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Joint Beamforming and Power Optimization for Cooperative Downlink MIMO Systems

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ABSTRACT

Herein, we propose a joint optimization algorithm to minimize the overall transmit power in multicell multiuser multiple-input multiple-output (MIMO) systems for B5G. The proposed algorithm is an iterative optimization algorithm that jointly computes the transmit/receive beamforming vectors and the transmit power. The superiority of the proposed method is demonstrated through simulations.

Key Words : B5G, MIMO, Beamforming, Joint optimization, Iterative optimization

Ⅰ. Introduction

Cooperative multiple-input multiple-output (MIMO) in multi-cell networks has been intensively investigated as an expansion of MIMO techniques for distributed broadcast channels in distributed manners[1,2]. The base stations are connected to each other by a reliable and fast backhaul; hence, they share the downlink channel and interference information. This enables base stations to choose the transmit beamformer and receive combiner jointly to maximize the downlink sum throughput or minimize the overall transmit power equivalently.

In this study, we propose a joint optimization algorithm to minimize the overall transmit power in multicell multiuser MIMO systems. Base stations cooperate to jointly minimize the overall transmission power, which can be considered as the total cost.

Ⅱ. System Model

In this paper, we consider a multi-cell multiuser MIMO system with N cells with N_t transmit antennas and K users with $N_r \geq N_t$ receive antennas in each cell. We assume that the number of scheduled user per cell is not more than the minimum number of transmit and receive antennas, i.e., $K \leq \min\{N_r, N_t\}$. Let $x_{i,j}$ denote a complex signal transmitted to the jth user in the ith cell. Let $\mathbf{H}_{i,j}$ denote the $N_r \times N_t$ channel matrix from the BS in the ith cell to jth user, and $\mathbf{G}_{n,i}$ denotes $N_r \times N_t$ interference signal matrix from nth cell to the user in ith cell. Channels $\mathbf{H}$ and $\mathbf{G}$ are assumed to be Rayleigh fading; hence, each element of $\mathbf{H}$ and $\mathbf{G}$ is independent and identically distributed (i. i.d.) with normalized Gaussian entries. Therefore, we assume that the channel has full rank with a probability of one. Each user receives signal from its own serving cell from the channel $\mathbf{H}$, without being interfered by the other cell interference from the channel $\mathbf{G}$. The received signal at the jth user in the ith cell is written as $y_{i,j}$ and $n_{i,j}$ denotes the zero-mean additive white Gaussian noise with variance σ^2 at the jth user in the ith cell.

Because we assume that only one stream per user is transmitted from each BS, we define the normalized precoder $\mathbf{f}_{i,j}$ and postcoder $\mathbf{w}_{i,j}$ for the jth user in the ith cell. Each user has its own power constraint; that is, $P_{i,j}$ is assigned to the jth user in the ith cell. Let $\mathbf{f}_{i,j}$ denote $N_t \times 1$ normalized precoding vector multiplied by the BS in the ith cell for the jth user. Let $\mathbf{w}_{i,}$ denote $N_r \times 1$ normalized post coding vector for user j in cell i. Then, the received signal for the jth user in the ith cell can be rewritten as

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$$y_{i,j} = \mathbf{w}_{i,j}^{*}\mathbf{H}_{i,j}\mathbf{f}_{i,j}\sqrt{P_{i,j}}x_{i,j} + \sum_{k\neq j}\mathbf{w}_{i,j}^{*}\mathbf{H}_{i,j}\mathbf{f}_{i,k}\sqrt{P_{i,k}}x_{i,k} + \sum_{n\neq i}\sum_{k}\mathbf{w}_{i,j}^{*}\mathbf{G}_{n,i}\mathbf{f}_{n,k}\sqrt{P_{n,k}}x_{n,k} + \mathbf{w}_{i,j}^{*} \tag{1}$$

The goal of this study was to design transmit beamforming vectors $\mathbf{f}_{i,j}$ and receive combined vectors $\mathbf{w}_{i,j}$ to maximize the signal-to-interference-plus-noise ratio (SINR) and minimize the total transmission power. With given beamforming vectors $\mathbf{f}_{i,j}$ and $\mathbf{w}_{i,j}$, $j = 1,\cdots,K$ and $i = 1,\cdots,N$, the SINR for the jth user in the ith cell can be expressed as

$$\Gamma_{i,j} = \frac{P_{i,j}\left|\mathbf{w}_{i,j}^{*}\mathbf{H}_{i,j}\mathbf{f}_{i,j}\right|^{2}}{\sum_{k\neq j}P_{i,k}\left|\mathbf{w}_{i,j}^{*}\mathbf{H}_{i,j}\mathbf{f}_{i,k}\right|^{2} + \Gamma_{i,j}^{I}} \tag{2}$$

where $\Gamma_{i,j}^{I} = \sum_{n\neq i}\sum_{k}P_{n,k}\left|\mathbf{w}_{i,j}^{*}\mathbf{G}_{n,i}\mathbf{f}_{n,k}\right|^{2} + \left|\mathbf{w}_{i,j}^{*}\right|^{2}\sigma_{i,j}^{2}$.

Because each user has its own quality-of-service requirement, we let $\gamma_{i,j}$ be the SINR target for the jth user in the ith cell. Then, the transmit power minimization problem can be written as

$$\begin{aligned} &\text{minimize } \sum_{i}\sum_{j}P_{i,j}\left|\mathbf{w}_{i,j}^{*}\mathbf{H}_{i,j}\mathbf{f}_{i,j}\right|^{2} \\ &\text{subject to } \Gamma_{i,j} \geq \gamma_{i,j} \\ &\text{where } i = 1,2,\dots,N,\ j = 1,2,\dots,K \end{aligned} \tag{3}$$

In the problem above, P_{ij} can be seen as a transmit power penalty (weighting) for the jth user in the ith cell.

Problem (3) solves the minimization problem independently for each user per cell. Hence, it can be regarded as an individual optimization problem (IOP). Finding a beamforming vector that satisfies the signal-to-noise ratio (SNR) is a simple convex optimization problem; hence, (3) provides the global optimal solution. However, the optimal solution for IOP does not necessarily guarantee a joint optimal solution.

Ⅲ. Iterative Joint Optimization Problem

In this section, we propose a new iterative joint optimization problem (I-JOP) consisting of two steps to solve the minimum transmit power problem.

1) The Beamforming Step: It is well known that the optimal solution for computing normalized beamforming vectors to maximize SINR $\Gamma_{i,j}$ is to nullify the interference and maximize the effective gain under that constraint. For a given transmit beamforming vector $\mathbf{f}_{i,j}$, the received normalized combining vector $\mathbf{w}_{i,j}$ can be written as

$$\mathbf{w}_{i,j} = \frac{\mathbf{H}_{i,j}\mathbf{f}_{i,j}}{\left\|\mathbf{H}_{i,j}\mathbf{f}_{i,j}\right\|}, \qquad i = 1,\dots,N, \quad j = 1,\dots,K \tag{4}$$

To simplify the analysis, an equal power per user was assumed. Because our solution is to maximize the SINR by eliminating the main interferers, the choice of the transmit power does not necessarily yield a better solution. To compute transmit beamforming vector for the jth user in the ith cell to maximize SINR, or equivalently nullify all the interference $\sum_{k\neq j}\mathbf{w}_{i,j}^{*}\mathbf{H}_{i,k}\mathbf{f}_{i,k} + \sum_{l\neq i}\sum_{j}\mathbf{w}_{l,j}^{*}\mathbf{G}_{l,j}\mathbf{f}_{l,j}$, $\mathbf{f}_{i,j}$ can be computed from the generalized eigen analysis [3], as

$$\sum_{k\neq j}\mathbf{w}_{i,j}^{*}\mathbf{H}_{i,k}\mathbf{f}_{i,k} + \sum_{l\neq i}\sum_{j}\mathbf{w}_{l,j}^{*}\mathbf{G}_{l,j}\mathbf{f}_{l,j} = 0 \tag{5}$$

$$\Leftrightarrow\ \mathbf{f}_{i,j}^{*}\mathbf{H}_{i,j}^{*}\left(\sum_{k\neq j}\mathbf{H}_{i,k}\mathbf{f}_{i,k} + \sum_{l\neq i}\sum_{j}\mathbf{G}_{l,j}\mathbf{f}_{l,j}\right) = 0 \tag{6}$$

For the simplest two user case, we could find the beamforming vectors as $\mathbf{f}_{1}^{*}\mathbf{H}_{1}^{*}\mathbf{H}_{2}\mathbf{f}_{2} = 0$ and $\mathbf{f}_{2}^{*}\mathbf{H}_{2}^{*}\mathbf{H}_{1}\mathbf{f}_{1} = 0$ easily because the choice of $\mathbf{f}_1$ and $\mathbf{f}_2$ are the generalized eigenvectors of $\mathbf{H}_{1}^{*}\mathbf{H}_{2}$ and $\mathbf{H}_{2}^{*}\mathbf{H}_{1}$. For more than three users, finding the transmit beamforming vector is non-trivial because the generalized eigendecomposition does not have such a high dimension. However, in our base station cooperation case, the main interferers are the neighboring cells, owing to the path loss exponent, which is usually a 4th order negative exponent. This implies that no cell has more than two main interferers; therefore, the beamformers can be selected on a three-cell basis.

2) Transmit Power Update Step: Our next step is to update the transmit power to minimize the overall transmit power. The proposed iterative algorithm for determining the joint power allocation algorithm at the *n*th iteration is expressed as

$$P_{i,j}^{n+1} = \gamma_{i,j} P_{i,j}^{n} \times \frac{\sum_{k\neq j}\left|\mathbf{w}_{i,j}^{*}\mathbf{H}_{i,k}\mathbf{f}_{i,k}\right|^{2} + \sum_{l\neq i}\sum_{j}\left|\mathbf{w}_{l,j}^{*}\mathbf{G}_{l,j}\mathbf{f}_{l,j}\right|^{2} + \sigma_{i,j}^{2}}{\left|\mathbf{w}_{i,j}^{*}\mathbf{H}_{i,j}\mathbf{f}_{i,j}\right|^{2}} \quad (7)$$

$$\approx \gamma_{i,j} P_{i,j}^{n} \frac{\sum_{k\neq j}\left|\mathbf{w}_{i,j}^{*}\mathbf{H}_{i,k}\mathbf{f}_{i,k}\right|^{2} + \sigma_{i,j}^{2}}{\left|\mathbf{w}_{i,j}^{*}\mathbf{H}_{i,j}\mathbf{f}_{i,j}\right|^{2}} = \frac{\gamma_{i,j} P_{i,j}^{n}}{\Gamma_{i,j}}$$

The convergence of the proposed algorithm was proven regardless of the starting point of an arbitrary $P_{i,j}$[4].

Ⅳ. Numerical Results

The simulation parameters are listed in Table I. Fig. 1 shows the SNR and SINR distributions of the maximum transmission-power method without BS cooperation. When the IOP algorithm is applied, in which each BS transmits with full power to meet the SINR requirement per user, a good SNR distribution is obtained. However, the SINR distribution considering interference from other cells is far worse than the SNR distribution because intercell interference is not considered at all in the IOP. Cell-edge users are in interference-limited situations; hence, the link throughput is significantly lower than the link capacity. Our simulation results show that the total capacity in this scenario is 135.0575 bits/s/Hz, and the capacity per user is 2.3694 bit/s/Hz.

Fig. 2 shows the performance results when the proposed I-JOP was applied. Each BS reduces its transmit power to avoid causing excessive interference to users in neighboring cells. Neighboring BSs interchange user information, such as geometry and transmit power. Then, each BS transmits to its users with the minimum power required to meet the target SINR values. The SNR distribution in the proposed algorithm appears to be worse than that of the maximum power method; however, the SINR performance is considerably better than that of the maximum power method. In this case, the total capacity is 183.1052 bits/s/Hz, and the capacity per user is 3.1345 bits/s/Hz.

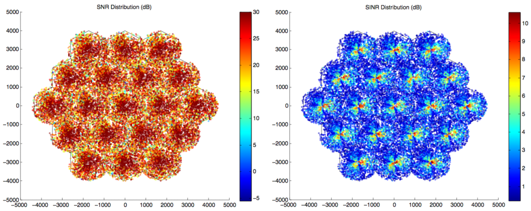

Fig. 1. SNR and SINR for IOP without BS cooperation

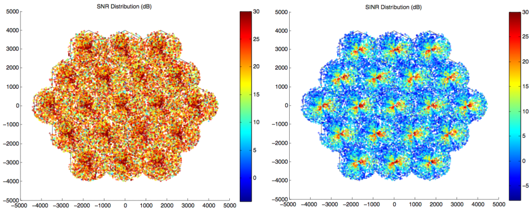

Fig. 2. SNR and SINR for the proposed I-JOP

Table 1. Simulation parameters

Parameter	Value
# cells	19 (57 sectors)
# scheduled users	1
Propagation model	28.6+35log10(d) dB
Shadowing	log normal with σ =8.9dB
N_0	-174 dBm/Hz
BS maximum power	10 watts
Cell radius	1 km
BS / MS antenna gain	15 dB / -1 dBi
MS noise figure	10 dB
Miscellaneous loss	10 dB

Ⅴ. Conclusion

In this study, we discuss the transmit-power minimization problem for a given SINR threshold per user. First, we introduce the system model, which is a beamforming and power optimization problem for multi-cell multiuser MIMO systems. The disadvantages of the IOP are then discussed, motivating the computation of the joint optimization problem (JOP). We proposed I-JOP, which always converges to a unique optimal solution. We then demonstrated the numerical performance of the proposed algorithms using Monte Carlo simulations.

References

[1] J. Kang and W. Choi, "Coordinated regularized zero-forcing beamforming with channel statistics based adaptive feedback for cooperative massive MIMO networks," *ICT Express*, vol. 7, no. 1, pp. 10-14, Mar. 2021.

[2] X. Ma, D. Zhang, M. Xiao, C. Huang, and Z. Chen, "Cooperative beamforming for RIS-Aided cell-free massive MIMO networks," *IEEE Trans. Wireless Com.* (https://doi.org/10.1109/ TWC.2023.3249241)

[3] R. A. Horn and C. R. Johnson, *Matrix Analysis*, 4th Ed., New York: University of Cambridge Press, 1990.

[4] F. Rashid-Farrokhi, L. Tassiulas, and K. Liu, "Joint optimal power control and beamforming in wireless networks using antenna arrays," *IEEE Trans. Commum.*, vol. 46, no. 10, pp. 1313-1324, Oct. 1998.