Multi-Mode Precoding Scheme Based on Interference Channel in MIMO-Based Cognitive Radio Networks

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***Abstract*—A precoding strategy is one of the representative interference management techniques in cognitive radio (CR) network which is a typical interference-limited environment. The interference minimization approach to precoding is an appropriate scheme to mitigate the interference efficiently while it may cause the capacity loss of the desired channel. The precoding scheme for the maximal capacity of the desired channel improves the capacity of the desired channel while it increases the interference power and finally causes the capacity loss of the interfered users. Therefore, we propose a precoding scheme which satisfies these two conflicting goals and manages the interference signal in such an interference-limited environment. The proposed scheme consists of two steps. First, the precoder nulls out the largest singular value of the interference channel to mitigate the dominant interference signal based on the interference minimization approach. Second, the transmitter calculates the sum capacities per mode and selects a mode to maximize the sum capacity. In the second step, each mode consists of the right singular vectors corresponding to the singular values except the largest singular value eliminated in the first step. Simulation results show that the proposed precoding scheme not only efficiently mitigate the interference signal, but also has the best performance in terms of the sum capacity in a MIMO-based CR network.**

***Index Terms*—Cognitive radio, spectrum-sharing, MIMO, multi-mode precoding, vitrual SINR**

I. Introduction

Multiple-input multiple output (MIMO)-based cognitive radio (CR) networks have been proposed in order to efficiently utilize radio spectrum which is a limited natural resource [1] [2] and satisfy the demand for high data rate multimedia wireless services [3]. Therefore the MIMO-based CR networks have recently received great attention [3] [4].

The spectrum-sharing environment of CR networks is a typical interference-limited system in which a precoding strategy is one of the representative interference management techniques [3] [4]. In spectrum-sharing environment of CR networks, the precoding techniques should deal with interference problem in advance. Simultaneously, it also provides the maximization of the sum capacity of all receivers.

In this paper, we propose an appropriate precoding scheme for MIMO-based CR networks. The interference minimization approach to precoding is appropriate scheme to mitigate the interference efficiently while it may cause the capacity loss of the desired channel. The precoding scheme for the maximal capacity of the desired channel improves the capacity of

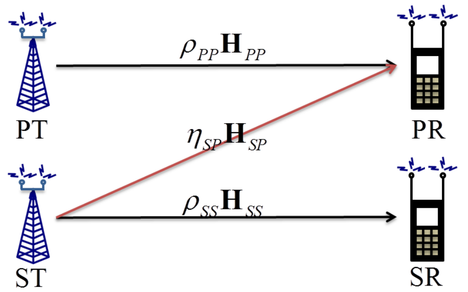

Fig. 1. System model for a MIMO-based CR network system.

desired channel while it increases the interference power and finally causes the capacity loss of the interfered users. Therefore, we propose a precoding scheme which satisfies these two conflicting goals and manages the interference signal in such an interference-limited environment. The proposed scheme is a multi-mode precoding technique based on the minimization of the interference channels. The proposed scheme consists of two steps. First, the precoder nulls out the largest singular value of the interference channel to mitigate the dominant interference signal based on the interference minimization approach. Second, the transmitter calculates the sum capacities per mode and selects a mode to maximize the sum capacity. In the second step, each mode consists of the right singular vectors corresponding to the singular values except the largest singular value eliminated in the first step. The virtual signal to interference plus noise ratio (SINR) consists of locally observed channel information [5], and the sum capacity can be calculated via the virtual SINR in a distributed way using the partial channel state information at the transmitter (CSIT) of the interference channel. The proposed precoding scheme can be implemented irrespective of the number of antennas at transmitters and receivers and improves the total throughput of a system which is the sum capacity in this paper in MIMO-based CR networks.

II. System Model and Conventional Schemes

A. System Model

We consider two transmitters, single primary receiver (PR) and secondary receiver (SR), and each transmitter or receiver has multiple antennas as shown in Fig. 1. The received signal vectors at the PR and the SR, $\mathbf{y}_P$ and $\mathbf{y}_S$, are given, respectively, as

$$\mathbf{y}_P = \frac{\sqrt{\rho_{PP}}\sqrt{P_{PT}}}{\sqrt{M_T}}\mathbf{H}_{PP}\mathbf{x}_P + \frac{\sqrt{\eta_{SP}}\sqrt{P_{ST}}}{\sqrt{M_T}}\mathbf{H}_{SP}\mathbf{x}_S + \mathbf{n}_P, \tag{1}$$

$$\mathbf{y}_S = \frac{\sqrt{\rho_{SS}}\sqrt{P_{ST}}}{\sqrt{M_T}}\mathbf{H}_{SS}\mathbf{x}_S + \mathbf{n}_S, \tag{2}$$

where M_T (M_R) is the number of transmit (receive) antennas and $\mathbf{H}_{PP}$, $\mathbf{H}_{SS}$ and $\mathbf{H}_{SP}$ are the $M_R \times M_T$ channel matrices between the primary transmitter (PT) and the PR, the secondary transmitter (ST) and the SR, and, the ST and the PR, respectively. These channels have complex entries which independently follow complex Gaussian distribution with zero mean and unit variance. ρ_{PP}, ρ_{SS} and η_{SP} are the channel gains for $\mathbf{H}_{PP}$, $\mathbf{H}_{SS}$ and $\mathbf{H}_{SP}$, respectively. P_{PT} (P_{ST}) is the transmit power of the PT (ST) and $\mathbf{x}_P$ ($\mathbf{x}_S$) is the transmitted signal vector for the PT (ST). We define a transmitted signal vector $\mathbf{x}_P$ ($\mathbf{x}_S$) as an information signal vector of the PT (ST) which has M_T independent Gaussian data streams with $E\left[\mathbf{x}_P\mathbf{x}_P^H\right] = \mathbf{I}_{M_T}$ ($E\left[\mathbf{x}_S\mathbf{x}_S^H\right] = \mathbf{I}_{M_T}$). $\mathbf{n}_P$ ($\mathbf{n}_S$) is an $M_R \times 1$ AWGN vector at the PR (SR) with variance of $N_0/2$ for each dimension.

The capacities of the PR and the SR with a precoding vector $\mathbf{w}$ at the ST, C_P and C_S, are given, respectively, as

$$C_P = \log_2 \det\left(\mathbf{I}_{M_R} + \frac{\rho_{PP}P_{PT}}{M_T}\mathbf{H}_{PP}\mathbf{H}_{PP}^H \cdot \left(\frac{\eta_{SP}P_{ST}}{\gamma_{\mathbf{w}}}\mathbf{H}_{SP}\mathbf{w}\mathbf{w}^H\mathbf{H}_{SP}^H + N_0\mathbf{I}_{M_R}\right)^{-1}\right), \tag{3}$$

$$C_S = \log_2 \det\left(\mathbf{I}_{M_R} + \frac{\rho_{SS}P_{ST}}{\gamma_{\mathbf{w}}}\frac{\mathbf{H}_{SS}\mathbf{w}\mathbf{w}^H\mathbf{H}_{SS}^H}{N_0}\right), \tag{4}$$

where $\gamma_{\mathbf{w}}$ is a normalization factor which is defined as $\gamma_{\mathbf{w}} \triangleq E\left[\|\mathbf{w}\cdot\mathbf{x}_S\|^2\right] = trace\left(\mathbf{w}\mathbf{w}^H\right)$.

It is assumed that the transmitters have locally observed information of the channels. The PT and the ST have information on the channels, $\mathbf{H}_{PP}$ and $\mathbf{H}_{SS}$, respectively. Also the ST knows the interference channels $\mathbf{H}_{SP}$ as in [3] [4] [6].

III. Distributed Multi-Mode Precoding Scheme Based on the Interference Minimization Approach

In this section, we proposed a precoding technique in CR networks. The proposed scheme is a multi-mode precoding technique based on the minimization of the interference channels. The proposed precoder maintains the ability to mitigate the interference via the interference minimization approach and guarantees the channel capacity of the desired user by the multi-mode precoder. The conventional multi-mode precoding scheme in [7] selects the singular value of the *desired channel* in descending order. However, the proposed multi-mode precoding scheme selects the singular value of the *interference channel* in ascending order.

In this section, in order to simplify the derivation of the proposed scheme, let us consider the number of receive antenna is equal to the number of transmit antenna, $M_R = M_T$.

A. Nulling Out the Largest Interference Based on Interference Minimization

This section introduces the first step to null out the largest singular value of the interference channel to mitigate the dominant interference signal based on the interference minimization approach in the proposed precoder. Under the assumption of the high SINR as in [8], (3) can be approximated as

$$\begin{aligned} C_P \approx\, & \log_2 \det\left(\frac{\rho_{PP}P_{PT}}{M_T}\mathbf{H}_{PP}\mathbf{H}_{PP}^H\right) \\ & \underbrace{-\log_2 \det\left(\frac{\eta_{SP}P_{ST}}{\gamma_{\mathbf{w}}}\mathbf{H}_{SP}\mathbf{w}\mathbf{w}^H\mathbf{H}_{SP}^H + N_0\mathbf{I}_{M_R}\right)}_{\alpha}. \end{aligned} \tag{5}$$

Maximization of C_P can be obtained by minimizing α in (5). Minimization of α can be obtained by letting the determinant component of α be zero since the logarithm function, $y = \log x$, is a monotonically increasing function for x which has the minimum value of -∞ at $x = 0$. The determinant term of α is given by

$$\det\underbrace{\left(\frac{\eta_{SP}P_{ST}}{\gamma_{\mathbf{w}}}\mathbf{H}_{SP}\mathbf{w}\mathbf{w}^H\mathbf{H}_{SP}^H + N_0\mathbf{I}_{M_R}\right)}_{\beta} = \widetilde{\sigma}_1^2\cdots\widetilde{\sigma}_{M_T}^2, \tag{6}$$

where $\widetilde{\sigma}_1^2, \ldots, \widetilde{\sigma}_{M_T}^2$ are the singular values of β since β is a symmetric matrix. To maximize C_P, at least one singular value should have zero among the singular values of β. To simplify the problem, let us assume that the high signal to noise ratio (SNR). The approach to the low SNR case is given in next paragraph. Then β can be approximated as $(\eta_{SP}P_{ST}/\gamma_{\mathbf{w}})\,\mathbf{H}_{SP}\mathbf{w}\mathbf{w}^H\mathbf{H}_{SP}^H$. Then the SVD of β is

$$\begin{aligned} k_I\mathbf{H}_{SP}\mathbf{w}\mathbf{w}^H\mathbf{H}_{SP}^H &= k_I\widetilde{\mathbf{U}}\widetilde{\mathbf{\Sigma}}\widetilde{\mathbf{V}}^H\cdot\widetilde{\mathbf{V}}\widetilde{\mathbf{\Sigma}}^H\widetilde{\mathbf{U}}^H \\ &= k_I\widetilde{\mathbf{U}}\widetilde{\mathbf{\Sigma}}\widetilde{\mathbf{\Sigma}}^H\widetilde{\mathbf{U}}^H \qquad (7) \\ &= \widetilde{\mathbf{U}}\cdot\begin{bmatrix} \widetilde{\sigma}_1^2 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \widetilde{\sigma}_{M_T}^2 \end{bmatrix}\cdot\widetilde{\mathbf{U}}^H, \qquad (8) \end{aligned}$$

where $\widetilde{\mathbf{U}}$, $\widetilde{\mathbf{\Sigma}}$ and $\widetilde{\mathbf{V}}$ are the SVD components of $\mathbf{H}_{SP}\mathbf{w}$ and $k_I = \eta_{SP}P_{ST}/\gamma_{\mathbf{w}}$. The SVD of the interference channel $\mathbf{H}_{SP}$ is given by

$$\begin{aligned} \mathbf{H}_{SP} &= \mathbf{U}_{SP}\mathbf{\Sigma}_{SP}\mathbf{V}_{SP}^H \\ &= [\mathbf{U}_1\cdots\mathbf{U}_{M_T}]\begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \sigma_{M_T} \end{bmatrix}\begin{bmatrix} \mathbf{V}_1^H \\ \vdots \\ \mathbf{V}_{M_T}^H \end{bmatrix} \\ &= \left[\sigma_1\mathbf{U}_1\mathbf{V}_1^H + \cdots + \sigma_{M_T}\mathbf{U}_{M_T}\mathbf{V}_{M_T}^H\right]. \end{aligned} \tag{9}$$

With the precoder $\mathbf{w}$ of $[\mathbf{V}_1, \ldots, \mathbf{V}_{k-1}, \mathbf{V}_{k+1}, \ldots, \mathbf{V}_{M_T}]$ for $1 \le k \le M_T$, we can make $\sigma_k\mathbf{U}_k\mathbf{V}_k^H$ of (9) a null matrix in the desired signal space, since $\mathbf{V}^H \cdot \mathbf{V}_j = \mathbf{0}$ for $i \neq j$ and $\mathbf{V}^H \cdot \mathbf{V}_j = 1$ for $i = j$. Then $\widetilde{\mathbf{\Sigma}}\widetilde{\mathbf{\Sigma}}^H$ of (7) is given by

$$\widetilde{\mathbf{\Sigma}}\widetilde{\mathbf{\Sigma}}^H = \mathrm{diag}\left(\sigma_1^2, ..., \sigma_{k-1}^2, \sigma_{k+1}^2, ..., \sigma_{M_T}^2, 0\right), \qquad (10)$$

for $1 \leq k \leq M_T$.

From (6), (7), (8) and (10), $\det(\beta) = \widetilde{\sigma}_1^2 \cdot \widetilde{\sigma}_2^2 \ldots \cdot \widetilde{\sigma}_{M_T}^2 = 0$. Therefore the proposed precoder can minimize the interference power by letting at least one singular value be zero.

However, at the low SNR, (6) can be expressed by

$$\begin{aligned} \det(\beta) &= \det\left(k_I \cdot \mathrm{diag}\left(\sigma_1^2, ..., \sigma_{M_T}^2\right) + N_0 \mathbf{I}_{M_R}\right) \\ &= \left(k_I \sigma_1^2 + N_0\right) \cdot \cdots \cdot \left(k_I \sigma_{M_T}^2 + N_0\right). \end{aligned} \qquad (11)$$

In order to minimize (11), we should null out the singular values as many as possible since the singular values are always positive values. However, as the number of the eliminated singular values by nulling out increases, the rank of the precoder decreases so that the number of data streams the ST can transmit also decreases. It can cause the capacity loss at the SR. Therefore, we utilize the virtual SINR to determine the number of singular values to eliminate by nulling out. That is, we compare the gain for the decreased interference power by nulling out the singular values with the loss of the desired channel capacity by the decreased data streams. But at least the largest one singular value should be zero to mitigate the dominant interference signal at low SNR and perfectly eliminate the interference signal at high SNR environment. In conclusion, the proposed rank-m precoder (which is called mode-m precoder in [7]) can be expressed by

$$\mathbf{w}_m = \left[\mathbf{V}_{M_T-m+1}, \mathbf{V}_{M_T-m+2}, \ldots, \mathbf{V}_{M_T}\right] \cdot \mathbf{B} \cdot \mathbf{P}_{WF}^{1/2}, \quad (12)$$

where $1 \leq m \leq M_T - 1$, $\mathbf{V}_j$ is the right singular vector of the interference channel $\mathbf{H}_{SP}$ for $1 \leq j \leq M_T$, $\mathbf{B}$ is the matrix composed of right singular vectors $\mathbf{H}_{SS} \cdot [\mathbf{V}_{M_T-m-1}, \mathbf{V}_{M_T-m+2}, \ldots, \mathbf{V}_{M_T}]$, and $\mathbf{P}_{WF}$ is the water-filling power allocation matrix.

B. Distributed Multi-Mode Precoding Scheme via Virtual SINR

This section introduces the second step to maximize the sum capacity in the proposed precoder after the first precoding step.

Given the locally observed information at the ST, [5] proposed a simple transmission scheme based on maximizing the virtual SINR-based capacity at the transmitter. The virtual SINR is defined as the ratio of the desired signal power received at the desired user to the sum of noise plus a weighted sum of the interference powers to the remaining users. In Fig. 1, the virtual SINR, $\gamma_{virtual}$, and the virtual SINR-based capacity, C_v, are given by

$$\gamma_{virtual} = \frac{\frac{\rho_{SS} P_{ST}}{\gamma_{\mathbf{w}}} \mathbf{H}_{SS} \mathbf{w}\mathbf{w}^H \mathbf{H}_{SS}^H}{\frac{\eta_{SP} P_{ST}}{\gamma_{\mathbf{w}}} \mathbf{H}_{SP} \mathbf{w}\mathbf{w}^H \mathbf{H}_{SP}^H + N_0 \mathbf{I}_{M_R}}, \qquad (13)$$

$$\begin{aligned} C_v &= \log_2 \det\left(\mathbf{I}_{M_R} + \gamma_{virtual}\right) \\ &= \log_2 \det\Bigg(\mathbf{I}_{M_R} + \frac{\rho_{SS} P_{ST}}{\gamma_{\mathbf{w}}} \mathbf{H}_{SS} \mathbf{w}\mathbf{w}^H \mathbf{H}_{SS}^H \\ &\qquad \cdot \left(\frac{\eta_{SP} P_{ST}}{\gamma_{\mathbf{w}}} \mathbf{H}_{SP} \mathbf{w}\mathbf{w}^H \mathbf{H}_{SP}^H + N_0 \mathbf{I}_{M_R}\right)^{-1}\Bigg), \end{aligned}$$

where $\gamma_{virtual}$ is the virtual SINR at the ST.

Let us assume that the received SINR is high, (3) and (4) can be approximated as

$$C_P \approx \log_2 \det\left(\frac{\frac{\rho_{PP} P_{PT}}{M_T} \mathbf{H}_{PP} \mathbf{H}_{PP}^H}{\frac{\eta_{SP} P_{ST}}{\gamma_{\mathbf{w}}} \mathbf{H}_{SP} \mathbf{w}\mathbf{w}^H \mathbf{H}_{SP}^H + N_0 \mathbf{I}_{M_R}}\right), \qquad (14)$$

$$C_S \approx \log_2 \det\left(\frac{\rho_{SS} P_{ST}}{\gamma_{\mathbf{w}}} \frac{\mathbf{H}_{SS} \mathbf{w}\mathbf{w}^H \mathbf{H}_{SS}^H}{N_0}\right), \qquad (15)$$

respectively. Then the sum capacity, C_{sr}, can be expressed as

$$\begin{aligned} C_{sr} &= C_P + C_S \\ &\approx \log_2 \det\left\{\left(\frac{k_P \|\mathbf{H}_{PP}\|^2}{k_I \|\mathbf{H}_{SP}\mathbf{w}\|^2 + N_0 \mathbf{I}}\right)\left(k_S \frac{\|\mathbf{H}_{SS}\mathbf{w}\|^2}{N_0}\right)\right\} \\ &= \log_2 \det\left\{\left(\frac{k_P \|\mathbf{H}_{PP}\|^2}{N_0}\right)\left(\frac{k_S \|\mathbf{H}_{SS}\mathbf{w}\|^2}{k_I \|\mathbf{H}_{SP}\mathbf{w}\|^2 + N_0 \mathbf{I}}\right)\right\} \\ &= \log_2 \det\left\{\left(\frac{k_P \|\mathbf{H}_{PP}\|^2}{N_0}\right) \cdot \gamma_{virtual}\right\}, \end{aligned} \qquad (16)$$

where $k_P = \rho_{PP} P_{PT}/M_T$, $k_I = \eta_{SP} P_{ST}/\gamma_{\mathbf{w}}$ and $k_S = \rho_{SS} P_{ST}/\gamma_{\mathbf{w}}$. Therefore, the maximum sum capacity can be achieved by maximizing the virtual SINR-based capacity such that we should select the precoder to have a maximum virtual SINR-based capacity.

After applying the precoding scheme based on the interference minimization in Section III.A, there are $M_T - 1$ kinds of available precoder (mode-$1, 2, \ldots, M_T - 1$) we can choose. In order to apply the multi-mode precoding scheme proposed in [7], which uses the mutual information of the desired channel, we have to define the mutual information, C_{UT}, as the virtual SINR-based capacity related information for the selection criteria in the proposed precoding scheme. Then the selection metric C_{UT} and the capacity based selection criterion can be expressed, respectively, by

$$\begin{aligned} C_{UT}(\mathbf{w}_M) &= \log_2 \det\Bigg(\mathbf{I}_M + \frac{\rho_{SS} P_{ST}}{\gamma_{\mathbf{w}}} \mathbf{w}_M^H \mathbf{H}_{SS}^H \mathbf{H}_{SS} \mathbf{w}_M \\ &\qquad \cdot \left(\frac{\eta_{SP} P_{ST}}{\gamma_{\mathbf{w}}} \mathbf{w}_M^H \mathbf{H}_{SP}^H \mathbf{H}_{SP} \mathbf{w}_M + N_0 \mathbf{I}\right)^{-1}\Bigg), \end{aligned} \qquad (17)$$

$$m' = \underset{1 \leq m \leq M_T - 1}{\arg\max}\; C_{UT}\left(\mathbf{w}_m\right). \qquad (18)$$

The mutual information per mode is obtained by (17). Given $M_T - 1$ mutual information per mode, the ST finally selects the mode corresponding to the largest mutual information, C_{UT}, as (18).

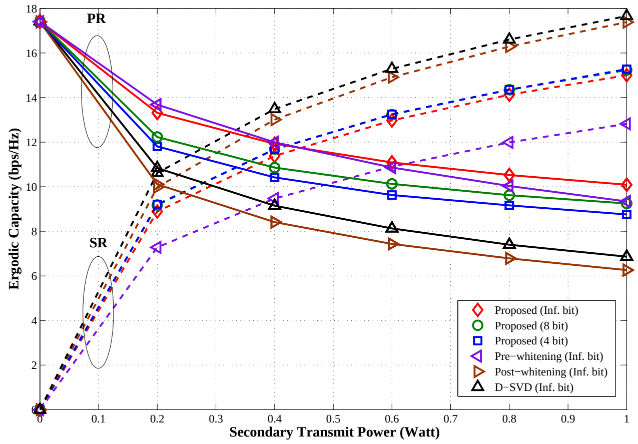

Fig. 2. Ergodic capacities for the various schemes when we vary P_{ST} at each receiver.

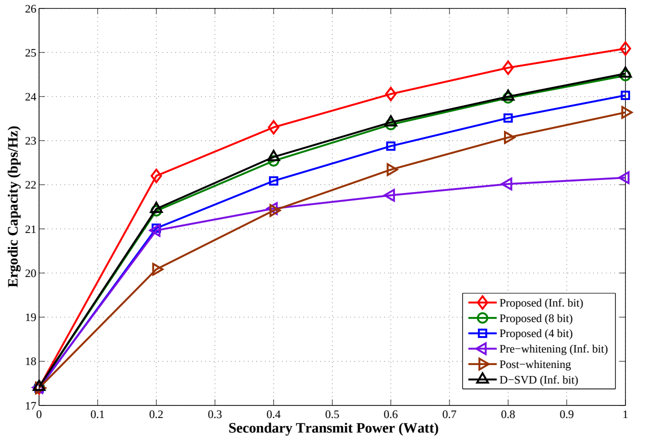

Fig. 3. Ergodic sum capacities for the various schemes when we vary P_{ST}.

IV. Simulation Results

The proposed scheme is compared with the post-whitening [9], pre-whitening [4] and D-SVD [3] schemes. It is assumed that the interference channel gain η_{SP} and the desired channel gains, ρ_{PP} and ρ_{SS}, are equally 0dB. In addition, $M_T = M_R = 4$. Fig. 2 and Fig. 3 show the ergodic capacities versus P_{ST} when P_{PT} = 1 and SNR = 10dB at the PR.

The paper [10] established a new way of finite-rate channel state information (CSI) feedback from the PR in a CR network. Under the assumption of limited feedback from the PR to the ST is available as in [10], we simulate the proposed scheme in such a limited feedback environment. In limited feedback of 4bit and 8bit cases, (5, 5, 6) and (85, 85, 86) codebooks are used in (mode-1, mode-2, mode-3), respectively.

Fig. 2 and Fig. 3 show the ergodic capacities for various precoding schemes at each receiver and sum of all receivers, respectively. In Fig. 2, the proposed scheme outperforms the conventional schemes at the PR while underperforms the D-SVD or post-whitening schemes at the SR. Although the proposed scheme has some loss of the desired power, it efficiently decreases the interference power to the PR. Therefore the proposed scheme is a suitable method to deal with interference. In Fig. 3, the proposed scheme with the perfect CSIT always outperforms the conventional schemes. Moreover, the proposed scheme with 8bit limited feedback is equal to the D-SVD with the perfect CSIT and the proposed scheme with 4bit limited feedback outperforms the pre-whitening scheme with the perfect CSIT.

V. Conclusion

A multi-mode precoding scheme based on the interference minimization is proposed in an interference-limited communication system such as MIMO-based CR networks. The proposed precoder not only let the interference power have a minimum effect on information signals, but also maximize the sum capacity via the virtual SINR maximization based mode selection. From the simulation results, the proposed precoding scheme is better than the pre-whitening scheme in terms of interference suppression, and also better than the D-SVD in terms of the total system capacity. The proposed scheme could be an effective precoding method even in limited feedback environment.

References

[1] I. F. Akyildiz, W. Y. Lee, M.C. Vuran and S. Mohanty, “A survey on spectrum management in cognitive radio networks,” *IEEE Commun. Magazine*, vol. 46, Issue. 4, pp. 40-48, April. 2008.

[2] S. Haykin, “Cognitive radio:brain-empowered wireless communications,” *IEEE J. Sel. Areas Commun.*, vol. 23, no. 2, pp. 201-220, 2005.

[3] R. Zhang and Y. C. Liang, “Exploiting multi-antennas for opportunistic spectrum sharing in cognitive radio networks,” *IEEE J. Sel. Topics. Signal Process.*, vol. 2, no. 1, pp. 88-102, Feb. 2008.

[4] M. Kang, B. Jung, D. Sung and W. Choi, “A pre-whitening scheme in a MIMO-based spectrum-sharing environment,” *IEEE Commun. Lett.*, vol. 12, no. 11, Nov. 2008.

[5] R. Zakhour and D. Gesbert, “Coordination in the MISO interference channel using the virtual SINR framework”, in *Proc. ITG WSA’09*, Berlin, Germany, Feb. 16-18, 2009.

[6] Z. Ka, H. Ming and D. Gesbert, “Spectrum sharing in multiple-antenna channels : A distributed cooperative game theoretic approach,” in *IEEE 19th International Symposium on, PIMRC 2008*, pp.1-5, Sept. 2008.

[7] D. Love and R. Heath, “Multi-mode precoding for MIMO wireless systems”, *IEEE Trans. Signal Process.*, vol. 53, no. 10, pp.3674-3687, Oct. 2005.

[8] B.O. Lee, H.W. Je, I. Sohn, O.S. Shin and K.B. Lee, “A novel uplink MIMO transmission scheme in a multicell environment,” *IEEE Trans. Wireless Commun.*, vol. 8, no. 10, pp. 4981-4987, Oct. 2009.

[9] R.S. Blum, “MIMO capacity with interference,” *IEEE J. Sel. Areas Commun.*, vol. 21, no. 5, June 2003.

[10] K.Huang and R. Zhang, “Cooperative feedback for multiantenna cognitive radio networks,” *IEEE Trans. Signal Process.*, vol. 59, no. 2, pp. 747-758, Feb. 2011.