

Low-Complexity Antenna Selection and User Scheduling in Cognitive MIMO Broadcast Systems[†]

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Abstract—In this paper, we consider the coexistence between a large number of cognitive radio users and a licensed user in order to enhance the spectrum efficiency. Zero-forcing beamforming (ZFB) is utilized as a downlink precoding technique that precancels inter-user interference in our multiuser cognitive multiple-input/multiple-output (MIMO) system. When there is a large number of users, the system performance can be significantly increased by selecting a subset of users and a set of receive antennas for each user. In particular, to reduce the complexity, we propose a receive antenna selection method followed by multi-user selection in order to maximize the downlink throughput as well as mitigate the interference to the primary user. Performance results show that our proposed method is able to achieve significant complexity reduction at the expense of a little sum-rate throughput loss.

I. INTRODUCTION

Recently, intense competition for spectrum usage has arisen, especially for the spectrum below 3 GHz. Studies from the Federal Communication Commission (FCC) have shown that the utilization of licensed spectrum only ranges from 15% to 85% [1]. To deal with the conflicts between spectrum congestion and spectrum under-utilization, the FCC needs a distributed and dynamic approach to manage radio frequencies in order to perform better spectrum sharing. To accomplish this, “cognitive radio” has been proposed as a smart and agile technology which allows non-legitimate users to utilize licensed bands opportunistically [2]. However here and in contrast to this conventional approach, we allow the cognitive radio to proceed with simultaneous transmission, if certain conditions are met. Thus, when sharing the spectrum with the primary user, one tries to find a way to increase the system performance while getting rid of the harmful interference caused to the primary user.

In a multiple-input/multiple-output (MIMO) system, multiple antennas can be used at the transmitter and receiver. A MIMO system takes advantage of the spatial diversity that is obtained by spatially separated antennas in a dense multipath scattering environment. MIMO systems may be implemented in a number of different ways to obtain either a diversity gain to combat signal fading or to obtain a capacity gain. Multiple antennas can be usually deployed at the base station, but they

cannot be used easily at the mobile users due to the size and cost constraints. Hence, the small number of antennas at the receiver may limit the performance of the system. One solution to this is to serve multiple users at the same time.

MIMO spatial multiplexing systems using linear receivers are important in practice due to their low complexity advantage. Compared to the optimal Maximum Likelihood receiver, linear receiver can lead to a loss of diversity which is critical in independent identically distributed (i.i.d.) Rayleigh fading channels. Antenna selection is a promising method which is capable of achieving high diversity order with low complexity implementation for MIMO systems with linear receiver. The main idea behind antenna selection is to select a small set of best antennas from a larger set of available antennas. The optimal selection is the exhaustive search over all the possible combinations in order to obtain the antenna that gives the best performance in terms of signal-to-noise ratio (SNR) or capacity [3]. However, the computational complexity required for such a selection scheme is very high and it was shown to grow exponentially with the total number of antennas. Various antenna selection algorithms have been presented in [3]. The simplest scheme is based on the power of received signals. However, this method is not optimal and breaks down when MIMO spatial multiplexing is applied for high capacity. For receive antenna selection, a good approach was proposed by Gorokhov [4] to find a near optimal subset selection based on maximizing the channel capacity, but this algorithm is considered to have a high complexity.

In our paper, we propose a novel receive antenna selection technique followed by user selection for MIMO spatial cognitive systems. For the receive antenna selection, each user selects the most favorable receive antenna. In particular, by applying SVD to all users’ channel matrices, only the eigenvectors whose corresponding singular values are the maximum are considered. Secondly, among these candidate eigenvectors, the algorithm chooses a set of size M users which are nearly orthogonal to each other and nearly orthogonal to the primary user based on *near-orthogonal* user selection scheme. Our algorithm combined with a zero-forcing beamforming (ZFB) is able to achieve a reduction of the complexity of search and required feedback, when the receive antennas are selected, at the expense a little loss in throughput.

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The rest of the paper is organized as follows. In Section II, the system model and the problem formulation are introduced. The proposed algorithm for user and receive antenna selection is described in Section III. In Section IV, the complexity computation is analyzed. Numerical results are presented and discussed in Section V. Finally, conclusions are drawn in Section VI.

II. SYSTEM MODEL

In our system, the primary network consists of a primary base station that transmits signals to a single primary user. In the same area, a cognitive radio network shares the same spectrum resource with the primary network. The secondary cognitive network has a single cognitive base station serving K secondary users. We consider the downlink of the cognitive radio network in which the base station, deployed by a uniformly spaced M -element antenna array, transmits independent signals to the K cognitive users, each equipped with N_k antennas, $k = 1, \dots, K$. Throughout this paper, we assume that $M \ll K$, and that the devices in the primary network are equipped with a single antenna. Due to sharing of the same frequency, the received signal at the primary user is interfered by the signals transmitted by the cognitive base station. Similarly, the received signals at the cognitive radios are interfered by the signal transmitted by the primary user.

Assume that in one time slot, a block of information symbol $\mathbf{s} = [s_1, s_2, \dots, s_K]^T$ are sent from the cognitive base station in which s_k , $(1, \dots, K)$ is the desired signal for user k . $(\cdot)^T$ stands for the transpose. We assume that $\mathbf{s}$ contains uncorrelated unit-power entries. The transmit signal is given by

$$\mathbf{x} = \mathbf{W}\mathbf{P}\mathbf{s}, \quad (1)$$

where $\mathbf{W} = [\mathbf{w}_1 \ \mathbf{w}_2 \ \dots \ \mathbf{w}_K]$ denotes the transmit beamforming matrix, and $\mathbf{P}$ accounts for power loading.

The receive signal at the k -th cognitive user is given by

$$\mathbf{y}_k = \mathbf{H}_k\mathbf{x} + \sqrt{P_p}\mathbf{g}_k s_p + \mathbf{n}_k, \quad (2)$$

where $\mathbf{H}_k \in \mathbb{C}^{N_k \times M}$ denotes the channel from the cognitive base station to the k -th cognitive user. The (n, m) -th entry $h_k(n, m) \sim \mathcal{CN}(0, 1)$ is i.i.d complex Gaussian with zero mean and unit variance and represents the complex channel gain from the transmit antenna m to the receive antenna n of the k -th cognitive user. P_p denotes the transmitted power of the primary user. $\mathbf{g}_k$ represents the $(N_k \times 1)$ channel vector between the primary base station and the k -th cognitive user, and s_p represents the transmitted signal from the primary base station. Finally, $\mathbf{n}_k$ is a $(N_k \times 1)$ vector of additive noise whose entries are i.i.d. complex Gaussian with zero mean and variance σ_k^2 . Note that $\mathbf{y}_k$, $(k = 1, \dots, K)$ are physically distributed across the K cognitive users. Multiuser decoding is therefore not feasible. Hence, each user treats the signals intended for other users as interference.

One of the drawbacks of using multiple antennas is the associated complexity. With this motivation, we use antenna

selection as a means to alleviate this complexity while exploiting the diversity provided by the transmit and receive antennas, in MIMO cognitive system. In our work, with the proposed receive antenna selection, each user selects the most favorable antenna at the receiver side. Hence, the MIMO system will be equivalent to a multiple-input/single output (MISO) system. Based on this fact, the capacity of the cognitive system can be written as

$$R = \sum_{k=1}^K \log(1 + \text{SINR}_k), \quad (3)$$

where SINR_k denotes the signal-to-interference and noise ratio of the k -th cognitive user. Using the received signal expression in (2), it can be expressed as

$$\text{SINR}_k = \frac{|\mathbf{h}_k^T \mathbf{w}_k|^2 P_k}{\sum_{q \neq k} |\mathbf{h}_k^T \mathbf{w}_q|^2 P_q + |g_k|^2 P_p + \sigma_k^2}, \quad (4)$$

where $\mathbf{h}_k$ is a $(M \times 1)$ vector and denotes the channel link between the cognitive base station and the k -th cognitive user.

To determine the beamforming weight, ZFB is investigated, in which the base station determines the beamforming vector associated with each selected user by optimizing a certain criterion to reach a specific purpose such as maximizing the throughput or minimizing the interference. The mutual interference among the selected users can be nulled by selecting appropriate weighting vectors according to the principle of ZFB [5] which transforms the broadcast channel into multiparallel independent and orthogonal sub-channels. In ZFB, the weight beamforming vectors are selected such that they satisfy the interference free condition $\mathbf{h}_k \mathbf{w}_j = 0$ for $j \neq k$. With ZFB, the beamforming weights vectors $\mathbf{W}(S)$ are obtained by inverting the channel matrix of the selected users $\mathbf{H}(S)$ so that an interference free between the cognitive channels can be achieved, where S is the set of the M selected cognitive users. $\mathbf{W}(S)$ is then given as

$$\mathbf{W}(S) = \mathbf{H}(S)^\dagger = \mathbf{H}(S)^H (\mathbf{H}(S)\mathbf{H}(S)^H)^{-1}. \quad (5)$$

In the above equation, $(\cdot)^\dagger$ and $(\cdot)^H$ stand for the pseudo-inverse and the conjugate transpose, respectively. The use of ZFB at the cognitive base station is aimed to significantly decrease the complexity of precoding in the proposed selection algorithm.

In this paper, we propose a spectrum sharing scheme that enables the opportunistic use of the cognitive users to coexist with the primary user in order to improve the spectrum efficiency. In particular, the core aim behind our work is to formulate a low-complexity algorithm that pre-selects the best receive antenna for each user, then a set of M cognitive users with single best antennas are selected in order to reduce the interference to the primary user. Furthermore, the receive antenna selection basically aims to reduce the complexity of search of the user selection.

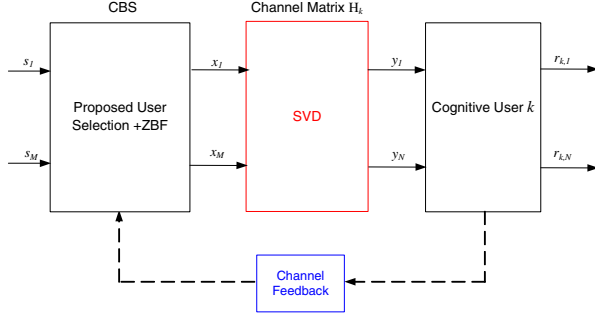


Fig. 1. MIMO SVD block diagram. The plot shows the proposed user selection algorithm for the MIMO downlink system.

III. PROPOSED USER AND RECEIVE ANTENNA SELECTION ALGORITHM

In this section, we develop an algorithm with low complexity that selects the best set of receive antennas, and then, from those candidates, the set of users that satisfies the system conditions are scheduled.

A. Receiver design

The receiver processing strategy adopted in this paper will be explained in the following. The SVD of the channel matrix $\mathbf{H}_k$ is given by

$$\mathbf{H}_k = \mathbf{U}_k \mathbf{\Lambda}_k \mathbf{V}_k^H, \quad k = 1, \dots, K \quad (6)$$

where $\mathbf{\Lambda}_k$ is an $(N_k \times M)$ diagonal matrix containing the singular values of $\mathbf{H}_k$, $\mathbf{U}_k$ and $\mathbf{V}_k$ are $(N_k \times N_k)$ and $(M \times M)$ unitary matrices, respectively. The received vector for the k -th user $\mathbf{y}_k$ in (2) can be rewritten as

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{x} + \tilde{\mathbf{n}}_k, \quad k = 1, \dots, K \quad (7)$$

where $\tilde{\mathbf{n}}_k = \sqrt{P_p} \mathbf{g}_k s_p + \mathbf{n}_k$. Let $\mathbf{u}_{k,n}$ be the n -th column of $\mathbf{U}_k$. Multiplying both sides of (7) by $\mathbf{u}_{k,n}^H$, we can get

$$r_{k,n} = \mathbf{f}_{k,n} \mathbf{x} + w_{k,n}, \quad k = 1, \dots, K, \quad n = 1, \dots, N_k \quad (8)$$

where

$$r_{k,n} = \mathbf{u}_{k,n}^H \mathbf{y}_k, \quad (9)$$

$$\mathbf{f}_{k,n} = \sqrt{\lambda_n(k)} \mathbf{v}_{k,n}^H, \quad (10)$$

and

$$w_{k,n} = \mathbf{u}_{k,n}^H \tilde{\mathbf{n}}_k \quad (11)$$

In the above equations, $\mathbf{v}_{k,n}$ denotes the n -th column of $\mathbf{V}_k$ and $\sqrt{\lambda_n(k)}$ is the n -th singular value of $\mathbf{H}_k$ corresponding to $\mathbf{v}_{k,n}$. The channel decomposition is depicted in the block diagram of a MIMO user in Fig. 1.

After the SVD, the resulting system can be viewed as a MIMO broadcast with $\sum_{k=1}^K N_k$ single antenna users with channel gains $\mathbf{f}_{k,n}$. In such scenario, different possibilities can be considered at the receiver side. The first case is to treat each receive antenna as an independent user, where there

will be $\sum_{k=1}^K N_k$ single antenna receivers. Then, each k -th user should feedback N_k times the amount of information since it has N_k channel links corresponding to each receive antenna. The second case is to assign at most one beam to each user. In such case, each user just feeds back its channel gain corresponding to the selection scheme and the corresponding index n for that channel gain. Another case is to assign multiple beams to each user. So, N_k beams are either assigned to the k -th user or no beams at all. As mentioned earlier, the first case is effectively the same as having $\sum_{k=1}^K N_k$ cognitive users with single receive antennas. The second case is a generalization of the case with $N = 1$, and it turns out that the analysis of this case is very similar to the case with $N = 1$. On the other hand, the last case is quite different from the previous two and requires more effort to be analyzed. In terms of the amount of feedback, clearly the first case requires N times more feedback than that of the second and the third cases.

In [6], based on SVD, the system is viewed as a MIMO channel with $\sum_{k=1}^K N_k$ and the selection can be applied to those single users. However, by applying this method, the antennas can be selected from the same user, which is not fair. Indeed, to guarantee fairness between users and multiuser diversity, all users should have the chance to be selected. In [7], for the MIMO case, each receive antenna at the receiver is treated as an individual user, then the system will be equivalent to $\sum_{k=1}^K N_k$ single antenna receiver. Based on the aforementioned receiver, it has been also shown that each receive antenna should be treated as an individual user in order to achieve the largest throughput. Therefore, the K user $(M \times N_k)$ system is converted to $(\sum_{k=1}^K N_k)$ -user $(M \times 1)$ system.

B. Receive antenna selection

In the following, the proposed antenna selection algorithm will be described. The key idea behind our scheduling algorithm is that each user selects at the first stage the most favorable receive antenna of index n . The receive antenna is selected based on the channel conditions, i.e., for each user we select the receive antenna with the best channel link. In particular, by applying SVD to all users' channel matrices, only the eigenvectors whose corresponding singular values are the maximum are considered. Using such a method, the amount of feedback and the size of selecting space for selecting the candidates is reduced. Let $\mathcal{A}$ denote the set of the selected receive antennas. The algorithm is described in the following.

Let p, q be the indices for the selected receive antenna and its corresponding user, respectively. After the antenna selection, the selected coordinate matrix can be written as

$$\mathbf{F} = [\mathbf{f}_{q_1, p_1}^T \quad \mathbf{f}_{q_2, p_2}^T \quad \dots \quad \mathbf{f}_{q_M, p_M}^T]^T, \quad (12)$$

where $\mathbf{f}$ is given in (10). After applying ZFB, $\mathbf{W} = \mathbf{F}^\dagger$, using (8), the received signal is given by

$$r_{q_l, p_l} = \lambda_{p_l}(q_l) \sqrt{P_l} s_l + w_{q_l, p_l}, \quad l = 1, \dots, M \quad (13)$$

where l is the index of the received signal. Obviously, applying ZFB is of great interest of decomposing the channel to M interference-free sub-channels among users.

Receive Antenna Selection

- 1) Initialization: $\mathcal{A} = \emptyset$.
 - 2) For $k = 1 : K$,
 - 2.1) Using SVD, the k -th cognitive user calculates the eigenvectors and singular values of its channel based on (6). Then, it sends back the maximum singular matrix values, along with their corresponding "right" eigenvectors, to the cognitive base station.
 - 2.2) Select the receive antenna n such that $n = \arg \max \lambda_n(k)$, $\mathcal{A} = \mathcal{A} \cup \{n\}$.
 - end
 - 3) Sort the elements in $\mathcal{A}$ in a descending order of $\sqrt{\lambda_n(k)}$.
-

The next step is the user selection. In this step, we apply a user selection on the K selected antennas.

C. Near-orthogonal user selection

We propose an efficient algorithm with low-complexity, which we refer to as *near-orthogonal* user selection [8], for selecting the set of the appropriate users in order to improve the system performance. The *near-orthogonal* user selection algorithm is performed in two sub-steps. Firstly, a cognitive user k is selected when the *near-orthogonality* condition to the primary user is satisfied. The *near-orthogonality* is defined as follows:

Let $\Delta(\mathbf{h}_i, \mathbf{h}_j) \triangleq \frac{|\mathbf{h}_i \mathbf{h}_j^H|}{\|\mathbf{h}_i\| \|\mathbf{h}_j\|}$, then, user i and j are *near-orthogonal* if and only if

$$\Delta(\mathbf{h}_i, \mathbf{h}_j) \leq \delta, \quad (14)$$

where δ is the threshold of orthogonality. The selected users are then sorted based on their channel magnitudes in order to guarantee that the scheduled users have relatively large channel gains. In the second step, if the number of users in the set $\mathcal{S}$ of the selected users satisfies $|\mathcal{S}| < M$, the algorithm proceeds to the selection part (i.e., the users are selected if they satisfy the *near-orthogonality* condition to each other). Otherwise, the algorithm is stopped. After this user selection, the interference of the selected users to the primary user and to each other is reduced. Besides, the selected users have a relative large channel gains.

IV. COMPLEXITY ANALYSIS

In this section, we investigate the complexity of our algorithm in terms of the amount of feedback required from the users to the base station, and the number of searches required for selection in both receive antenna and user selection.

A. Receive antenna selection

The use of the receive antennas selection will allow us to further decrease the complexity of the user selection. In

this subsection, we investigate the complexity of our proposed algorithm in terms of the amount of feedback required from the users to the cognitive base station and the search complexity.

As can be observed in the proposed algorithm, only the eigenvectors that belong to $\mathcal{A}$, must be sent back to the base station, along with their corresponding singular values. In fact, $2M$ values should be fed back to the cognitive base station for each eigenvector and singular value. In our algorithm, each cognitive user selects one receive antenna. Hence, the total number of real values to be fed back is $2MK$. As such, the amount of feedback is reduced compared to the one in [7], which is equal to $2NMK$.

Our method is also able to reduce the search complexity. In the step of receive antenna selection, only one eigenvector for each cognitive user is pre-selected. Therefore, the size of search space for the user selection stage decreases from $(\sum_{k=1}^K N_k)$ as in [6] to K , when we use our proposed receive antenna selection algorithm.

B. User selection

For simultaneous transmission, Dirty Paper Coding (DPC) [9] was shown to be the optimal strategy in MIMO broadcast channels. However, DPC is known to be difficult to implement in practical systems. In the following, the complexity of the our proposed algorithm is analyzed and compared with that of DPC

- The complexity of DPC is presented by an optimization problem that can be solved by a sum-power iterative algorithm with high complexity [10]. Compared to DPC, the complexity of our scheme is obviously reduced using *near-orthogonal* user selection algorithm.
- To obtain the beamforming weight vectors, DPC requires many matrix multiplications and inversions along with singular value decompositions [11]. However, using our proposed scheme, only one matrix inversion is needed to get the beam weight vectors.
- DPC needs to perform pre-coding that uses concatenated coding with high complexity [12]. For our scheme, because of the use of ZFB, there is no interference pre-subtraction required.

Obviously, the proposed user selection algorithm is able to lower the complexity compared to the exhaustive search. Besides, the receive antenna selection is capable to further reduce the complexity of search.

V. SIMULATION RESULTS

Note that δ_p and δ_c are the thresholds of orthogonality to the primary user and the cognitive user, respectively. In Fig. 2, the sum-rate of cognitive users under the proposed algorithm and the TDMA scheme, averaged over the channel distributions, as a function of the number of users, for $M = 2$, $N = 2$, $\delta_p = 0.9$ and $\delta_c = 0.9$, is presented. With the TDMA scheme, the user with the best channel condition is scheduled. The plots show that the performance of our proposed user and antenna selection algorithm is better than the system deploying TDMA transmission scheme.

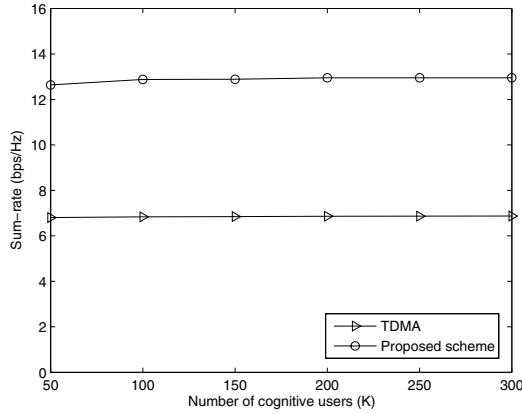


Fig. 2. Proposed selection algorithm vs. TDMA.

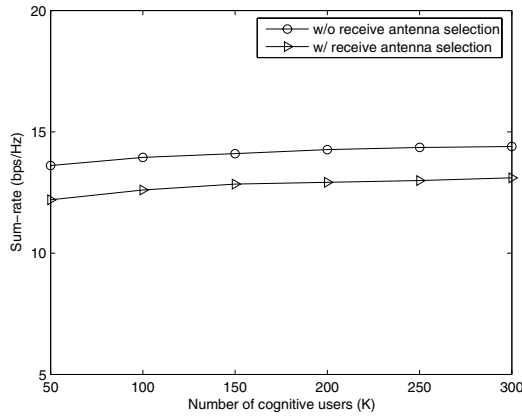


Fig. 3. Sum-rate versus Number of users with and without receive antenna selection.

Fig. 3 compares the sum-rate throughput of the proposed algorithm with and without receive antenna selection, when $M = 2$, $\delta_p = 0.8$ and $\delta_c = 0.7$. It can be seen that *near-orthogonal* user selection with receive antenna selection has worse performance than *near-orthogonal* user selection without receive antenna selection. We define the selection without antenna selection by the case where the system is equivalent to the one with $\sum_{k=1}^K N_k$ single users. This is expected, since in scheduling schemes, the multiuser diversity is exploited. In fact, a system with $\sum_{k=1}^K N_k$ cognitive users achieves a better performance compared to a system with only K users.

Fig. 4 compares the sum-rate throughput of the proposed algorithm with different number of antennas at the cognitive users $N = 2, 4$, ($k = 1, \dots, K$). In this plot, the number of transmit antenna is fixed to 2, $\delta_p = 0.8$ and $\delta_c = 0.7$. When the number of antennas at the receivers is large, the sum-rate throughput increases, which exploits the receive antenna diversity.

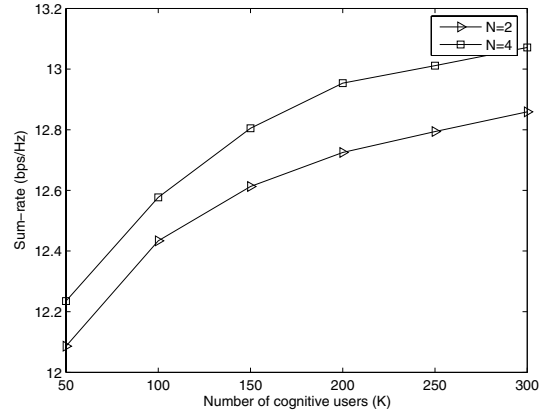


Fig. 4. Sum-rate versus Number of users with different number of antennas at the receiver.

VI. CONCLUSION

In this paper, we have considered the co-existence between cognitive users and a primary user. For this purpose, we have proposed a low-complexity receive antenna scheme followed by user selection in order to maximize the sum-rate throughput of the MIMO cognitive system and limit the interference to the primary user. Simulation results have shown that, when users are equipped with multiple antennas, our proposed user selection along with receive antenna selection is capable to further reduce the complexity of the selection with little loss of the sum-rate throughput.

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