal α is also better than the one with fixed $\alpha = 0.5$ in most of the range of $d_{ST, PT}$.

4 Conclusion

This paper proposes a SINR-based cooperative spectrum sharing scheme for MIMO cognitive radio systems, in which PU leases a fraction of its transmission time to SU in exchange for SU cooperatively relaying the PU's data. In the scheme, the SINR-balancing based corresponding beamforming vectors are designed and time-division is also optimized. Thus compared to conventional opportunistic spectrum sharing scheme, the proposed cooperative spectrum sharing scheme can effectively enhance the achievable rate of both PU and SU and provide an effective cooperation mechanism for PU and SU to determine whether to request cooperation. Future work in this direction can take into account the specific revenue models of PU and SU to establish incentive mechanism of cooperation and optimize the corresponding time-power allocation problem.

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