Orthogonality-Based User and Receive Antenna Selection for MIMO Broadcast Channels

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***Abstract*—In MIMO broadcast channels, the Block Diagonalization (BD) transmit precoding performs better than the Zero-Forcing (ZF) transmit precoding when the user equipment has multiple receive antennas and can support multiple data streams. The number of users simultaneously supported by BD is much less than the total number of users in the system, so selecting proper users and/or receive antennas is important to achieve high overall sum capacity. So far, the capacity-based and norm-based user and receive antenna selection algorithms are proposed, which are greedy based and have much lower complexity than the brute-force based algorithms. In this paper, the orthogonality-based user and receive antenna selection algorithms are employed. The idea of the algorithm is simple, however, we show by detailed complexity analysis and extensive simulations that the orthogonality-based user and receive antenna selection achieves much better complexity and performance tradeoff than the existing capacity-based and norm-based algorithms. So, the orthogonality-based algorithms are more attractive for practical MIMO broadcast systems.**

***Index Terms*—MIMO, Multiuser, Scheduling, Broadcast Channels, Capacity, Precoding, Block Diagonalization**

I. INTRODUCTION

In MIMO broadcast channels, it has been shown that the dirty paper coding (DPC) [1] can achieve the sum-rate capacity (maximum throughput) [2]. However, its complexity is too high, and is difficult to be utilized in practical systems. So, BD [3] and ZF [11] are alternative low-complexity linear transmission precoding techniques, which perform asymptotically to the DPC in many scenarios [4] [11]. Comparing with ZF, the advantage of BD is that it can support multiple data streams for each user better. In the LTE-Advanced systems [5], each user is allowed to have two data streams. Thus, BD is more desired in practical systems. The drawback of the BD (also the drawback of ZF) is that it can only support up to $\lfloor N_T/N_R \rfloor$ users simultaneously, where N_T and N_R are number of transmit and receive antennas, respectively. Without loss of generality, in this paper, we assume that all the users have equal number of receive antennas. For example, if $N_T = 8$ and $N_R = 2$, then it can only support 4 users, and it is far less than the total number of users in the system. Therefore, a scheduling algorithm has to be devised to select users while being able to maximize the system capacity. So far, there have been many papers considered this problem, see for example [6]–[9]. In [6], it is assumed that the number of data streams for each user is fixed, and suboptimal capacity-based and norm-based user selection algorithms are proposed. In [7], joint user and receive antenna selection algorithms are proposed. In these algorithms, the users or receive antennas are selected based on the capacity or norm criterion. So, when doing the selection, we need to calculate and compare the capacity or norm for each candidate user or receive antenna. When calculating the capacity or norm, the BD needs to be performed in order to get the precoding matrix. Each time we perform BD, the Singular Value Decomposition (SVD) needs to be carried out multiple times. This increases the complexity quite a lot, especially when the number of users or receive antennas is large.

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By noticing the drawbacks of the existing algorithms [6]–[8] and observing that the objective of BD is to orthogonalize the channel matrix for different users, we extend the orthogonality-based user scheduling proposed for ZF [9]–[12] to the BD. This extension is somewhat straightforward. However, remarkably, we show that this orthogonality-based user and receive antenna scheduling can approach the sum capacity achieved by the existing capacity-based or norm-based algorithms [6]–[8] with much lower complexity. Thus it is more attractive for practical systems. [13] applied the orthogonality to the scheduling for BD as well, but the detailed steps are different and they did not do any complexity analysis and performance comparison with the existing capacity-based and norm-based algorithms [6]–[8].

This paper is organized as follows. In Section II, the multiuser MIMO system model and the BD algorithm are introduced, then the existing capacity-based and norm-based scheduling methods are briefly reviewed. In Section III, the orthogonality-based algorithms are described. The detailed complexity analysis and the simulation results are introduced in Section IV and V, respectively. Finally, the conclusions are given in Section VI.

II. SYSTEM MODEL AND BLOCK DIAGONALIZATION

In MIMO broadcast channels, assume that the total number of users in the system is $\tilde{K}$, and the number of users simultaneously supported during the broadcasting is K. Then the

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received signal by user k can be written as

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{T}_k \mathbf{x}_k + \mathbf{H}_k \sum_{j=1, j \neq k}^{K} \mathbf{T}_j \mathbf{x}_j + \mathbf{n}_k, \tag{1}$$

where $\mathbf{x}_k$ is the $L_k \times 1$ transmitted symbol vector and L_k is the number of data streams, $\mathbf{T}_k$ is the $N_T \times L_k$ precoding matrix, $\mathbf{H}_k$ is the $N_R \times N_T$ channel matrix with each element i.i.d. $\mathcal{CN}(0,1)$ distributed, and $\mathbf{n}_k \sim \mathcal{CN}(0, \sigma_n^2 \mathbf{I}_{N_R})$ is the $N_R \times 1$ noise vector. Assume P_k is the average transmit power constraint for user k, $P = \sum_{k=1}^{K} P_k$ is the total power constraint, and the noise is normalized, i.e., $(\sigma_n^2 = 1)$.

In BD, the inter-user interferences are eliminated at the transmitter and the intra-user interferences are eliminated at the receiver. So, the zero-interference constraint is $\mathbf{H}_j \mathbf{T}_k = \mathbf{0}$ for $j \neq k$. Define the channel matrix for all users except the user k as

$$\widetilde{\mathbf{H}}_k = \left[\mathbf{H}_1^T \ \cdots \ \mathbf{H}_{k-1}^T \ \mathbf{H}_{k+1}^T \ \cdots \mathbf{H}_K^T\right]^T,$$

then, $\mathbf{T}_k$ should lie in the null space of $\widetilde{\mathbf{H}}_k$. Define $\widetilde{L}_k = \text{rank}(\widetilde{\mathbf{H}}_k)$. Do SVD of $\widetilde{\mathbf{H}}_k$, we have

$$\widetilde{\mathbf{H}}_k = \widetilde{\mathbf{U}}_k \widetilde{\mathbf{\Sigma}}_k \left[\widetilde{\mathbf{V}}_k^{(1)} \ \widetilde{\mathbf{V}}_k^{(0)}\right]^H,$$

where $\widetilde{\mathbf{V}}_k^{(0)}$ holds the last $N_T - \widetilde{L}_k$ right singular vectors, which forms an orthogonal basis of the null space of $\widetilde{\mathbf{H}}_k$. To eliminate the inter-user interferences, we can treat $\mathbf{H}_k \widetilde{\mathbf{V}}_k^{(0)}$ as the equivalent single user MIMO channel matrix for user k. Then, the right singular vectors of $\mathbf{H}_k \widetilde{\mathbf{V}}_k^{(0)}$ can be used as the capacity achieving precoding matrix. Define $\bar{L}_k = \text{rank}(\mathbf{H}_k \widetilde{\mathbf{V}}_k^{(0)})$, do SVD of $\mathbf{H}_k \widetilde{\mathbf{V}}_k^{(0)}$, we have

$$\mathbf{H}_k \widetilde{\mathbf{V}}_k^{(0)} = \mathbf{U}_k \begin{bmatrix} \mathbf{\Sigma}_k & 0 \\ 0 & 0 \end{bmatrix} \left[\mathbf{V}_k^{(1)} \ \mathbf{V}_k^{(0)}\right]^H,$$

where $\mathbf{V}_k^{(1)}$ represents the first $\bar{L}_k$ singular vectors. The product $\widetilde{\mathbf{V}}_k^{(0)} \mathbf{V}_k^{(1)}$ generates an orthogonal basis of dimension $\bar{L}_k$, if used as the precoding matrix, can satisfy the zero interference constraint and maximize the rate for user k. Then the BD precoding matrix for user k can be written as

$$\mathbf{T}_k = \widetilde{\mathbf{V}}_k^{(0)} \mathbf{V}_k^{(1)} \mathbf{\Lambda}_k^{\frac{1}{2}},$$

where $\mathbf{\Lambda_k}$ is the power allocation matrix for the data streams of user k, and the diagonal elements of $\mathbf{\Lambda_k}$ satisfy the user k's average power constraint, i.e., trace$\{\mathbf{\Lambda}_k\} \leq P_k$, and can be adjusted to maximize the capacity by the water-filling method.

As explained before, when BD is used, a well-designed scheduling algorithm is needed. The objective of the scheduler is to select K among the total $\tilde{K}$ users to maximize the following sum capacity

$$C_{BD} = \sum_{k=1}^{K} \log_2 \left| \mathbf{I}_{N_R} + \mathbf{H}_k \mathbf{T}_k \mathbf{T}_k^H \mathbf{H}_k^H \right|. \tag{2}$$

To maximize the sum capacity, the brute-force method searches all possible combinations among the total $\tilde{K}$ users, when $\tilde{K}$ is large, the complexity is too high. So, in practice, the greedy based methods are usually used.

In [6], the authors proposed the *user* selection algorithms, where each time one user is selected and added to the active user set. The users are selected based on two criteria, one is the capacity-based criterion, and the other is norm-based criterion. In the capacity-based criterion, when trying each user candidate, the BD is performed and the sum capacity C_{BD}, i.e., (2) is calculated. Only the users that can increase the sum capacity are added to the active user set. In the norm-based criterion, the users are preselected based on the summed norm of the projected channel matrix, and then the capacity-based method is used to select the users in the preselected set. Because of the reduced cardinality, the complexity of the norm-based criterion is lower than that of the capacity-based criterion. Similarly, in [7], the capacity-based and the norm-based criteria are proposed to do *receive antenna* selection, and the difference is only in the granularity of the selection, where each time a *receive antenna* instead of a *user* is selected.

For both capacity-based and norm-based user [6] and receive antenna selections [7], the BD needs to be performed each time a comparison is made. When performing BD, we need to do SVD twice for each user in the assumed active user set. So, when the total number of users is large, the complexity of these methods are still very high. In the following, we extend the orthogonality-based method used in the ZF precoding [9]–[12] to the BD case to do user and receive antenna selection. It is somewhat straightforward, however, we will show later that, comparing with the existing methods [6] [7], surprisingly, the orthogonality-based methods have huge complexity reduction and negligible sum capacity loss.

III. Orthogonality-Based User and Receive Antenna Selection Algorithms

Since the BD is designed to orthogonalize the channel for different users, so heuristically, it is desired to select users that are already as orthogonal as possible to each other before the BD. In the following, Section III-A and Section III-B introduce the orthogonality-based user selection and receive antenna selection, respectively.

A. Orthogonality-Based User Selection

In the orthogonality-based user selection algorithm, the user whose channel is most orthogonal to the existing users is selected. At the beginning, the user with the largest capacity is selected. The algorithm is summarized as follows.

1) Use $\mathcal{U}_i$ and $\mathcal{S}_i$ to denote the sets of unselected and selected users at iteration i, respectively. Initialize $\mathcal{U}_0 = \{1, 2, \ldots \tilde{K}\}$ and $\mathcal{S}_0 = \emptyset$.
2) Set $i = 1$, calculate:

$$s_i = \arg\max_{k \in \mathcal{U}_0} \log_2 \left| \mathbf{I}_{N_R} + \mathbf{H}_k \mathbf{T}_k \mathbf{T}_k^H \mathbf{H}_k^H \right|,$$

update the set $\mathcal{U}_i = \mathcal{U}_{i-1} - \{s_i\}$, $\mathcal{S}_i = \mathcal{S}_{i-1} + \{s_i\}$, and calculate the capacity for this selected user,

$$C_i = \log_2 \left| \mathbf{I}_{N_R} + \mathbf{H}_{s_i} \mathbf{T}_{s_i} \mathbf{T}_{s_i}^H \mathbf{H}_{s_i}^H \right|.$$

3) For $i = 2$ to $\left\lfloor \frac{N_T}{N_R} \right\rfloor$, loop the following:

a) Project each remaining channel in $\mathcal{U}_{i-1}$ onto the orthogonal complement of the subspace spanned by the channels of the selected users. That is, for every $k \in \mathcal{U}_{i-1}$, calculate

$$r_k = \left\|\mathbf{H}_k \mathbf{P}_{i-1}^{\perp}\right\|_F^2,$$

where $\mathbf{P}_{i-1}^{\perp}$ is the projection matrix, and is calculated as:

$$\mathbf{P}_{i-1}^{\perp} = \mathbf{I}_{N_T} - \mathbf{H}_{\mathcal{S}_{i-1}}^H \left(\mathbf{H}_{\mathcal{S}_{i-1}} \mathbf{H}_{\mathcal{S}_{i-1}}^H\right)^{-1} \mathbf{H}_{\mathcal{S}_{i-1}},$$

where $\mathbf{H}_{\mathcal{S}_{i-1}} \triangleq \left[\mathbf{H}_{s_1}^H \ \mathbf{H}_{s_2}^H \ \cdots \ \mathbf{H}_{s_{i-1}}^H\right]^H$ is the combined channel matrix for the selected users.

b) Find the user with maximum r_k, i.e, calculate

$$s_i = \arg\max_{k \in \mathcal{U}_{i-1}} r_k.$$

c) Assuming BD precoding is applied, use (2) to calculate the throughput achieved by the user set $\{\mathcal{S}_{i-1},\ s_i\}$, and denote it as C_i. If $C_i > C_{i-1}$[1], then update the unselected and selected user set, i.e., set $\mathcal{U}_i = \mathcal{U}_{i-1} - \{s_i\}$, $\mathcal{S}_i = \mathcal{S}_{i-1} + \{s_i\}$, else break the loop.

4) Terminate the algorithm, and use $\mathcal{S}_i$ as the final active user set.

B. Orthogonality-Based Receive Antenna Selection

The algorithm in Section III-A selects one user at a time, however, sometimes one user's entire channel matrix may not give the best orthogonality. By selecting the receive antenna (i.e., each row of the user's channel matrix) whose channel is more orthogonal to those selected antennas, the performance will be enhanced. Also, by using selected good receive antennas instead of all the receive antennas to receive the signal, the cost and the power consumption of the receiver can be reduced. The following summarizes the algorithm.

1) Use $\mathcal{U}_{i,k}$ and $\mathcal{S}_{i,k}$ to denote the sets of unselected and selected antennas of user k at iteration i, respectively. Use $\mathcal{U}_i = \bigcup_{k=1}^{\tilde{K}} \mathcal{U}_{i,k}$, and $\mathcal{S}_i = \bigcup_{k=1}^{\tilde{K}} \mathcal{S}_{i,k}$ to denote the total unselected and selected antennas. Initialize $\mathcal{U}_{0,k} = \{1, 2, \dots N_R\}$ and $\mathcal{S}_{0,k} = \emptyset$.
2) Set $i = 1$, find the receive antenna with the maximum Frobenius norm, i.e., to calculate

$$\left(\bar{k}, \bar{j}\right) = \arg\max_{k \in \{1,2,\dots,\tilde{K}\}, j \in \{1,2,\dots N_R\}} \left\|\mathbf{h}_{k,j}\right\|_F^2,$$

where $\mathbf{h}_{k,j}$ is the channel between the transmitter and the j-th receive antenna of user k. Update the sets, i.e., $\mathcal{U}_{i,\bar{k}} = \mathcal{U}_{i-1,\bar{k}} - \{\bar{j}\}$ and $\mathcal{S}_{i,\bar{k}} = \mathcal{S}_{i-1,\bar{k}} + \{\bar{j}\}$. Calculate the capacity after the first selection

$$C_i = \log_2\left(1 + \mathbf{h}_{\bar{k},\bar{j}} \mathbf{T}_{\bar{k}} \mathbf{T}_{\bar{k}}^H \mathbf{h}_{\bar{k},\bar{j}}^H\right).$$

[1]Please note that adding one more user does not necessarily guarantee the overall sum rate increase. Because the adding user may cause the performance degradation of the existing users, so only when the rate of the adding user is greater than the sum of the performance loss of all the existing users, do we have gain if this user is added. The same is true for the receive antenna selection.

3) For $i = 2$ to N_T, loop the following:

a) For each user k, project the channel vector for each receive antenna $j \in \mathcal{U}_{i-1,k}$, onto the orthogonal complement of the subspace spanned by the channel vectors of the selected antennas, i.e., calculate

$$r_{k,j} = \left\|\mathbf{h}_{k,j} \mathbf{P}_{i-1}^{\perp}\right\|_F^2,$$

where the projection matrix is

$$\mathbf{P}_{i-1}^{\perp} = \mathbf{I}_{N_T} - \mathbf{H}_{\mathcal{S}_{i-1}}^H \left(\mathbf{H}_{\mathcal{S}_{i-1}} \mathbf{H}_{\mathcal{S}_{i-1}}^H\right)^{-1} \mathbf{H}_{\mathcal{S}_{i-1}},$$

where $\mathbf{H}_{\mathcal{S}_{i-1}} \triangleq \left[\mathbf{H}_{\mathcal{S}_{i-1,1}}^H \ \mathbf{H}_{\mathcal{S}_{i-1,2}}^H \ \cdots \ \mathbf{H}_{\mathcal{S}_{i-1,\tilde{K}}}^H\right]^H$ is the combined channel matrix of selected antennas.

b) Calculate

$$\left(\bar{k}, \bar{j}\right) = \arg\max_{k=\{1,2,\dots,\tilde{K}\}, j \in \mathcal{U}_{i-1,k}} r_{k,j}.$$

c) Assuming BD precoding is applied, use (2) to calculate the throughput achieved by the antenna set $\{\mathcal{S}_{i-1},\ \bar{j}\}$, and denote it as C_i. If $C_i \geq C_{i-1}$, then update the unselected and selected antenna sets. That is, firstly copy the unselected and selected antenna set in previous iteration, i.e., do $\mathcal{U}_i = \mathcal{U}_{i-1}$ and $\mathcal{S}_i = \mathcal{S}_{i-1}$, and then set $\mathcal{U}_{i,\bar{k}} = \mathcal{U}_{i-1,\bar{k}} - \{\bar{j}\}$, $\mathcal{S}_{i,\bar{k}} = \mathcal{S}_{i-1,\bar{k}} + \{\bar{j}\}$. If $C_i \leq C_{i-1}$, break the loop.

4) Terminate the algorithm, and use $\mathcal{S}_i$ as the final active user and receive antenna set.

Comparing with the capacity-based and norm-based algorithms, we can see that the orthogonality-based algorithms do not need to perform BD when doing comparison for each candidate. Only after a user or receive antenna is selected, the BD is performed and the capacity is calculated, see step 3c) in Section III-A and Section III-B.

IV. Computational Complexity Analysis

Section III described the orthogonality-based user and receive antenna selection. It is somewhat straightforward. In this section, we compare the complexity of the orthogonality-based algorithm with the existing capacity-based and norm-based algorithms. We will see that the huge complexity reduction of the orthogonality-based algorithms.

For brevity, we denote the capacity-based and norm-based user selection algorithms in [6] as "c-alg" and "n-alg", respectively. And denote the capacity-based and norm-based receive antenna selection algorithms in [7] as "c-u/a alg" and "n-u/a alg", respectively. Also, use "o-alg" and "o-u/a alg" to denote the orthogonality-based user and receive antenna selection algorithms proposed in our paper.

Since the major time-consuming operations in these algorithm are SVD, Frobenius-Norm, and Gram-Schmidt, so in the complexity analysis, we count the number of these operations for each algorithm. Without loss of generality, we use T_S, T_N and T_G to denote the average time consumed by the SVD, the Frobenius-Norm, and the Gram-Schmidt operations,

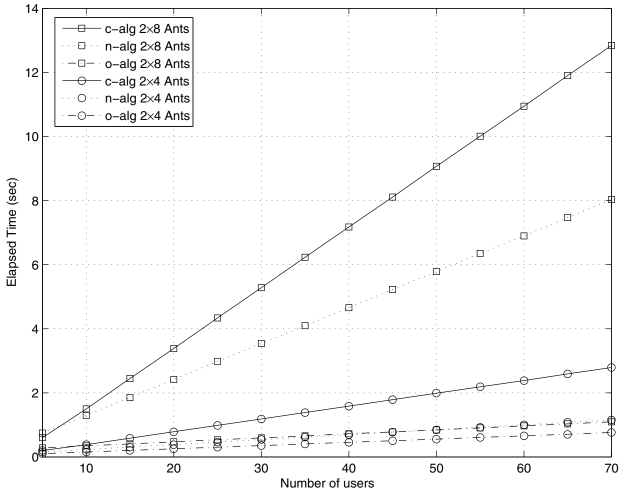

Fig. 1. Elapsed time vs. number of users for the user selection algorithms.

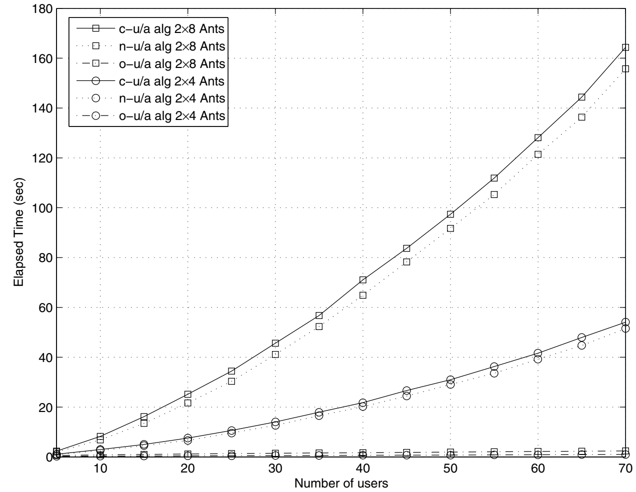

Fig. 2. Elapsed time vs. number of users for the receive antenna selection algorithms.

respectively. Then the elapsed time of these algorithms are approximated as below.

$$\begin{aligned}
T_c &\approx \left[\tilde{K} + \sum_{i=2}^{K} 2i\left(\tilde{K} - i + 1\right)\right] T_S \\
T_n &\approx \left[K + \sum_{i=2}^{K} 2i(K - i + 1)\right] T_S + \\
&\quad \left[\tilde{K} + \sum_{i=2}^{K} i\left(\tilde{K} - i + 1\right)\right] T_N \\
&\quad + \left[1 + \sum_{i=2}^{K} \left(\tilde{K} - i + 1\right)(i-1) + 1\right] T_G \\
T_o &\approx \left[\tilde{K} + \sum_{i=2}^{K} 2i\right] T_S + \sum_{i=2}^{K} \left(\tilde{K} - i + 1\right) T_N \\
T_{c-u/a} &\approx \sum_{i=2}^{N_T} 2i\left(\tilde{K}N_R - i + 1\right) T_S + \tilde{K}N_R T_N \\
T_{n-u/a} &\approx \sum_{i=2}^{N_T} 2i\left(\tilde{K}N_R - i + 1\right) T_S + \tilde{K}N_R T_N \\
T_{o-u/a} &\approx \left(1 + \sum_{i=2}^{N_T} 2i\right) T_S + \sum_{i=1}^{N_T} \left(\tilde{K}N_R - i + 1\right) T_N
\end{aligned}$$

In above equations, from the first to the last, the times are for "c-alg","n-alg","o-alg","c-u/a alg","n-u/a alg", and "o-u/a alg", respectively.

From the above equations, we can see that, for the "c-alg", "n-alg", "c-u/a alg" and "n-u/a alg", in the summation, the i is scaled by $\tilde{K}$ or $\tilde{K}N_R$, which counts for the BD performed for each candidate. While for the "o-alg" and "o-u/a alg", we do not need to scale i by $\tilde{K}$. So, it is expected that the orthogonality-based algorithms will have lower complexity than the capacity-based and norm-based algorithms.

In Fig.1 and Fig.2, we show the elapsed simulation time of these algorithms, where the elapsed time is counted using "tic" and "toc" in MATLAB. In the simulation, for each user point, we averaged over 100 channel realizations, and the 2×4 and 2×8 antenna configurations are evaluated at SNR=10dB. From the plots, we can see the "c-alg" and "c-u/a alg" have the highest complexity, "o-alg" and "o-u/a alg" have the lowest complexity, while "n-alg" and "n-u/a alg" are in the middle. The run time of "c-alg" is about tens of times longer than the "o-alg", and the "c-u/a alg" is hundreds of times longer than the "o-u/a alg". The orthogonality-based algorithms have huge complexity savings, however, in the following, we show that they achieve the sum capacity of the existing capacity-based and norm-based algorithms.

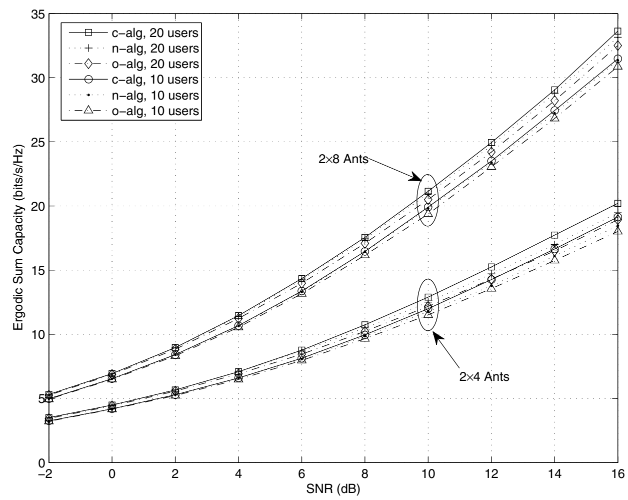

Fig. 3. Sum capacity vs. SNR comparison for user selection algorithms.

V. Numerical Results

In this section, we compare the performance of the algorithms proposed in [6]–[8] and the orthogonality-based user and receive antenna selection algorithms proposed in this paper.

Fig.3 illustrates the ergodic sum capacity versus the SNR for three different *user* selection algorithms. The antenna

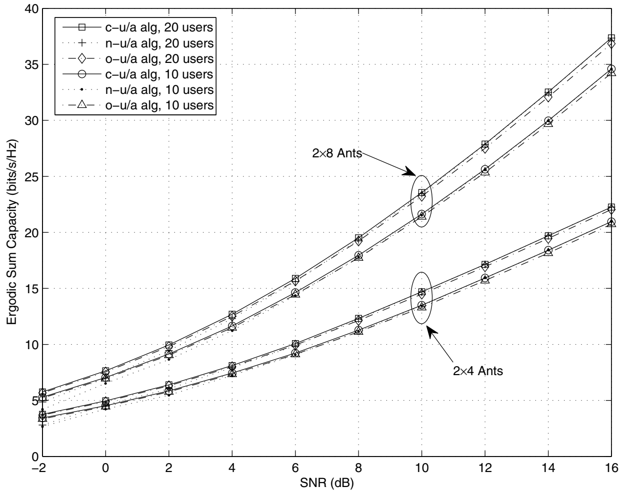

Fig. 4. Sum capacity vs. SNR comparison for receive antenna selection algorithms.

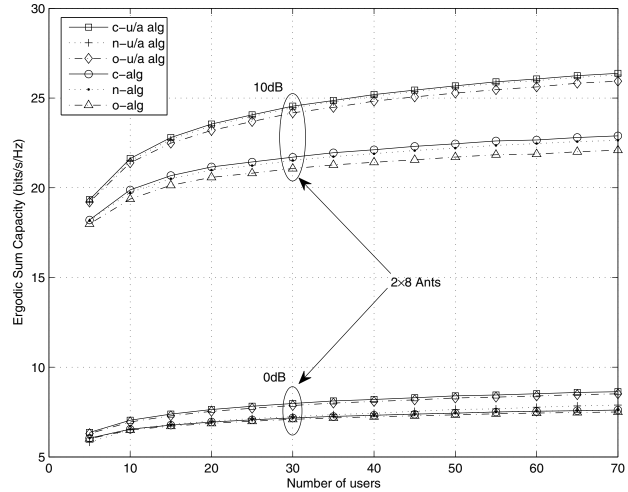

Fig. 5. Sum capacity vs. number of users.

configuration 2×4 and 2×8 are evaluated, and the capacity is averaged over 1000 channel implementations. From the curves we can see that when $N_T = 4$,"o-alg" achieves more than 94% capacity of "c-alg" and 98% of "n-alg", and when $N_T = 8$ it achieves more than 97% capacity of "c-alg" and 98% of "n-alg". At SNR=16dB, the largest performance gap between "c-alg" and "o-alg" is only 1 bit/sec/Hz.

Similarly, Fig.4 compares the sum capacity for "c-u/a alg", "n-u/a alg" and "o-u/a alg". From the curves, we can see that "o-u/a alg" achieves more than 98.5% capacity of both "c-u/a alg" and "n-u/a alg" at $N_T = 4$ and $N_T = 8$. One interesting phenomenon is that at low SNR (around 0dB), "o-u/a alg" performs better than the "n-u/a alg" with much lower complexity. This is because the "n-u/a alg" is based on an approximation of the sum capacity at high SNR. At low SNR, when this approximation is not accurate, the performance becomes worse.

Fig.5 shows how the ergodic sum capacity changes with the total number of users in the system when $N_T = 8$. SNR=0dB and SNR=10dB are shown. Because of the multiuser diversity, the sum capacity increases with the total number of users. From the curves, we can see that, at SNR=0dB, there is no difference between the orthogonality based algorithms and the capacity-based, while at SNR=10dB, the difference is less than 1 bit/sec/Hz.

VI. Conclusions

In this paper, the orthogonality-based user and receive antenna selection algorithms are proposed for the MIMO broadcast channels with BD precoding. The idea is simple, however, comparing with the existing capacity-based and norm-based algorithms, it achieve much better performance and complexity tradeoff. This is illustrated by the detailed complexity calculation and the extensive simulations. So the orthogonality-based algorithms are more attractive than the existing algorithms for practical MIMO broadcast systems, for example, the LTE-Advanced systems.

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