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다중 셀 환경에서 적은 복잡도를 갖는 준 최적 하향 빔형성

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Simplified Near Optimal Downlink Beamforming Schemes in Multi-Cell Environment

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요 약

다중 안테나 전송은 단일 셀 환경에서 큰 성능 이득을 제공하는 반면에 다중셀 환경에서는 간섭에 의해서 다중 안테나의 이득이 많이 사라지게 된다. 또한, 다중셀 환경에서 효율적인 빔 형성 방법을 계산하는 것은 여전히 어려운 문제중에 하나이다. 먼저 이 논문에서는 다중셀 환경에서 점근적으로 낮은 SNR과 높은 SNR에서 최적의 하향링크 빔형성 방법이 MRT 빔형성과 ZF 빔형성임을 보인다. 둘째, 이 점근적 최적 빔 형성 결과를 이용하여 쌍대 역방향 문제로부터 얻어진 MMSE 빔형성 형태를 갖는 두가지의 준최적 하향 빔형성 방식을 제안한다. 각 빔 형성 방식에 대해서 복잡도에 따라서 세가지의 다른 부클래스 알고리즘을 고려한다. 모의 실험을 통하여 제안된 준 최적 알고리듬은 복잡도와 성능 사이에 트레이드 오프를 제공함을 보인다.

Key Words : MIMO, multi-cell, beamforming, duality, MISO, sum rate maximization

ABSTRACT

Despite enormous performance gain with multi-antenna transmission in the single cell environment, its gain diminishes out in the multi-cell environment due to interference. It is also very hard to solve the efficient downlink beamforming with low complexity in multi-cell environment. First, this paper shows that the asymptotically sum rate optimal downlink beamformings at low and high SNR are maximum ratio transmit (MRT) and zero forcing (ZF) beamforming in the multi-cell system, respectively. Secondly, exploiting the asymptotically optimal downlink beamforming, we develop simple two types of near optimal downlink beamforming schemes having the form of minimum mean squared error (MMSE) beamforming obtained from the dual uplink problem. For each type, three different subclasses are also considered depending on the computational complexity. The simulation results show that the proposed near optimum algorithms provide the trade-off between the complexity and the performance.

Ⅰ. Introduction

It is widely known that the multi-antenna transmission provides enormous potential gain through multiplexing or diversity[1]. However, this is not the case in the multi-cell environment where other interference works as additional noise, which lowers the signal to interference plus noise ratio

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(SINR)[2]. Interference will be particularly problematic in the current cellular system where base stations (BSs) are densely installed with frequency usage of frequency reuse-1 due to the scarce frequency resource. Thus, efficient downlink transmission is necessitated to deal with this problem.

Most of previous research on the transmission with multi-antenna in the interference-limited system can be categorized depending on how BSs are cooperating. The simplest BS coordination includes the orthogonal transmission of multiple BSs either in time or frequency domain while the most complex BS coordination can be a case that all BSs works as a giant single BS where a single centralized controller decides scheduling and transmission over all BSs. BS coordination can be implemented either in centralized way or distributed way, which provides the tradeoff between the performance and complexity[3-6]. However, the practical implementation is still obstructed by the processing power required for increased complexity resulting from BS coordination, and delay in sharing channel information and transmit data due to the limited backhaul capacity. On the other hand, independent

downlink transmission at each individual BS with available channel information can be an alternative. Linear precoding for the downlink of multi-user multi input multi output (MIMO) system based on the maximal signal to jamming and noise ratio (SJNR) criterion[7] can be directly applicable to the downlink beamforming in the multi-cell environment. Similarly, the downlink beamforming using the channel covariance information for other-cell interference mitigation was shown to be efficient in spatially correlated channel[8]. Even when the interference information is not available at the transmitter, a downlink beamforming algorithm to guarantee the target packet error rate by using statistics of the interference only at the mobile was proposed[9].

However, it is often had to solve the downlink problem due to nonconvex problem structure in the SINR. To deal with this problem, equivalent dual uplink problem was formulated[10]. Even though this dual uplink problem formulation suggests that the optiaml downlink beamforming is in the form of minimum mean squared error (MMSE) beamforming, it is not strightforward to solve this MMSE beamforming directly due to undetermined parameters such as signal power and noise power in solving MMSE beamforming. To the best of author’s knowledge, the near-optimal downlink beamforming algorithm in the multi-cell environment, which exploits the optimal beamforming in the dual uplink problem, has also never been properly addressed.

The main contribution of this paper is to derive the asymptotically optimal beamforming and its sum rate performance for high and low signal to noise ratios (SNR) and to propose simple near optimal downlink beamforming schemes from the MMSE beamforming structure in the dual uplink. It is widely known that the optimal uplink beamforming at low SNR is maximum ratio combining, and zero forcing (ZF) beamforming at high SNR[11]. From the asymptotic analysis based on dual uplink, it will be shown that this also holds for downlink beamforming in the multi-cell environment.

The calculation of the downlink beamforming vector through dual uplink problem algorithm to solve this problem requires the complicated iterative updates of the three different types of optimizing variables, and a good initialization for the iterative implementation as well[12]. Rather than implementing the algorithm iteratively, therefore, we propose to select the best one among the candidate sets of beamforming vectors generated from the MMSE criterion with different signal and noise power allocations in the dual uplink. Thus, our scheme searches over possibly good downlink beamforming vectors and selects one supporting the largest sum rate. While the maximum ratio transmission (MRT) beamforming to maximize the energy of signal or zero forcing (ZF) beamforming to nullify the interference are conventionally used for downlink beamforming, the proposed MMSE beamforming chosen from possibly good candidates beam vectors is likely to provide good performance by properly positioning signal direction between signal space and its null space.

This paper is organized as follows. In Section 2, we describe the system model and reproduce uplink-downlink beamforming sum rate duality with per BS constraint in multi-cell environment[10]. In Section 3, the asymptotic optimal beamforming at both high and low SNRs, and its corresponding sum rate is analyzed. From the asymptotic analysis in the dual uplink problem, two types of the simple and near-optimal downlink beamforming algorithm with different subclasses depending on the implementation complexity are proposed in Section 4. The asymptotic analysis is numerically verified and the performances of the proposed algorithms are evaluated in Section 5. Conclusions are made in Section 6.

Ⅱ. System Model

Fig.1 illustrates an example of the multi-cell system of interest consisting of three BSs, where each BS with transmit antennas selects a single MS with a single receive antenna by using its predesinged scheduler for communication. Specifically, the example shows that three MSs in the cell edge are being served while interfering other MSs of other cells.

The received signal at the th MS can be expressed as

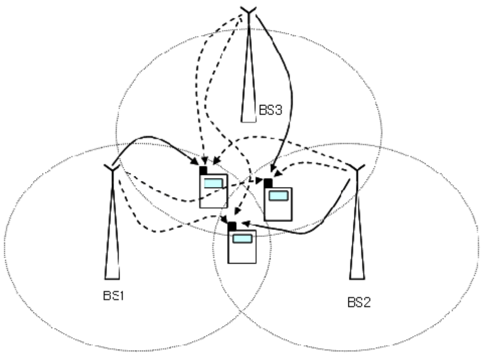

Fig. 1. Multi-cell system model (solid line represents the transmission of the information signal while the dotted one implies the interference to the MSs in other cells.)

$$y_b = \sqrt{p_b}\, h_{b,b}^H u_b s_b + \sum_{b' \neq b}^{B} \sqrt{p_{b'}}\, h_{b',b}^H u_{b'} s_{b'} + z_b \qquad (1)$$

where p_b is the transmit power from the bth BS, $h_{b',b} \in C^{M \times 1}$ is the channel vector from the b'th BS to the bth MS, whose elements are independently and identically distributed Gaussian with unit power, $u_b \in C^{M \times 1}$ is the transmit beamforming vector with unit norm at the bth BS, s_b is the modulation symbol with unit average power, B is total number of BSs in the system, and z_b is additive white Gaussian noise (AWGN) with variance $E\{|z_b|^2\} = \sigma_n^2$ for $b = 1,2,...,B$. The corresponding SINR γ_b at the bth MS can be calculated as follows

$$\gamma_b = \frac{p_b |h_{b,b}^H u_b|^2}{\sum_{b' \neq b} p_{b'} |h_{b',b}^H u_{b'}|^2 + \sigma_n^2} \qquad (2)$$

It is easily noted that due to the nature of the SINR definition, it is very hard to solve the optimal beamforming which maximizes the sum rate of the system.

To solve the optimal downlink beamforming, the equivalent dual uplink problem was developed in [10]. To take advantage of [10] for developing some of the simplified near optimal downlink beamforming schemes, we reproduce the main result of [10]

Theorem 1[10] : The multicell downlink beamforming

sum rate maximization problem with per-BS power constraints is defined as

$$\max\left\{ \sum_b \log(1+\gamma_b) \mid P_T, u_b \in U_1, \forall b \right\} \qquad (3)$$

where $P_{T=}[P_{T,1},...,P_{T,B}]$, is a BS transmit power vector, $U_1 = \{u \mid \|u\| = 1, u \in C^{M \times 1}\}$, and $\| \cdot \|$ is the norm of the vector. The dual uplink problem can be expressed as

$$\min_{\overline{q_b}} \max_{u_{b},\overline{g_b}} \left\{ \begin{array}{l} \sum_b \log(1+\overline{\gamma_b}) | \widehat{C_1}, \widehat{C_2}, \widehat{C_3}, \widehat{C_4},\ \overline{\gamma_b} = \\ \dfrac{\overline{g_b} |\boldsymbol{h}_{\boldsymbol{b,b}}^{\boldsymbol{H}} \boldsymbol{u_b}|^2}{\sum_{b' \neq b} \overline{g_{b'}} |\boldsymbol{h}_{\boldsymbol{b',b}}^{\boldsymbol{H}} \boldsymbol{u_{b'}}|^2 + \overline{q_b}}, \boldsymbol{u_b} \in U_1 \end{array} \right\} \tag{4}$$

$$\widehat{C_1}: 1_{\boldsymbol{B}}^{\boldsymbol{T}} \overline{\boldsymbol{g}} \leq 1_{\boldsymbol{B}}^{\boldsymbol{T}} \boldsymbol{P_T}, \widehat{C_2}: \overline{\boldsymbol{q}^{\boldsymbol{T}}} \boldsymbol{P_T} \leq \sigma_n^2 1_{\boldsymbol{B}}^{\boldsymbol{T}} \boldsymbol{P_T}$$

vector, $\bar{\boldsymbol{q}} = \left[\overline{q_1}, \ldots, \overline{q_B}\right]$ is a BS thermal noise power vector, and $1_{\boldsymbol{B}}$ is a $B \times 1$ vector whose every element is 1.

Proof : See the proof in [10].

$\overline{\gamma_b}$ in (4) can be considered as the SINR of the uplink at the bth BS that involves interference from $B-1$ other cells and the thermal noise power level of $\overline{q_b}$. From this theorem, the optimal downlink beamforming $\boldsymbol{u}_{\boldsymbol{b}}^{*}$ can be calculated as MMSE uplink beamforming[10].

$$\boldsymbol{u}_{\boldsymbol{b}}^{*} = \zeta_b \left(\sum_{b' \neq b} \overline{g_b^{*}} \boldsymbol{h}_{\boldsymbol{b,b'}} \boldsymbol{h}_{\boldsymbol{b,b'}}^{\boldsymbol{H}} + \overline{q_b^{*}} I_{M \times M} \right)^{-1} \boldsymbol{h}_{\boldsymbol{b,b}} \tag{5}$$

where $\overline{g_b^{*}}$ is optimal signal power allocation, $\overline{q_b^{*}}$ is optimal thermal noise power allocation, and ζ_b is a normalizing constant such that the norm of the beamforming vector is 1. It is noted that (5) requires the optimal signal power allocation and thermal noise power allocation with the constraints defined in (4), which may be found out through the iterative joint optimization of the signal power allocation, noise power allocation, and uplink beamforming. Even though (4) facilitates the nonconvex optimization of the primal downlink sum rate maximization problem, however, it still requires complex iterative implementation. To deal with this problem, asymptotically optimal beamformings will be found first, and suboptimal beamforming schemes based on those will be developed in subsequent sections.

Ⅲ. Asymptotically Optimal Downlink Beamforming

The asymptotic analysis at high and low SNRs may be useful for the system designer to estimate the upper bound of the sum rate performance at the cell or sector edge. We will look into the cases that the solution of (4) may have a closed form for asymptotic conditions such as high SNR, low SNR. These asymptotic solutions will also be used to propose near optimal solutions later on.

When the SNR is low, (4) can be approximated as follows

$$\min_{\overline{q_b}} \max_{u_{b},\overline{g_b}} \left\{ \sum_b \frac{\overline{g_b} |\boldsymbol{h}_{\boldsymbol{b,b}}^{\boldsymbol{H}} \boldsymbol{u_b}|^2}{\overline{q_b}} | \widehat{C_1}, \widehat{C_2}, \widehat{C_3}, \widehat{C_4}, \boldsymbol{u_b} \in U_1 \right\} \tag{6}$$

where we used $x/(x+y) \approx x/y$ for $x \ll y$ and $\log(1+x) \approx x$ for $0 \leq x \ll 1$ for approximation with asymptotically low SNR. The optimal beamforming reduces to a maximum ratio transmit (MRT) beamforming which does not depend on the signal power allocation and noise power allocation.

When the SNR is high, we focus on the asymptotic analysis with condition of $M \geq B$ for simplicity. With asymptotically high SNR assumption, (4) can be approximated as follows.

$$\min_{\overline{q_b}} \max_{u_{b},\overline{g_b}} \left\{ \begin{array}{l} \sum_b \log\left(\dfrac{\overline{g_b} |\boldsymbol{h}_{\boldsymbol{b,b}}^{\boldsymbol{H}} \boldsymbol{u_b}|^2}{\sum_{b' \neq b} \overline{g_{b'}} |\boldsymbol{h}_{\boldsymbol{b',b}}^{\boldsymbol{H}} \boldsymbol{u_{b'}}|^2} \right) | \\ \widehat{C_1}, \widehat{C_2}, \widehat{C_3}, \widehat{C_4}, \boldsymbol{u_b} \in U_1 \end{array} \right\} \tag{7}$$

where approximation follows from $\log(1+x) \approx \log(x)$ for $x \gg 1$. The maximizing solution of beamforming vector in (7) is clearly ZF beamforming regardless of signal and noise power allocation. This is in line with the fact that ZF beamforming is asymptotically optimal at high SNR in the multi-user uplink beamforming system.

Ⅳ. Near Optimal Downlink Beamforming Algorithm

Even though Theorem-1 provides a more solvable form for calculating the optimal downlink beamforming in the multi-cell environment, it still has a major drawback. One may devise an iterative algorithm to solve this problem, which is very hard to find a proper one with global convergence, or one may have to depend on brute-force search over all parameters in the feasible set. Thus, we propose two types of suboptimal downlink beamforming algorithms with advantage of complexity reduction, each of which has three different subclasses offering different levels of complexity. Since the optimal beamforming has the form of the MMSE beamforming, methodology of developing beamforming algorithm ends up with finding the good MMSE beamforming with proper signal and noise power allocation.

4.1 MMSE beamforming with interpolation of asymptotic signal power allocations (MMSE- IAPA)

In the previous section, it was shown that the signal and noise power allocation with asymptotically optimal beamforming in the dual uplink are different at low and high SNR. From this observation, we heuristically propose to calculate the signal and noise power allocations by taking advantage of the asymptotic power allocations and determine MMSE beamforming vectors for those parameters. Fig. 2 summarizes the proposed algorithm, where it computes the power allocation based on the interpolation of those found for asymptotic conditions, so that the power allocation is interpolated as a function of SNR In Fig. 2, $[a]_b$ is the bth element of the vector a, and ξ is an interpolation exponent.

Step-1 : Calculate Interpolation Constant

$$\alpha_b = \exp(-\xi\rho_b)$$

Step-2 : Calculate Signal Power Allocation

$$\mathbf{g}_{high} = \frac{P_T}{B}\mathbf{1}$$

$$\mathbf{g}_{low} = P_T\left[\frac{\|\mathbf{h}_{1,1}\|^2 P_{T,1}}{\sum_b \|\mathbf{h}_{b,b}\|^2 P_{T,b}} \quad \cdots \quad \frac{\|\mathbf{h}_{B,B}\|^2 P_{T,B}}{\sum_b \|\mathbf{h}_{b,b}\|^2 P_{T,b}}\right]$$

$$\mathbf{g}_{MMSE-IAPA,b} = \alpha_b \mathbf{g}_{low} + (1-\alpha_b)\mathbf{g}_{high}$$

Step-3 : Calculate Noise Power Allocation

$$q_{high} = \frac{\sigma_n^2 P_T}{BP_{T,b}}, \; q_{low} = \frac{\sigma_n^2 P_T \sqrt{g_{pu2,b}\|\mathbf{h}_{B,B}\|^2}}{\sqrt{P_{T,B}}\sum_b \sqrt{P_{T,b} g_{pu2,b}\|\mathbf{h}_{b,b}\|^2}}$$

$$q_{MMSE-IAPA,b} = \alpha_b q_{low} + (1-\alpha_b) q_{high}$$

Step-4 : Caluculate Beamforming Vector

$$\mathbf{u}_{MMSE-IAPA,b} = \varsigma_b \left(\sum_{b' \neq b} [\mathbf{g}_{MMSE-IAPA,b}]_{b'} \mathbf{h}_{b,b'} \cdot \mathbf{h}_{b,b'}^H + q_{MMSE-IAPA,b} I\right)^{-1} \mathbf{h}_{b,b}$$

Fig. 2. Algorithm description of the MMSE beamforming with interpolation of asymptotic signal power allocations (MMSE-IAPA).

There can be many ways of interpolating power allocation based on SNR. We set the exponent for interpolation of signal power allocation as negative such that it can choose g_{high} when the SNR is high. Even though this can be done with inversely linear model such as $\max(1-\phi/\rho_b, 0)$ where ϕ is a proportionality constant, we chose exponential type interpolation since it has better performance for several numerical evaluations. After several heuristic schemes were considered, it was turned out that the interpolating based on the exponential of the negative exponent of the scaled SNR was a good choice. Finally, the downlink beamforming is calculated from the MMSE beamforming with the resultant signal and noise power allocation.

4.2 MMSE Beamforming with Downlink Power Allocation (MMSE-DPA)

The proposed MMSE-IAPA does not require any iterative update for computing the beamfoming vectors. However, it still requires the calculation of the signal power allocation and noise power allocation at high SNR and low SNR. One simple intuitive way to overcome this complexity is that the power allocation to each MS in the dual uplink is forced to be the same as the transmit power allocation in each BS of primal problem, and the thermal noise power at each BS is set to be the same as one at its own MS. The corresponding MMSE beamforming with downlink power allocation (MMSE-DPA) can be represented as

$$\boldsymbol{u}_{MMSE-DPA,b} = \zeta_b \left(\sum_{b' \neq b} P_{T,b'} \boldsymbol{h}_{b,b'} \boldsymbol{h}_{b,b'}^H + \sigma_n^2 \boldsymbol{I}\right)^{-1} \boldsymbol{h}_{b,b} \tag{8}$$

(8) may be considered as downlink precoding based on maximal signal to jamming and noise ratio (SJNR)[7], in the condition that each BS transmits the same power.

4.3 Selective MMSE beamforming (S-MMSE)

While assessing the optimal downlink performance through dual uplink problem, it was observed that the likelihood of zero power being allocated to some of MSs in the dual uplink was not negligible. This phenomenon was prevalent especially when some channels are highly correlated, since it is likely to be beneficial to allocate the power to some MSs in order to avoid generating excessive cochannel interference. However, the proposed MMSE-IAPA and MMSE-DPA have almost no opportunities of putting zero power allocation to some MSs, resulting in the performance loss in the occurrence of highly correlated cochannels. Thus, the natural extension of the proposed algorithms is to select the best downlink beamforming among

MMSE beamformings in the dual uplink that were obtained from all the possible cases of zero power allocation to some MSs. The total number of such zero power allocations is 2^B-2. In each case, the power re-allocation to the MSs with nonzero power allocation is made by allocating scaled downlink power allocation to those MSs to satisfy the total power constraint. In each transmission time, therefore, all the sum rates of 2^B-1 different sets of beamforming vectors for each of the MMSE-IAPA or the MMSE-DPA power allocation schemes are calculated and the set of beamforming vectors with the highest sum rate is chosen, which is called "selective MMSE (S-MMSE) beamforming".

Step-1 : Genenration of Candidate Signal Power Allocation

$$\{\mathbf{x}_l=[x_l(1)\ \cdots\ x_l(B)]^T \mid x_l(m)\in\{0,1\},\mathbf{x}_l\neq\mathbf{0},\mathbf{x}_l\neq\mathbf{1}\}$$

$$\mathbf{g}_{c,l}=\frac{P_T}{\sum_{b=1}^{B}P_{T,1}x_l(b)}\left[P_{T,1}x_l(1)\ \cdots\ P_{T,B}\,x_l(B)\right]\ for\ l=1,\cdots,2^B-2$$

$$\mathbf{g}_{c,0}=\mathbf{g}_{MMSE-IAPA}$$

$$\mathbf{g}_{low}=P_T[\frac{\left\|\mathbf{h}_{1,1}\right\|^2P_{T,1}}{\sum_b\left\|\mathbf{h}_{b,b}\right\|^2P_{T,b}}\ \cdots\ \frac{\left\|\mathbf{h}_{B,B}\right\|^2P_{T,B}}{\sum_b\left\|\mathbf{h}_{b,b}\right\|^2P_{T,b}}]$$

Step-2 : Calculate Noise Power Allocation, Beamforming Vector, and Sum Rate

for $l=0,\cdots,2^B-2,\ and\ b=1,\cdots,B$

$$q_{high}=\frac{\sigma_n^2P_T}{BP_{T,b}},\ q_{low}=\frac{\sigma_n^2P_T\sqrt{[\mathbf{g}_{low}]_b\left\|\mathbf{h}_{b,b}\right\|^2}}{\sqrt{P_{T,B}}\sum_{b'}\sqrt{P_{T,b'}[\mathbf{g}_{low}]_{b'}\left\|\mathbf{h}_{b',b'}\right\|^2}}$$

$$q_{S-MMSE-IAPA,b}=\alpha_b\mathbf{q}_{low}+(1-\alpha_b)\mathbf{q}_{high}$$

$$\mathbf{u}_{c,l,b}=\varsigma_b\left(\sum_{b'\neq b}[\mathbf{g}_{c,l}]_{b'}\mathbf{h}_{b,b'}\cdot\mathbf{h}_{b,b'}^H+q_{S-MMSE-IAPA,b}I\right)^{-1}\mathbf{h}_{b,b}$$

$$R_l=\sum_b\log(1+\frac{[\mathbf{g}_{c,l}]_b\,|\mathbf{u}_{c,l,b}^H\mathbf{h}_{bb}|^2}{\sum_{b'\neq b}[\mathbf{g}_{c,l}]_{b'}\,|\mathbf{u}_{c,l,b}^H\mathbf{h}_{bb'}|^2+q_{S-MMSE-IAPA,b}})$$

Step-3 : Choose the beamforming vector set which has the largest sum rate

$$\{\mathbf{u}_{S-MMSE-IAPA,b}\}=\{\mathbf{u}_{c,l^*,b}\}\ \text{where}\ l^*=\arg\max_l R_l$$

Fig. 3. Algorithm description of the selective MMSE beamforming with interpolation of asymptotic power allocations (S-MMSE-IAPA).

These algorithms are summarized in Fig. 3. and Fig. 4. The sum rate R_l will be calculated for each MMSE beamforming vector for the power on-off vector x_l, and the beamforming vector with the maximum sum rate will be selected for each algorithm, which we call S-MMSE beamforming. Since we consider all possible cases of zero power allocation to some MSs, the total number of such zero power allocation will be 2^B-2. With consideration of the beamforming vector from the MMSE-IAPA and the MMSE-DPA, total number of candidate power allocation will be 2^B-1 for each algorithm.

Step-1 : Genenration of Candidate Signal Power Allocation

$$\mathbf{x}_l=[x_l(1)\ \cdots\ x_l(B)]^T \mid x_l(m)\in\{0,1\},\mathbf{x}_l\neq\mathbf{0}\}$$

$$\mathbf{g}_{c,l}=\frac{P_T}{\sum_{b=1}^{B}P_{T,1}x_l(b)}\left[P_{T,1}x_l(1)\ \cdots\ P_{T,B}\,x_l(B)\right]\ for\ l=0,\cdots,2^B-2$$

Step-2 : Calculate Noise Power Allocation, Beamforming Vector, and Sum Rate

for $l=0,\cdots,2^B-2,\ and\ b=1,\cdots,B$

$$q_{S-MMSE-UPA,b}=\sigma_n^2$$

$$\mathbf{u}_{c,l,b}=\psi\left(\sum_{b'\neq b}[\mathbf{g}_{c,l}]_{b'}\mathbf{h}_{b,b'}\cdot\mathbf{h}_{b,b'}^H+q_{S-MMSE-UPA,b}I_{M\times M}\right)^{-1}\mathbf{h}_{b,b}$$

$$R_l=\sum_b\log(1+\frac{[\mathbf{g}_{c,l}]_b\,|\mathbf{u}_{c,l,b}^H\mathbf{h}_{bb}|^2}{\sum_{b'\neq b}[\mathbf{g}_{c,l}]_{b'}\,|\mathbf{u}_{c,l,b}^H\mathbf{h}_{bb'}|^2+q_{S-MMSE-UPA,b}})$$

Step-3 : Choose the beamforming vector set which has the largest sum rate

$$\{\mathbf{u}_{S-MMSE-UPA,b}\}=\{\mathbf{u}_{c,l^*,b}\}\ \text{where}\ l^*=\arg\max_l R_l$$

Fig. 4. Algorithm description of the selective MMSE beamforming with downlink power allocations (S-MMSE-DPA).

4.4 Simplified Selective MMSE beamforming (SS-MMSE)

The S-MMSE seems to be an effective way to provide the tradeoff between the complexity and performance. However, the number of candidate beamforming vectors increases exponentially with number of BSs. Thus, one may dramatically reduce the size of candidate beamforming vectors by simply concentrating total sum power to the single MS in the dual uplink. Since beamforming vectors from this condition is in the null space of subspace spanned by channel of the transmitting MS and noise subspace, it is likely to result in interference avoidance to the BSs which have zero power allocation in the corresponding MSs in the dual uplink. When there are many BSs in the system, the occurrence of the power concentration to the single user in dual uplink happens frequently in optimal beamforming, leading up to the substantial reduction of the size of candidate beamforming vector sets. Thus, when there are BSs in the system, one needs to calculate the sum rate of the beamforming sets and choose one with the largest sum rate. In the following, we abbreviate this scheme as SS-MMSE-IAPA and SS-MMSE-DPA for simplified selected MMSE beamforming with interpolation of asymptotic power allocations and simplified selected MMSE beamforming with downlink power allocations respectively.

Ⅴ. Simulation Results

Numerical results of the sum-rate performance of the asymptotic case and the proposed downlink beamforming algorithms are presented. Channel is assumed to be zero-mean i.i.d complex Gaussian channel unless otherwise stated. Perfect channel state information and perfect synchronization are assumed so that we study the achievable performance without channel impairment. It is assumed that each MS is equipped with a single receive antenna and each BS is equipped with equal number of transmit antennas. For every simulation, transmit power of each BS is set to be equal. For this particular case, MMSE-DPA corresponds to the downlink beamforming based on maximum SJNR criterion. SNR is defined as ratio of the transmit power to thermal noise power ratio. For each simulation case, the performance was evaluated over 10000 independent channel realizations. We evaluate both the average sum rate and 1% outage sum rate to characterize the performance of the proposed beamforming schemes where 1% outage sum rate corresponds to 1% percentile of the sum rate distribution. In every simulation, the sum rate represents the spectral efficiency normalized by the number of BSs.

The proposed algorithms have a dependency on interpolation exponent ξ. To determine the proper value of this parameter, we evaluated the performance of proposed algorithms in Fig. 5. when there are two BSs with two transmit antennas. We evaluated the performance for ξ starting from 0.0005 with 3dB step. The normalized throughput was calculated with normalization by maximum value for each algorithm. The exponential exponent can be chosen robustly over the wide range for average throughput. However outage performance is observed to degrade with increasing interpolation exponent for low SNR. This can be expected since the large value of interpolation exponent results in large interpolation weight to signal power allocation in high SNR, which again causes parameter mismatch. From this result, we can expect that the average performance of the proposed algorithms may be similar to each other while outage performance may be different. Considering very slight performance degradation in very low ξ, we set ξ to be 0.004 for subsequent simulations.

Fig. 6. and Fig. 7. show the average sum rate and 1% outage sum rate respectively when the number of BSs is 2 and number of transmit antennas per BS is 2. For this particular case, we evaluated the performance over the ''real'' i.i.d Gaussian channel

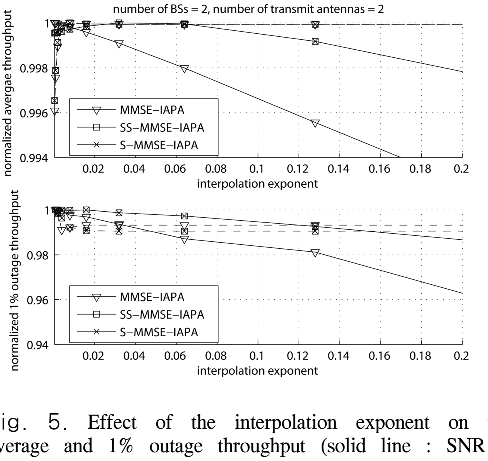

Fig. 5. Effect of the interpolation exponent on the average and 1% outage throughput (solid line : SNR = 0dB, dotted line : SNR = 20dB).

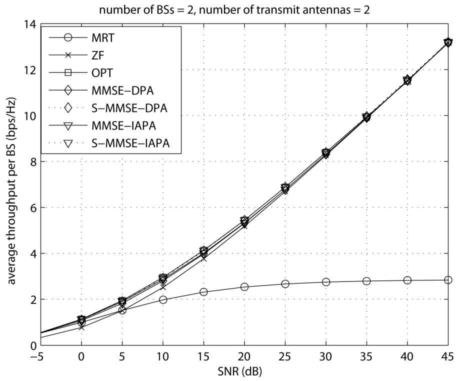

Fig. 6. Average sum rate comparison of the proposed algorithms, MRT, ZF and OPT (optimal beamforming) for the mullti-cell system with two BSs with each having the two transmit antennas.

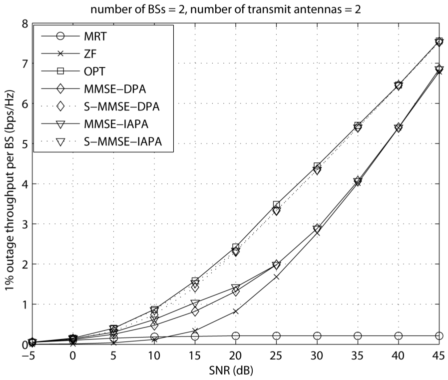

Fig. 7. 1% outage sum rate comparison of the proposed algorithms, MRT, ZF and OPT (optimal beamforming) for the mullti-cell system with two BSs with each having the two transmit antennas.

to compare the asymptotically optimal ZF and MRT beamforming with optimal one. Brute force search over 1000 beamforming vectors uniformly distributed over 2π angle for each BS, which results in total one million candidate vectors was executed to find optimal downlink beamforming vectors. At SNR of -5dB, the MRT beamforming shows nearly the same sum rate as that of the optimal beamforming even for 1% outage sum rate, which verifies that optimal beamforming converges to the MRT beamforming in low SNR regime. At high SNR of 45dB, ZF beamforming shows the almost the same sum rate as that of optimal beamforming, even though the difference of 1% outage sum rates is not negligible. However, it is noted that difference in 1% outage sum rate decreases as the SNR increases, which implies that the difference is most likely to be negligible as the SNR goes higher. This verifies the asymptotic optimality of the ZF beamforming in the multi-cell environment at high SNR.

The performance of the proposed beamforming schemes was compared also in Fig. 6, and Fig. 7. All the proposed algorithms show the better performance than MRT and ZF beamforming at all SNR, and offer the near optimal performance for average sum rate. However, the difference in 1% outage sum rate is noticeable. Since S-MMSE and SS-MMSE subclasses are the same when there are two BSs in the system, we plotted the S-MMSE performance only. The S-MMSE-DPA and S-MMSE-IAPA shows nearly the same 1% outage sum rate as that of the optimal beamforming at all SNR considered. Since S-MMSE-DPA and S-MMSE-IAPA have candidate beam vectors which reduces the interference to the channels of the MSs having nonzero power in the dual uplink, we conjecture that both algorithms may have an opportunity to have a good tradeoff between the interference avoidance and power enhancement from beamforming. The difference in 1% outage sum rate performance between the beamformings belonging to the different subclasses comes from the different number of candidate beamformings. This implies that the occurrence of the power concentration to the some MSs in the dual uplink with optimal power allocation is not negligible.

Considering all the simulation results, the following observations can be made. In every simulation, the MMSE-DPA type algorithm shows almost the identical performance to the MMSE-IAPA algorithm, which makes it preferable in the consideration of the complexity.

Ⅵ. Conclusions

In this paper, the asymptotically optimal downlink beamforming in a multi-cell environment was shown to be MRT beamforming at low SNR, and ZF beamforming at high SNR. As an alternative to the complicated optimal downlink beamforming resulting from an iterative implementation over three different types of optimizing variables, simple and efficient downlink beamforming algorithms were developed from the dual uplink problem formulation, which resultantly enforces its form to be MMSE beamforming. The optimality of the asymptotic beamforming was verified through numerical simulation. It was also shown that some of the proposed downlink beamforming provide the almost the same performance as optimal beamforming. The proposed algorithm showed the tradeoff between the performance and complexity, from which the choice of the proper one among proposed algorithms can be made depending on the system setup.

References

〔1〕 E. Telatar, “Capacity of multi-atenna Gaussian channels,” AT\&T-Bell Technical Memorandum, 1995..

〔2〕 S. Catreux, P. F. Driessen, and L. J. Greenstein, “‘Simulation results for an interference-limited multiple-input multiple- output cellular system,” *IEEE Commun. Lett.*, vol.4, pp.334-336, Nov. 2000.

〔3〕 H. Zhang and H. Dai, “Cochannel Interference Mitigation and Cooperative Processing in Downlink Multicell Multiuser MIMO Networks,” European Journal on Wireless Communications and Networking, 4th quarter 2004.

〔4〕 S. A. Jafar, G. Foschini, A. Goldsmith, PhantomNet: Exploring optimal multicellular multiple antenna systems, EURASIP Journal on Applied Signal Processing, Special Issue on MIMO Communications and Signal Processing, No.5, pp. 591-605, May 2004.

〔5〕 J. G. Andrews, W. Choi, and R. W. Heath, Jr., ‘‘Overcoming Interference in Spatial Multiplexing MIMO Cellular Networks,’’ IEEE Wireless Comm. Mag. vol. 14, no. 6, pp.95-104, Dec. 2007.

〔6〕 Ng B., Evans J, and Hanly S, “Distributed Downlink Beamforming in Cellular Networks, ’’ IEEE ISIT, France, June. 2007.

〔7〕 Y. Wu, J. Zhang, M. Xu, S. Zhou, and X. Xu, “Multiuser MIMO downlink precoder design based on the maximal SJNR criterion,” in Proc. IEEE Globecom, vol. 5, pp.2694-2698, Nov. 2005.

〔8〕 K. Lee, J. Ko, and Y. Lee, “Downlink Beamforming for Other-cell Interference Mitigation in Correlated MISO Channels,” European Wireless, France, Apr. 2007.

〔9〕 T. Ren, and R. J. La, “Downlink Beamforming Algorithms with Inter-Cell Interference in Cellular Networks,” IEEE Trans. Wireless Comm. vol.5, pp.2814-2822, Oct. 2006

〔10〕 J. Yang and D. Kim, “Multi-cell Uplink/Downlink Beamforming Throughput Duality based on Lagrangian Duality With Per-Base Station Power Constraint,” IEEE Comm. Lett, vol. 12, no. 4, pp. 277-279, Apr. 2008.

〔11〕 R. A. Monzingo and T. W. Miller, Introduction to Adaptive Arrays. New York: Wiley, 1980.

〔12〕 Gascuel, and G. Caraux, ‘‘Bounds on expectations of order statistics via extremal dependences,“ *Statistics and Probability Letters,* vol. 15, pp. 143-148, Sept. 1992.

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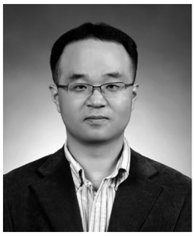

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