두 셀 대칭적 간섭 채널환경에서 협력적 불규칙 빔형성 방법의 성능에 대한 연구

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On The Performance of Coordinated Random Beamforming Schemes in A Two-Cell Symmetric Interference Channel

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요 약

본 논문에서는 두 셀 대칭적 간섭 채널 환경에서 세 가지 방식의 협력적 불규칙 빔형성 방법을 분석한다. 먼저, 기지국 선택을 통한 간단한 형태의 부분 협력 빔형성 방법은 연계적 인코딩을 적용한 불규칙 빔형성 방법과 동일한 평균 합 전송률을 갖는다는 것을 증명한다. 또한, 전송 모드 선택 방법을 적용하는 경우에 시스템의 사용자가 많을 때에 부가적인 합 전송율의 이득이 발생하는 것을 증명하였다. 모의 실험 결과를 통해서 성능에 대한 분석이 유효함과 정확성을 확인하였다.

Key Words : MIMO, network MIMO, Cell Coordination, limited feedback, precoding

ABSTRACT

In this paper, three coordinated random beamforming (CRBF) schemes are analyzed in a two-cell symmetric interference channel. A simple partial coordination of RBF with base station selection (BSS) is shown to achieve the same average sum rate performance of CRBF with joint encoding (JE). To improve the sum rate performance further, we also propose a transmission mode selection (TMS) between the BSS and JE which is shown to have additional sum rate gain for the large number of users. Siumulation results verify the eectiveness of the proposed CRBF schemes and accuracy of the proposed analysis.

Ⅰ. Introduction

A transmission with multiple antennas is known to provide potentially significant improvement of data rate and link reliability. However its performance degrades significantly in a multi-cellular environment, when other cell interference (OCI) dominates the thermal noise[1]. To deal with this problem, several coordinated transmission schemes over the cells have been proposed[2,3]. However, they are often either very complex or require large feedback overhead, which preclude the coordinated transmission from being exploited.

In a single cell environment, random beamforming (RBF) is known to be simple and ecient transmission scheme with partial feedback[4]. RBF was

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proven to have asymptotically optimal sum rate growth for the large number of users where the sum rate is defined to the sum of transmission rate of each beam in RBF[5]. Articulated RBF with multiple sets of random beam vectors or dierent number of orthonormal beams also could improve the performance with very minimal additional complexity[6]. However, to the best of authors' knowledge, the coordinated RBF (CRBF) has never been addressed properly despite of its simplicity and efficiency. Based on this observation, we propose several CRBF schemes for downlink coordinated transmission schemes and analyze their performance to find out a proper CRBF scheme in an interference channel.

Ⅱ. System Model

We consider a multi-cell downlink system with exploiting RBF for multi-antenna transmission. For simplicity, we focus on a system with two cells having $2K$ users in a symmetric channel where it is assumed that the serving base station (BS) of the first K users is the BS 1 and the second K users are served by the BS 2. To make the system description clearer, a simple system with two transmit antennas and 4 users per cell is illustrated in Fig 1. It is also assumed that each beam is transmitted with equal power under total power ρ per BS. Each BS transmits with M antenna and each MS receives with a single antenna. When each BS transmits M different beams with independent encoding, the signal to interference plus noise ratio (SINR) at the user k for the beam m of the BS i can be expressed as in [5]

$$\gamma_{m,i,k} = \frac{|\boldsymbol{w}_{i,m}^H \boldsymbol{h}_{i,k}|^2}{\sum_{j=1, j\neq m}^{M} |\boldsymbol{w}_{i,j}^H \boldsymbol{h}_{i,k}|^2 + \sum_{j=1}^{M} |\boldsymbol{w}_{c(i),j}^H \boldsymbol{h}_{c(i),k}|^2 + M/\rho} \quad (1)$$

where $c(i)$ is an interfering cell index such that $c(1)=2$ and $c(2)=1$, $\boldsymbol{h}_{i,k} \in C^{M\times 1}$ is circularly symmetric complex Gaussian channel between the user k, and the BS i with independently and identically distributed (i.i.d) elements with zero mean and unit variance, and

$\boldsymbol{w}_{i,m}$ is orthonormal random beamforming vector of the beam m of the BS i. Since signal power in (1) has $\chi^2(2)$ distribution while interference power in (1)) has $\chi^2(4M-2)$ distribution, the cumulative distribution function (CDF) $F_X(x)$ of the SINR can be easily derived from [5] as follows.

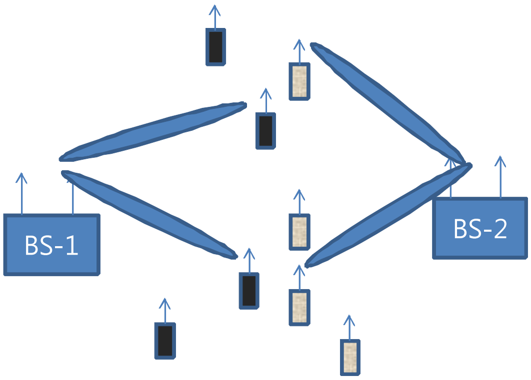

Fig. 1. System model ($M=2, K=4$, MSs with dark-filled rectangular are served by BS-1 while ones with light-filled rectangular are served by BS-2)

$$F_X(x) = 1 - \frac{e^{-\frac{M}{\rho}x}}{(1+x)^{2M-1}} \quad (2)$$

Compared to the SINR distribution of the RBF in a single cell[5], the exponent of the denominator of the second term in (2), was changed from $M-1$ to $2M-1$, which naturally follows from

the increase in the number of interference from $M-1$ to $2M-1$. Since channels from different BSs are independent, for simplicity, without loss of generality, we set $\boldsymbol{w}_{1,m} = \boldsymbol{w}_{2,m} = \boldsymbol{w}_m$ for $m=1,\ldots,M$.

Ⅲ. Coordinated Random Beamforming Schemes

In this section, three simple but efficient cell coordinated joint RBFs and schedulings are proposed to improve the performance of RBF in a multi-cell environment. Throughout the paper, the scheduling policy is limited to the max rate scheduling such that users are selected to maximize the sum rate at each instance, and feedback of the single largest SINR and its corresponding beam information is assumed..

3.1 BS selection (BSS)

Under the assumption that each BS encodes disjointly, each MS measures the SINRs of all beams from each BS, selects the largest SINR and reports it to the corresponding BS, which we call "BS selection" (BSS). Based on the explained feedback policy the largest SINR associated with the beam m of the BS i can be expressed as $\max_{k \in U_{BSS}(m,i)} \gamma_{m,i,k}$ where $U_{BSS}(m,i)$ is the set of indices of users reporting SINR of the beam m of the BS i. The corresponding average sum rate per cell can be written as

$$R_{BSS} = \frac{1}{2} E\left\{ \sum_{i=1}^{2} \sum_{m=1}^{M} \log\left(1 + \max_{k \in U_{BSS}(m,i)} \gamma_{m,i,k}\right) \right\} \quad (3)$$

This partial coordination scheme can be one of the simplest forms of the cell coordination.

3.2 Joint Encoding (JE)

When joint encoding over two BSs are applied, a simple and systematic way to construct the codebook for joint encoding is to extend the set of random beam vectors of dimension $2M$ by 1 by using Hadamard structure as follows.

$$W_c = \frac{1}{\sqrt{2}} \begin{bmatrix} W & W \\ W & -W \end{bmatrix} \quad (4)$$

where $W = [w_1, ..., w_M]$ with $w_i \in C^{M \times 1}$ for $i = 1, 2, ..., M$, $w_i^H w_j = 1$ for $i = j$ and $w_i^H w_j = 0$ for $i \neq j$. Since W is an orthonormal matrix, W_c is also an orthonormal one, which naturally satisfies the BS power constraint. The measured SINR of RBF with joint encoding can be written as in [5]

$$\overline{\gamma}_{m,k} = \frac{|\overline{w}_m^H \overline{h}_k|^2}{\sum_{i \neq m}^{2M} |\overline{w}_i^H \overline{h}_k|^2 + M/\rho} \quad (5)$$

where $\overline{w}_m = [W_c]_m$, $[A]_m$ denotes the mth column of matrix A, and $\overline{h} = [h_{1,k}^H h_{2,k}^H]^H$. It is noted that since signal power and total interference power have the same probability distribution as in (1), the SINR of RBF with joint encoding has the same CDF as (2). Since JE over two BSs works in the same way as in the disjoint encoding over single BS with two times more transmit antennas, the largest SINR of the beam m can be expressed as $\max_{k \in U_{JM}(m)} \overline{\gamma_{m,k}}$ where $U_{JM}(m)$ is the set of indices of users reporting SINR of the beam m in (5). Since there are $2M$ beams in the system, the average sum rate per cell of this scheme can be written as

$$R_{JE} = \frac{1}{2} E\left\{ \sum_{m=1}^{2M} \log\left(1 + \max_{k \in U_{JM}(m)} \overline{\gamma_{m,k}}\right) \right\} \quad (6)$$

By comparing (3) and (6), we can have interesting observation as follows.

Theorem 1: CRBF with BS selection achieves the same average sum rate of random beamforming with joint encoding. i.e.

$$R_{RSS} = R_{JE} \quad (7)$$

Proof Since (1) and (5) have the same CDF, and the total number of beams are the same for both schemes, the same average sum rate naturally follows. □

This theorem has a practical implication that a simple partial cell coordination of RBF with the BSS can achieve the same average sum rate performance of CRBF with JE, which removes the necessity of a centralized processor for scheduling. It is also noted that BSS can be applicable when two BS have different numbers of transmit antennas, while JE can not.

3.3 Transmission Mode Selection between the BSS and the JE (TMS)

If BSs can choose the transmission mode between the BSS and the JE at each instance such that the sum rate can be maximized, which we call “transmission mode selection (TMS)”, the resulting sum rate may be improved. To do so, each user need to measure the SINRs with and without joint encoding and report the largest SINR. Since the system chooses the transmission mode with higher sum rate at each scheduling instance, the average sum rate of the TMS can be written as

$$R_{TMS}= \frac{1}{2}E\left\{ \max\left(\sum_{m=1}^{2M}\log(1+\max_{k\in U_{TMS}^{J}(m)}\overline{\gamma_{m,k}}), \sum_{i=1}^{2}\sum_{m=1}^{M}\log(1+\max_{k\in U_{TMS}^{D}(m,i)}\gamma_{m,i,k})\right)\right\} \quad (8)$$

where $U_{TMS}^{J}(m)$ is the set of indices of users reporting theSINR of the beam m for joint encoding, and $U_{TMS}^{D}(m,i)$ is the set of indices of users reporting the SINR of the beam m of BS i for disjoint encoding. The TMS with the largest SINR report is likely to provide the larger sum rate when the number of users in the cell is large, since the mode diversity can dominate the multiuser diversity, which will be shown in the next section with approximation for the large number of users. To make the tramission mode understood clearly, Fig. 2 provides a conceptual illustration of each transmission mode with very simple system setup.

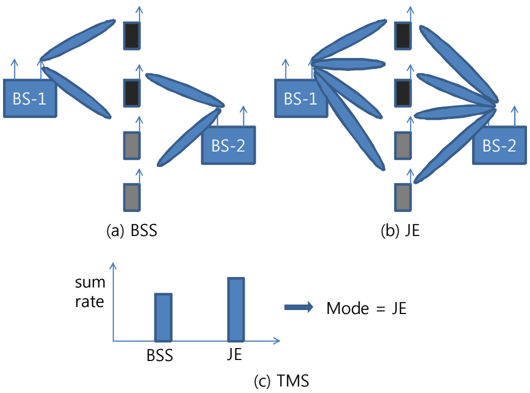

Fig. 2. Conceptual illustrations of the transmission modes when there are two BSs with two transmit antennas and two users per each cell. (MSs with dark-filled rectangle are served by BS-1 while ones with light-filled rectangle are by BS-2)

Ⅳ. Sum rate approximation of CRBF schemes

Since the SINR distribution of the proposed CRBF schemes follows the same type of the SINR distribution of RBF in a single environment, we can take an advantage of approximating the sum rate of the proposed schemes by exploiting the results in a single cell environment. The limiting distribution of the data rate for each beam of RBF in a single cell was shown to be the Gumbel distribution[8]. To derive the parameters associated with limiting distribution of the data rate for each beam with large number of users, first, we introduce the inverse function of the CDF of the data rate for each beam[6]

$$F_Y^{-1}(z)=\log(\xi^{-1}W(\xi e^{\xi-\frac{\log(1-z)}{2M-1}})) \quad (9)$$

where $Y=\log(1+X)$, $\xi=\frac{M}{\rho(2M-1)}$, $W()$, is the Lambert W function, and X is a random variable which follows the distribution in (2). The limiting distribution of $\max_{1\le k\le n}\frac{Y_k-b_n}{a_n}$ where Y_ks are i.i.d, was shown to have the Gumbel distribution[8]. The normalizing constants a_n and b_n can be set as [9]

$$b_n=F_Y^{-1}(1-\frac{1}{n}),\ a_n=F_Y^{-1}(1-\frac{1}{\neq})-b_n \quad (10)$$

By applying (9) to (10), the normalizing constants a_n and b_n can be calculated as

$$\begin{aligned} a_n &= \log(\xi^{-1}W(\xi e^{\xi+\frac{\log(n)}{2M-1}})) \\ b_n &= \log(W(\xi e^{\xi+\frac{\log(\neq)}{2M-1}})/W(\xi e^{\xi+\frac{\log(n)}{2M-1}})) \end{aligned} \quad (11)$$

Since standard Gumbel random variable has the mean γ[9] where γ is Euler constant which is approximately 0.57722, $\max_{1 \le k \le n} Y_k$ can be approximated as

$$E\{\max_{1 \le k \le n} Y_k\} = a_n\gamma + b_n \quad (12)$$

Similarly, the average sum rate of BSS and JE can be approximated as

$$R_{BSS} = R_{JE} \approx M(a_{2K}\gamma + b_{2K}) \quad (13)$$

Noting that the SINRs of joint encoding and disjoint encoding for a given user are not guaranteed to be independent, derivation of an approximation for average sum rate of the TMS requires the following bounds on expectations of order statistics which are applicable to random variables with non-identical distributions.

Proposition 1 [10]: Let v_i and σ_i be the mean, and the variance of the random variable X_i, and $(1/p)\sum_{i=1}^{p} v_i$ be denoted by $\bar{v}$. Then

$$\bar{v} \le E\{\max x_i\} \le \sqrt{\frac{p-1}{p}\sum_{i=1}^{p}\left[\sigma_i^2 + (v_i - \bar{v})^2\right]} \quad (14)$$

From (14), we make an approximation of the expectation of maximum of dependent random variables as simple average of the upper and lower bound of (15)

$$E\{\max x_i\} \approx \bar{v} + \frac{1}{2}\sqrt{\frac{p-1}{p}\sum_{i=1}^{p}\left[\sigma_i^2 + (v_i - \bar{v})^2\right]} \quad (15)$$

To approximate the average sum rate of the TMS, variances of sum rate of the JE and the BSS, σ^2_{BSS} and σ^2_{JE} need to be approximated as follows

$$\sigma^2_{BSS} = \sigma^2_{JE} \approx Ma^2_{2K}\pi^2/12 \quad (16)$$

which follows from the fact that the standard Gumbel random variable has the variance of $\pi^2/6$[9]. By putting together (13), and (16) into (15)

$$R_{TMS} \approx M(a_{2K}\gamma + b_{2K}) + \sqrt{Ma^2_{2K}\frac{\pi^2}{48}} \quad (17)$$

Comparison of (17) with (13) shows that the TMS scheme can provide the larger sum rate than the JE or the BSS approximately by $\sqrt{Ma^2_{2K}\frac{\pi^2}{48}}$ for a large number of users, since it can exploit the mode diversity from selecting the transmission scheme with better instantaneous sum rate. It is noted that since RBF is optimal in the asymptotic sum rate growth for a large number of users[5], CRBF with JE is also an optimal coordinated precoding scheme in the asymptotic sum rate growth. Since CRBF with BSS has the same average sum rate as CRBF with JE, and TMS outperforms it, all proposed CRBF schemes achieve the asymptotic optimal sum rate growth.

V. Numerical Results and Conclusions

In this section, the proposed CRBF schemes are evaluated and the validity of the analysis is verified with numerical evaluation in Fig.3. Unless otherwise stated, simulation setup follows the system model and assumptions in the section 2. For fixed SNR and system setup, the number of users are increased to find out the efficiency of the transmission mode.

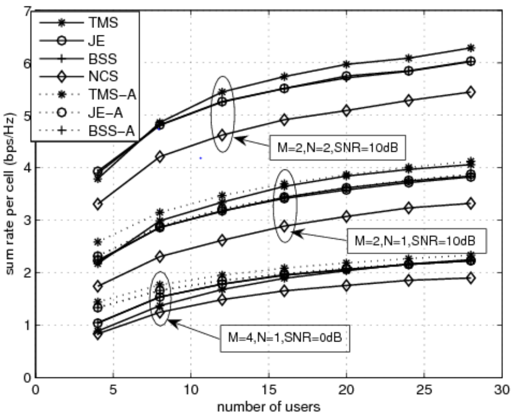

Fig. 3. The sample average of sum rates of the proposed CRBF schemes and closed form approximations for increasing number of users (solid line : sample average, dotted line : approximation, N : number of receive antennas))

The unit of average sum rate is bps/Hz/cell for every simulation case. All the proposed CRBF schemes significantly outperform RBF with no coordination scheduling (NCS). It is noted that even though the performance improvement of proposed CRBF schemes is noticeable, but not as much in the case of joint precoding with perfect channel state information (CSI)[3], since the performance of RBF is already limited by the inter-beam interference. It can be seen that JE and BSS provide about 10%~15% sum rate improvement over NCS while TMS provides about 5~10% additional improvement. As stated in Theorem-1, the average sum rate performances of JE and the BSS are found to be the same. Following from the tradeoff between mode diversity and multiuser diversity, the TMS performs better than other two CRBF schemes for the large number of users while getting worse for the small number of users. The proposed sum rate approximation also provides very tight match to the sample average even when the number of users is not so large. We also compared performance of the proposed CRBF schemes with two receive antennas where the minimum mean squared error (MMSE) receive combining is adopted. It can be seen that the performance characteristics of the CRBF schemes with two receive antennas is similar to those with a single receive antenna.

In this paper, we proved that the simple partial cell coordination of RBF with the BSS achieves the same sum rate performance as CRBF with JE. As a more articulated CRBF scheme, the proposed TMS which exploits the mode diversity between the BSS and JE was shown to improve the performance for the larger number of users through simulation and analysis.

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