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Distributed Cooperative Multicell Precoding Based on Local Channel State Information

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Abstract

Cooperative multicell precoding is an attractive way of improving the performance in multicell downlink scenarios especially for terminals at cell edges. Multiple base stations in a given area serve each terminal after precoding, which can coordinate the inter-cell interference and achieve higher performance. Most previous work in the area has focus on centralized precoding which requires gathering all transmitters' channel state information (CSI) at central station (CS) through backhaul and then precoding at CS. However, the requirements on backhaul signaling and computational power scales rapidly in large and dense networks, which usually make such fully centralized approaches impractical. In this paper, we study two practical precoding strategies with only local CSI under a relatively realistic scenario. Performance is finally illustrated through numerical simulations.

Keywords: *cooperative mulicell precoding, distributed precoding, virtual SINR, block diagonalization*

1. Introduction

In recent years, with multiple-input multiple-output (MIMO) techniques, the performance of cellular communication systems can be greatly improved. Many algorithms have been proposed for single-cell downlink scenario, where a base station communicates with many users. However, in multi-cell downlink scenario, these single-cell algorithms are obliged to treat the interference from adjacent cells as noise, which results in a fundamental limitation on the system performance. Recently, base station coordination (also known as Network MIMO) has been analyzed as a means of handling inter-cell interference.

Ideally, all base stations might share their channel state information (CSI) and data through backhaul links, which would enable coordinated precoding design that can manage the co-user interference as in the single-cell scenario [1-3]. In practice, there are limitations in terms of delay and capacity on the backhaul and computational power at the transmitters [4-7], which makes it necessary to investigate distributed forms of cooperation that reduce the backhaul signaling and precoding complexity, while still benefiting from a robust interference control [8-9]. An information theoretic approach was proposed in [10] to determine the dependence of multi-cell rates on backhaul capacity. A practical iterative message passing procedure was taken in [11] to exchange information between neighboring cells.

Herein, we address the problem of distributed multicell MIMO precoding where the cooperating base stations share knowledge of the data symbols but have only local CSI, thereby much reducing the feedback load on the uplink and avoiding cell-to-cell CSI exchange. In this paper, we provide two practical precoding strategies with only local CSI under virtual SINR framework. One is beamforming vectors achieved by Generalized Rayleigh Quotient, the other is distributed block diagonalization algorithm with MPR power allocation. Finally, we provide simulation results under MISO IC scenarios and multicell precoding scenarios respectively and illustrate the performance.

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2. System Model

2.1. System Configuration

We consider a communication scenario with K_t transmitters (e.g., base station in a cellular system) which equipped with N_t antennas each and $K_r \leq N_t$ single-antenna receivers (e.g., mobile station). The transmitters and receivers are denoted BS_j and MT_k, respectively, for $j \in \{1,\cdots,K_t\}$ and $k \in \{1,\cdots,K_r\}$. The BS_j only knows the channel between itself and all receivers which are within its range, either through user feedback or, in a TDD system, form those users' transmission in the uplink. And there is no exchange of CSI between transmitters. We assume that the data symbols intended for all receivers are available at both transmitters, which enable joint multicell precoding.

2.2. Channel Model

In mobile cellular scenarios, the radio propagation can be characterized by three independent phenomena: path loss variation with distance, large-scale shadowing, and small-scale fading. All of them will be incorporated in this paper. Here we assumed that the channel between BS_j and MT_k is narrow-band and frequency-flat block fading. Therefore it is can be modeled as $K_r \times K_t$ random matrix.

$$H_{j,k} = \sqrt{cd_{j,k}^{-\alpha} s_{j,k}} W_{j,k}, \quad j = 1,\cdots,K_t, k = 1,\cdots,K_r \tag{1}$$

Where, $-cd_{j,k}^{-\alpha}$ denotes the path loss. $d_{j,k}^{-\alpha}$ is the distance (in km) between the BS_j and MT_k; α is the path loss exponent, typically taking a value between 3.0 and 5.0; and c is the median of the mean path loss at the reference distance of 1 km.

$-s_{j,k}$ is a log-normal distributed shadowing variable, i.e.,

$$10\log_{10}(s_{j,k}) \in N(0,\sigma_{sh}^2), \ \forall j,k$$

$-W_{j,k}$ represents the small-scale fading. The entries of $W_{j,k}$ are $i.i.d.$ circularly symmetric complex Gaussian random variables with zero mean and unit variance.

The random variables $d_{j,k}$, $s_{j,k}$ and matrices $W_{j,k}$ are assumed to be independent of each other and independent for all j,k.

2.3. Downlink Signal Model

Let $x_j \in C^{N_t}$ be the signal transmitted by BS_j and the corresponding received signal at MT_k be denoted by $y_k \in C$.

$$x_j = \sum_{k=1}^{K_r} \sqrt{p_{j,k}} w_{j,k} s_k \tag{2}$$

Where $s_k \in CN(0,1)$ is the data symbol intended for MT_k and is assumed to be available at all transmitters. $w_{j,k}$ is beamforming vectors which have unit norms (i.e., $\|w_{j,k}\| = 1$) and $p_{j,k}$ represents the power allocated for transmission to MT_k form BS_j. Where BS_j is subject to an individual average power constraint of P_j, that is $E\left\{\|x_j\|^2\right\} = \sum_{k=1}^{K_r} p_{j,k} \leq P_j$.

$$y_k = \sum_{j=1}^{K_t} H_{j,k} x_j + n_k \quad (3)$$

Where $H_{j,k}$ is the channel between BS_j and MT_k, $n_k \in CN(0,\sigma^2)$ is white additive noise.

3. Distributed Precoding Algorithms

3.1. Virtual SINR Framework

Reference [12] notes that the same rate region may be achieved in the uplink (for a reciprocal channel, in the virtual uplink otherwise) and downlink directions using the same set of receive and transmit beamforming respectively, but with different power constraint. This is one form of what is referred to as uplink-downlink duality.

In its most general form, a virtual SINR at BS_j is defined as the ratio between the useful signal power received at its served user MT_k and the sum of noise plus the interference power which causes at the remaining users $MT_{\bar{k}}$. For certain choices of parameters, the virtual SINR can be seen as the SINR achieved in the uplink (or virtual uplink) if the same filters were used.

Thus:

$$\gamma_{j,k}^{virtual} = \frac{p_{j,k} \left| H_{j,k} w_{j,k} \right|^2}{\sigma^2 + p_{j,k} \sum_{\bar{k} \neq k} \left| H_{j,\bar{k}} w_{j,k} \right|^2} \quad (4)$$

Here, $w_{j,k}$ is used to process the received signal at BS_j from MT_k and $MT_{\bar{k}}$.

3.2. Beamforming Vectors Achieved by Generalized Rayleigh Quotient

Consider the virtual uplink channel, virtual SINR is achieved at (4). Where $p_{j,k} \left| H_{j,k} w_{j,k} \right|^2$ is the desired signal power transmitted from MT_k and $p_{j,k} \sum_{\bar{k} \neq k} \left| H_{j,\bar{k}} w_{j,k} \right|^2$ is the interference generated from $MT_{\bar{k}}$ at BS_j. In general, the goal of beamforming is to maximize the signal power at the intended terminal while minimizing the interference caused at other terminals. These ambitions are counteracting and represented by maximum ratio transmission (MRT) and zero-forcing (ZF), respectively. MRT strategy focus on maximizing the useful signal received at one's own receiver and the generated interference is completely ignored, while ZF strategy mainly focus on reducing the interference caused to others. Remarkably, both the strategies are consistent with the distributed channel state information at transmitter (CSIT).

$$w_{j,k}^{(MRT)} = \frac{H_{j,k}}{\left\| H_{j,k} \right\|} \quad (5)$$

$$w_{j,k}^{(ZF)} = \frac{\Pi_{H_{j,\bar{k}}}^{\perp} H_{j,k}}{\left\| \Pi_{H_{j,\bar{k}}}^{\perp} H_{j,k} \right\|} \quad (6)$$

Where $\Pi_{H_{j,\bar{k}}}^{\perp}$ is the projection matrix onto the null space of $H_{j,\bar{k}}$.

In [11], the authors stated that rate tuples on the Pareto boundary of two user MISO IC can be achieved by beamforming vectors that are linear combinations of distributed MRT and ZF.

$$w_i(\lambda_i)=\frac{\lambda_i w_i^{MRT}+(1-\lambda_i)w_i^{ZF}}{\left\|\lambda_i w_i^{MRT}+(1-\lambda_i)w_i^{ZF}\right\|},\ i=1,2 \tag{7}$$

Where $0\le\lambda_i\le 1$ are optimization coefficients. [14] has worked out the optimization coefficient λ_i and shown to attain the Pareto boundary of MISO interference channels (IC) with this beamforming strategy.

A more generalized method is the generalized Rayleigh quotient whose solution is actually a linear combination of the MRT and ZF vectors.

Strategy 1. The virtual SINR framework can be applied to balance the signal and interference powers. As the objective is to have a distributed algorithm which relies only on information local to each base station, we propose that each transmitter solve a virtual SINR maximization problem, which can be stated as follows [12]:

$$\begin{aligned}
w_{j,k} &= \arg\max_{\|w_{j,k}\|=1}\frac{p_{j,k}\left|H_{j,k}w_{j,k}\right|^2}{\sigma^2+p_{j,k}\sum_{\bar{k}\neq k}\left|H_{j,\bar{k}}w_{j,k}\right|^2}\\
&=\arg\max_{\|w_{j,k}\|=1}\frac{\left|H_{j,k}w_{j,k}\right|^2}{\frac{\sigma^2}{p_{j,k}}+\sum_{\bar{k}\neq k}\left|H_{j,\bar{k}}w_{j,k}\right|^2}\\
&=\arg\max_{\|w_{j,k}\|=1}\frac{w_{j,k}^H H_{j,k}^H H_{j,k}w_{j,k}}{w_{j,k}^H\frac{\sigma^2}{p_{j,k}}w_{j,k}+\sum_{\bar{k}\neq k}w_{j,k}^H H_{j,\bar{k}}^H H_{j,\bar{k}}w_{j,k}}\\
&=\arg\max_{\|w_{j,k}\|=1}\frac{w_{j,k}^H\left(H_{j,k}^H H_{j,k}\right)w_{j,k}}{w_{j,k}^H\left(\frac{\sigma^2}{p_{j,k}}+\sum_{\bar{k}\neq k}H_{j,\bar{k}}^H H_{j,\bar{k}}\right)w_{j,k}}\\
&=\arg\max_{\|w_{j,k}\|=1}\frac{w_{j,k}^H A w_{j,k}}{w_{j,k}^H B w_{j,k}}
\end{aligned} \tag{8}$$

Where $A=H_{j,k}^H H_{j,k}$ and $B=\frac{\sigma^2}{p_{j,k}}+\sum_{\bar{k}\neq k}H_{j,\bar{k}}^H H_{j,\bar{k}}$.

Expression (8) is the Generalized Rayleigh Quotient if matrix A and B are Hermitian matrix, and B is positive definite. We can find that:

$$A^H=(H_{j,k}^H H_{j,k})^H=H_{j,k}^H H_{j,k}=A \tag{9}$$

$$\begin{aligned}
B^H &=\left(\frac{\sigma^2}{p_{j,k}}+\sum_{\bar{k}\neq k}H_{j,\bar{k}}^H H_{j,\bar{k}}\right)^H\\
&=\left(\frac{\sigma^2}{p_{j,k}}\right)^H+\sum_{\bar{k}\neq k}\left(H_{j,\bar{k}}^H H_{j,\bar{k}}\right)^H\\
&=\frac{\sigma^2}{p_{j,k}}+\sum_{\bar{k}\neq k}H_{j,\bar{k}}^H H_{j,\bar{k}}\\
&=B
\end{aligned} \tag{10}$$

$$\lambda(B) = \frac{\sigma^2}{p_{j,k}} I + \lambda(\sum_{\bar{k} \neq k} H_{j,\bar{k}}^H H_{j,\bar{k}}) \tag{11}$$

And $H_{j,\bar{k}}^H H_{j,\bar{k}}$ is non-negative define matrix, $\lambda\left(H_{j,\bar{k}}^H H_{j,\bar{k}}\right) \geq 0$, then:

$$\lambda(\sum_{\bar{k} \neq k} H_{j,\bar{k}}^H H_{j,\bar{k}}) \geq 0 \tag{12}$$

At the same time, $\frac{\sigma^2}{p_{j,k}} > 0$. So,

$$\lambda(B) > 0 \tag{13}$$

Now we can draw a conclusion that expression (6) satisfies the conditions mentioned above and is Generalized Rayleigh Quotient. It can be solved by eigen value techniques. The widely known solution to this problem is such that:

$$Aw_{j,k} = \lambda_{j,k} Bw_{j,k} \tag{14}$$

According to this specific solution, the expression (7) is maximized when the column of $w_{j,k}$ are the dominating eigenvectors of $B^{-1}A$ corresponding to the highest eigen values.

Strategy 2. Since the signals transmitted from different transmitters experience different macroscopic fading, efficient power allocation over the transmitters will enhance significantly the SNR at the receivers and increase the capacity or the diversity gain of the cooperative multicell system. This paper we introduce the maximal path loss ratio (MPR) approach, which follows the intuition of allocating more power to strong terminals, since weak terminals hopefully are served more effectively by other base stations.

$$p_{j,k} = \frac{tr\left\{H_{j,k} H_{j,k}^H\right\}}{\sum_{\bar{k}=1}^{K_r} tr\left\{H_{j,\bar{k}} H_{j,\bar{k}}\right\}} P_j \tag{15}$$

Where P_j is the maximal transmitting power at BS_j.

3.3. Distributed Block Diagonalization Algorithm with MPR Power Allocation

Define $\tilde{H}_{j,k} = \left[H_{j,1}^H \cdots H_{j,k-1}^H H_{j,k+1}^H \cdots H_{j,Kr}^H\right]^H$. We can eliminate all multi-user interference through forcing $w_{j,k}$ to lie in the null space of $\tilde{H}_{j,k}$. Data can be transmitted to MT_k if the null space of $\tilde{H}_{j,k}$ has a dimension greater than 0. This is satisfied when $rank(\tilde{H}_{j,k}) < N_t$. Let $\tilde{r}_{j,k} = rank(\tilde{H}_{j,k})$, and define the singular value decomposition (SVD).

$$\tilde{H}_{j,k} = \tilde{U}_{j,k} \tilde{\Sigma}_{j,k} \left[\tilde{V}_{j,k}^{(1)} \quad \tilde{V}_{j,k}^{(0)}\right]^H \tag{16}$$

Where $\tilde{V}_{j,k}^{(0)}$ holds the last $(N_t - r_{j,k})$ right singular vectors, and $\tilde{V}_{j,k}^{(1)}$ holds the first $r_{j,k}$ right singular vectors. $\tilde{V}_{j,k}^{(0)}$ forms an orthogonal basis for the null space of $\tilde{H}_{j,k}$, and its columns are candidates for the bamforming vectors $w_{j,k}$. Assuming that the independence condition is satisfied for all mobile stations, we define the matrix $H_s = H_{j,k}\tilde{V}^{(0)}_{j,k}$ and $r_{j,k} = rank(H_s)$, now the system capacity under the zero-interference constraint can be written as:

$$C = \max_{w_{j,k}} \log_2 \left| I + \frac{1}{\sigma_n^2} H_s w_{j,k} w_{j,k}^H H_s^H \right| \tag{17}$$

The problem is now to find a matrix $w_{j,k}$ that maximizes the determinant, and the solution is to let $w_{j,k}$ be the right singular vectors of H_s, weighted by MPR power allocation approach on the corresponding singular values. Here we choose MPR rather than water-filling because it's more realistic. Define the SVD:

$$H_{j,k}\tilde{V}^{(0)}_{j,k} = U_{j,k} \begin{bmatrix} \Sigma_{j,k} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V^{(1)}_{j,k} & V^{(0)}_{j,k} \end{bmatrix}^H \tag{18}$$

Where $\Sigma_{j,k}$ is $r_{j,k} \times r_{j,k}$ and $V^{(1)}_{j,k}$ represents the first $r_{j,k}$ singular vectors. Then $w_{j,k} = \tilde{V}^{(0)}_{j,k} V^{(1)}_{j,k} \sqrt{p_{j,k}}$ is the beamforming vectors that can maximize the information rate subject to producing zero interference.

4. Simulation Results

4.1. MISO IC Scenarios

We consider the MISO interference channel where $K_t = 2$ transmitters with $N_t = 2$ antennas each and $K_r = 2$ single antenna receivers. Each transmitter, which has only the data information intended for its own receivers and the CSI between itself and all users, communicates with a single receiver [7, 8].

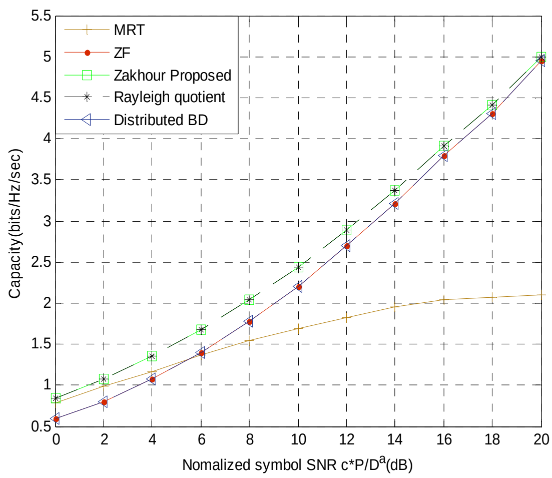

Figure 1. Illustrates the available channel capacity of the different beamforming strategies which are MRT, ZF, Zakhour proposed approach, Rayleigh quotient and distributed BD

From the figures, we can see that in this scenario distributed BD equivalent to ZF, and Rayleigh quotient acquires identical and best performance with Zakhour Proposed approach. So we can draw the conclusion that Rayleigh quotient approach can get the optimal performance Since has proved that Zakhour proposed approach arrived the rate tuple on the Pareto boundary.

4.2. Multicell Precoding Scenarios

In this section, we illustrate the precoding performance in a scenario with $K_t = 2$ base station with $N_t = 2$ antennas each and $K_r = 2$ single antenna mobile terminals. Each base station knows the data information transmitted for all mobile terminals and has CSI that can be obtained locally.

The available capacity of Rayleigh quotient and Distributed BD are given. As a comparison, we give the capacity of MRT, ZF and Centralized BD. From Figure 2 we can see that the performance of Distributed BD and Rayleigh quotient are similar and better than MRT and ZF. Interestingly, the performance loss when compared with Centralized BD which has global CSI is only no more than 2 bits/Hz/sec. At the same time, we reduce the computational demands since there is no exchange of CSI between base stations. So they are more practical schemes.

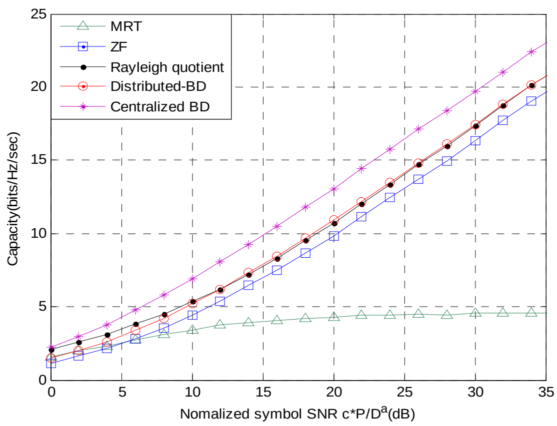

Figure 2. Illustrate the precoding performance in a scenario with $N_t = 2$ base station with $N_t = 2$ antennas each and $K_r = 2$ single antenna mobile terminals

5. Conclusion

In this paper, we have addressed the problem of distributed multicell MIMO precoding where the cooperative base stations do not share knowledge of the data symbols but have only local CSI. Under virtual SINR framework, we provided two practical precoding strategies with only local CSI. One can be obtained by generalized Rayleigh quotient, and the other was an application of block diagonalization with MPR power allocation. The distributed precoding algorithms reduced the feedback load on the uplink and avoided cell-to-cell CSI exchange. Simulation results show that the proposed two distributed algorithms can achieve similar available rate performance which is much better than MRT and ZF. Although there is a limited performance loss compared with centralized algorithms, the proposed two distributed algorithms are more practical schemes since there is no exchange of CSI between base stations.

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