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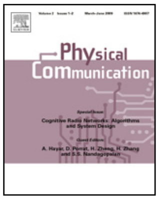

Full length article

Interference mitigation for cognitive radio MIMO systems based on practical precoding

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ABSTRACT

In this paper, we propose two subspace-projection-based precoding schemes, namely, full-projection (FP)- and partial-projection (PP)-based precoding, for a cognitive radio multiple-input multiple-output (CR-MIMO) network to mitigate its interference to a primary time-division-duplexing (TDD) system. The proposed precoding schemes are capable of estimating interference channels between CR and primary networks, and incorporating the interference from the primary to the CR system into CR precoding via a novel sensing approach. Then, the CR performance and resulting interference of the proposed precoding schemes are analyzed and evaluated. By fully projecting the CR transmission onto a null space of the interference channels, the FP-based precoding scheme can effectively avoid interfering the primary system with boosted CR throughput. While, the PP-based scheme is able to further improve the CR throughput by partially projecting its transmission onto the null space.

1. Introduction

A cognitive radio (CR) [1–4] system may coexist with a primary network on an either interference-free or interference-tolerant basis [5,6]. For the former case, the CR system only exploits the unused spectra of the primary network. While, for the latter case, the CR system is allowed to share the spectra assigned to primary network under the condition of not imposing detrimental interference on the primary network. Therefore, the interference from the CR network to the primary system (CR-primary interference) should be carefully managed and canceled in order to protect the operation of the primary system. Various interference mitigation (IM) techniques applicable to CR networks have been reported in [7]. As for multiple antenna CR networks, transmit beamforming [8–12] and precoding in [13–15] are effective approaches to proactively cancel the CR-primary interference. On one hand, it steers the CR transmission to avoid interfering with the primary network. On the other hand, it exploits the diversity or the multiplexing gain of the CR system to enhance the reliability or efficiency of the CR network.

However, in [8–15], perfect or partial channel state information (CSI) of CR interference channels to primary

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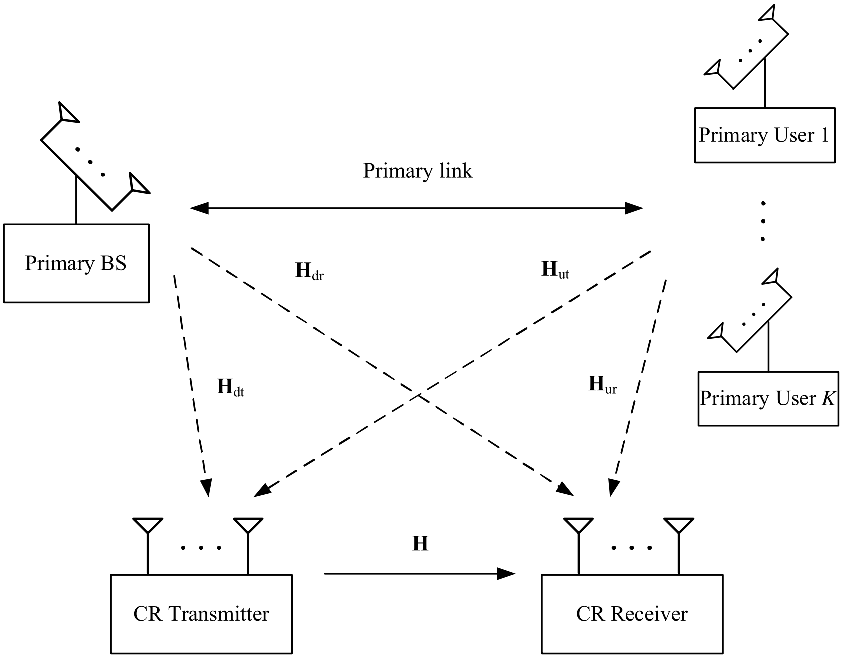

Fig. 1. A CR MIMO transmitter–receiver pair coexists with a primary TDD system.

network (CR-primary interference channels) is required at the CR transmitter (Tx) side to guarantee no/constrained interference to the primary system. Therefore, extra signaling between primary and CR networks is inevitable to obtain the CSI, which jeopardizes the applicability of these beamforming and precoding schemes. A more practical precoding scheme—sensing projection (SP)-based precoding, which learns the CSI using subspace estimation [16] and does not require a priori CSI, has been proposed for a CR multiple-input multiple-output (MIMO) link coexisting with a primary time-division-duplexing (TDD) system in [17,18]. However, such a precoding scheme does not account for the interference from primary Txs to the CR receiver (Rx) (primary-CR interference), which leads to a CR throughput loss. In [19,20], it is proposed to remove the primary-CR interference at the CR Rx via null-space Rx beamforming, which sacrifices the CR throughput as well. Moreover, the CR network in [19,20] has to work in a TDD mode aligned with the primary system in order to facilitate the null-space Rx beamforming.

In this paper, two enhanced SP-based precoding schemes, namely, full-projection (FP)- and partial-projection (PP)-based precoding, are proposed for CR MIMO systems by incorporating the primary-CR interference. As the name suggests, the FP-based scheme nulls the CR transmission by fully projecting the transmission onto the estimated null space of the CR-primary interference channels. Instead of removing the primary-CR interference using null-space Rx beamforming, the proposed precoding schemes account for the primary-CR interference via sensing. This, on one hand, improves the CR throughput, and on the other hand, introduces more flexibility into the CR deployment, i.e., the CR network does not have to work in a TDD mode as in [19,20]. The PP-based precoding can further improve the CR throughput by projecting the CR transmission onto a subspace that partially spans the estimated null space of the CR-primary interference channels. As a result, the CR throughput is further improved at the cost of introducing extra interference to the primary network.

The remainder of this paper is organized as follows. The system model is given in Section 2. The working principle of the SP-based precoding is introduced in Section 3. Then, we propose two new precoding schemes in Section 4. The performance of the proposed precoding schemes is evaluated in Section 5. Finally, we conclude the paper in Section 6.

Notation: Vectors are denoted by bold-face lower-case letters, e.g., $\mathbf{x}$, and bold-face upper-case letters are used for matrices, e.g., $\mathbf{X}$. For a matrix $\mathbf{X}$, $\mathrm{Tr}\{\mathbf{X}\}$, $\mathbf{X}^H$, and $\mathbf{X}^\dagger$ denote its trace, Hermitian transpose and pseudoinverse, respectively. $\mathbb{E}\{\cdot\}$ stands for the statistical expectation operator. $\mathbb{C}^{x\times y}$ denotes the space of $x \times y$ matrices with complex entries.

2. System model and problem formulation

We consider a CR system shown in Fig. 1, where a CR Tx–Rx pair shares the same spectrum with a primary TDD network. Multiple antennas are mounted at the CR nodes and possibly at each of the primary users. The CR Tx, CR Rx, primary base station (BS) and the kth primary user are equipped with M_t, M_r, M_{bs} and M_k ($k = 1, \ldots, K$) antennas, respectively. Block-fading channels are assumed for the primary and CR systems.

For a narrowband transmission, the received symbol at the CR Rx can be expressed as

$$\mathbf{y} = \mathbf{HFs} + \mathbf{n} + \mathbf{z} \tag{1}$$

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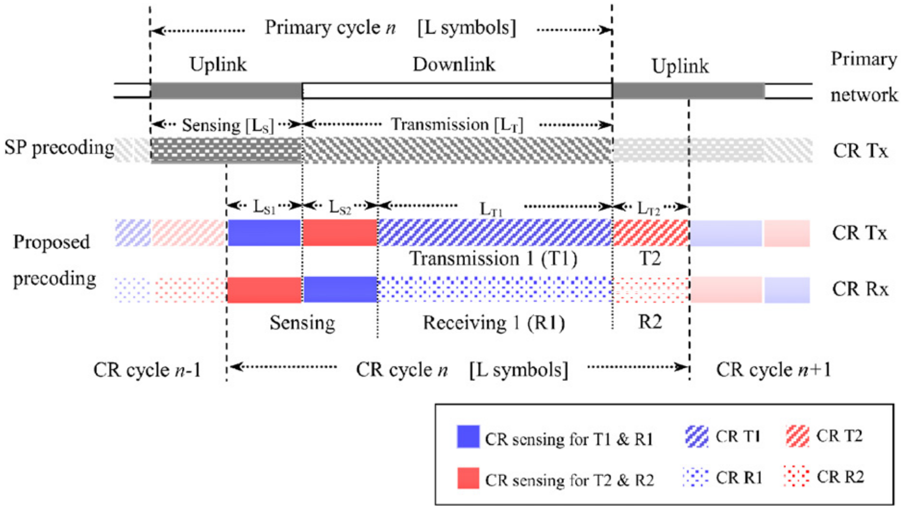

Fig. 2. System diagram for the proposed precoding schemes.

where $\mathbf{y} \in \mathbb{C}^{M_r \times 1}$ is the received signal vector at the CR Rx, $\mathbf{s} \in \mathbb{C}^{M_t \times 1}$ and $\mathbf{F} \in \mathbb{C}^{M_t \times M_t}$ are the transmit information vector with $\mathbb{E}\{\mathbf{s}\mathbf{s}^H\} = \mathbf{I}$ and precoding matrix of the CR Tx, respectively, $\mathbf{H} \in \mathbb{C}^{M_r \times M_t}$ is the channel matrix from the CR Tx to CR Rx, whose elements are independent and identically distributed (i.i.d.) complex Gaussian random variables with zero mean and variance σ_H^2, and $\mathbf{n} \in \mathbb{C}^{M_r \times 1}$ stands for the additive white Gaussian noise (AWGN) vector with zero mean and covariance matrix $\mathbb{E}\{\mathbf{n}\mathbf{n}^H\} = \sigma_n^2 \mathbf{I}$. Moreover, $\mathbf{z} \in \mathbb{C}^{M_r \times 1}$ denotes the interference from the primary network to CR Rx. It can be expressed as

$$\mathbf{z} = \begin{cases} \mathbf{H}_{\text{ur}} \mathbf{x}_u, & \text{during primary uplink} \\ \mathbf{H}_{\text{dr}} \mathbf{x}_d, & \text{during primary downlink} \end{cases} \tag{2}$$

where $\mathbf{H}_{\text{ur}} \in \mathbb{C}^{M_r \times \sum_{k=1}^{K} M_k}$ and $\mathbf{H}_{\text{ut}} \in \mathbb{C}^{M_t \times \sum_{k=1}^{K} M_k}$ (see Fig. 1) represent the interference channels from all the K active primary users to CR Rx and to CR Tx, respectively, during primary uplink. Similarly, $\mathbf{H}_{\text{dr}} \in \mathbb{C}^{M_r \times M_{bs}}$ in (2) together with $\mathbf{H}_{\text{dt}} \in \mathbb{C}^{M_t \times M_{bs}}$ (see Fig. 1) stand for the interference matrices from the primary BS to CR Rx and to CR Tx during primary downlink. All these interference matrices ($\mathbf{H}_{\text{ur}}, \mathbf{H}_{\text{ut}}, \mathbf{H}_{\text{dr}}$ and $\mathbf{H}_{\text{dt}}$) have i.i.d. complex Gaussian random elements with zero mean and covariances $\sigma_{\text{ur}}^2, \sigma_{\text{ut}}^2, \sigma_{\text{dr}}^2$ and σ_{dt}^2, respectively. Moreover, $\mathbf{x}_u \in \mathbb{C}^{\sum_{k=1}^{K} M_k \times 1}$ and $\mathbf{x}_d \in \mathbb{C}^{M_{bs} \times 1}$ are the transmitted signal vectors of all the K primary users and primary BS, respectively. We define the interference covariance matrix as $\mathbf{Z} \triangleq \mathbb{E}\{\mathbf{z}\mathbf{z}^H\}$.

3. Principle of SP-based precoding

The precoding problem for CR transmission can be expressed as the following optimization problem [14]

$$\max_{\mathbf{F}} \ \log_2 \det \left(\mathbf{I} + \frac{\mathbf{H}\mathbf{F}\mathbf{F}^H\mathbf{H}^H}{\sigma_n^2} \right) \tag{3}$$

$$\text{subject to } \mathtt{Tr}\{\mathbf{F}\mathbf{F}^H\} \le P_{cr} \tag{4}$$

$$\mathtt{Tr}\{\mathbf{G}_k\mathbf{F}\mathbf{F}^H\mathbf{G}_k^H\} \le \Gamma_k \quad k = 1, \ldots, K. \tag{5}$$

In (5), $\mathbf{G}_k \in \mathbb{C}^{M_k \times M_t}$ is the channel matrix from the CR Tx to the kth primary user. Thus, the channel matrix from the CR Tx to all primary users becomes $\mathbf{H}_{\text{ut}}^H = [\mathbf{G}_1^T, \ldots, \mathbf{G}_K^T]^T$ due to channel reciprocity. The constraints on the CR transmission power and the maximum allowed interference perceived at each primary user are given by (4) and (5), respectively.

The projected channel singular value decomposition (SVD) or P-SVD precoding has been proposed in [14] as a suboptimal solution for the optimization problem (3)–(5). It can be expressed as

$$\mathbf{F} = \mathbf{U}_\perp \left[(\mu \mathbf{I} - \boldsymbol{\Lambda}_\perp^{-1})^+ \right]^{\frac{1}{2}} \tag{6}$$

where $(\cdot)^+ \triangleq \max(0, \cdot)$, μ denotes the power level for a water-filling (WF) algorithm, and $\mathbf{U}_\perp$ and $\boldsymbol{\Lambda}_\perp$ originate from the SVD of the effective CR channel matrix $\mathbf{H}_\perp$

$$\mathbf{H}_\perp \triangleq \mathbf{H}(\mathbf{I} - \mathbf{U}_G \mathbf{U}_G^H), \tag{7}$$

with $\mathbf{H}_\perp = \mathbf{V}_\perp \boldsymbol{\Lambda}_\perp^{1/2} \mathbf{U}_\perp^H$, and $\mathbf{U}_G$ in (7) is from another SVD $\mathbf{H}_{\text{ut}}^H = \mathbf{V}_G \boldsymbol{\Lambda}_G^{1/2} \mathbf{U}_G^H$, which is estimated via sensing in the SP precoding [17,18] as shown in Fig. 2. It is worth noting that the P-SVD precoding given in (6) actually guarantees that $\mathtt{Tr}\{\mathbf{G}_k \mathbf{F}\mathbf{F}^H \mathbf{G}_k^H\} = 0$ ($k = 1, \ldots, K$), i.e., no interference is introduced to primary users. This eventually tightens the constraint (5). Therefore, the P-SVD precoding is a suboptimal solution for the optimization problem (3)–(5).

By analogy with the multiple signal classification technique [16], the signal covariance matrix is decomposed into signal and noise subspaces to estimate $\mathbf{U}_G$, that is

$$\hat{\mathbf{R}}_{\text{ut}} = \frac{1}{L_S} \sum_{i=1}^{L_S} \mathbf{r}_{\text{ut}}(i) \mathbf{r}_{\text{ut}}^H(i) \tag{8}$$

$$= \hat{\mathbf{U}} \hat{\boldsymbol{\Lambda}} \hat{\mathbf{U}}^H \tag{9}$$

$$= \hat{\mathbf{U}}_G \hat{\boldsymbol{\Lambda}}_G \hat{\mathbf{U}}_G^H + \hat{\mathbf{U}}_n \hat{\boldsymbol{\Lambda}}_n \hat{\mathbf{U}}_n^H. \tag{10}$$

In (16), $\mathbf{r}_{\text{ut}}(i) = \mathbf{H}_{\text{ut}} \mathbf{x}_u(i) + \mathbf{n}(i)$ is the ith received symbol at the CR Tx, and its estimated covariance matrix is denoted

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as $\hat{\mathbf{R}}_{\text{ut}}$. An eigenvalue decomposition is then performed on $\hat{\mathbf{R}}_{\text{ut}}$ in (17), where $\hat{\mathbf{\Lambda}} = \text{diag}(\lambda_1, \ldots, \lambda_{M_t})$ is a diagonal matrix with descendingly ordered eigenvalues of $\hat{\mathbf{R}}_{\text{ut}}$ and $\hat{\mathbf{U}} \in \mathbb{C}^{M_t \times M_t}$ contains the corresponding eigenvectors. The matrix $\hat{\mathbf{R}}_{\text{ut}}$ is further decomposed into interference and noise components in (18) with $\hat{\mathbf{U}}_G$ and $\hat{\mathbf{U}}_n$ being the first $K_p = \text{rank}(\mathbf{H}_{\text{ut}})$ and the remaining $(M_t - K_p)$ columns of $\hat{\mathbf{U}}$, respectively, and $\hat{\mathbf{\Lambda}}_G$ and $\hat{\mathbf{\Lambda}}_n$ being their corresponding eigenvalue matrices. A rank estimate for K_p can be carried out by using, e.g., an Akaike information criterion (AIC) or minimum description length (MDL) estimator [21]. The sensing phase is followed by a CR transmission, where a precoding matrix obtained from (6) is applied.

The merit of the SP precoding over the P-SVD approach is that no CSI is required due to the interference space estimation in (16)–(18). However, both of the precoding algorithms in [17,18] do not consider the interference from the primary network to the CR receiver, which eventually leads to rate loss for the CR link.

4. Proposed precoding schemes

In this section, we elaborate the CR precoding during the primary downlink.[1] When incorporating the primary-CR interference, the precoding problem for the CR Tx during the primary downlink can be expressed as follows

$$\max_{\mathbf{F}} \ \log_2 \det \left(\mathbf{I} + \frac{\mathbf{H}\mathbf{F}\mathbf{F}^H\mathbf{H}^H}{\mathbf{Z} + \sigma_n^2 \mathbf{I}} \right) \tag{11}$$

$$\text{subject to } \mathtt{Tr}\{\mathbf{F}\mathbf{F}^H\} \le P_{cr} \tag{12}$$

$$\mathtt{Tr}\{\mathbf{G}_k\mathbf{F}\mathbf{F}^H\mathbf{G}_k^H\} \le \Gamma_k, \quad k = 1, \ldots, K. \tag{13}$$

The constraints on the CR transmission power and the maximum allowed interference perceived at each primary user are given by (12) and (13), respectively. In (13), $\mathbf{G}_k \in \mathbb{C}^{M_k \times M_t}$ is the channel matrix from the CR Tx to the kth primary user. Thus, the channel matrix from the CR Tx to all primary users becomes $\mathbf{H}_{\text{ut}}^H = [\mathbf{G}_1^T, \ldots, \mathbf{G}_K^T]^T$ due to channel reciprocity.

Then, the precoding matrix for CR transmission during the downlink can be written as [22]

$$\mathbf{F}_d = \mathbf{U}_d \left[(\mu_d \mathbf{I} - \mathbf{\Lambda}_d^{-1})^+ \right]^{\frac{1}{2}} \tag{14}$$

where μ_d is the power level for the water-filling algorithm and $\mathbf{U}_d$ is obtained through the following eigenvalue decomposition (EVD)

$$\begin{aligned} \mathbf{U}_d\mathbf{\Lambda}_d\mathbf{U}_d^H &= \mathbf{H}_\perp^H(\mathbf{Z} + \sigma_n^2\mathbf{I})^{-1}\mathbf{H}_\perp \\ &= (\mathbf{I} - \mathbf{U}_G\mathbf{U}_G^H)^H\mathbf{H}^H(\mathbf{Z} + \sigma_n^2\mathbf{I})^{-1}\mathbf{H}(\mathbf{I} - \mathbf{U}_G\mathbf{U}_G^H). \end{aligned} \tag{15}$$

Similar to the P-SVD precoding, the precoding matrix given by (14) is a suboptimal solution for the optimization problem (11)–(13) due to the fact that it tightens the constraint (13) by forcing Γ_k to 0.

In (15), the effective CR channel matrix is defined as $\mathbf{H}_\perp \triangleq \mathbf{H}(\mathbf{I} - \mathbf{U}_G\mathbf{U}_G^H)$, where $\mathbf{U}_G$ is estimated by decompositing the CR received signal covariance matrix into signal and noise subspaces. It can be expressed as

$$\begin{aligned} \hat{\mathbf{R}}_{\text{ut}} &= \frac{1}{L_S}\sum_{i=1}^{L_S} \mathbf{r}_{\text{ut}}(i)\mathbf{r}_{\text{ut}}^H(i) && (16) \\ &= \hat{\mathbf{U}}\hat{\mathbf{\Lambda}}\hat{\mathbf{U}}^H && (17) \\ &= \hat{\mathbf{U}}_G\hat{\mathbf{\Lambda}}_G\hat{\mathbf{U}}_G^H + \hat{\mathbf{U}}_n\hat{\mathbf{\Lambda}}_n\hat{\mathbf{U}}_n^H. && (18) \end{aligned}$$

In (16), $\mathbf{r}_{\text{ut}}(i) = \mathbf{H}_{\text{ut}}\mathbf{x}_u(i) + \mathbf{n}(i)$ is the ith received symbol at the CR Tx, and its estimated covariance matrix is denoted as $\hat{\mathbf{R}}_{\text{ut}}$. An EVD is then performed on $\hat{\mathbf{R}}_{\text{ut}}$ in (17), where $\hat{\mathbf{\Lambda}} = \text{diag}(\lambda_1, \ldots, \lambda_{M_t})$ is a diagonal matrix with descendingly ordered eigenvalues of $\hat{\mathbf{R}}_{\text{ut}}$. It is further decomposed into interference and noise components in (18) with $\hat{\mathbf{U}}_G$ and $\hat{\mathbf{U}}_n$ being the first $K_p = \text{rank}(\mathbf{H}_{\text{ut}})$ and the remaining $(M_t - K_p)$ columns of $\hat{\mathbf{U}}$, respectively, and $\hat{\mathbf{\Lambda}}_G$ and $\hat{\mathbf{\Lambda}}_n$ being their corresponding eigenvalue matrices.

It can be seen from (14) and (15) that in order to obtain the CR precoding matrix, the interference-plus-noise covariance matrix $\mathbf{R}_{\text{ur}} \triangleq \mathbf{Z} + \sigma_n^2\mathbf{I}$ needs to be estimated at the CR Rx, besides the estimation of the interference subspace $\mathbf{U}_G\mathbf{U}_G^H$ at the CR Tx.

4.1. *Full-projection-based precoding*

To enable the estimation of $\mathbf{U}_G\mathbf{U}_G^H$ and $\mathbf{R}_{\text{ur}}$, we propose an enhanced precoding scheme, which is demonstrated in Fig. 2. Each CR cycle consists of sensing and transmission phases. We name the CR transmission during the primary downlink as T1 and uplink as T2. For T1, the space $\mathbf{U}_G\mathbf{U}_G^H$ is estimated at the CR Tx during the primary uplink according to (16)–(18) over L_{S1} symbols. The estimation of $\mathbf{R}_{\text{ur}}$ is performed at the CR Rx at the beginning of the primary downlink for a batch of L_{S2} symbols via a procedure similar to (16). After obtaining these two estimates, the CR Tx starts transmission T1 using the precoding matrix obtained by (14). Then T2 follows immediately after T1 but right before the sensing phase for the next CR cycle. The CR precoding matrix for T2 can be obtained by other two sensing sessions concurrent with the sensing phase for T1. This precoding scheme fully projects its transmission onto the estimated null space of the CR-primary interference channels. Therefore, it is termed as FP precoding.

It can be seen from Fig. 2 that the proposed FP precoding scheme shifts the CR cycle of the SP precoding rightwards in time. By doing this, several benefits are obtained. Firstly, introducing CR Rx sensing phases improves the CR throughput by incorporating the interference-plus-noise covariance matrix into precoding. Secondly, shifting the CR cycle diverts part of the CR transmission from the primary downlink to the uplink which reduces the time that primary Rxs expose themselves to CR-primary interference. This is beneficial to the primary network, since primary users are usually more susceptible to interference than the primary BS.

Theoretically, the proposed FP precoding can completely mitigate the CR-primary interference if there is no error in the interference space estimation (18). However,

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[1] A similar precoding for the primary uplink can be easily obtained, which is ignored here for brevity.

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its IM ability degrades rapidly when the CR interference-to-noise ratio, INR $\triangleq \sigma_{\mathrm{ut}}^2/\sigma_n^2$, drops below a threshold. This is due to the fact that in (18) some components in the noise subspace may swap with those in the interference subspace when the noise amplitude σ_n is relatively large compared to the interference channel gain σ_{ut}. This phenomenon is known as a *subspace swap*[2] [25].

For low INR, the interference subspace has a high probability to swap with the noise subspace. When a subspace swap happens, (15) can be rewritten as

$$\begin{aligned}\mathbf{U}_d\mathbf{\Lambda}_d\mathbf{U}_d^H &\approx (\mathbf{I}-\hat{\mathbf{U}}_n\hat{\mathbf{U}}_n^H)^H\mathbf{H}^H(\mathbf{Z}+\sigma^2\mathbf{I})^{-1}\mathbf{H}(\mathbf{I}-\hat{\mathbf{U}}_n\hat{\mathbf{U}}_n^H)\\ &= \hat{\mathbf{U}}_G\hat{\mathbf{U}}_G^H\mathbf{H}^H(\mathbf{Z}+\sigma^2\mathbf{I})^{-1}\mathbf{H}\hat{\mathbf{U}}_G\hat{\mathbf{U}}_G^H \qquad (19)\end{aligned}$$

which means that $\mathbf{F}_d$ and $\mathbf{H}_{\mathrm{ut}}^H$ span the same space. Thus, the average CR-primary interference at low CR INR becomes

$$I_l^{FP} = \mathbb{E}\{\mathtt{Tr}\{\mathbf{H}_{\mathrm{ut}}^H\mathbf{F}_d\mathbf{F}_d^H\mathbf{H}_{\mathrm{ut}}\}\} \propto P_{cr}\sigma_{\mathrm{ut}}^2. \qquad (20)$$

This suggests that the average interference power at primary users is proportional to the channel gain between CR and primary users at low CR INR.

The average CR-primary interference in the high CR INR regime can be expressed as

$$\begin{aligned}I_h^{FP} &= \mathbb{E}\{\mathtt{Tr}\{\mathbf{H}_{\mathrm{ut}}^H\hat{\mathbf{U}}_d(\mu_d\mathbf{I}-\mathbf{\Lambda}_d^{-1})^+\hat{\mathbf{U}}_d^H\mathbf{H}_{\mathrm{ut}}\}\} \qquad (21)\\ &= \mathbb{E}\{\mathtt{Tr}\{\mathbf{H}_{\mathrm{ut}}^H(\hat{\mathbf{U}}_d-\mathbf{U}_d)(\mu_d\mathbf{I}-\mathbf{\Lambda}_d^{-1})^+\\ &\quad\times(\hat{\mathbf{U}}_d-\mathbf{U}_d)^H\mathbf{H}_{\mathrm{ut}}\}\} \qquad (22)\\ &\approx \mathbb{E}\{\mathtt{Tr}\{\mathbf{H}_{\mathrm{ut}}^H(\mathbf{X}^H\mathbf{H}_{\mathrm{ut}})^\dagger\mathbf{N}^H\mathbf{U}_d(\mu_d\mathbf{I}\\ &\quad-\mathbf{\Lambda}_d^{-1})^+\mathbf{U}_d{}^H\mathbf{N}(\mathbf{H}_{\mathrm{ut}}^H\mathbf{X})^\dagger\mathbf{H}_{\mathrm{ut}}\}\} \qquad (23)\\ &= \sigma_n^2P_{cr}\mathbb{E}\{\mathtt{Tr}\{\mathbf{H}_{\mathrm{ut}}^H(\mathbf{X}^H\mathbf{H}_{\mathrm{ut}})^\dagger(\mathbf{H}_{\mathrm{ut}}^H\mathbf{X})^\dagger\mathbf{H}_{\mathrm{ut}}\}\} \qquad (24)\\ &= \frac{\sigma_n^2P_{cr}}{L_{S1}}\mathtt{Tr}\{\mathbf{Q}_u\} \qquad (25)\end{aligned}$$

where (22) is due to the fact that $\mathbf{H}_{\mathrm{ut}}^H\mathbf{U}_d = \mathbf{0}$; (23) is obtained using the fact that $\hat{\mathbf{U}}_d-\mathbf{U}_d \approx -(\mathbf{X}^H\mathbf{H}_{\mathrm{ut}})^\dagger\mathbf{N}^H\mathbf{U}_d$ for high INR [26] with $\mathbf{X} \triangleq [\mathbf{x}_u(1), \mathbf{x}_u(2), \dots, \mathbf{x}_u(L_{S1})]$, and $\mathbf{N} \triangleq [\mathbf{n}(1), \mathbf{n}(2), \dots, \mathbf{n}(L_{S1})]$; (24) follows from the independence of $\mathbf{X}^H\mathbf{H}_{\mathrm{ut}}$ and $\mathbf{N}$ and $\mathbb{E}\{\mathbf{N}^H\mathbf{Y}\mathbf{N}\} = \sigma_n^2\mathtt{Tr}\{\mathbf{Y}\}\mathbf{I}$ for any matrix $\mathbf{Y}$. Note that $\mathbf{Q}_u \triangleq \mathbb{E}\{\mathbf{x_u}\mathbf{x_u}^H\}$ in (25) is the transmit covariance matrix for the primary user. An interesting fact can be observed from (25) that at high CR INR the average CR-primary interference does not depend on the interference channel $\mathbf{H}_{\mathrm{ut}}$. It is proportional to the channel noise σ_n^2 and inversely proportional to the sensing length L_{S1}.

4.2. Partial-projection-based precoding

The PP precoding works in a similar manner to the above proposed FP precoding except for the selection of the interference space. For the downlink CR precoding, a subspace $\hat{\mathbf{U}}_m\hat{\mathbf{U}}_m^H$ partially spanning the interference space is obtained by choosing m eigenvectors corresponding to the first m largest eigenvalues of $\hat{\mathbf{\Lambda}}$ in (17), where m can be determined according to various criteria. One candidate criterion is

$$\frac{\sum_{i=m+1}^{M_{\min}}\lambda_i}{\sum_{i=1}^{m}\lambda_i} \le r_{t/d} \qquad (26)$$

with $M_{\min} \triangleq \mathtt{min}(M_t, \sum_{k=1}^K M_k)$. We call $r_{t/d}$ the trivial over dominant interference ratio (TDIR). This selection process chooses m dominant interference subchannels to form an estimate of the interference space and ignores the other $(M_{\min}-m)$ trivial ones. Finally, substituting the estimated subspace $\hat{\mathbf{U}}_m\hat{\mathbf{U}}_m^H$ for $\hat{\mathbf{U}}_G\hat{\mathbf{U}}_G^H$, the precoding matrix $\mathbf{F}_d$ for the downlink CR transmission can be obtained via (14). However, we may fail to find a value of m satisfying (26). In this case, the proposed FP precoding is used.

The joint probability density function (PDF) of the ordered eigenvalues $\lambda \triangleq [\lambda_1, \lambda_2, \dots, \lambda_{M_{\min}}]$ of $\hat{\mathbf{R}}_{\mathrm{ut}}$, with $\lambda_1 \ge \lambda_2 \ge \dots \ge \lambda_{M_{\min}} \ge \sigma_n^2$ is [27]

$$\begin{aligned}f_\lambda(\lambda_1, \lambda_2, \dots, \lambda_{M_{\min}}) &= \frac{1}{P_p{}^{M_{\min}}}f_{\tilde{\lambda}}\\ &\quad\times\left(\frac{\lambda_1-\sigma_n^2}{P_p}, \frac{\lambda_2-\sigma_n^2}{P_p}, \dots, \frac{\lambda_{M_{\min}}-\sigma_n^2}{P_p}\right) \qquad (27)\end{aligned}$$

where P_p is the transmission power of each primary user antenna and $f_{\tilde{\lambda}}(\tilde{\lambda}_1, \tilde{\lambda}_2, \dots, \tilde{\lambda}_{M_{\min}})$ with $\tilde{\lambda}_1 \ge \tilde{\lambda}_2 \ge \dots \ge \tilde{\lambda}_{M_{\min}}$ is given by

$$\begin{aligned}f_{\tilde{\lambda}}(\tilde{\lambda}_1, \tilde{\lambda}_2, \dots, \tilde{\lambda}_{M_{\min}}) &= \frac{\prod_{i=1}^{M_{\min}} e^{-\tilde{\lambda}_i}\tilde{\lambda}_i^{M_{\max}-M_{\min}}\prod_{i=1}^{M_{\min}-1}\left[\prod_{j=i+1}^{M_{\min}}(\tilde{\lambda}_i-\tilde{\lambda}_j)^2\right]}{\prod_{i=1}^{M_{\min}}(M_{\max}-i)!\prod_{i=1}^{M_{\min}}(M_{\min}-i)!} \qquad (28)\end{aligned}$$

with $M_{\max} \triangleq \mathtt{max}(M_t, \sum_{k=1}^K M_k)$. Therefore, the probability for the occurrence of (26) is

$$p_m = \int_{\mathbf{S}} f_\lambda(\lambda_1, \lambda_2, \dots, \lambda_{M_{\min}})\, d\lambda_1\, d\lambda_2 \cdots d\lambda_{M_{\min}} \qquad (29)$$

where $\mathbf{S} \triangleq \{(\lambda_1, \lambda_2, \dots, \lambda_{M_{\min}})|\,(26) \cap \lambda_1 \ge \lambda_2 \ge \dots \ge \lambda_{M_{\min}} \ge \sigma_n^2\}$.

In other words, for the PP precoding scheme the probabilities of using the 'genuine' PP (m satisfying (26) exists) and using FP are p_m and $(1-p_m)$, respectively. Therefore, the CR Tx uses $(1-p_m)\sum_{k=1}^K M_k + p_m m$ and $\sum_{k=1}^K M_k$ degrees of freedom (DoF) for IM in the PP and FP precoding schemes, respectively. This means that compared to the proposed FP precoding the PP precoding scheme transfers $p_m(\sum_{i=1}^K M_k - m)$ DoF from interference mitigation to CR transmission, which leads to a higher throughput for the CR link. It can be seen from (27)–(29) that in the large INR regime, p_m is fixed for a given noise power σ_n^2 and P_p. Considering the fact from (25) that at

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[2] The lower bound on the probability of the subspace swap has been investigated in [23,24].

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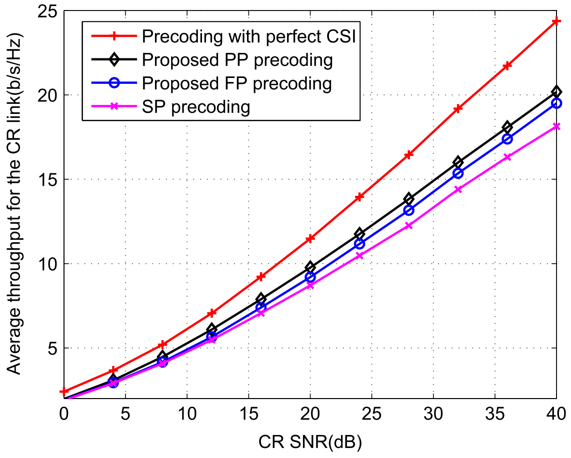

Fig. 3. CR throughput under different precoding schemes ($M_t = M_r = 4$, $M_{\mathrm{bs}} = 2$, $K = 2$, $M_1 = M_2 = 1$, $L_{S1} = L_{S2} = L_{T2} = 50$, $L_{T1} = 350$, $\sigma_H^2 = \sigma_{\mathrm{ut}}^2 = 1$, $P_{cr} = 1$, and $r_{t/d} = 0.1$).

high INRs the average interference power of FP I_h^{FP} is fixed and the average interference power resulting from ‘real’ PP I^{PP} is proportional to the square of the interference channel gain σ_{ut}^2, the overall average interference of the PP precoding $I_h^{PP} = p_m I^{PP} + (1 - p_m) I_h^{FP}$ is linearly proportional to σ_{ut}^2 for large INRs.

5. Numerical results & discussions

Consider a scenario where a CR MIMO system coexists with a primary TDD system which has one 2-antenna BS and two single-antenna users. We assume that the number of antennas for primary users is known to the CR system. Therefore, the rank estimation of K_p used in (18) is not needed in our simulations. Each CR node is equipped with four antennas. The primary network works as a downlink-broadcast and an uplink multiple-access system. The transmission power of the CR and primary networks is 1. All the obtained results are averaged over 2000 simulation runs.

First, we evaluate the throughput of the CR system with the proposed precoding schemes over different values of signal-to-noise ratios, SNR$\triangleq \sigma_H^2/\sigma_n^2$. In Fig. 3, the throughputs (average mutual information in (11)) of the two proposed precoding schemes are compared with that of the SP precoding of [17,18] and the P-SVD precoding with perfect CSI of [14]. It can be seen that the proposed FP/PP precoding schemes lead to higher CR throughput than the SP precoding, and the throughput gain becomes larger as the SNR increases.

Fig. 4 evaluates the impact of CR INR on the CR throughput and the resulting CR-primary interference under different precoding schemes. It has the same setup as that of Fig. 3 with $\sigma_n^2 = 10^{-4}$. By comparing Fig. 4(a) with Fig. 4(b), it can be seen that the proposed FP/PP precoding schemes outperform the SP counterpart at low INRs, since they lead to higher CR throughput without introducing extra interference. At high INRs, both the proposed FP and SP precoding schemes have fixed interference, and there is a fairly good agreement between the derived and simulated interference of the FP precoding. Another phenomenon which can be seen from Fig. 4(b) is that the interference of the SP precoding is slightly smaller than that of the FP precoding. This is due to the fact that the sensing of the SP precoding is longer than the uplink sensing of the FP precoding. Moreover, at high INRs the interference of the proposed PP precoding is linearly proportional to the CR INR, which supports our analysis in Section 4.2.

6. Conclusions

In this paper, two SP-based precoding schemes, namely, FP and PP precoding, have been proposed for CR MIMO systems to mitigate the CR-primary interference and improve the CR throughput. These two precoding schemes are capable of estimating the CSI of primary-CR interference channels and can account for the primary-CR interference via a novel sensing approach. Therefore, no extra signaling is required between primary and CR systems, which consequently eases the deployment of CR networks. The performance of the proposed precoding schemes has also been

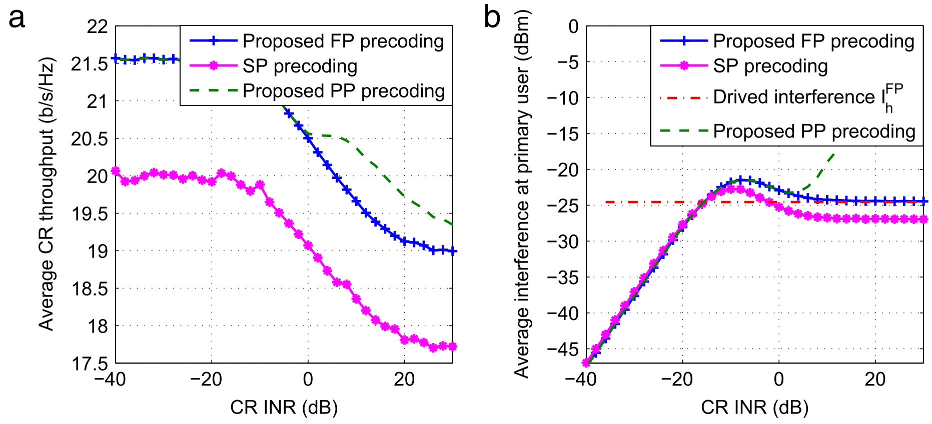

Fig. 4. (a) CR throughput and (b) resulting interference of different precoding schemes ($M_t = M_r = 4$, $M_{\mathrm{bs}} = 2$, $K = 2$, $M_1 = M_2 = 1$, $L_S = 100$, $L_{S1} = L_{S2} = L_{T2} = 50$, $L_{T1} = 350$, $\sigma_H^2 = 1$, $P_{cr} = 1$, $r_{t/d} = 0.1$, and $\sigma_n^2 = 10^{-4}$).

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evaluated. It has been demonstrated that the FP precoding can boost the CR throughput without introducing extra CR-primary interference in the low INR regime. The PP precoding can further improve the CR throughput if the primary system can tolerate some extra interference.

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References

[1] S. Haykin, Cognitive radio: brain-empowered wireless communications, IEEE J. Sel. Areas Commun. 2 (2005) 201–220.
[2] I.F. Akyildiz, W.Y. Lee, M.C. Vuran, S. Mohanty, NeXt generation/dynamic spectrum access/cognitive radio wireless networks: a survey, Comput. Netw. 13 (2006) 2127–2159.
[3] Q. Zhao, B.M. Sadler, A survey of dynamic spectrum access, IEEE Signal Process. Mag. 3 (2007) 79–89.
[4] X. Hong, C.-X. Wang, H.-H. Chen, Y. Zhang, Secondary spectrum access networks: recent developments on the spatial models, IEEE Veh. Technol. Mag. 2 (2009) 36–43.
[5] C.-X. Wang, X. Hong, H.-H. Chen, J. Thompson, On capacity of cognitive radio networks with average interference power constraints, IEEE Trans. Wireless Commun. 4 (2009) 1620–1625.
[6] X. Hong, C.-X. Wang, M. Uysal, X. Ge, S. Ouyang, Capacity analysis of hybrid cognitive radio networks with distributed VAAs, IEEE Trans. Veh. Technol. 7 (2010) 3510–3523.
[7] X. Hong, Z. Chen, C.-X. Wang, S.A. Vorobyov, J. Thompson, Cognitive radio networks: interference cancellation and management techniques, IEEE Veh. Technol. Mag. 4 (2009) 76–84.
[8] J. Zhou, J. Thompson, Linear precoding for the downlink of multiple input single output coexisting wireless systems, IET Commun. 6 (2008) 742–752.
[9] T.K. Phan, S.A. Vorobyov, N.D. Sidiropoulos, C. Tellambura, Spectrum sharing in wireless networks via QoS-aware secondary multicast beamforming, IEEE Trans. Signal Process. 6 (2009) 2323–2335.
[10] G. Zheng, K.-K. Wong, B. Ottersten, Robust cognitive beamforming with bounded channel uncertainties, IEEE Trans. Signal Process. 12 (2009) 4871–4881.
[11] L. Zhang, Y.-C. Liang, Y. Xin, H.V. Poor, Robust cognitive beamforming with partial channel state information, IEEE Trans. Wireless Commun. 8 (2009) 4143–4153.
[12] G. Zheng, S. Ma, K.-K. Wong, T.-S. Ng, Robust beamforming in cognitive radio, IEEE Trans. Wireless Commun. 2 (2010) 570–576.
[13] L. Bixio, G. Oliveri, M. Ottonello, M. Raffetto, C.S. Regazzoni, Cognitive radios with multiple antennas exploiting spatial opportunities, IEEE Trans. Signal Process. 8 (2010) 4453–4459.
[14] R. Zhang, Y.-C. Liang, Exploiting multi-antennas for opportunistic spectrum sharing in cognitive radio networks, IEEE J. Sel. Top. Sign. Proces. 1 (2008) 88–102.
[15] G. Scutari, D.P. Palomar, S. Barbarossa, Cognitive MIMO radio: competitive optimality design based on subspace projections, IEEE Signal Process. Mag. 6 (2008) 46–59.
[16] R. Roy, T. Kailath, ESPRIT-estimation of signal parameters via rotational invariance techniques, IEEE Trans. Acoust. Speech Signal Process. 7 (1989) 984–995.
[17] H. Yi, H. Hu, Y. Rui, K. Guo, J. Zhang, Null space-based precoding scheme for secondary transmission in a cognitive radio MIMO system using second-order statistics, in: Proc. IEEE ICC, 2009.
[18] R. Zhang, F. Gao, Y.-C. Liang, Cognitive beamforming made practical: effective interference channel and learning-throughput tradeoff, IEEE Trans. Commun. 2 (2010) 706–718.
[19] H. Yi, Nullspace-based secondary joint transceiver scheme for cognitive radio MIMO networks using second-order statistics, in: Proc. IEEE ICC, 2010.
[20] F. Gao, R. Zhang, Y.-C. Liang, X. Wang, Design of learning-based MIMO cognitive radio systems, IEEE Trans. Veh. Technol. 4 (2010) 1707–1720.
[21] O. Somekh, O. Simeone, Y. Bar-Ness, W. Su, Detecting the number of transmit antennas with unauthorized or cognitive receivers in MIMO systems, in: Proc. IEEE MILCOM, 2007.
[22] Z. Chen, S.A. Vorobyov, C.-X. Wang, J. Thompson, Pareto region characterization for rate control in multi-user systems and Nash bargaining, IEEE Trans. Automatic Control 57 (12) (2012).
[23] J. Thomas, L. Scharf, D. Tufts, The probability of a subspace swap in the SVD, IEEE Trans. Signal Process. 3 (1995) 730–736.
[24] M. Hawkes, A. Nehorai, P. Stoica, Performance breakdown of subspace-based methods: prediction and cure, in: Proc. IEEE ICASSP, 2001.
[25] D.W. Tufts, A.C. Kot, R.J. Vaccaro, The analysis of threshold behavior of SVD-based algorithms, in: Proc. XXIst Annu. Asilomar Conf. Signals. Syst. Comput., 1987.
[26] F. Li, H. Liu, R.J. Vaccaro, Performance analysis for DOA estimation algorithm: unification, simplification and observations, IEEE Trans. Aerosp. Electron. Syst. 4 (1993) 1170–1184.
[27] M. Chiani, M.Z. Win, A. Zanella, R.K. Mallik, J.H. Winters, Bounds and approximations for optimum combining of signals in the presence of multiple co-channel interferers and thermal noise, IEEE Trans. Commun. 2 (2003) 296–307.

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