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두 셀 시스템 환경에서 하이브리드 모드 빔형성 성능에 대한 연구

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On The Performance of a Hybrid Mode Beamforming in A Two-Cell System

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요 약

본 논문에서는 연계 빔형성과 비연계 빔형성 방법이 동시에 가능한 하이브리드 모드 빔형성 (HMB) 방법을 제안한다. HMB는 점근적으로 합 전송 증가율에 있어서 최적의 빔형성 방법임을 증명한다. 다양한 모의 실험을 통해서 HMB는 대칭 간섭 채널 환경에서 연계 빔형성 방법과 거의 동일한 성능을 달성함을 보인다. 또한, 보다 현실적인 비대칭적 간섭 채널 환경에서는 비대칭 채널 환경에서 연계 빔형성의 전력 비효율성으로 인한 성능의 저하를 갖지만, 연계 빔형성 방법보다는 우수한 성능을 갖는다는 것을 보인다.

Key Words : MIMO, network MIMO, Cell Coordination, Random Beamforming, Multi-Cell

ABSTRACT

In this paper, hybrid mode beamforming (HMB) which allows simultaneous transmission of joint beamforming and disjoint beamforming is proposed. HMB is proven to be asymptotically optimal beamforming for sum rate growth. Extensive simulations show that HMB achieves nearly the same performance as joint encoding (JE) in symmetric interference channel. It is also shown that it outperforms JE in a more realistic asymmetric interference channel environment, though it still experiences some performance degradation due to power inefficiency of joint beamforming in asymmetric channel.

Ⅰ. Introduction

A transmission with multiple antennas in a multi-cell environment with frequency reuse-1 is known to be problematic due to other cell interference[1]. A classical solution to this problem is to reuse the same spectral resource with some physical distance such that each signal does not interfere with each other, which has been used in GSM[2]. However, this type of interference mitigation scheme may not be properly applicable to wideband system to support high data since the number of available spectral resources may not be large enough to apply frequency reuse effectively. The other solution is to allow a mobile station (MS) in other cell interference (OCI) limited region to be

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served by multiple BSs which could have given strong inter-cell interference otherwise.

While interference reduction technique currently used in a commercial cellular system is rather passive, recently significant attention has been paid to more articulated cell coordination schemes for transmission with multi-antennas[3]. Cell coordination scheme with perfect CSI often provides an upper bound performance achievable with cell coordination[4]. To avoid BS synchronization problem and huge computation complexity of inter cell processing, a simple BS selection using intercell scheduling was shown to be a practical solution[5,6]. Considering the limited capacity in feedback channel, several cell coordination schemes with partial CSI have been proposed. For a two cell scenario, the optimal linear filtering based on game theory with a guess on the type of linear filtering of the other BS was shown to be a possibly practical solution[7]. Joint opportunistic beamforming and scheduling (JOBS) with cell coordination was proposed where users were selected to minimize the interference to each other over coordinating BSs[8]. However this scheme assumes a single beam transmission per BS at every instance and requires a large number of SINR reports.

Recently, as a practical solution for cell coordinated transmission, several coordinated random beamforming (CRBF) schemes in a two cell environment were proposed[9]. SINRs of CRBF schemes were shown to have the same probability density function as the one with two times more antennas in a single cell. This means that CRBF is an asymptotically optimal beamforming with a large number of users for sum rate growth. However, the performance of CRBF was studied under symmetric channel environments only. Joint encoding (JE) can incur performance degradation when it is applied in asymmetric channel environment due to inefficient power allocation. That is, a signal of BS far away from the user tends to have minor contribution to total received signal power compared to the signal from BS nearby the user. In this case, disjoint encoding over each BS may improve sum rate performance. As an alternative to this problem, we propose a hybrid mode beamforming (HMB) which allows JE and disjoint beamforming simultaneously. The performance of HMB will be compared with CRBF schemes in [9] for both symmetric and asymmetric channel environments through simulation.

This paper is organized as follows. In section-2, a system model is given for two cell environment. In section-3, we propose HMB and analyze its performance. In section-4, the numerical evaluation of the proposed HMB and comparison with existing CRBFs are made. Conclusions are drawn in section-5.

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 users in a homogeneous channel. Each BS transmits with antenna and each MS receives with a single antenna. Perfect channel estimation and perfect synchronization of each BS are assumed. The error-free feedback channel is also assumed. Two BSs are assumed to be connected through the backhaul with unlimited capacity, so that there would be no delay in sharing both feedbacks from MSs and information symbols. The scheduling policy is limited to max rate scheduling such that users are selected to maximize the sum rate at each instance. When each BS transmit different beams with independent encoding, the received signal at the MS can be written as

$$r_k = \sqrt{\frac{\rho}{M}} \sum_{m=1}^{M} \boldsymbol{h}_{1,m}^{H} w_{1,m} s_{1,m} + \sqrt{\frac{\rho}{M}} \sum_{m=1}^{M} \boldsymbol{h}_{2,m}^{H} w_{2,m} s_{2,m} + n_k \tag{1}$$

where ρ is total transmit power of each BS, $\boldsymbol{h}_{i,k} \in C^{M \times 1}$ is circularly symmetric complex Gaussian vector of the channel between the user k, and BS i with independently and identically distributed (i.i.d.) elements with zero mean and unit variance, $w_{i,m}$ is orthonormal random beamforming vector of the beam m of BS i, $s_{i,m}$ is information symbol for the beam m of BS i with unit variance, and n_k is additive complex white Gaussian noise with mean zero and unit variance. When there is no coordination between two BSs, it is assumed that the serving BS of the first K users is BS 1 and the second K users are served by BS 2. When disjoint encoding is applied, SINR at the user k for the beam m of BS i can be expressed as

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

where $c(1)=2$ and $c(2)=1$. It is noted that since each BS sends the signal with orthonormal random beamforming and unitary transformation of the vector does not change the norm of the vector, other cell interference does not depend on the user selection of the other BS. Since signal power in (2) has $\chi^2(2)$ distribution while interference power in (2) has $\chi^2(4M-2)$ distribution, the cumulative distribution function (CDF) $F_X(x)$ of the SINR is shown [9] as follows.

$$F_X(x) = 1 - \frac{e^{-\frac{M}{\rho}x}}{(1+x)^{2M-1}} \tag{3}$$

Since channels from different BSs are independent and the statistics of SINR are indifferent no matter what orthonormal beam vectors are used in other cells, we assume each BS uses the same set of orthonormal random beam vectors for simplicity. i.e. $w_{1,m} = w_{2,m} = w_m$ for $m = 1,\cdots,M$ where w_m is a orthonormal random beam vector which can be generated from isotopic distribution[10].

Ⅲ. Hybrid Mode Beamforming

Even though JE among CRBFs in [9] is a simple and efficient coordinated transmission scheme, it may experience performance degradation in asymmetric channel environments due to inefficient power usage. If there is a transmission scheme which allows joint encoding for users in the symmetric channel environment and distjoint encoding for ones in the asymmetric channel environment, then it may provide performance improvement compared to JE in a multi-cell environment.

There can be many ways to realize the above idea. For simplicity, we focus on HMB based on RBF which has the equal number of beams with joint encoding and disjoint encoding. We also consider this scheme only for even number of transmit antennas. Since the articulated codebook design for HMB is not of our focus in this paper, we propose a construction of random beamforming vectors for HMB by using originally generated random beam vector w_m in the following way.

$$\begin{aligned} \boldsymbol{W}_c &= \frac{1}{\sqrt{2}}\begin{bmatrix} \boldsymbol{W} & \boldsymbol{W} \\ \boldsymbol{W} & -\boldsymbol{W} \end{bmatrix} \\ \boldsymbol{W}_H^J &= \left[[\boldsymbol{W}_c]_1,\cdots,[\boldsymbol{W}_c]_{M/2},[\boldsymbol{W}_c]_{1+M},\cdots,[\boldsymbol{W}_c]_{M/2+M}\right] \\ \boldsymbol{W}_H^D &= \left[[\boldsymbol{W}_c]_{M/2+1},\cdots,[\boldsymbol{W}_c]_M\right] \end{aligned} \tag{4}$$

where $\boldsymbol{W} = [w_1,\cdots w_M]$, $\boldsymbol{W}_c^J$ is a reference matrix for generating random beams for HMB, $\boldsymbol{W}_H^J$ is a set of random beam vectors for joint encoding, and $\boldsymbol{W}_H^D$ is one for disjoint encoding, and $[\,]_i$ is the ith column vector of the matrix in bracket. It is observed from (4) that first $M/2$ beams of $\boldsymbol{W}$ are used for construction of beams for joint encoding, and others for distjoint encoding. With this set of random vectors, the orthogonality among the beams for the same type of encoding is kept. For beams between different types of encoding, the orthogonality can not be guaranteed. With this set of HMB vectors, SINR of HMB can be written as

$$\begin{aligned} \widehat{\gamma^J_{m,k}} &= \frac{|\boldsymbol{w}_{J,m}^{H}\overline{\boldsymbol{h}_k}|^2}{\psi - |\boldsymbol{w}_{J,m}^{H}\overline{\boldsymbol{h}_k}|^2 + M/\rho} \\ \widehat{\gamma^D_{m,j,k}} &= \frac{|\boldsymbol{w}_{D,m}^{H}\overline{\boldsymbol{h}_k}|^2}{\psi - |\boldsymbol{w}_{D,m}^{H}\overline{\boldsymbol{h}_k}|^2 + M/\rho} \end{aligned} \tag{5}$$

where

$$\psi = \sum_{i=1, i \neq m}^{M} |\boldsymbol{w}_{J,i}^{H} \overline{\boldsymbol{h}_k}|^2 + \sum_{i=1}^{M/2} (|\boldsymbol{w}_{D,i}^{H} \boldsymbol{h}_{1,k}|^2 + |\boldsymbol{w}_{D,i}^{H} \boldsymbol{h}_{2,k}|^2),$$

$\overline{\boldsymbol{h}_k} = [\boldsymbol{h}_{1,k}^{H} \boldsymbol{h}_{2,k}^{H}]^{H}$, $\widehat{\gamma_{m,k}^{J}}$ is SINR of the mth beam vector with joint encoding, $\widehat{\gamma_{m,j,k}^{D}}$ is SINR of the mth beam vector of BS j with disjoint encoding, $w_{J,i}$ and $w_{D,i}$ are the ith column vectors of $\boldsymbol{W}_{H}^{J}$ and $\boldsymbol{W}_{H}^{D}$ respectively. Interestingly, SINRs in (5) have the following statistical property.

Lemma 1 : $\widehat{\gamma_{m,k}^{J}}$ and $\widehat{\gamma_{m,j,k}^{D}}$ have the same CDF as (3)

Proof : We prove that $\widehat{\gamma_{m,k}^{J}}$ has the same CDF as (3). The proof for $\widehat{\gamma_{m,j,k}^{D}}$ can be easily proved in the same way as for $\widehat{\gamma_{m,k}^{J}}$. $|\boldsymbol{w}_{J,i}^{H} \overline{\boldsymbol{h}_k}|^2$ has the i.i.d. chi-square distribution with d.o.f. 2, since random beam vectors are orthonormal. $|\boldsymbol{w}_{D,i}^{H} \boldsymbol{h}_{1,k}|^2$ and $|\boldsymbol{w}_{D,i}^{H} \boldsymbol{h}_{2,k}|^2$ have the i.i.d chi-square distribution with d.o.f. 2 with the same reason. Independence between $|\boldsymbol{w}_{J,m}^{H} \overline{\boldsymbol{h}_k}|^2$ and $|\boldsymbol{w}_{D,i}^{H} \boldsymbol{h}_{1,k}|^2$ is guaranteed, since $\boldsymbol{w}_{J,m}^{H} \overline{\boldsymbol{h}_k}$ is the sum of two Gaussian random variables independent of $|\boldsymbol{w}_{D,i}^{H} \boldsymbol{h}_{1,k}|^2$ from the generation of the random beam vector. The same argument holds for independence between $|\boldsymbol{w}_{J,m}^{H} \overline{\boldsymbol{h}_k}|^2$ and $|\boldsymbol{w}_{D,i}^{H} \boldsymbol{h}_{2,k}|^2$. Consequently the total interference in $\widehat{\gamma_{m,k}^{J}}$ has the chi-square distribution with d.o.f. $2M-1$ since interferences and signal are i.i.d. distributed. Thus, $\widehat{\gamma_{m,k}^{J}}$ has the same statistical distribution as (2).

When the single largest SINR report is enforced, the corresponding average sum rate can be calculated as

$$R_{HMB} = E\left\{ \begin{array}{l} \sum_{m=1}^{M} \log(1 + \max_{k \in U_{HMB}^{J}(m)} \widehat{\gamma_{m,k}^{J}}) \\ + \sum_{m=1}^{M/2} \log(1 + \max_{k \in U_{HMB}^{D,1}(m)} \widehat{\gamma_{m,1,k}^{D}}) \\ + \sum_{m=1}^{M/2} \log(1 + \max_{k \in U_{HMB}^{D,2}(m)} \widehat{\gamma_{m,2,k}^{D}}) \end{array} \right\} \tag{6}$$

where $U_{HMB}^{J}(m)$ is the set of indices of users reporting SINR of the beam m with full joint encoding, $U_{HMB}^{D,1}(m)$ and $U_{HMB}^{D,2}(m)$ are sets of indices of users reporting the largest SINR of the beam m from BS1 and BS2.

Since CDF of HMB has the same type of CDF of RBF in a single cell, asymptotic linear scaling of the sum rate can be analyzed by exploiting the approach and result having been obtained in the asymptotic analysis of random beamforming in a single cell environment.

Theorem 1: For fixed M and ρ, $\lim_{K \to \infty} \frac{R_{HMB}}{M \log\log K} = 1$

Proof : Since each SINR in (6) is distributed according to (3), the transmission rate of this type of SINR has growth rate of $\log\log K$ [10], and there are beams in the system, the sum rate growth of the HMB follows $2M \log\log K$ which proves the theorem.

Ⅳ. Simulation Results

In this section, the performances of proposed HMB are evaluated and compared with other CRBFs through numerical simulations. The unit of average sum rate is bps/Hz for every simulation case. Unless otherwise stated, the simulation setup follows the system description in the section 2. Comparing CRBF schemes are JE, base station selection (BSS) which selects the best serving BS with larger SINR while disjoint RBF is performed, and Non-cooperative (NC) disjoint RBF[9]. For clarity, they are defined in the following way from [9]. For simplicity, we abuse notation on $\widehat{\gamma_{m,i,k}^{D}}$ and $\widehat{\gamma_{m,k}^{J}}$ while they are calculated from $\boldsymbol{W}$ and $\boldsymbol{W}_c$ respectively so that M disjoint beams and $2M$ jointly encoded beams can be defined.

NC is a well known RBF except that it experiences additional intercell interference of which SINR follows distribution of $\widehat{\gamma_{m,j,k}^{D}}$. Corresponding sum rate can be defined as

$$R_{NC}=E\left\{\sum_{i=1}^{2}\sum_{m=1}^{M}\log\left(1+\max_{k\in U_{NC}(m,i)}\widehat{\gamma^{D}_{m,i,k}}\right)\right\} \tag{7}$$

where $U_{NC}(m,i)$ is a set of indices of users reporting SINR of the beam m of BS i, and each user reports to the fixed serving BS always. On the contrary, in BSS, each user reports index and SINR of the beam having the largest SINR to BS to which the beam belongs. Corresponding sum rate can be expressed as

$$R_{BSS}=E\left\{\sum_{i=1}^{2}\sum_{m=1}^{M}\log\left(1+\max_{k\in U_{BSS}(m,i)}\widehat{\gamma^{D}_{m,i,k}}\right)\right\} \tag{8}$$

where $U_{JE}(m)$ is a set of indices of users reporting SINR of the beam m of BS i. JE is the same as RBF except that it is applied over $2M$ antennas. Thus, the sum rate of JE can be written as

$$R_{JE}=E\left\{\sum_{m=1}^{2M}\log\left(1+\max_{k\in U_{JE}(m)}\widehat{\gamma^{J}_{m,k}}\right)\right\} \tag{9}$$

where $U_{JE}(m)$ is a set of indices of users reporting SINR of the jointly encoded beam m.

In Fig.-1, the performances of the proposed HMB are compared with those of CRBFs for different number of users and different SNRs, when there are two BSs in the system and symmetric channel environments are assumed. In this figure, except the graph of NC, graphs of HMB, JE, and BSS can not be discernable for each SNR, since they have almost identical performance. It is noted that regardless of SNRs and the numbers of users, the performance of HMB is almost identical to those of JE and BSS, which can be expected from the distribution of the SINR of HMB.

However, this is not the case when HMB and other CRBFs are applied in an asymmetric two cell environment, which is shown in Fig.-2. To simulate the asymmetric two cell channels, two BSs are assumed to be in a line with distance of 2. K users are dropped with uniform distance distribution over [0,1] for each serving BS. For each drop, 2000 Rayleigh flat block fading channels are generated, and users are scheduled according to proportional fair (PF) scheduling policy with averaging time constant of 0.005. Since max rate scheduling defined in the previous section scarcely selects uses located far away from BS in asymmetric channel environment, PF scheduling is considered for fair and meaningful comparison in asymmetric channel environment. The 100 drops are executed to average out the locations of users. For simplicity, shadowing is not considered, and the path loss exponent was chosen to be 3.5. The cell edge SNR was set to be

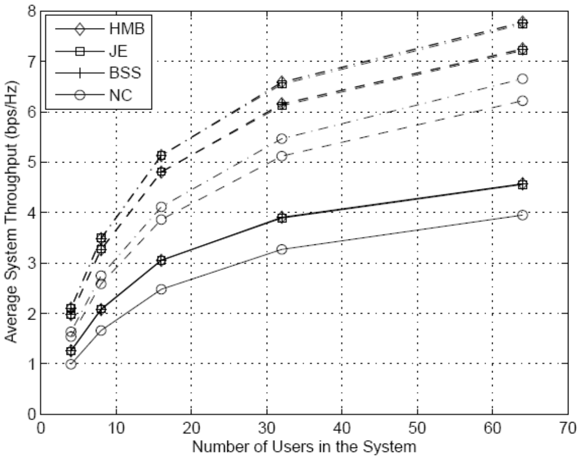

Fig. 1. Comparison of the sum rates of the HMB with other CRBFs in a two cell symmetric channel (= 4, solid line : SNR = 0dB, dashed line : SNR = 10dB, dashdot line : SNR = 20dB).

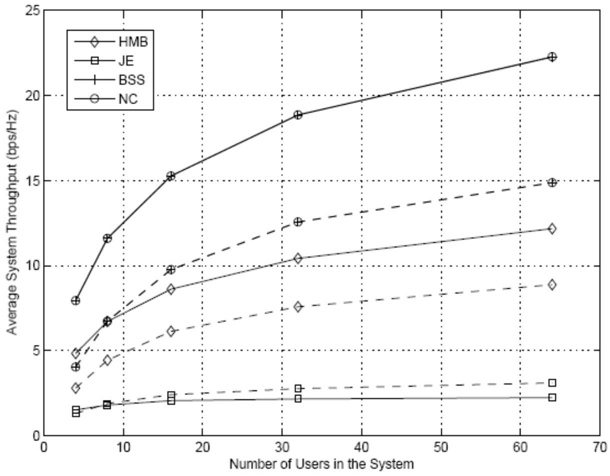

Fig. 2. Comparison of the sum rates of the HMB with other CRBFs in two cell asymmetric channel (solid line : M = 2, dotted line : M = 4).

$10dB$ when $d=1$. Thus, the SNR of the user when the user is located with distance d from closer BS can be calculated as $10d^{-3.5}$. On the contrary to the symmetric channel case, NC outperforms the JE and HMB. As expected, HMB compensates the power loss incurring from JE. However, since it keeps half of beams to be JE, its performance is much worse than NC or BSS. while BSS shows better performance than NC in a symmetric multi-cell channel, it shows almost identical performance to that of NC. BS selection gain in BSS diminishes out as the number of users benefitting from BS selection decreases. Thus, when the performance and complexity are considered, the NC or BSS among CRBF schemes may be the proper transmission schemes in multi-cell environments.

Ⅴ. Conclusions

In this paper, we proposed HMB as an alternative to JE. It was shown that HMB is asymptotically optimal beamforming in sum rate growth for two-cell symmetric channel. Simulation results showed that HMB can perform as well as JE. However, CRBF schemes including joint beamforming such as JE and HMB showed the performance degradation due to power inefficiency in two-cell asymmetric channel.

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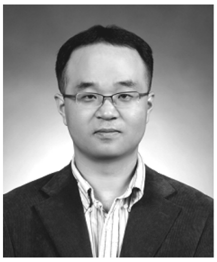

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