Iterative Transceiver Design for Opportunistic Interference Alignment in MIMO Interfering Multiple-Access Channels

Weipeng Jiang, Kai Niu, and Zhiqiang He
School of Information and Communication Engineering, Beijing University of Posts and Telecommunications
Beijing 100876, China
Email: jwpqjty@gmail.com; {niukai, hezq}@bupt.edu.cn

Abstract —In this paper, we propose an iterative transceiver design algorithm for opportunistic interference alignment in MIMO interfering multiple-access channels. The proposed algorithm iteratively optimizes the transmit beamforming vectors, the receive matrices and the user selection set, which digs into the multiuser diversity gain. Specifically, data transmission can be operated in each iteration using the updated transceiver and the selected user set, which means that no additional processing delay is introduced. Simulation results demonstrate the improved average rate per cell performance of the proposed algorithm compared to the conventional ones.

Index Terms—Interference alignment, OIA, user scheduling, iterative

I. Introduction

In the wireless communication networks, how to share the limited bandwidth among multiple users is the primary challenge. Interference alignment (IA), as a promising technique to eliminate the interference and achieve the optimal degrees of freedom (DoF), also known as multiplexing gain, has shown the bandwidth available to each user can be significantly improved.

Different interference alignment algorithms are studied for various scenarios. For the K user interfering channel, it is proved in [1] that each user can get half of the interference free channel capacity, even though the number of users, K , can be arbitrarily large. For the multiple-input multiple-output (MIMO) X network [2], the DoF outer bound is derived, where every transmitter has an independent message for every receiver. In [3], subspace interference alignment is proposed for cellular networks. However, the optimal DoF gain is usually achieved with global channel state information (CSI), which is not practical. Thus limited-feedback interference alignment algorithms like [4] and blind interference alignment algorithms like [5] have been proposed. Nevertheless, these algorithms either need the feedback bits to scale fast or require many time, frequency, or space domain extensions.

Manuscript received November 19, 2014; revised February 26, 2015.
This work is supported by National High-tech R&D Program of China (863 Program) (SS2015AA011303), National Natural Science Foundation of China (61171099, 61171100, 61271178), Huawei Technologies Co. Ltd. Project (YB2013120018).
Corresponding author email: jwpqjty@gmail.com.
doi:10.12720/jcm.10.2.101-106

In [6]-[8], opportunistic interference alignment (OIA) is proposed for MIMO interfering multiple-access channels (IMAC). Different from the above interference alignment methods, OIA takes advantage of the multiuser diversity (MUD). Only partial CSI is needed, and there is no requirement for time, frequency, or space domain extensions. Each user obtains its beamforming vector by minimizing the leakage of interference (LIF), and the optimal DoF can be achieved through user selection only if the user number scales fast enough. Similar OIA schemes have been proposed in [9] and [10] for the downlink transmission. Although OIA is DoF optimal as SNR (signal to noise ratio) approaches infinity, it is not optimal in the sense of sum rate, especially at intermediate SNR values. In [11], the sum rate is enhanced by considering the efficient signal link based on the signal to leakage and noise ratio (SLNR). In [12], an energy efficient algorithm with power constraints at the transmitter is proposed. Instead of optimizing each cell's achievable DoF, [13] gives priority to increasing the possibility for perfect IA in one cell (named as active OIA). When the number of users does not meet the scaling condition, all the cells are interference-limited for the other schemes above. However, the average rate per cell (ARPC) for the active OIA scheme can still have linear growth with the SNR, because one cell is perfectly interference aligned with no interference left. Obviously, fairness among cells is sacrificed.

The key idea of OIA is to get the multiuser diversity gain. However, the conventional OIA schemes mentioned above have potential shortcomings in user selection. Theoretically, the user selection should be optimized jointly with the transmit beamforming vectors and the receive matrices. However, user selection in all the above methods depends on the receive matrices, which are randomly generated. Although [13] attempts to optimize the receive matrices after user selection, the user set is still not changed. Hence, the selected users are actually those who match the given signal space, which is not optimal for achieving the MUD gain.

In [14]-[15], iterative interference alignment algorithms are proposed for K-user interference channel, which achieve much gain in terms of sum rate. However, these iteration algorithms cannot be used for OIA in MIMO IMAC because no user scheduling is considered.

In both algorithms, the user set should be decided before the calculation of both the transmit beamforming vectors and the receive matrices. In this situation, only the beamforming vectors of the selected users can be updated. Thus even with the updated transmit beamforming vectors, the selected user set will not change in the iteration.

In this paper, we propose an iterative transceiver design and user selection algorithm for OIA in MIMO IMAC channels. Firstly, at the transmitter side, SLNR maximization is adopted as the design criterion, and both the transmit beamforming vectors and the selected user set are optimized. Secondly, at the receiver side, SINR maximization is adopted as the performance criterion, and the receive matrices are optimized. The two steps are iteratively executed until converging or reaching the maximum number of iterations. Extensive simulations show the improved performance in terms of ARPC compared with the conventional schemes.

The rest of this letter is organized as follows. In Section 2, the model of the K-cell uplink MIMO IMAC system is introduced. The proposed iterative transceiver design and user scheduling algorithm is developed in Section 3. In Section 4, numerical examples are provided to show the improved performance of the proposed algorithm over the conventional schemes. Conclusions are drawn in Section 5.

II. System Model

We consider a K cell MIMO IMAC working in TDD mode as shown in Fig. 1. Every cell has one base station (BS) equipped with M antennas and N users each equipped with L antennas. In each cell, only S users ($S \le M$) out of the N users are selected to transmit signals simultaneously. The selected user set of cell k is defined as $\mathcal{I}_k = \{k_1, \cdots, k_S\}$, where $k_i \in \{1, \cdots, N\}$ denotes the ith selected user in cell k. It is assumed that every selected user transmits a single spatial stream. Each BS only decodes the signals from the selected users in its own cell and treats the signals from other cells as interference. In Fig. 1, the interfering links and the effective signal links are denoted using dotted and solid lines, respectively.

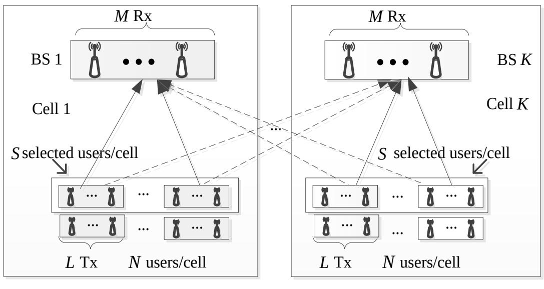


Fig. 1. K cell MIMO IMAC model.

We use $\boldsymbol{H}_{i,j}^{k}$, which is an $M \times L$ Gaussian random matrix with i.i.d. zero mean and unit variance entries, to denote the fading channel matrix between the jth user in the ith cell and the BS of the kth cell. $\boldsymbol{v}_{i,j}$ is the beamforming vector with unit energy for user j in the ith cell. The transmit message of user j in the ith cell is denoted by $m_{i,j}$. We assume that the average power of the transmit message at each transmitter is $E(m_{i,j} m_{i,j}^{*}) = P$, where $(\cdot)^{*}$ stands for the complex conjugate. The selected users in different cells transmit in the same time using the same frequency band. Thus the received signal vector at the kth BS can be written as

$$\boldsymbol{y}_k = \sum_{j=1}^{S} \boldsymbol{H}_{k,j}^{k} \boldsymbol{v}_{k,j} m_{k,j} + \sum_{i=1, i\neq k}^{K} \sum_{j=1}^{S} \boldsymbol{H}_{i,j}^{k} \boldsymbol{v}_{i,j} m_{i,j} + \boldsymbol{n}_k \tag{1}$$

where $\boldsymbol{n}_k$ denotes the $M \times 1$ additive noise vector, each element of which is an i.i.d. complex Gaussian random variable with zero mean and unit variance. Thus the SNR at each transmitter is defined identically as $SNR = P/1 = P$. The expression $\sum_{j=1}^{S} \boldsymbol{H}_{k,j}^{k} \boldsymbol{v}_{k,j} m_{k,j}$ is the desired signal part from the S selected users in cell K. The expression $\sum_{i=1, i\neq k}^{K} \sum_{j=1}^{S} \boldsymbol{H}_{i,j}^{k} \boldsymbol{v}_{i,j} m_{i,j}$ is the interference from the selected users of other cells. Using a linear receiver, the estimated signal vector is given by

$$\boldsymbol{r}_k = [r_{k,1}, \cdots, r_{k,S}]^{\mathrm{T}} = \boldsymbol{U}_k^{\mathrm{H}} \boldsymbol{y}_k \tag{2}$$

where $\boldsymbol{U}_k$ is the $M \times S$ receive matrix for BS k . $(\cdot)^{\mathrm{T}}$ and $(\cdot)^{\mathrm{H}}$ denote matrix (vector) transpose and Hermitian transpose, respectively. $\boldsymbol{U}_k = [\boldsymbol{U}_{k,1}, \cdots, \boldsymbol{U}_{k,S}]$ is full column rank, in other words the signal space has S dimensions. Each column $\mathbf{U}_{k,i}, i \in \mathcal{I}_k$ has unit energy and corresponds to the receive vector of the selected user k_i . The conventional OIA scheme is proposed for achieving the optimal DOF, but its ARPC performance can be further improved.

A globally optimal algorithm should jointly optimize the receive matrices, the beamforming vectors and the selected user set together to get full MUD gain. The sum rate optimization problem can be formulated as

$$\arg \max_{\boldsymbol{U}_{k,l}, \boldsymbol{v}_{k,l}, \mathcal{I}_k} \sum_{k=1}^{K} \sum_{l \in \mathcal{I}_k} \log(1 + SINR_{k,l}) \tag{3}$$

where $SINR_{k,l}$ is the signal to interference plus noise power ratio of the lth user in cell k , which can be written as Eq. (4)-(6)

$$SINR_{k,l} = \frac{\boldsymbol{U}_{k,l}^{\mathrm{H}} \boldsymbol{C}_{k,l} \boldsymbol{U}_{k,l} SNR}{\boldsymbol{U}_{k,l}^{\mathrm{H}} \boldsymbol{D}_{k,l} \boldsymbol{U}_{k,l}} \tag{4}$$

$$\boldsymbol{C}_{k,l} = \boldsymbol{H}_{k,l}^{k} \boldsymbol{v}_{k,l} \boldsymbol{v}_{k,l}^{\mathrm{H}} (\boldsymbol{H}_{k,l}^{k})^{\mathrm{H}} \tag{5}$$

$$\begin{aligned} \boldsymbol{D}_{k,l} = \boldsymbol{I}_M &+ \sum_{i=1}^{K} \sum_{j \in \mathcal{I}_k} \boldsymbol{H}_{i,j}^{k} \boldsymbol{v}_{i,j} \boldsymbol{v}_{i,j}^{\mathrm{H}} (\boldsymbol{H}_{i,j}^{k})^{\mathrm{H}} SNR \\ &- \boldsymbol{H}_{k,l}^{k} \boldsymbol{v}_{k,l} \boldsymbol{v}_{k,l}^{\mathrm{H}} (\boldsymbol{H}_{k,l}^{k})^{\mathrm{H}} SNR \end{aligned} \tag{6}$$

where $\boldsymbol{I}_M$ denotes the $M \times M$ identity matrix. $\boldsymbol{D}_{k,l}$ is the correlation matrix of the interference and the noise.

III. The Proposed Iterative Transceiver Design and User Scheduling Algorithm

In this section, we present our iterative transceiver design and user scheduling algorithm. The problem Eq. (3) is nonconvex, and the collection variables I_k make it more difficult to solve. Moreover, the receive matrices, beamforming vectors and the selected user set of different cells or users are highly coupled, which further makes the globally optimal solution intractable. To get a near-optimal solution, the iteration scheme is worth considering. The critical question is how to decouple the users' beamforming vectors and the BSs' receive matrices.

The proposed algorithm is a SLNR-SINR bi- criteria combined iteration algorithm. Compared with the algorithms in [11] and [13], the proposed algorithm has better performance for the joint optimization of the beamforming vectors, the receive matrices and the user selection. Compared with the iteration algorithms using only SINR criteria, the proposed algorithm has lower complexity, because each user can optimize its own beamforming vectors using SLNR criteria without need of iterations among different users. Besides, the selected user set can be easily updated in the iteration process.

At the transmitter side, given the receive matrices of each cell, each user calculates the optimal beamforming vector that maximizes its SLNR. At the receiver side, each BS selects the users of its cell according to the reported SLNRs. Given the beamforming vectors of each user, each BS also optimizes the receive matrices by maximizing the SINR. Iterations are carried out until convergence or until the maximum number of iteration. The selected user set, the beamforming vectors and the receive matrices are all updated in each iteration. This way, every BS can optimize its $\boldsymbol{U}_{k,l}$ and I_k independently. Every user can optimize its $\boldsymbol{v}_{k,l}$ without knowing the beamforming vectors of the other users.

In the following, we give the algorithm steps as follows:

Step1. Each BS randomly generates and broadcasts the $M \times S$ receive matrix $\boldsymbol{U}_k$, the columns of which are linearly independent unit vectors. S and M are defined in Section II. Set $SumRate0 = 0$, which is the initialized sum rate of all the K cells; The broadcast of the receive matrix is only performed once for the initialization. Start iteration.

Step2. Each user calculates the SLNR according to Eq. (7)-(9), and gets the optimal transmit beamforming vector by optimizing Eq. (10). Each user sends the computed SLNR to its cell's BS.

Details are as follows:

The jth user in the ith cell can calculate its SLNR independently only using its own transmit beamforming vector $\boldsymbol{v}_{i,j}$. The SLNR is written as Eq. (7)-(9),

$$SLNR_{i,j} = \frac{\boldsymbol{v}_{i,j}^{\mathrm{H}} \boldsymbol{A}_{i,j} \boldsymbol{v}_{i,j} SNR}{\boldsymbol{v}_{i,j}^{\mathrm{H}} \boldsymbol{B}_{i,j} \boldsymbol{v}_{i,j}} \tag{7}$$

$$\boldsymbol{A}_{i,j} = (\boldsymbol{H}_{i,j}^{i})^{\mathrm{H}} \boldsymbol{U}_i \boldsymbol{U}_i^{\mathrm{H}} \boldsymbol{H}_{i,j}^{i} \tag{8}$$

$$\boldsymbol{B}_{i,j} = \boldsymbol{I}_L + \sum_{k=1}^{K} \sum_{k \neq i} (\boldsymbol{H}_{i,j}^{k})^{\mathrm{H}} \boldsymbol{U}_k \boldsymbol{U}_k^{\mathrm{H}} \boldsymbol{H}_{i,j}^{k} SNR \tag{9}$$

, where $\boldsymbol{I}_L$ denotes the $L \times L$ identity matrix. $\boldsymbol{H}_{i,j}^{i}$ is the effective data link between the jth user in the ith cell and the ith BS. $\boldsymbol{H}_{i,j}^{k}, k = 1 \cdots K, k \neq i.$ is the leakage signal link between the jth user in the ith cell and the kth BS.

The overall procedure of our protocol is based on the channel reciprocity of TDD systems. Due to the channel reciprocity, the receive matrices can be obtained using downlink pilot signaling. Because the optimal receive matrices in the uplink are also the optimal transmit matrices in the downlink, the expression $\boldsymbol{U}_i^{\mathrm{H}} \boldsymbol{H}_{i,j}^{i}$ can be fully estimated as equivalent channel $(\boldsymbol{H}_{i,j}^{i})^{\mathrm{H}} \boldsymbol{U}_i$ in the downlink transmission.

So according to Eq. (7)-(9) and the equivalent channel estimation, the optimization objective can be written as

$$\arg \max_{\boldsymbol{v}_{i,j}} SLNR_{i,j} \tag{10}$$

which is a generalized Rayleigh quotient maximization problem [16]. The maximal value is the largest generalized eigenvalue of $\boldsymbol{A}_{i,j} \boldsymbol{B}_{i,j}^{-1}$, and the optimal $\boldsymbol{v}_{i,j}$ is the corresponding eigenvector.

Step3. Each BS selects the S users who have the S largest SLNRs. Using Eq. (4)-(6), each BS calculates the SINRs for the selected users and gets the new receive vector $\mathbf{U}_{k,i}, i \in \boldsymbol{I}_k$ for the corresponding selected user by optimizing Eq. (11).

Details are as follows:

In Eq. (4)-(6), $\mathbf{H}_{k,l}^{k}$ is the effective data link between the lth user in the kth cell and the kth BS. $\mathbf{H}_{i,j}^{k}, \mathrm{i} = 1 \cdots \mathrm{K}, i \neq k$ is the interference link from the jth user in the ith cell to the kth BS. The beamforming vectors can be obtained by the BS in the same way during uplink transmission, that is, $\boldsymbol{H}_{k,l}^{k} \boldsymbol{v}_{k,l}$ is fully estimated as the equivalent channel.

So according to Eq. (4)-(6) and the equivalent channel estimation, the optimization objective can be written as

$$\arg \max_{\boldsymbol{U}_{k,l}} SINR_{k,l} \tag{11}$$

which is also a generalized Rayleigh quotient maximization problem. The maximal value is the largest generalized eigenvalue of $\boldsymbol{C}_{k,l} \boldsymbol{D}_{k,l}^{-1}$, and the optimal $\boldsymbol{U}_{k,l}$ is the corresponding eigenvector.

Step 4. Compute the new sum rate $SumRate1$, if $SumRate1 - SumRate0 > \varepsilon$, update the selected user set, let $SumRate0 = SumRate1$, and go to step (2); otherwise, iteration ends.

Details are as follows:

Sum rate of all the cells is calculated using Eq. (12)

$$R_{sum} = \sum_{k=1}^{K}\sum_{l=1}^{S} R_{k,l} = \sum_{k=1}^{K}\sum_{l=1}^{S} \log(1+SINR_{k,l}) \qquad (12)$$

Some sort of collaboration is needed for the BSs to calculate the sum rate (though the overhead of collaboration is minimal). For example, the quantified rate information can be transmitted using the X2 interface in LTE systems.

Remark: Precise values of the SLNR are not required to feed back for comparison, which leaves much space for feedback compression. It is noted that all configurations of the transceiver, such as the receive matrices, the beamforming vectors and the selected user set, should be updated in each iteration. The iterative algorithm is an online process, that is, all the optimal solutions in the current iteration can be utilized to configure the transceiver in the next transmission.

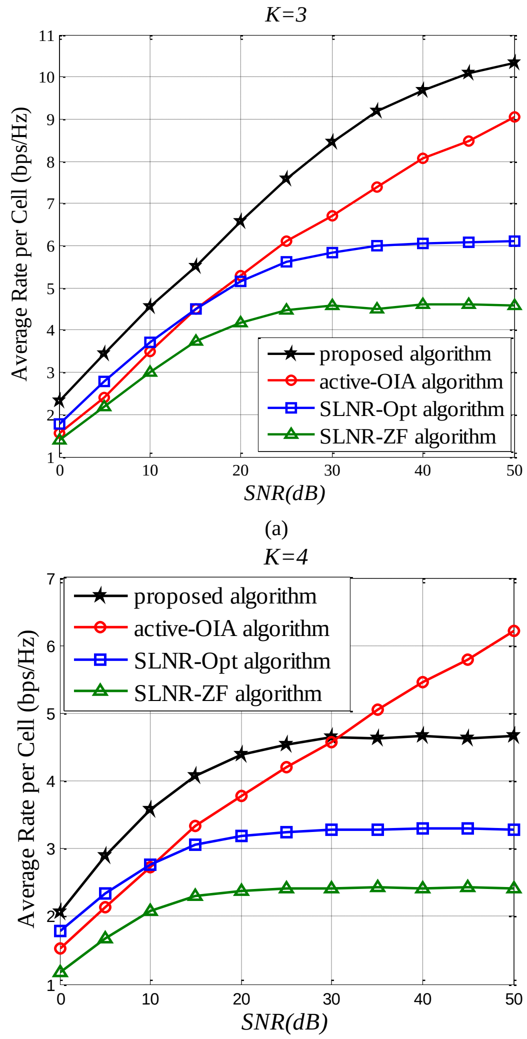
In the iteration process, given the selected users and the beamforming vectors, the updated receive matrices will achieve higher SINRs, which mean better ARPC performance. Given the receive matrices, the updated selected users and beamforming vectors can ensure higher SLNRs, but it's not always better for ARPC performance because the SLNR metric is not optimal in terms of capacity. Nevertheless, using the SLNR metric is helpful to decouple the beamforming vectors of the different users effectively, which simplifies the iteration progress. Moreover, it has better performance than other metrics such as the LIF metric.

The average power between every user and every base station is assumed to be equal. Similar with the conventional OIA algorithms, we assume perfect local CSI estimation and that the channels remain constant throughout the duration of the operation. Once the algorithm has converged, each base station would be in contact with only S selected users per cell. If the channel matrices are constant, the left $N-S$ users will not be served until channels change.

IV. Numerical Results

In this section, we study the performance of the proposed iterative transceiver design and the user scheduling algorithm through numerical simulations. For the convenience of comparison with the conventional algorithms, we choose the same simulation parameters as those in [11] or [13] as follows: We consider a K cell MIMO IMAC working in TDD mode as shown in section II. K is 3 or 4 for different degrees of interference. There are $M=2$ antennas at each BS and $L=2$ antennas at each user. We set the noise power to 1, and the transmit SNR changes with the signal power. For the sake of simplicity, we choose $S=1$ in the simulation. ARPC is used as the overall performance metric, which is defined as $\bar{R} = E(\sum_{k=1}^{K}\sum_{l=1}^{S} R_{k,l}/K)$, where $R_{k,l} = \log(1+SINR_{k,l})$.

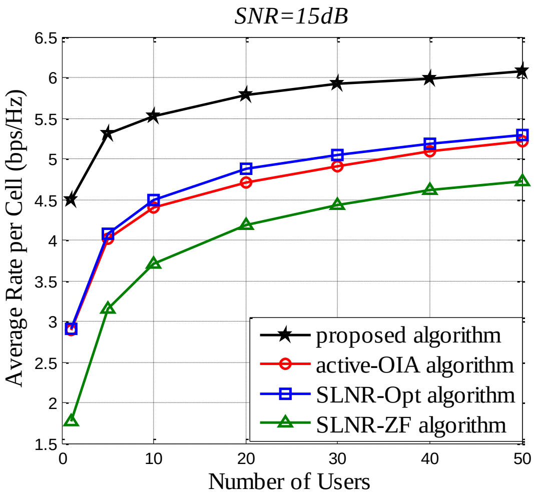
We compare the performance of our proposed algorithm with the following three algorithms: 1) the SLNR metric based algorithm in [11] with ZF receiver (referred to as the SLNR-ZF algorithm); 2) the SLNR metric based algorithm with optimal receiver (referred to as the SLNR-Opt algorithm); 3) the algorithm named CATB-Sb-Opt Rx in [13] (referred to as the active OIA algorithm). All simulation results are averaged over 10^4 independent channel realizations.



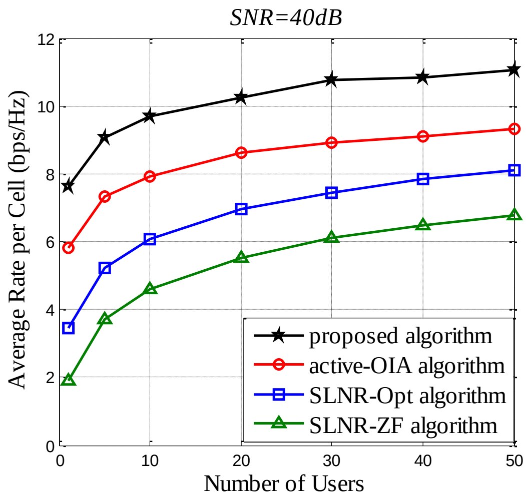
(b)

Fig. 2. ARPC vs SNR for different numbers of cells K. Number of users N=10.

In the first simulation example of Fig. 2, we compare the ARPC performance versus the SNR of the four algorithms. Fig. 2 shows that the proposed algorithm has better performance than the conventional algorithms at all SNRs for the mild interference case with $K=3$. For strong interference case with $K=4$, the proposed algorithm is still better at low-to-medium SNR ($SNR < 30$ dB), while the active OIA algorithm performs better at SNR higher than 30dB. This can be explained as follows. At $SNR > 30dB$, the interference, instead of noise, is the key factor which affects the performance. The interference can be aligned simultaneously in the three cells when $K=3$, and then the interference can be fully eliminated. So SINR is equivalent to SNR in this situation, and the rate increases with SNR at high SNR region. However, there is no solution to align the interference in four cells simultaneously, which means that the interference cannot be fully eliminated. In this situation, at high SNR, the noise is negligible compared with the interference. Thus the ARPC performance of the proposed algorithm reaches a floor at high SNR. However, the ARPC of the active OIA algorithm can still have linear growth with the SNR, because one of the four cells is given priority to align interference perfectly. The average rate of this cell increases which makes the ARPC of the four cells increase.



(a)

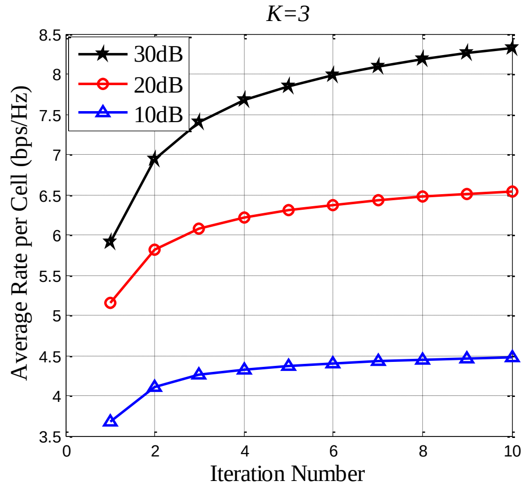


(b)

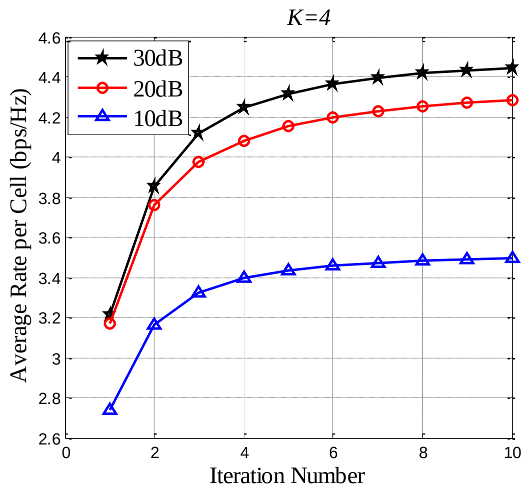
Fig. 3. ARPC vs number of users for different SNR. Number of cells K=3.

In the second simulation example, shown in Fig. 3, we estimate the ARPC performance versus the number of users with mild interference ($K=3$). It is demonstrated that the proposed algorithm performs better than its counterparts under all numbers of users for both medium $SNR=15$ dB and high $SNR=40$ dB, which translates to larger MUD gain.

The third simulation example of Fig. 4 shows the convergence performance of the proposed algorithm. The ARPC performance for the first iteration is equivalent to the SLNR-Opt algorithm, which also proves the reliability of the simulation results. It is seen that the ARPC improves rapidly at the beginning, which demonstrates the gain from iteration. More iterations are needed at higher SNR, and the algorithm approximately approaches the final performance after seven iterations in most cases.



(a)



(b)

Fig. 4. ARPC vs number of iterations for different number of cells K. Number of users N=10.

Through the simulation results above, we can conclude that the proposed algorithm outperforms the conventional algorithms in most cases. Although the active OIA algorithm performs better at $SNR > 30$ dB with $K=4$, which means better DoF gain, the proposed algorithm is more practical because the SNR is usually small than 30dB under the wireless fading channel. The signaling overheads of the four algorithms are almost the same except that the proposed algorithm and the active OIA algorithm need some sort of minor collaboration between the BSs.

Finally, we compare the computational complexity of the algorithms. For the sake of notational simplicity, we assume the antenna number at all nodes equals to N_a. In each of the simulated algorithms, the complexity order of one basic calculation is $O((N_a)^3)$, which mainly involves matrix multiplication and matrix eigen value decomposition. The complexity of the proposed algorithm is higher than the other three algorithms for the need of iteration. In Fig. 2 and Fig. 3, the iteration number is eight. But the average complexity of the algorithm is not like eight times high because the optimized beamforming vectors, receive matrices and user selection set in each iteration can be used for the data transmission in the next iteration.

V. Conclusions

In this paper, an iterative transceiver design and user scheduling algorithm is proposed, which further digs into the multiuser diversity. The proposed algorithm is a SLNR-SINR bi-criteria combined iteration algorithm, which jointly optimizes the transmit beamforming vectors, the receive matrices and the user selection set. Although iteration is needed between the users and the BSs, no extra processing delay is introduced. The optimization results in each iteration can be used for the transmission of the next iteration, which is important for practical applications. Simulation results show performance gains to the conventional algorithms.

Acknowledgment

The authors would like to thank the editor and anonymous reviewers for their valuable comments and suggestions that improved the quality of the paper.

References

[1] V. Cadambe and S. A. Jafar, "Interference alignment and degrees of freedom of the K-user interference channel," *IEEE Trans. Inf. Theory*, vol. 54, pp. 3425-3441, Aug. 2008.

[2] V. Cadambe and S. A. Jafar, "Interference alignment and the degrees of freedom of wireless X networks," *IEEE Trans. Inf. Theory*, vol. 55, no. 9, pp. 3893-3908, Sept. 2009.

[3] C. Suh and D. Tse, "Interference alignment for cellular networks," in *Proc. Allerton Conf. Commun., Control, and Computing*, Sept. 2008, pp. 1037-1044.

[4] X. Rao, L. Ruan, and V. K. N. Lau, "Limited feedback design for interference alignment on MIMO interference networks with heterogeneous path loss and spatial correlations," *IEEE Trans. Signal Process.*, vol. 61, no. 10, pp. 2598-2607, May. 2013.

[5] T. G. Gou, C. W. Wang, and S. A. Jafar, "Aiming perfectly in the dark-blind interference alignment through staggered antenna switching," *IEEE Trans. Signal Process.*, vol. 59, no. 6, pp. 2734-2744, June 2011.

[6] B. C. Jung and W. Y. Shin, "Opportunistic interference alignment for interference-limited cellular TDD uplink," *IEEE Commun. Lett.*, vol. 15, pp. 148-150, Feb. 2011.

[7] B. C. Jung, D. Park, and W. Y. Shin, "Opportunistic interference mitigation achieves optimal degrees-of-freedom in wireless multi-cell uplink networks," *IEEE Trans. Commun.*, vol. 60, no. 7, pp. 1935-1944, July. 2012.

[8] H. J. Yang, W. Y. Shin, B. C. Jung, and A. Paulraj, "Opportunistic interference alignment for MIMO interfering multiple-access channels," *IEEE Trans. Wire. Commun.*, vol. 12, no. 5, pp. 2180-2192, May 2013.

[9] T. M. Nguyen, T. Q. S. Quek, and H. Shin, "Opportunistic interference alignment in MIMO femtocell networks," in *Proc. IEEE International Symposium on Information Theory Proceedings*, July 2012, pp. 2631-2635.

[10] H. J. Yang, W. Y. Shin, B. C. Jung, and C. Suh, "Opportunistic interference alignment for MIMO interfering broadcast channels," in *Proc. IEEE International Conference on Acoustics, Speech and Signal Processing*, May 2014, pp. 2425-2429.

[11] S. H. Hur, B. C. Jung, and B. Rao, "Sum rate enhancement by maximizing SGINR in an opportunistic interference alignment scheme," in *Proc. Asilomar Conf.*, Pacific Grove, CA, Nov. 2011, pp. 354-358.

[12] J. Yoon, W. Y. Shin, and H. S. Lee, "Energy-efficient opportunistic interference alignment," *IEEE Commun. Lett.*, vol. 18, no. 1, pp. 30-33, Jan. 2014.

[13] H. Gao, J. Leithon, C. Yuen, and H. A. Suraweera, "New uplink opportunistic interference alignment: An active alignment approach," in *Proc. Wireless Communications and Networking Conference*, Apr. 2013, pp. 3099-3104.

[14] K. R. Kumar and F. Xue, "An iterative algorithm for joint signal and interference alignment," in *Proc. IEEE International Symposium on Information Theory Proceedings*, Jun. 2010, pp. 2293-2297.

[15] K. Gomadam, V. R. Cadambe, and S. A. Jafar, "A distributed numerical approach to interference alignment and applications to wireless interference networks," *IEEE Trans. Inf. Theory*, vol. 57. no. 6, pp. 3309-3322, Jun. 2011.

[16] R. Horn and C. Johnson, *Matrix Analysis*, New York: Cambridge University Press, 1990.

Weipeng Jiang received the B.Eng. degree from Beijing University of Posts and Telecommunications, Beijing, China, in 2010. He is currently working towards the Ph.D. degree in the School of Information and Communication Engineering, Beijing University of Posts and Telecommunications, Beijing, China. His current research interests include wireless communications, cooperative communication systems and interference alignment.

Kai Niu received a B.S. degree in information engineering and a Ph.D. in signal and information processing from Beijing University of Posts and Telecommunications (BUPT), Beijing, China, in 1998 in 2003, respectively. Currently he is an associate professor in the School of Information and Communication Engineering of BUPT. His research interests are in the area of channel coding and broadband wireless communication, particularly on the practical design of polar codes and study of polar decoding algorithms.

Zhiqiang He received the B.E. degree and Ph.D. degree (with distinction) from Beijing University of Posts and Telecommunications, China, all in signal and information processing, in 1999 and 2004, respectively. Since July 2004, He has been with the School of Information and Communication Engineering, Beijing University of Posts and Telecommunications, where he is currently an Associate Professor and the director of the Center of Information Theory and Technology. His research interests include signal and information processing in wireless communications, networking architecture and protocol design, and underwater acoustic communications.

