

Joint User Scheduling and Receive Antenna Selection in Multiuser MIMO Downlink with Other-cell Interference

Ahmadreza Ghaznavi, Mehrdad Ardebilipoor

Abstract—Recent researches have greatly considered allocation of space resources in multiuser MIMO systems. The studies have proposed techniques to select the optimum group of users and their antennas greedily or fairly and transmit precoding methods to transmit multiple streams simultaneously to selected users with suppressed or minimum inter-user interference. According to our understanding, a new research trend in cellular multiuser MIMO systems is the consideration of other-cell interference in the scheduling and precoding methods. In fact, scheduling techniques have not been considered as much as precoding ones in such a system. So, in this article we propose some user and antenna selection methods in a system with other-cell interference. We also propose another modification to a modified BD precoding method for this system to lower the channel state information feedback rate.

Index Terms—Multiuser MIMO Downlink, Broadcast channel, Precoding, User Scheduling, User selection and Antenna Selection.

I. INTRODUCTION

MIMO system has been known as a key technology of the next generation wireless systems[?]. Recently, more attention has been paid to the multiuser MIMO systems. Multi-user diversity is an important gain in the downlink of this systems. This diversity is the possibility of the best group of users selection from a large number of users to whom we allocate available space resources. Multiplexing of more data streams in the space domain or space division multiple access (SDMA) seems as a way to approach the capacity region of the multiuser MIMO downlink or MIMO broadcast channel. This idea is realized with the suppression of inter-user stream interference with transmit precoding. Precoding is really the space labeling of data streams to make their discrimination feasible at receivers. It is possible when the channel state information of all users is available fully or partially at the base station. Dirty Paper Coding(DPC)has been known as the optimal precoding to acheive the capacity of MIMO broadcast channel[2]. There are nonlinear and linear approaches to implement DPC. Nonlinear techniques are generally more efficient than linear ones but also more complicated. So linear techniques are usually more considered.

There are different linear precoding technique to omit the inter-user interference completely. Zero-forcing (ZF) or

channel inversion is the simplest one[3] but it suffers from noise enhancement and needs extra power in low SNRs. In another method called Block Diagonalization (BD), the precoded signal of a user lies in the null space of the other users' channel[4] to prevent inter-user interference. However, the number of possible precoders are finite. So, mode(the number of user's data streams) selection becomes necessary. All users' precoders are generated at once with power allocation to maximize the sum capacity in BD method. In another method called successive optimization(SO)[5], each user's precoder is generated successively with the null space of the previous users and power allocation is done in respect to the individual rate of users.

In multicell systems, other-cell common channel interference (CCI) can degrade the performance and capacity. Multi-cell DPC is the optimum approach which omits the inter-user interference [6]. However, this method is very complex. Another proposed method is to use the estimated covariance matrix of othe-cell interference in each cell and use it precoding[7]. We review the latter method and propose a modification to it in this article.

As we said, according to the precoding structure, mode selection (number of data stream for each user) is necessary in systems with larger number of users than space resources. In general, mode selection is considered as user selection since different modes belongs to different users. In multiuser systems, different subgroups can be selected and so there is a kind of multi-user diversity to optimally allocate the resources. Many researches have proposed different user selection methods[3],[8]. Of course, it is shown that joint selection of users and their receive antennas, provide higher degree of multiuser diversity [9],[10]. Anyway, user selection or scheduling is done with two approaches. In greedy approach, users with the best channel condition are always selected and the sum capacity is maximized[10]. In the fair approach, users with poor channel are also given the opportunity with the expense of loss in sum capacity. Round-Robin selection which is the combination of TDMA and SDMA and proportional fairness which is the maximization of weighted sum capacity are two important fair scheduling methods[3],[11].

So far, individual or joint User, mode and antenna selection methods have been studied in one-cell multiuser MIMO downlink. On the other hand, precoding methods are modified and developed for multi-cell systems but for finite number of users[7]. In this article we consider a multi-cell multiuser MIMO system in which user selection or scheduling is nec-

A.Ghaznavi is with the Spread Spectrum Laboratory on the supervision of Dr M.Aredibilipoor ,KNTU University of Technology,Tehran, Iran. E-mail: ar.ghaznavi@ee.kntu.ac.ir and mehrdad@kntu.ac.ir.

This work have been supported by Iran Telecommunication Research Center.

essary since the space resources are not enough in respect to the number of users. First, we modify the precoding method proposed for multi-cell systems in [7]. Then we apply user and joint user and antenna selection methods proposed in [3] and [11] with some modifications in the considered system.

This paper is organized as follows. In section II, we explain the system model and notations. In section III, the precoding method is expressed. Section IV gives a review of applied user and antenna selection methods and section V is dedicated to the simulation results and the last section is the conclusion of the research.

II. SYSTEM MODEL AND NOTATIONS

Before describing the system model, we introduce the notations used throughout the paper. \mathbf{A}^T , \mathbf{A}^H , and \mathbf{A}^{-1} signify respectively the transpose, conjugate transpose and pseudo-inverse of matrix \mathbf{A} . To show the l^{th} element of vector \mathbf{a} , $(l, m)^{th}$ element of matrix \mathbf{A} and the choice of $m - l + 1$ columns from the l^{th} column of the matrix \mathbf{A} , we use respectively the $(\mathbf{a})_l$, $(\mathbf{A})_{(l,m)}$ and $(\mathbf{A})_{(l:m)}$. For a $m \times n$ matrix \mathbf{A}_i , $i = 1, \dots, k$, $\mathbf{A} = \text{diag}(\mathbf{A}_1, \dots, \mathbf{A}_k)$ signifies a $mk \times nk$ block diagonal matrix with \mathbf{A}_i as the block diagonal element. Finally, considering the $\text{Tr}(\cdot)$ as the trace operation, $\|\mathbf{A}\|_F^2$ is the Frobenius norm of the matrix \mathbf{A} .

We consider a multi-cell multiuser MIMO system that consists of multiple antenna base stations and users. As we focus on the downlink or broadcast channel, base stations are considered as transmitters and users are considered as receivers. We consider a cell as the main one and the others are considered as interferers. The main cell consists of a base station with N_T antennas and K users each has $N_{R,k}$ antennas as k^{th} user. K_0 users among all might be selected with $n_{r,k}$ selected or activated antennas. The channel is assumed to be flat fading with Rayleigh distribution. In addition, Path loss and antenna correlations are also considered in the channel model based on the model described in [12]. On the other hand, we assume that the channel state information of all users are known at the base station. Fig.1 shows the system model assumed in this article. In fact, this model is based on the model in [7] with a bit difference in the structure which is to apply the block \mathbf{W}_k after \mathbf{U}_k at the receiver. This change and the structure is described in the following section.

According to the results shown in [13], $N_{I,k}$ effective cochannel interferers are assumed from the neighboring cells. The received signal at k^{th} receiver is given by

$$\begin{aligned} y_k &= \mathbf{H}_k \mathbf{F}_k s_k + \mathbf{H}_k \sum_{i=1, i \neq k}^K \mathbf{F}_i s_i + \mathbf{H}_{I,k} x_{I,k} + n_k \\ &= \mathbf{H}_k x_k + \mathbf{H}_k \sum_{i=1, i \neq k}^K x_i + z_k, \end{aligned} \quad (1)$$

In (1), s_k is the transmit signal with the average power $P_k = E\{s_k^H s_k\}$ and x_k is the precoded signal with the precoding matrix \mathbf{F}_k . $x_{I,k}$ is a $N_{I,k} \times 1$ interference vector with the average power $P_{I,k} = E\{x_{I,k}^H x_{I,k}\}$. n_k is additive complex

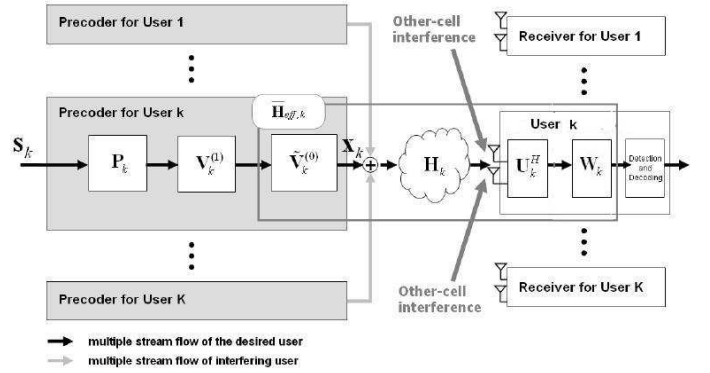


Fig. 1. Downlink multiuser MIMO with modified BD precoding and other-cell interference. (Extracted form [7] and edited)

Gaussian noise vector with zero mean and covariance matrix $\sigma_n^2 \mathbf{I}_{N_{R,k}}$, \mathbf{H}_k is the k^{th} user's $N_{R,k} \times N_T$ channel matrix, $\mathbf{H}_{I,k}$ is the $N_{R,k} \times N_{I,k}$ effective interference (OCI) channel matrix for k^{th} user, and $z_k = \mathbf{H}_{I,k} x_{I,k} + n_k$ is the equivalent noise at the receiver input. The $N_{R,k} \times N_{R,k}$ covariance matrix of noise plus interference is given by $R_{I,k} = E\{z_k z_k^H\}$. The estimation of $R_{I,k}$ is possible at receiver by different methods whose references are pointed out in [7].

III. MODIFIED PRECODING AND OCI SUPPRESSION

In this section we discuss the application of block diagonalization (BD) as the precoding method and also the OCI suppression technique. In addition, related capacity formulations are expressed.

As we noted in the previous section, our receiver structure has a difference with that proposed in [7]. In fact, we have changed the placement order of OCI whitening filter and decoding or channel paralleling blocks. according to their proposal, the received signal is first passed through the $N_{R,k} \times N_{R,k}$ whitening filter matrix whose calculation will be discussed in the following. So, in this structure, the signal at the input of decoding block is $r_k = \mathbf{W}_k y_k$. Assuming $\mathbf{H}_{r,k} = \mathbf{W}_k \mathbf{H}_k$ and $z_{r,k} = \mathbf{W}_k z_k$ and using (1), r_k is given in their structure by

$$r_k = \mathbf{H}_{r,k} x_k + \mathbf{H}_{r,k} \sum_{i=1, i \neq k}^K x_i + z_{r,k}, \quad (2)$$

As proposed in [7] and according to (2), transmit precoding which is aimed to suppress the second term, as the other-user interference, can be done on the knowledge of $\mathbf{H}_{r,k}$. in the other word, \mathbf{W}_k must be send back to the transmitter through a feedback channel while feedback rate is an important issue in MIMO systems. The other-cell interference is also dealt at receiver with whitening filter. We thought that suppressing the second term in (1) is enough to cancel the in-cell inter-user interference. So, we tried to show that precoding can just be done on the knowledge of \mathbf{H}_k . In this way, the feedback rate is also reduced. We also changed the receiver structure that is to pass first the received signal from the paralleling block and then from the whitening one. According to this structure and assuming $\mathbf{H}_{r,k}$ as $\mathbf{W}_k \mathbf{U}_k^H \mathbf{H}_k$ and $z_{r,k}$

as $\mathbf{W}_k \mathbf{U}_k^H \mathbf{z}_k$, received signal defined with equation (2), is reconstructed. The covariance matrix of noise plus interference which is used to define the whitening block matrix, is also modified as $\mathbf{R}_{1,k} = E\{z_{r,k} z_{r,k}^H\}$ and given by

$$\begin{aligned} \mathbf{R}_{1,k} &= \mathbf{U}_k \mathbf{H}_{1,k} E\{x_{1,k} x_{1,k}^H\} \mathbf{H}_{1,k}^H \mathbf{U}_k^H + \sigma_n^2 \mathbf{I}_{N_k} \\ &= \mathbf{U}_k \mathbf{H}_{1,k} \mathbf{Q}_{1,k} \mathbf{H}_{1,k}^H \mathbf{U}_k^H + \sigma_n^2 \mathbf{I}_{N_k}, \end{aligned} \quad (3)$$

We have discussed the aspects of block diagonalization method application here up to now. In fact, we do not talk about the details of this method because there are good references about that[4],[7],[8]. However, citing ambiguities to these references, we give a brief review of BD here. As we said, suppressing the second term can cancel the inter-user interference. This happens if the precoding matrix of k^{th} user, $\mathbf{F}_k = \mathbf{B}_k \mathbf{D}_k$, lies in the nullspace of the aggregate channel matrix of the other users(4).

$$\tilde{\mathbf{H}}_k = [\tilde{\mathbf{H}}_{r,1}^T \dots \tilde{\mathbf{H}}_{r,k-1}^T \tilde{\mathbf{H}}_{r,k+1}^T \dots \tilde{\mathbf{H}}_{r,K}^T]^T, \quad (4)$$

Using the singular value decomposition, $\tilde{\mathbf{H}}_k = \tilde{\mathbf{U}}_k [\tilde{\Lambda}_k \mathbf{0}] [\tilde{\mathbf{V}}_k^{(1)} \tilde{\mathbf{V}}_k^{(0)}]^H$, the first part of the precoder, $\mathbf{B}_k = (\tilde{\mathbf{V}}_k^{(0)})_{(1 : L_k)}$, is defined. $\tilde{\mathbf{V}}_k^{(0)}$ denotes the right singular vectors corresponding to zero singular values of $\tilde{\mathbf{H}}_k$. L_k is the number of transmitted streams to k^{th} user. To satisfy the dimensionality constraint, $L_k \leq \min(N_{R,k}, N_T - \sum_{i=1, i \neq k}^K N_{R,i})$. This condition forces the total number of multiplexed streams not to be more than N_T . We define $\mathbf{H}_{eff,k}$ as $\mathbf{H}_k \mathbf{B}_k$ and repeat the singular value decomposition for $\mathbf{H}_{eff,k}$ to define the second part of the precoder, \mathbf{D}_k . If we assume the $\mathbf{H}_{eff,k} = \mathbf{U}_k \begin{pmatrix} \Lambda_k \\ 0 \end{pmatrix} \mathbf{V}_k^H$, \mathbf{D}_k is equal to $\mathbf{V}_k P_k^{1/2}$. P_k is the allocated power to the k^{th} user. Power allocation can be done uniformly or with waterfilling algorithm[?]. \mathbf{U}_k is also the paralleling block matrix at receiver. Applying precoders, the received signal in (2) can be rewrote as

$$r_k = \mathbf{W}_k \mathbf{U}_k^H \mathbf{H}_{eff,k} \mathbf{D}_k s_k + z_{r,k}, \quad (5)$$

We assume $\tilde{x}_k = \mathbf{D}_k s_k$ with covariance matrix \mathbf{Q}_k and $\tilde{\mathbf{H}}_{eff,k} = \mathbf{W}_k \mathbf{U}_k^H \mathbf{H}_{eff,k} \mathbf{D}_k$. Now, The average sum capacity of the channel is defined as

$$C_{BD} = \max_{\sum P_k \leq P_T} \sum_{i=1}^K \log_2 \det(\mathbf{I}_{N_{R,k}} + \tilde{\mathbf{H}}_{eff,k} \mathbf{Q}_k \tilde{\mathbf{H}}_{eff,k}^H \mathbf{K}_{1,k}^{-1}), \quad (6)$$

We have $\mathbf{K}_{1,k}^{-1} = \mathbf{W}_k^H \mathbf{R}_{1,k} \mathbf{W}_k$. So, the whitening block matrix \mathbf{W}_k is calculated such that $\mathbf{K}_{1,k}^{-1} = \mathbf{I}_{N_{R,k}}$ or $\mathbf{W}_k \mathbf{W}_k^H = \mathbf{R}_{1,k}$. In [7], it is said that $\mathbf{W}_k = \mathbf{R}_{1,k}^{-1/2}$. However, it does not work unless $\mathbf{R}_{1,k}$ is real. We propose to use Cholesky decomposition of $\mathbf{R}_{1,k}$ to find a solution for whitening matrix based on the equation $\mathbf{W}_k \mathbf{W}_k^H = \mathbf{R}_{1,k}$.

At the end of this section, we present a graph which shows that the knowledge of whitening matrix only make benefits when the other-cell interference is extremely high. Fig.2 gives a comparison between the sum capacity of the channel, using

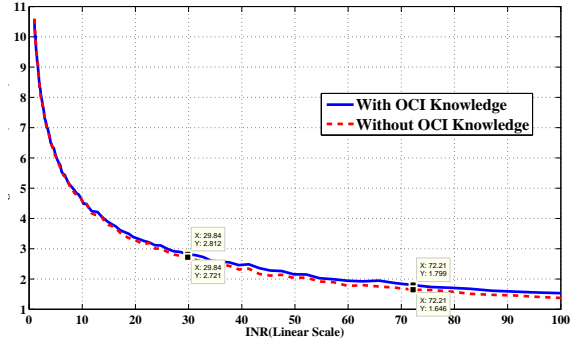


Fig. 2. The comparison between Sum capacity versus Interference plus noise using precoding with and without the knowledge of OCI at transmitter

transmit precoding with or without the knowledge of the whitening matrix at the base station.

IV. JOINT USER AND ANTENNA SELECTION

We noticed that the capacity of MIMO broadcast channel is achieved with transmit precoding methods which multiplex multiple streams with space labeling in a same time or frequency slot. Furthermore, we denoted that stream selection is needed since the number of multiplexed streams are limited because of the precoding structure. As another point of view, we mentioned that user selection can be done in fair or greedy manner. In greedy scheduling, we attend to downlink sum capacity maximization while in fair scheduling, individual users' rates are important.

Fair scheduling has been implemented by Round-Robin and proportional fair approaches. Round-Robin allocates space resources to all users in successive time slots and proportional method selects users which maximizes the weighted average sum capacity in each time slot. In the other word, each user has a selection weight in i^{th} selection time slot $\mu_k(i)$ which is defined by $\mu_k(i) = 1/\bar{R}_k(i)$. This weight multiplies with every selection metric. So, After some time slot a user with high selection metric would not be selected since his weight is decreasing. Of course, Round Robin method ensures all users scheduling neither does the proportional method.

In the following, we try to conceptually introduce applied scheduling algorithms in this article in brief. First, We denote some special notations for this section. $\Gamma = \{1, 2, \dots, K\}$ is the main set of all users with $\Psi = \{\psi_1, \psi_2, \dots, \psi_K\}$ as its respective receive antenna number set. It means that k^{th} user has ψ_k antennas. if K_0^{-1} users can be selected in a time slot, $S_i = \{\pi_1, \pi_2, \dots, \pi_{K_0}\}$, $\Theta_i = \{\theta_1, \theta_2, \dots, \theta_{K_0}\}$ and $\gamma_i = \Gamma - S_i$ are respectively the set of selected users, selected antennas and remaining uses in the i^{th} time slot. $|\pi_i| \leq K$, $|i| \leq K_0$ is the index of selected user in the i^{th} iteration, $|\theta_i| \leq \psi_{\pi_i}$, $|i| \leq K_0$ is the set of selected antennas for the user π_i and $\mathbf{H}_{\pi_i, \theta_i}$

¹Since we use BD precoding and the number of each user's streams is supposed to be equal to the number of his selected antennas, K_0 is determined in a such a way that the number of total active receive antennas become equal to the number of base station transmit antennas.

TABLE I
ROUND ROBIN FAIR SCHEDULING GENERAL ALGORITHM

Do 0-10 while $i \leq n$ (n : total number of selection slots).
0 : $i = 1, \bar{R}(i) = 0$
1 : $\gamma_i = \Gamma$,
2 : if $\gamma_i \neq \phi$
3 : Update S_i from γ_i using a user selection metric,
4 : Update Θ_i for S_i using an antenna selection metric,
5 : Update $\gamma_{i+1} = \gamma_i - S_i$,
6 : Update set of selected channels. i.e. $\{\mathbf{H}_{\pi_i, \theta_i}\}$,
7 : Calculate $\bar{R}(i) = \bar{R}(i) + C_{BD}(i)/n$, using (6),
8 : $i = i + 1$,
9 : else
10 : Go to 1,

denotes the subchannel in relation to the selected antennas of a selected user. We also assume $R_k(i), k = 1, \dots, K$ as the maximum rate or channel capacity of k^{th} selected user in the i^{th} time slot. In the i^{th} time slot, $R_k(i) \neq 0$ for a selected user and $\mu_k(i)$ can be updated by (7). By contrast, $R_k(i) = 0$ for an unselected user and $\mu_k(i)$ can be updated by (8).

$$\frac{1}{\mu_k(i+1)} = (1 - \frac{1}{i}) \frac{1}{\mu_k(i)} + \frac{1}{i} R_k(i), k \in S_i \quad (7)$$

$$\frac{1}{\mu_k(i+1)} = (1 - \frac{1}{i}) \frac{1}{\mu_k(i)}, k \notin S_i \quad (8)$$

$$C_{i,w} = \sum_{k=1}^{K_0} \mu_k(i) R_k(i) \quad (9)$$

Table.I shows utilized Round Robin fair scheduling algorithm in this article. As we said this method is a combination of TDMA and SDMA method to schedule all users in successive time slots. Table.II shows the weighted average sum capacity maximization scheduling algorithm. In the other word, the algorithm implements greedy scheduling in case of $\mu_k(t) = 1$ and proportional fair(pf) scheduling if $\mu_k(t)$ is updated by $1/\bar{R}_k(t)$. Both algorithms contain a loop which repeats during the scheduling time slots.

In each step of user and antenna selection two sets of metrics are calculated for all users indexed in the γ_i . The metrics of user selection which are generally $\omega_{u,k}(i) | k \in \gamma_i$ for the i^{th} slot, are collected in $\Omega_u(i)$. Of course, we consider modified metric as $\mu_k(i) \cdot \omega_{u,k}(i) | k \in \gamma_i$ which make the fair scheduling possible. In the other word, we have greedy scheduling if $\mu_k(i) = 1$ and fair scheduling if $\mu_k(i)$ is updated with (7) and (8). We denote that $\mu_k(i)$ proportional to the reverse of average rate of the i^{th} user so the updated modified metric prevents the greedy growth of a user. We can also define $\Omega_{a,k}(i) | k \in S_i$ as the antenna selection metric set for each selected user in S_i .

As a general process, $\Omega_u(i)$ is calculated in each time slot with a typical algorithm and updated with the set of weights to give the modified metrics. The selected user in each slot is the one with the maximum metric norm. After user selection, a set of antenna selection metrics is calculated for the selected user and the set of antennas ($n_{R,k}$ for k^{th} user) is also determined with maximum metric norm criterion. Of course, The selection process is optimized for low complexity and high speed.

TABLE II
WEIGHTED AVERAGE SUM CAPACITY MAXIMIZATION ALGORITHM

Do 0-8 while $i \leq n$ (n : total number of selection slots).
0 : $i = 1, \bar{R}(i) = 0$
1 : Update S_i from $\gamma_i = \Gamma$ using a user selection metric,
2 : Update Θ_i for S_i using an antenna selection metric,
3 : Update set of selected channels and calculate each channel capacity $R_k(i)$, with (6)($K = 1$) and weights with (7) and (8),
4 : Calculate the $C_{i,w}$, the weighted sum capacity, using (9),
5 : Calculate $\bar{R}(i) = \bar{R}(i) + C_{i,w}/n$,
6 : $i = i + 1$,
7 : else
8 : Go to 1,

V. SIMULATION RESULTS

We consider a cellular system with multi-antenna users and base stations. We focus on the downlink of a main cell with a base station and its related in-cell users suppose other base stations as interferers. We have considered symmetric and asymmetric distribution models. In symmetric model, users distances are equal from the main base station and approximately from the interferers. Since the users do not have any priority to each other, this model is the worst case for greedy scheduling and suitable for showing a typical greedy algorithm performance. On the other hand, in asymmetric model users get away linearly from the main base station and become closer to interferers. Since closer users to the main base station have better channel condition and priority to be selected, this model is better to show a typical fair algorithm performance to select far users with poor channels. Our system parameters are as follows. $N_t = 8, N_{R,k} = 4$ and $n_{R,k} = 2$ in case of antenna selection, $P_T = \sum P_k = 10$ and $P_I = \sum P_{1,k} = 10$.

Fig. 3 shows the sum capacity comparison of greedy scheduling algorithms versus transmit antenna correlation factor, ρ_T , (refer to the correlation model in [12]) in symmetric distribution model. The capacity of all methods degrade with the increase of antenna correlation at transmitter. In fact, more correlation decreases the multi-user diversity. We can also see the advantage of BD based methods over SO methods in greedy scheduling, the advantage of joint user and antenna selection over just user selection, the advantage of capacity based method (Metric I) over norm based method (Metric II) and the advantage RASII (less correlated antenna selection) over RASI (higher channel energy antenna selection). According to the same advantage of each method over another with different, we assume $\rho_T = \rho_R = 0.5$ after this.

Fig. 4 and 5 compares respectively the fairness using individual users' capacity and the sum capacity for three categories of greedy, Proportional fair and Round Robin scheduling in asymmetric distribution model. Observing two figures, we can conclude that greedy methods offer more sum capacity selecting the best users but fair ones offer more individual capacity for far users with poor channels.

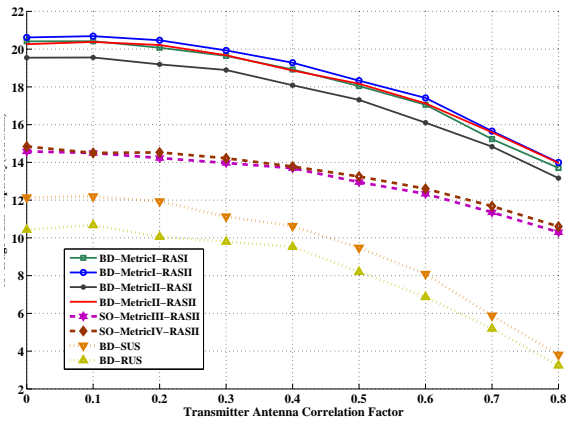


Fig. 3. Average sum capacity versus transmit antenna correlation factor in greedy scheduling.

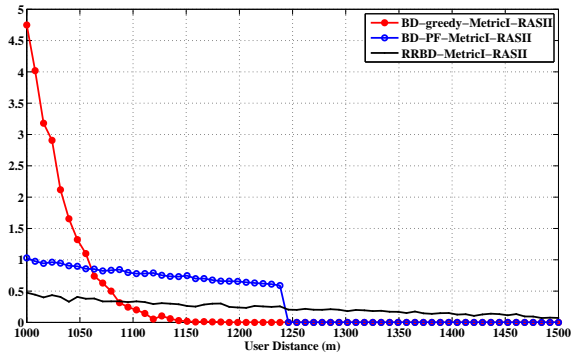


Fig. 4. Individual capacity of 65 user versus their distance from the main base station.

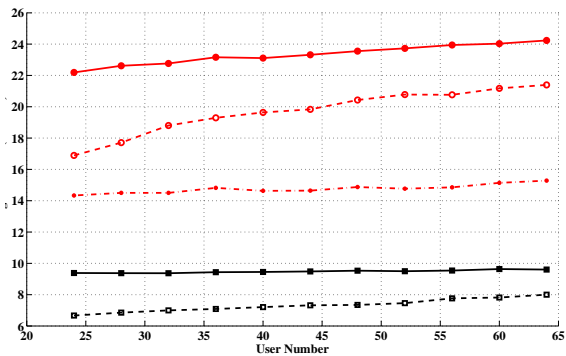


Fig. 5. Average sum capacity of greedy and fair methods versus number of users.

VI. CONCLUSION

In this article modified the BD precoding technique to be used in multi-cell MIMO broadcast system. We also applied some joint user and antenna selection techniques with some changes in multi-cell environment with the modified BD precoding that does not need the feedback of other-cell interference covariance matrix.

REFERENCES

- [1] V.Tarokh, M.Seshadri, and A.R.Calderbank, "Space-time codes for high data rate wireless communications: Performance analysis and code construction," vol. 44, no. 2, pp. 744-765, March 1998.
- [2] M. Costa, "Writing on dirty paper," IEEE Trans. on Inform. Theory, vol. 29, p. 439-441, May 1983.
- [3] T. Yoo and A. Goldsmith, "On the optimality of multiantenna broadcast scheduling using zero-forcing beamforming," IEEE J. Sel. Areas Commun., vol. 24, no. 3, pp. 528541, Mar. 2006.
- [4] Q.H. Spencer, A.L. Swindlehurst, and M. Haardt, "Zero-forcing methods for downlink spatial multiplexing in multiuser MIMO channels," IEEE Transactions on Signal Processing, vol.52, No.2, Feb.2004, pp. 461-471.
- [5] Shreeram Sigdel and Witold A. Krzymien, "Antenna and User Subset Selection in Downlink Multiuser Orthogonal Space-Division Multiplexing," Wireless Personal Communications, May 2008.
- [6] Sheng Jing et al., "multi-cell downlink capacity with coordinated processing," EURASIP Journal on Wireless Communications and Networking, no. 5, Jan 2008.
- [7] S. Shim and R.W. Heath, "Block Diagonalization for Multi-User MIMO with Other-Cell Interference," IEEE Transactions on Wireless Communications, Vol. 7, No. 7, July 2008, pp. 2671-2681.
- [8] Brain L. Evans, "Low Complexity User Selection Algorithms for Multiuser MIMO Systems with Block Diagonalization," IEEE Transactions on Signal Processing, Vol.54, No.9 Sep. 2006, pp.3658-3663.
- [9] Shreeram Sigdel and Witold A. Krzymien, "Antenna and User Subset Selection in Downlink Multiuser Orthogonal Space-Division Multiplexing," Wireless Personal Communications, May 2008.
- [10] S. Sigdel, W. A. Krzymien, Simplified channel-aware greedy scheduling antenna selection algorithms for multiuser MIMO systems employing orthogonal space division multiplexing, Chapter 2 in Advances in Mobile and Wireless Communications Views of the 16th IST Mobile and Wireless Communication Summit. Heidelberg, Germany: Springer 2008, pp. 23 - 52.
- [11] S. Sigdel, W.A. Krzymien, Simplified fair scheduling and antenna selection algorithms for multiuser MIMO orthogonal space division multiplexing downlink, IEEE Transactions on Vehicular Technology, Vol.58 , No.3 ,March 2009 , pp.1329-1344 .
- [12] Seung-Hwan Lee, John Thompson, "A Simple Channel Model for Investigation of Multiuser Scheduling in MIMO Broadcast Channels," IEEE Vehicular Technology Conference, 2008. VTC 11-14 May 2008, pp.513 - 517
- [13] M.Kwak, H.Kang, Y.Li, and G.L.Stber, "Effects of spatial correlation on MIMO adaptive antenna system with optimum combining," IEEE Trans. Wireless commun., vol. 6, no. 5, pp 1722-1731, May 2007.