Beamformings for Spectrum Sharing in Cognitive Radio Networks

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Abstract: - Cognitive radio is regarded as one the most promising technology for supporting spectrum sharing which secondary (cognitive) users coexist with users in primary network whose radio band is licensed. Two conflicting challenges are how to maintain the interferences generated by the cognitive radio network to the primary network below an acceptable threshold level while maximizing the sum-rate of the cognitive radio network. We present two beamforming methods, modified zero forcing beamforming and transmit-receive beamforming. The zero forcing beamforming is modified by adding the channel gain between the cognitive radio base station and the primary user to meet the two conflicting goals. The orthogonality of transmit beams in MIMO beamforming by Gram-Schmidt method achieves the first goal that the primary user is interference free. To satisfy the second goal, self-interference is reduced by the constrained minimization of the mean output array of cognitive receivers. To reduce complexity of the system, the number of cognitive radio users must be limited. Criteria to select the number of best cognitive radio users should increase the sum-rate of cognitive-radio network. Subspace-based scheduling scheme selects the cognitive radio users orthogonal each other as much as possible so that the self-interference is mitigated. Simulation results are given to evaluate the performances of the proposed methods in forms of bit error rates, symbol error rates and sum-rates.

Key-Words: - beamforming, cognitive radios, constrained optimization

1 Introduction

With the popularity of various wireless technologies and fixed spectrum allocation strategy, spectrum is becoming a major bottleneck, due to the fact that the most of the available spectrum has been allocated. Moreover, the increasing demand for new wireless services, especially multimedia applications, together with the growing number of wireless users and demand of high quality of services have resulted in overcrowding of the allocated spectrum bands, leading to significantly reduced levels of user satisfaction. Particularly, spectrum congestion is a serious problem in communication-intensive situations such as after a ball-game or in a massive emergency. According to Federal Communication Commission (FCC) [1], some spectrum band remains unused at a given time and location, indicating that a more flexible allocation strategy could solve the spectrum scarcity problem. For example, cellular network bands are overloaded in most parts of the world but television broadcasting, amateur radio and paging have been found to be grossly underutilized.

This motivates a new paradigm of either through opportunistic spectrum sharing or through spectrum sharing for exploiting the spectrum resources in a dynamic way. Cognitive radio (CR) [2-5] allows the secondary users (SUs) (lower priority) to share the licensed spectrum originally allocated to the primary users (PUs) (higher priority). In opportunistic spectrum access, the SUs, also called cognitive radio users (CRUs) needs to sense the radio environment and identify the temporally vacant spectrum, i.e. the secondary and primary users do not operate on the same spectrum simultaneously. Quickly and accurately detection of the presence of PUs is an important and difficult task so that the SUs can search and move to other empty spectrums within a certain time [6]. On one hand, if the PUs do occupy their spectrum too long that the SUs have no chance to access, the spectrum usage of such CR systems would not be efficient. If the PUs and SUs can concurrently share, the regional spectrum efficiency would be increased dramatically. In spectrum sharing scenario, the SUs can coexist with the PUs all the time as long as (1) the interference generated by the SUs to PUs is below certain accepted threshold as well as (2) maximize its own transmit throughput.

As the first step of exploring of CR technology, IEEE 802.22 Wireless Regional Access Network

(WRAN) [7] started in November 2004 provides more service capacity and coverage than the current standards of wireless networks. Many prior researches on CR technology have focused on spectrum sharing. To trade off two conflict goals, multiple transmit antennas techniques have been exploited [8-9]. Since the number of transmit beams is limited by the number of antennas, the criteria to select CRUs are also crucial to increase the sum-rate of CR system. In [10-11], zero forcing beamforming is used to null the self-interference among CRUs selected by the orthogonal user selection algorithms. However, the resulting transmit weights do not handle the interferences generated by the cognitive radio base station (CRBS) to the PUs and it needs two steps in the proposed multiuser selection algorithm. Power allocation is used in [12] to solve the drawback of the zero forcing beamforming and the subspace-based secondary user selection scheme is presented. Orthogonal transmit beamforming is generated by Gram-Schmidt orthogonalization to enable transmitting data from the CRBS to CRUs without interfering to the PU [13]. Although no interference to the PU, CRUs still suffer from the self-interferences among CRUs scheduled by the opportunistic beamforming method. In [14], the number of secondary users is fixed and two iterative algorithms for joint optimal power control and beamforming for two different scenarios: with and without cooperation between the primary and secondary networks are considered. The protection of the PU from excessive interference induced by the SUs as well as to satisfy SINR requirement of each SU are done by constrains of the optimization problem. Similarly, minimizing the transmit beamforming vectors of CRBS while keeping the SINR of CRUs above certain level and interference introduced by CRUs below specific thresholds simultaneously is regarded as a second order cone programming (SOCP) problem [15].

Multiple input multiple output (MIMO) systems have a great potential to increase the capacity of CR system. The system model considers a CR network which base stations and users of primary and secondary networks are equipped with multiple antennas. In [16], the transmit and receive beamformings are still found by minimizing the transmit beamforming vectors of CRBS while keeping SINR at the CRU above an acceptable threshold as well as a low interference to the PU. Receive antenna selection is presented in [17] for a MIMO downlink scheduling algorithm in order to reduce the complexity of the user selection. Transmit beamforming is given by a linear pre-processing scheme to perform the interference cancellation at the primary receiver [18] but this method can apply only one CRU. In [19], transmit and receive beamforming vectors are designed by the SINR maximization and the user selection strategy requires two steps: CRUs are pre-selected so as to maximize the sum-rate and then the PU verifies the outage probability constraint and a number of CRUs are selected from those pre-selected CRUs. The optimization problem in [20] which maximizes the minimum SINR of CRUs subject to the maximum tolerable interference of the PUs and the maximum transmission power to the CRUs is solved by the genetic algorithm.

Our proposed approach includes the uses of multiple transmit antennas and MIMO antenna array where the users are using multiple antennas for CR systems. In multiple transmit antennas, the transmit beamforming vectors are designed by the modified zero forcing beamforming which achieves two conflict objectives: causes no interference at the primary receiver and no self-interferences among CRUs. In transmit-receive (MIMO) beamforming, the orthogonality of the transmit beamforming vectors are generated for the interference-free to the PU. The optimization problem are formulated to generate the receive beams by minimizing the mean output power constrained to the unity response at the considered CRU and null responses at other CRUs. For comparison, the receive beamforming obtained by the SINR maximization is derived. In CR system where a large number of CRUs are operating in the same frequency band as the PU, a scheduling scheme is needed to select the best CRUs. Subspace-base cognitive user selection is presented to select CRUs orthogonal as much as possible.

The rest of paper is organized as follows. In Section II, system and signal model for cognitive radio networks is introduced. In Section III, two beamforming strategies are presented which are the modified zero forcing beamforming and transmit-receive (MIMO) beamforming. In Section IV, the algorithm of subspace-based cognitive user selection is shown. Simulation results are provided in Section V. Finally, conclusions are drawn in Section VI.

Throughout the paper, we use uppercase boldface letters for matrices and lowercase boldface for vectors. The Euclidean norm is denoted by $\|\cdot\|$. $(\cdot)^T$ and $(\cdot)^H$ stand for the transpose and the conjugate transpose, respectively.

2 System and Signal Model for Cognitive Radio Networks

The system model of a CR network considered in this paper is composed of heterogeneous wireless systems (primary and secondary networks) as illustrated in Fig. 1. The primary and secondary networks coexist and share the same spectrum in underlay way [21]. The primary network consists of a primary base (PBS) that transmits signals to a single primary user (PU), and both are equipped with single antenna. For secondary cognitive network, there is a single cognitive radio base station (CRBS) with N_t transmit antennas serving K cognitive radio users (CRUs), $CRU_1, CRU_2, \ldots, CRU_K$. Each CRU is equipped with N_r receive antennas. The number of CRUs is larger than the number of transmit antennas $K \gg N_t$. A subset of CRUs is selected. The number of selected CRUs corresponds to the maximum number of transmit beams which is equal to $N_t - 1$. The objective of the invention of CR network is to opportunistically utilize a frequency band initially allocated to a primary network by providing communications among CRUs (lower priority) and avoiding interferences to the PU (higher priority). As a result of sharing spectrum, the PU is interfered by the signals sent by CRBS. Likewise, the received signals of CRUs are also corrupted by the signals transmitted from PBS. Therefore, CRBS has to trade off between two conflict goals at the same time: one is to maximize its own transmit sum-rate; and other is to minimize the amount of interference it produces at the PU.

In the system model depicted in Fig. 1, we assume that CRBS has perfect knowledge of all channel information between CRBS and CRUs, CRBS and PU which can be easily measured from uplink in Time Division Duplexing (TDD) systems such as IEEE 802.16 d/e. As another example, CRBS needs to transmit pilot symbols to allow CRUs and PU to obtain channel estimates which reliably transmitted back to the CRBS via feedback channel.

Consider the downlink of the primary network. The signal that the PU receives is modeled as

$$y_p = \sqrt{P_p}\, g_p s_p + \sum_{k=1}^{N_t-1} \sqrt{P_k}\, \mathbf{h}_p^H \mathbf{w}_{tk} s_k + z_p \qquad (1)$$

where P_p and P_k denote the transmitted power for the PU and the k-th cognitive data stream, respectively. s_p and s_k are the modulated signals for the PU and the k-th CRU, respectively. g_p is the channel link between the PU and PBS while $\mathbf{h}_p$ is the $N_t \times 1$ channel from the CRBS to the PU. z_p is noise at the primary receiver which is a zero-mean Gaussian random variable with variance σ_p^2. The weight vector $\mathbf{w}_{tk} = \left[w_{tk,1}\ w_{tk,2} \ldots w_{tk,N_t} \right]^T$ denotes a transmit beamforming vector for the k-th CRU. The weight vector has unit energy, i.e. $\left\| \mathbf{w}_{tk} \right\| = 1$ $\forall k$. The signal to interference and noise ratio (SINR) of the PU can be written as

$$SINR_p = \frac{P_p \left| g_p \right|^2}{\sum_k P_k \left| \mathbf{h}_p^H \mathbf{w}_{tk} \right|^2 + \sigma_p^2}. \qquad (2)$$

The sum-rate of the primary system is defined as $R_p = \log\left(1 + SINR_p\right)$. The baseband received signal model at the k-th CRU is given by

$$\begin{aligned} y_k = {} & \sqrt{P_k}\, \mathbf{w}_{rk}^H \mathrm{H}_k \mathbf{w}_{tk} s_k + \sum_{j \neq k}^{N_t-1} \sqrt{P_j}\, \mathbf{w}_{rk}^H \mathrm{H}_k \mathbf{w}_{tj} s_j \\ & + \sqrt{P_p}\, \mathbf{w}_{rk}^H \mathbf{g}_k s_p + \mathbf{w}_{rk}^H \mathbf{z}_k \end{aligned} \qquad (3)$$

where $\mathbf{H}_k$ is the $N_r \times N_t$ channel matrix from the CRBS to the k-th CRU. $\mathbf{g}_k$ is the N_r-component channel vector between the PBS and N_r antennas of CRU_k. $\mathbf{z}_k$ is the $N_r \times 1$ complex Gaussian noise vector with entries being identically independent distributed random variables with mean zero and variance σ_k^2. $\mathbf{w}_{rk} = \left[w_{rk,1}\ w_{rk,2} \ldots w_{rk,N_r} \right]^T$ denotes the receive beamforming vector at the k-th CRU. The weight vector has unit energy, i.e. $\left\| \mathbf{w}_{rk} \right\| = 1$ $\forall k$. In Eq. (3), the received signal of certain CRU_k is interfered by three terms as follows: 1) interference given by other CRUs, 2) interference from the PBS and 3) additive noise. Then, the SINR of the k-th CRU is

$$SINR_k = \frac{P_k \left| \mathbf{w}_{rk}^H \mathbf{H}_k \mathbf{w}_{tk} \right|^2}{\sum_{j \neq k} P_j \left| \mathbf{w}_{rk}^H \mathbf{H}_k \mathbf{w}_{tj} \right|^2 + P_p \left| \mathbf{w}_{rk}^H \mathbf{g}_k \right|^2 + \sigma_k^2} \qquad (4)$$

The sum-rate of CR system is defined as

$$R_c = \sum_{k \in S} \log(1 + SINR_k) \quad (5)$$

where S is a set of the CRUs selected to share the channels.

In order to take into consideration two conflicting objectives of CR system: 1) achieve high sum-rate of CR system and 2) limit interference created to the PU as small as possible, we should investigate on appropriate power, transmit and receive beamforming weights to distribute across K cognitive radio users. Moreover, by joiningly consider beamforming and scheduling, one can be able to select some cognitive users from K cognitive radio users that have less effect on the PU and enlarge the sum-rate of CR system at the same time.

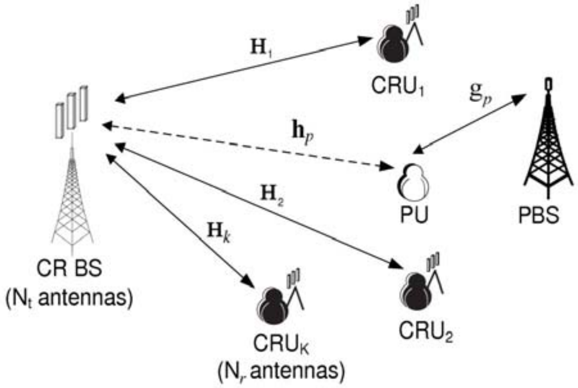

Figure 1 Multiple antennas of cognitive radio system

3 Two Beamforming Strategies

Beamforming is a strategy used by the CRBS in order to minimize the interferences. In CR system, one should deal with not only thev interferences among CRUs, but also the interferences to the PU. In this section, we propose two beamforming algorithms that can guarantee no interference to the PU and minimize self interferences among CRUs. Consequently, this allows the unlicensed (secondary) users can concurrently across the spectrum allocated to the licensed (primary) users and satisfies the previously two mentioned goals.

3.1 Modified Zero Forcing Beamforming (MZFB)

Transmit antenna arrays have been exploited as a strategy of transmit diversity and spatial multiplexing in wireless systems. In this paper, we modify the simple principle of zero forcing beamforming [10,12, 17] to design the transmit beamforming weight $\mathbf{w}_{tk}$. In this case, the SU's channel is multiple-input single-output (MISO), i.e. there is only single antenna ($N_r = 1$) at the secondary receiver. We assign $\mathbf{w}_{rk}$ =1. The number of CRUs that allowed to share spectrum is limited to $N_t - 1$. Scheduling algorithm is used to select the best $N_t - 1$ CRUs out of total K CRUs. The CRBS determines the transmit beamforming $\mathbf{w}_{tk}$ for the k-th CRU by the following criteria.

$$\mathbf{h}_p^H \mathbf{w}_{tj} = 0 \qquad j = 1, 2, \ldots, N_t - 1 \quad (6)$$

$$\mathbf{h}_k^H \mathbf{w}_{tj} = \begin{cases} 1 & j = k \\ 0 & j \neq k \end{cases} \quad (7)$$

where $\mathbf{h}_k$ is the $N_t \times 1$ channel gain vector between the CRBS and CRU_k. The weight vectors are selected so than the PU has interference-free. That is, $\mathbf{h}_p^H \mathbf{w}_{tj} = 0 \ \forall j$. Also, they null interference among cognitive data streams. That is, $\mathbf{h}_k^H \mathbf{w}_{tj} = 0$ for $j \neq k$. Eqs. (6) and (7) can be written in a matrix form as

$$\mathbf{HW} = \mathbf{I}_0 \quad (8)$$

where $\mathbf{H}$ is the $N_t \times N_t$ channel matrix expressed as

$$\mathbf{H} = \left[\mathbf{h}_p, \mathbf{h}_1, \mathbf{h}_2, \ldots, \mathbf{h}_{(N_t-1)} \right]^T. \quad (9)$$

The matrix $\mathbf{W}$ denotes $N_t \times (N_t - 1)$ transmit beamforming weights which is

$$\mathbf{W} = \left[\mathbf{w}_{t1} \ \mathbf{w}_{t2} \ldots \mathbf{w}_{t(N_t-1)} \right]. \quad (10)$$

The variable $\mathbf{I}_0$ is defined as

$$\mathbf{I}_0 = \begin{bmatrix} \mathbf{0}_{1 \times (N_t-1)} \\ \mathbf{I}_{(N_t-1) \times (N_t-1)} \end{bmatrix} \quad (11)$$

where $\mathbf{I}$ is an identity matrix. Transmit beamforming weights can be easily found by inverting the channel matrix of the PU and $N_t - 1$ selected users which is given as

$$\mathbf{W} = \left(\mathbf{H}^H\mathbf{H}\right)^{-1}\mathbf{H}^H\mathbf{I}_0 . \quad (12)$$

The modified zero forcing beamforming can be extended to incorporate multiple PUs. Due to no interference power caused by the CRUs at the PU using Eq. (6), then, Eq. (1) is reduced to

$$y_p = \sqrt{P_p}g_p s_p + z_p . \quad (13)$$

Meanwhile, Eq. (7) satisfies the interference-free among the CRUs. Then, Eq. (3) becomes

$$y_k = \sqrt{P_k}s_k + \sqrt{P_p}g_k s_p + z_k . \quad (14)$$

Eqs. (13) and (14) indicate that the CR system can successfully coexist with the primary system under a tolerable interference to the CRUs generated from the PBS.

3.2 Transmit-receive (MIMO) Beamforming

For wireless transmission, multiple-input multiple-output (MIMO) system is a great potential method to enlarge capacity without bandwidth expansion, enhance transmission reliability via space-time coding and cancel interferences for multiuser transmission. In this second method, both transmit and receive weight vectors in the CR system are therefore designed to protect the primary system from harmful interference and minimize the self-interferences.

At the CRBS, Gram-Schmidt orthogonalization is utilized to create the orthogonal transmit beams ($\mathbf{w}_{tk}$ for $k = 1,\ldots,N_t - 1$). At the CRU, the receive beams ($\mathbf{w}_{rk}$ for $k = 1,\ldots,N_t - 1$) are obtained by minimizing the mean output power of the antenna array constrained to maintaining the unity response at the considered CRU and small sum responses from other CRUs. For comparison, we also show the receive beamforming weight obtained by maximizing the SINR for each CRU.

3.2.1 Orthogonal Transmit Beamforming Generated by Gram-Schmidt Orthogonalization

According to Gram-Schmidt method, the CRBS with N_t antennas firstly generates $N_t - 1$ beams orthogonal to the PU's channel $\mathbf{h}_p$. This allows the CRBS transmits data to CRUs without interfering the PU. The procedure of Gram-Schmidt orthogonalization to create orthogonal transmit beams is as follows [13]:

1. Generate independent N_t vectors $\mathbf{v}_k$ for $k = 1,2,\ldots,N_t$ by using $\mathbf{v}_1 = \mathbf{h}_p$. Let N_t arbitrary vector set $\mathbf{v}_k$ be obtained from $\mathbf{h}_p$ as

$$\mathbf{v}_k = \left[h_{p,1}, h_{p,2}, \ldots, h_{p,k} + \alpha, \ldots, h_{p,N_t}\right]^T \quad (15)$$

where α denotes an arbitrary number for linear independency with $\mathbf{h}_p$.

2. Generate orthogonal N_t vectors by

$$\mathbf{u}_k = \mathbf{v}_k - \sum_{j=1}^{k-1}\frac{\mathbf{u}_j^H\mathbf{v}_k}{\mathbf{u}_j^H\mathbf{u}_j}\mathbf{u}_j \quad \text{for} \quad k = 2,\ldots,N_t - 1 \quad (16)$$

where $\mathbf{u}_1 = \mathbf{v}_1$.

3. The transmit beamforming weight is the normalization of

$$\mathbf{w}_{tk} = \frac{\mathbf{u}_k}{\left\|\mathbf{u}_k\right\|} \quad \text{for } k = 1,2,\ldots,N_t - 1 \quad (17)$$

It satisfies that $\mathbf{h}_p^H\mathbf{w}_{tk} = 0 \ \forall k$. Consequently, the CRBS can completely null interferences to the PU. This property yields an expression of Eq. (1) as same as Eq. (13) which is $y_p = \sqrt{P_p}g_p s_p + z_p$.

3.2.2 Receive Beamforming

In this subsection, two receive beamforming techniques are presented. The first objective is to minimize the mean output power constrained that the main beam has a unit response at the desired CRU and the side lobes have small responses at other CRUs. The objective of the second algorithm is to maximize the SINR at the CRU receiver.

3.2.2.1 Receive Beamforming Generated by Constrained Minimization of the Mean Output Power

The receive beamforming weight is the solution of the following optimization problem.

$$\min_{\mathbf{w}_{rk}} \ \mathbf{w}_{rk}^{H}\mathbf{R}_k\mathbf{w}_{rk} \tag{18}$$

$$\text{subject to} \quad \mathbf{w}_{rk}^{H}\mathbf{H}_k\mathbf{w}_{tk} = 1 \tag{19}$$

$$\sum_{j\neq k}^{N_t-1}\sqrt{P_j}\,\mathbf{w}_{rk}^{H}\mathbf{H}_k\mathbf{w}_{tj} = \varepsilon \tag{20}$$

where $\mathbf{R}_k = \mathbf{r}_k\mathbf{r}_k^H$ is a correlation matrix estimated by using the received signal at the k-th CRU given by

$$\mathbf{r}_k = \sum_{j=1}^{N_t-1}\sqrt{P_j}\,\mathbf{H}_k\mathbf{w}_{tj}s_j + \sqrt{P_p}\,\mathbf{g}_k s_p + \mathbf{z}_k \tag{21}$$

and ε is a small positive value. Although, this is to minimize the mean output power of the receive antenna array, it still keep a unity response at the desired direction and null interferences at other undesired directions. The optimal weight can be solved using Lagrange multiplier (λ_1, λ_2) as

$$\mathbf{w}_{rk} = \frac{1}{2}\mathbf{R}_k^{-1}\left[\lambda_1\left(\mathbf{H}_k\mathbf{w}_{tk}\right) + \lambda_2\left(H_k\sum_{j\neq k}^{N_t-1}\mathbf{w}_{tj}\right)\right] \tag{22}$$

$$\mathbf{w}_{rk}^{H}\mathbf{H}_k\mathbf{w}_{tk} - 1 = 0 \tag{23}$$

$$\sum_{j\neq k}^{N_t-1}\sqrt{P_j}\,\mathbf{w}_{rk}^{H}\mathbf{H}_k\mathbf{w}_{tj} - \varepsilon = 0 \tag{24}$$

These three equations can be solved to find three unknown variables $(\mathbf{w}_{rk}, \lambda_1, \lambda_2)$. If we reduce the constrain by only maintaining the unity response at the desired CRU, the problem then becomes finding $\mathbf{w}_{rk}$ to satisfy

$$\min_{\mathbf{w}_{rk}} \ \mathbf{w}_{rk}^{H}\mathbf{R}_k\mathbf{w}_{rk} \quad \text{subject to} \quad \mathbf{w}_{rk}^{H}\mathbf{H}_k\mathbf{w}_{tk} = 1 \tag{25}$$

We use the Lagrange multiplier method

$$L\left(\mathbf{w}_{rk}, \lambda\right) = \mathbf{w}_{rk}^{H}\mathbf{R}_k\mathbf{w}_{rk} - \lambda\left(\mathbf{w}_{rk}^{H}\mathbf{H}_k\mathbf{w}_{tk} - 1\right). \tag{26}$$

Taking the derivative of Eq. (26) with respect to $\mathbf{w}_{rk}$ and setting it to zero.

$$\frac{\partial L}{\partial \mathbf{w}_{rk}} = 2\mathbf{R}_k\mathbf{w}_{rk} - \lambda\mathbf{H}_k\mathbf{w}_{tk} = 0 \tag{27}$$

$$\mathbf{w}_{rk} = \frac{1}{2}\lambda\mathbf{R}_k^{-1}\mathbf{H}_k\mathbf{w}_{tk}. \tag{28}$$

In order to calculate the value of λ, take the derivative of Eq. (26) with respect to λ and set it to zero.

$$\frac{\partial L}{\partial \lambda} = \mathbf{w}_{rk}^{H}\mathbf{H}_k\mathbf{w}_{tk} - 1 = 0 \tag{29}$$

Substitute Eq. (28) into Eq. (29),

$$\left(\frac{1}{2}\lambda\mathbf{R}_k^{-1}\mathbf{H}_k\mathbf{w}_{tk}\right)^{H}\mathbf{H}_k\mathbf{w}_{tk} = 1 \tag{30}$$

$$\lambda = 2\left(\mathbf{w}_{tk}^{H}\mathbf{H}_k^{H}\mathbf{R}_k^{-1}\mathbf{H}_k\mathbf{w}_{tk}\right)^{-1}. \tag{31}$$

Substituting Eq. (31) into Eq. (28), it yields

$$\mathbf{w}_{rk} = \frac{\mathbf{R}_k^{-1}\mathbf{H}_k\mathbf{w}_{tk}}{\left\|\mathbf{R}_k^{-1}\mathbf{H}_k\mathbf{w}_{tk}\right\|}. \tag{32}$$

3.2.2.2 Receive Beamforming Generated by Maximum SINR Reception

From Eq. (4), the $SINR_k$ at the k-th CRU is expressed as

$$SINR_k = \frac{P_k\left|\mathbf{w}_{rk}^{H}\mathbf{H}_k\mathbf{w}_{tk}\right|^2}{\sum_{j\neq k}P_j\left|\mathbf{w}_{rk}^{H}\mathbf{H}_k\mathbf{w}_{tj}\right|^2 + P_p\left|\mathbf{w}_{rk}^{H}\mathbf{g}_k\right|^2 + \sigma_k^2} \tag{33}$$

$$= \frac{P_k\left(\mathbf{w}_{rk}^{H}\mathbf{H}_k\mathbf{w}_{tk}\right)^{H}\left(\mathbf{w}_{rk}^{H}\mathbf{H}_k\mathbf{w}_{tk}\right)}{\mathbf{w}_{rk}^{H}\left(\sum_{j\neq k}P_j\mathbf{H}_k\mathbf{w}_{tj}\mathbf{w}_{tj}^{H}\mathbf{H}_k^{H} + P_p\mathbf{g}_k\mathbf{g}_k^{H} + \sigma_k^2\mathbf{I}_{N_r\times N_r}\right)\mathbf{w}_{rk}}. \tag{34}$$

We define the total interference plus noise covariance matrix at the k-th CRU as

$$\mathbf{C}_k = \sum_{j\neq k}^{N_t-1}P_j\mathbf{H}_k\mathbf{w}_{tj}\mathbf{w}_{tj}^{H}\mathbf{H}_k^{H} + \mathbf{g}_k\mathbf{g}_k^{H} + \sigma_k^2\mathbf{I}_{N_r\times N_r}. \tag{35}$$

Eq. (34) can be formulated as follows

$$SINR_k = \frac{P_k\left(\mathbf{w}_{rk}^H\mathbf{H}_k\mathbf{w}_{tk}\right)^H\left(\mathbf{w}_{rk}^H\mathbf{H}_k\mathbf{w}_{tk}\right)}{\mathbf{w}_{rk}^H\mathbf{C}_k\mathbf{w}_{rk}} \quad (36)$$

$$= P_k\left(\mathbf{w}_{rk}^H\mathbf{H}_k\mathbf{w}_{tk}\right)^H\left(\mathbf{w}_{rk}^H\mathbf{C}_k\mathbf{w}_{rk}\right)^{-1}\left(\mathbf{w}_{rk}^H\mathbf{H}_k\mathbf{w}_{tk}\right) \quad (37)$$

$$= P_k\mathbf{w}_{tk}^H\mathbf{H}_k^H\mathbf{C}_k^{-1}\mathbf{H}_k\mathbf{w}_{tk}. \quad (38)$$

From Eq. (38), the receive beamforming vector can be expressed as [19]

$$\mathbf{w}_{rk} = \mathbf{C}_k^{-1}\mathbf{H}_k\mathbf{w}_{tk}. \quad (39)$$

The optimal receive beamforming weight vector can be normalized and given be

$$\mathbf{w}_{rk} = \frac{\mathbf{C}_k^{-1}\mathbf{H}_k\mathbf{w}_{tk}}{\left\|\mathbf{C}_k^{-1}\mathbf{H}_k\mathbf{w}_{tk}\right\|}. \quad (40)$$

Accordingly, the optimal receive beamforming weights of both designs can be determined if the transmit beams is given with prior knowledge of the channel state information. Notice that Eq. (40) is the same as Eq. (32) because $\mathbf{C}_k = \mathbf{R}_k$ if the magnitude of symbol equal to one. This verifies that the receive beamforming weight generated by the constrained minimization of the mean output power outperforms the method by the maximum SINR reception because the constraint includes the self-interference mitigation which is not considered in the maximum SINR reception method.

4 Subspace-based Cognitive User Selection

In MIMO system, the number of CRUs is limited by the number of antennas equipped in the CRBS. Moreover, as the number of CRUs increases, the accumulated self-interferences also increase. This may cause the sum-rate of the CR network decreases. Then, a subset of CRUs should be selected. However, due to the proposed orthogonal transmit beamforming method, it can guarantee no interference to PUs, even if the number of CRUs is large. Consequently, CRUs that have large channel gain and uncorrelated should be selected regardless of the PU's channel gain. We propose a multiuser selection strategy based on the subspace theory [12] which can maintain the orthogonality among CRUs as much as possible. The procedure can be illustrated as follows:

```
Initialization  $S = \phi\{\text{empty set}\}$
                $T = \{1, 2, \ldots, K\}$
while $|S| < N_t - 1$
    for $k \in T - S$
        $\mathbf{H}_k^{proj} = \mathbf{H}_k\left[\mathbf{I}_{N_r\times N_r} - \sum_{i\in|S|}\mathbf{H}_i\left(\mathbf{H}_i^H\mathbf{H}_i\right)^{-1}\mathbf{H}_i^H\right]$
    end
        $k^* = \arg\max_{k\in T-|S|}\left\|\mathbf{H}_k^{proj}\right\|$
        $S = S \cup \{k^*\}$
end
```

In the proposed subspace-based user selection algorithm, we calculate its component orthogonal to the row space spanned by secondary links of those CRUs selected out already. Then, the CRU with maximal norm of orthogonal component will be added into set S. This is repeated until $|S| = N_t - 1$.

5 Simulation Results

In order to evaluate the performance, bit error rates (BERs) and symbol error rates (SERs) are first considered. Throughout the simulation, we set the number of transmit antennas $N_t = 4$. In the case of MIMO beamforming, the number of receive antennas, $N_r = 4$ is used. We assign $\varepsilon = 0.1$, $P_p = 1\,\text{dB}$, $P_k = \frac{1}{3}\,\text{dB}$ for $k = 1, 2, 3$ and assume that channel is Rayleigh fading with zero mean and variance = 0.5. 50,000 Monte Carlo trials are run per SNR (signal to noise ratio). Figures 2 and 3 show the BERs and SERs versus SNRs at the PU receiver, respectively. The results from modified zero forcing beamforming (MZFB), Gram-Schmidt and MIMO beamforming are exactly the same as the ideal case (Eq. (13)). This proves that the CR system causes no interference to the PU. Figures 4 and 5 show BERs and SERs versus CRU's SNRs at the one of the considered CRU receiver. For comparison, "idealMZFB" and "idealMIMO" are the cases the received signal of the considered CRU has no the second term appearing in Eq. (3). The considered CRU is suffered from interferences generated by PU and the rest two CRUs. The performance using the Gram-Schmidt method is used as an upper bound since it is not designed to cancel the self-interference. As a lower bound, both

MZFB and "idealMZFB" are the best and close to each other. The MIMO beamforming and "idealMIMO" begin to separate for high SNRs. As expectedly, MZFB is more efficient than MIMO beamforming since MZFB is able to cancel the self-interferences better than MIMO beamforming.

The performance of the proposed subspace-based cognitive user selection is secondly considered. In this simulation, we fix the variance of noise equal to one. Figure 6 shows the sum-rate of CRUs versus the number of CRUs. It outperforms choosing users randomly no matter of MZFB method and MIMO beamforming method.

The influence of transmit power to the sum-rate of the primary and secondary systems is illustrated. Accordingly to Fig. 7, the power transmitted by the CRBS has no impact to the sum-rate of the primary system regardless of any scheduling schemes since both MZFB and MIMO beamforming methods cause interference-free to the PU. However, the CRUs are affected by the PBS transmit power. In Fig. 8, the power transmitted by PBS increases, the sum-rate of CR system decreases, especially, using MZFB beamforming. Definitely, the sum-rate of CR system increases as the transmit power of CRBS increases as shown in Fig. 9.

The performance of MIMO beamforming varying to the constrained value ε is shown in Fig. 10. This plot indicates if we set the constrain high, the sum-rate of CR system is worse due to the increase of the self-interferences. The proposed subspace-based user selection increases the sum-rate of the CR system more than the random selection.

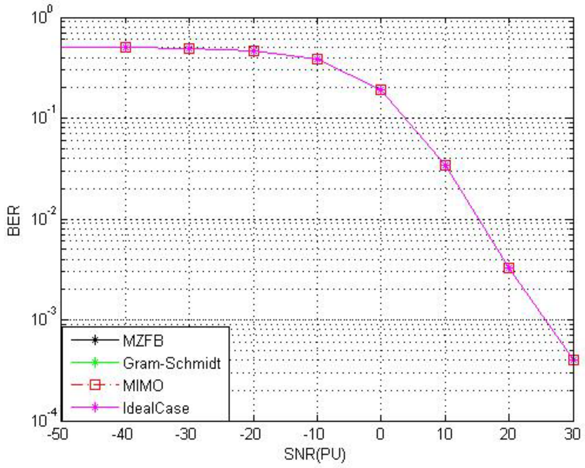

Figure 2 BERs at the PU receiver versus PU's SNRs using BPSK

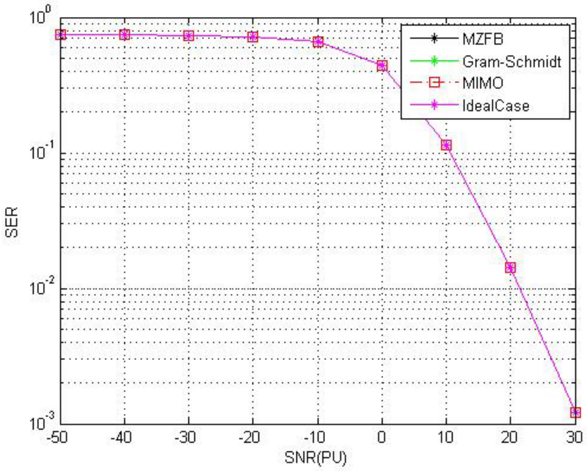

Figure 3 SERs at the PU receiver versus PU's SNRs using QPSK

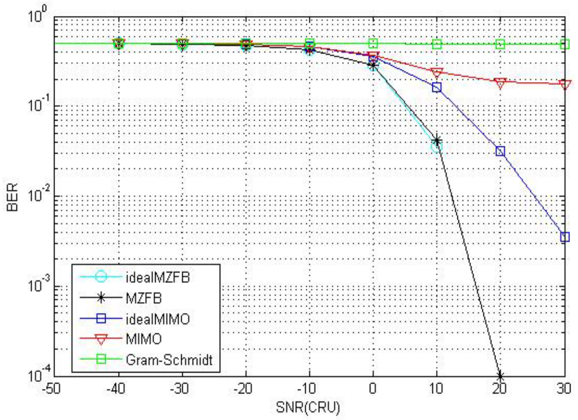

Figure 4 BERs at the considered CRU receiver versus CRU's SNRs using BPSK

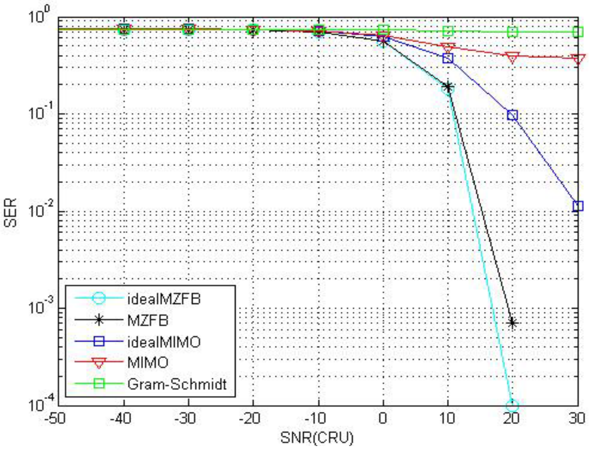

Figure 5 SERs at the considered CRU receiver versus CRU's SNRs using QPSK

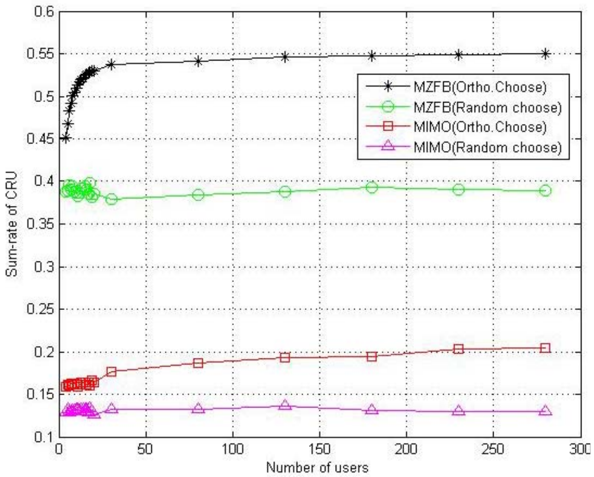

Figure 6 Sum-rate of CR system versus the number of CRUs

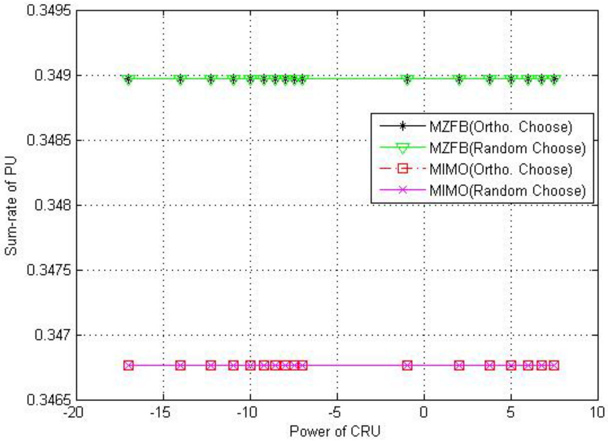

Figure 7 Sum-rate of primary system versus the CRBS transmission power

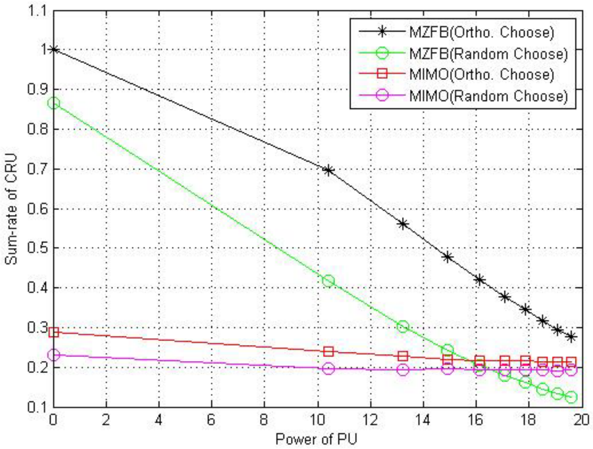

Figure 8 Sum-rate of CR system versus the PBS transmission powers

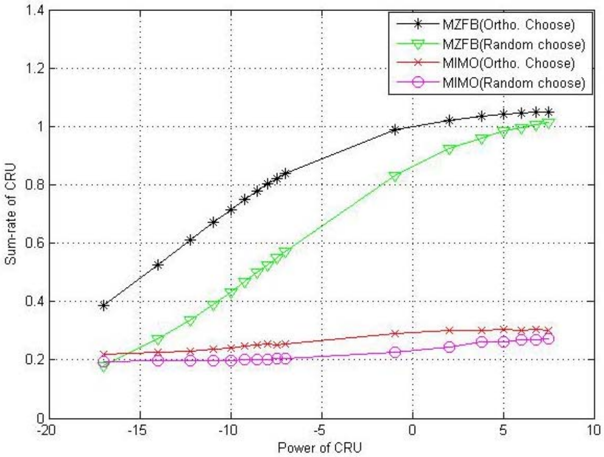

Figure 9 Sum-rate of CR systems versus CRBS transmission power

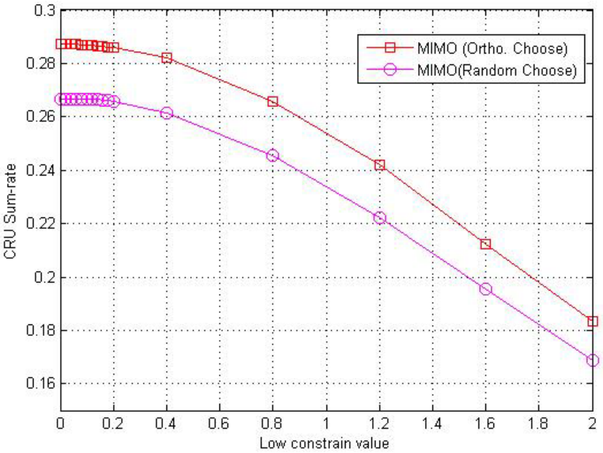

Figure 10 Sum-rate of CR systems versus the constrain value ε

6 Conclusions

We proposed the modified zero forcing beamforming and MIMO beamforming for spectrum sharing in the downlink of cognitive radio networks. Modified zero forcing beamforming is capable of protect the primary user from interferences generated by the cognitive radio base station as well as cancel the self-interference among the cognitive radio users. In MIMO beamforming, orthogonal transmit beams designed by Gram-Schmidt method provides PU interference-free. Receive beams is designed by minimizing of the mean output array constrained to a unity response at the desired cognitive radio user and null responses to other users. A solution of the optimization problem between the maximum SINR reception and minimizing of the mean output array constrained to a unity response at the desired cognitive radio user are shown to guarantee the generated receive beams. Presented scheduling method to select the cognitive radio users that are orthogonal as much as possible can increase the sum-rate of the cognitive radio networks.

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