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가상 MIMO 다중 셀 시스템을 위한 역방향 전력 제어 방법

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Uplink Power Control Scheme for Virtual MIMO Multi-Cell Systems

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요 약

본 논문은 단일 송신안테나를 갖는 다수의 모바일 터미널이 가상 MIMO 링크를 구성하는 MIMO 시스템에서의 역방향 전력 제어 방법을 제안한다. 기존의 성능을 향상 시키기 위하여 전력 벌칙 항을 추가하는 게임이론 기반의 전력 제어 방식과 달리, 전체 유효 간섭 전력에 대한 제한 조건 하에서 선형 수신 빔형성을 이용한 전송율의 유틸리티 함수를 최대화 하는 방법을 고려하였다. 또한, 전력제어 과정에 이너시아를 도입하여 제안 전력 제어가 수렴함을 보였다. 모의 실험을 통하여 간섭이 지배적인 다중셀 시스템에서 제안 전력 제어 방법이 시스템의 성능을 크게 향상 시킴을 입증하였다.

Key Words : power control, virtual MIMO, multi-cell, beamforming, uplink system

ABSTRACT

This paper considers an uplink power control scheme for a virtual multi-input multi-output (MIMO) multi-cell system where multiple mobile stations with single transmit antenna form a virtual MIMO link. Unlike the conventional approach of the game theoretic formulation to add a power penalty term to improve the performance, a constraint on the total effective interference power is introduced to the maximization of the utility function of the transmission rate with linear receive beamforming. Introducing inertia, we show that the proposed power control is guaranteed to converge. The simulation results verify that the proposed power allocation can significantly improve the performance in an interference limited multi-cell system.

Ⅰ. Introduction

The multi-input multi-output (MIMO) system is known to improve the capacity of the system significantly[1]. The capacity grows linearly with minimum of the transmit antenna and receiver antenna[1]. However, its performance is significantly degraded in the presence of interference[2,13]. Interference limited performance is often observed in practical systems such as ad-hoc network of simultaneous transmission of the arbitrary transmitters and multi-cell network operating at frequency reuse of one.

One of the simple and efficient methods to deal

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with this problem will be to control the power level such that other cell interference can be minimized to improve the performance. The multicell scheduling and power allocation for maximizing the sum transmission rate was formulated and approximately solved through distributed on-off power allocation [3]. As an implicit power allocation scheme, denser BS deployment shows the better performance in minimum served spectral efficiency than full coordination with zero forcing beamforming without power allocation[4]. Recently, several power allocation schemes in MIMO interference links have been studied. A centralized global power optimization based gradient projection algorithm was shown to outperform the iterative waterfilling based on noncooperative game where utility was set to be maximization of the mutual information[5]. A unified set of sufficient condition for global convergence of the iterative waterfilling over interfering MIMO links for maximizing the utility of the mutual information based on noncooperative game theory was shown to be determined by structure of the normalized interference matrix, which was developed from the interpretation of the waterfilling solution into the projection onto a certain polyhedral set[6]. A hierarchical power control consisting of negotiating the number of streams with each other, and maximizing the mutual information with constraint on the number of data streams improves the efficiency of the equilibrium of the noncooperative power control over the MIMO interfering links[7]. Power control for maximizing the minimum target SINR for single user MIMO was shown to effectively increase the service coverage where No transmit precoding at the mobile and MMSE receiver at the BSs are assumed[8]. In [9], a distributed joint power control and spreading gain allocation algorithm with peak power constraint was proposed to maximize the sum throughput. However, this approach may not be directly applicable to OFDMA system where intercell interference is major source of co-channel interference and operating SINR is not very low. To the best of the author's knowledge, the power control over a virtual MIMO uplink system with linear receiver in the interference channel has not been addressed properly.

This paper focuses on developing an uplink power control (UPC) for the virtual MIMO system over the multi-cell system where several MSs with single transmit antenna and BSs with multiple receive antenna virtually comprise MIMO channel. Instead of adding a power penalty factor to the utility function to improve the performance in the conventional game theoretic formulation[10], we introduce a constraint on total effective interference power to improve the performance by controlling the power penalty more effectively. Since the formulated problem is nonconvex, we introduce inertia to updating procedure to guarantee the convergence as in[7]. However, the numerical evaluation shows that a single iteration with initial maximum power allocation is enough to provide the best performance in most cases, which reduces the implementation complexity significantly. Simulation results verify that the proposed algorithm improves the performance of transmission rate significantly for all considered receive beamforming schemes such as maximum ratio combining (MRC), zero forcing (ZF), and minimum mean squared error (MMSE) receive beamforming schemes.

This paper is organized as follows. In section-II, system model and problem formulation based on noncooperative game are given. The power control game with constraint on total effective interference power is formulated, and convergence of the proposed algorithm is provided in section III. Numerical results verify the performance of the proposed power allocation schemes in section IV. Some concluding remarks are made in section V.

Ⅱ. System Model

We consider a multi-cell uplink system with B BSs equipped with M antennas. It is assumed that M users selection for each BS is already made with a predefined scheduling policy. Each MS is assumed to have a single transmit antenna. We also assume that every channel from the BSs to the MSs is independently and identically distributed (i.i.d) circularly complex Gaussian vector with zero mean and unit variance. Since we focus on power allocation itself, MS scheduling is assumed to be round-robin.

The received signal at the BS b can be represented as

$$\boldsymbol{r_b} = \sum_{m=1}^{M} \sqrt{P_{b,m} g_{b,b,m}}\, \boldsymbol{h_{b,b,m}} x_{b,m} + \sum_{b' \neq b}^{B} \sum_{m=1}^{M} \sqrt{P_{b',m} g_{b',b,m}}\, \boldsymbol{h_{b',b,m}} x_{b',m} + \boldsymbol{n_b} \quad (1)$$

where $P_{b,m}$ is the transmit power of the mth scheduled user of the BS b, and $g_{b',b,m}$ and $\boldsymbol{h_{b',b,m}} \in C^{M\times 1}$ are the path loss and channel from the mth scheduled user of the BS b' to the BS b, $x_{b,m}$ is the information symbol of the mth scheduled user of the BS b with unit power, and $\boldsymbol{n_b} \in C^{M\times 1}$ is the complex additive white Gaussian noise (AWGN) with each element having variance of σ_n^2. The system-wise sum rate maximization problem with linear receiver for the system model given in (1) can be stated as

$$\max_{\boldsymbol{P}} \sum_{b=1}^{B} \sum_{m=1}^{M} R_{b,m}(\boldsymbol{P})$$
$$\text{subject to } P_{b,m} \le P_{\max,b,m} \text{ for } \forall\, b,m \quad (2)$$

$$R_{b,m} = \log(1 + P_{b,m}\zeta_{b,m})$$
$$\zeta_{b,m} = \frac{\kappa_{b,b,m}}{\eta_b - P_{b,m}\kappa_{b,b,m} + \sigma_n^2}$$

where $\kappa_{b',b,m} = g_{b',b,m} |\boldsymbol{w_{b,m}^H h_{b',b,m}}|^2$, and $\eta_b = \sum_{b'=1}^{B} \sum_{m'=1}^{M} P_{b',m'} \kappa_{b',b,m'}$, and $P = [P_{1,1}, \ldots, P_{b,m}, \ldots, P_{B,M}]$ is the $BM\times 1$ power allocation vector with nonnegative element, and $w_{b,m}$ is a receive beamforming vector for the mth scheduled MS of the BS b.

However, this is a centralized nonconvex optimization problem which can not be solved easily. Rather than finding an optimum solution for this problem, one can consider a distributed suboptimum solution with game theoretic approach. For simplicity, we focus on the noncooperative game only. In game theoretic formulation, three components define a game [11]. One of the simplest form of the power control game can be defined as follows. Players are scheduled users, strategies are power allocation ranging from 0 to maximum power, and each utility is the transmission rate of each scheduled MS which can be expressed as

$$U_{b,m}(\boldsymbol{P}) = R_{b,m}(P_{b,m}, \boldsymbol{P}_{-b,-m}) \quad (3)$$

where $\boldsymbol{P}_{-b,-m}$ is a $(BM-1)\times 1$ vector of other players' strategy which can be made by excluding $P_{b,m}$ from $\boldsymbol{P}$. For a noncooperative game, a steady state of the game where no player can unilaterally deviate to increase the utility given the actions of other players is called Nash Equilibrium (NE)[11]. From this definition, the NE of the power control game with utitlity in (2) can be expressed as

$$P_{b,m}^{*} = \max_{P_{b,m}} R_{b,m}(P_{b,m}, \boldsymbol{P}^{*}_{-b,-m}) \quad (4)$$

for $\forall\, b$ and $\forall\, m$. The corresponding power allocation can be trivially calculated as $P_{\max,b,m}$. Since noncooperative game tries to maximize its own utility without consideration of its influence on other user's utility, this can not be a good solution to maximize the system throughput. In many existing literatures, a penalty term has been added to the utility to incorporate the effect of its strategy to other utilities implicitly[10]. This penalty may be considered as a constraint term to the utility function. Thus, we formulate the game having utility with an additional articulated constraint term which indirectly controls the effect of the strategy on other players' utilities.

Ⅲ. Uplink Power Control for Virtual MIMO System

One may improve the system sum rate performance by allowing the BS to coordinate the scheduled users. This can be realized by defining a proper power control game with BSs being players. In this section, we propose a BS centric power control game to coordinate the powers of scheduled MSs, which can result in controlling the intracell and intercell interference to improve the performance.

3.1. Problem Formulation

We consider a BS centric power control (BC-PC) game where players are BSs. The BC-PC takes a different total effective interference power constraint as follows

$$\sum_{m=1}^{M} q_{b,m}^{-u} P_{b,m} \leq \chi_T \qquad (5)$$

where χ_T is the maximum total effective interference power to other cell, and $q_{b,m}$ is the average downlink SINR at the MS m served by BS b. The low average downlink SINR in an interference limited system implies that it suffers from excessive other cell interference. Thus the mobile with low downlink SINR is likely to result in excessive interference to other cells. Since each transmit power is weighted by inverse of the downlink SINR with exponent u, sum of these can be considered as total effective interference from the MSs in the BS b.

With the modified constraint, we can express the BC-PC game G_B in the following.

$$(G_B): \max_{P_b} \sum_{m=1}^{M} R_{b,m}(\boldsymbol{P}_b, \boldsymbol{P}_{-b})$$
$$\text{subject to } P_b \in S_{B,b} \text{ for } \forall b \in N_B \qquad (6)$$

where $\boldsymbol{P}_b \in R^{M\times 1}$ is a strategy vector of the BS b, $\boldsymbol{P}_{-b}$ is a strategy vector of the BS except the BS b, and $S_{B,b} = \boldsymbol{p} \in R^{M\times 1} | 0 \leq [\boldsymbol{p}]_m \leq P_{\max,b,m}, \sum_{m=1}^{M} q_{b,m}^{-u} [\boldsymbol{p}]_m \leq \chi_T$ is the set of admissible power strategy of the BS b, $[\boldsymbol{p}]_m$ is the mth element of the vector $\boldsymbol{p}$, and $N_B = 1,2,\ldots,B$ is the set of players for BC-PC game. Since the power vector in the game G_B is determined to maximize the sum rate of each cell, it may improve the performance by controlling the power to have tradeoff between individual rate increase and intracell interference increase. However, since utility function is no longer a convex function over strategy vectors, we are not able to prove the existence of the NE with pure strategy. Thus, in the next subsection, we will introduce an iterative algorithm with guaranteed convergence for suboptimal solution.

3.2. Algorithm

Since the constrained maximization problem for a player is a nonconvex problem and some receive beamforming is associated with power allocation, it is very hard to find an optimum solution for this game. Thus, we propose a suboptimal iterative solution to this problem by modifying the optimization problem as convex one as follows.

$$P_b(n+1) = \arg max_{P_b} \sum_{m=1}^{M} \log(1 + P_{b,m}\zeta_{b,m}(n))$$
$$\text{subject to } P_b \in S_{B,b} \text{ for } \forall b \in N_B \qquad (7)$$

where n is the iteration index, and

$$\zeta_{b,m}(n) = (1-n^{-1})\zeta_{b,m}(n-1) + n^{-1}\frac{\kappa_{b,b,m}}{\eta_b(n) - P_{b,m}(n)\kappa_{b,b,m} + \sigma_n^2} \qquad (8)$$

The solution to the above optimization problem can be written as

$$x_{b,m} = \{ \begin{array}{ll} 0, & \text{if } A \& B \\ \frac{q_{b,m}^u}{c} - \frac{1}{\zeta_{b,m}(n)}, & \text{if } (\sim A) \& \text{B} \& \text{C} \\ P_{\max,b,m} & , else \end{array} \qquad (9)$$

where A denotes the condition, $c > \zeta_{b,m}(n) q_{b,m}^u$, B does $\sum_{m=1}^{M} P_{\max,b,m} q_{b,m}^{-u} < \chi_T$, C does

$\dfrac{\zeta_{b,m}(n)q^{u}_{b,m}}{1+P_{\max,b,m}\zeta_{b,m}(n)} < c$, and $\sim$ does logical not. c is chosen such that it can satisfy $\sum_{m=1}^{M}\bar{q}^{u}_{b,m}\left[\dfrac{q^{u}_{b,m}}{c}-\dfrac{1}{\zeta_{b,m}(n)}\right]_{0}^{P_{\max,b,m}}=\chi_T$ where $[A]_a^b$ is a for $A<a$, b for $A>b$, or A for $a\le A\le b$. The detailed derivation is provided in appendix-A.

Even though the original game G_B may not guarantee the steady state equilibrium, introduction of inertia to the update of the normalized uplink SINR makes the suboptimal iterative algorithm converge to a point. The uniqueness of the convergence and independence of the initial point can not be addressed properly. We leave theoretical analysis for future research. Instead, we will treat this problem in more detail through numerical simulation in the subsequent sections.

3.3. MAC Layer Design

Since the power levels of the scheduled MSs are jointly determined, we consider a signaling structure for supporting power control at the BS. Each MS transmits the pilot signal with designated power level known to the BS. The BS measures the SINRs of the scheduled MSs and updates the power levels based on (9) and informs the scheduled MSs of updated power levels. Pilot transmission of the scheduled MSs, BS power calculation, and reports of determined power levels to the scheduled MSs repeat until the algorithm converges. This scheme may need heavy signaling overhead in both the uplink and downlink. One may limit the number of iteration with sacrifice of the marginal performance to reduce the signaling overhead.

Ⅳ. Numerical Results

In this section, we evaluate the performance of the proposed multi-cell power control scheme based on numerical simulation. For simplicity, the cellular system consisting of three BSs is considered in Fig-1. The BSs are located along the unit circle with

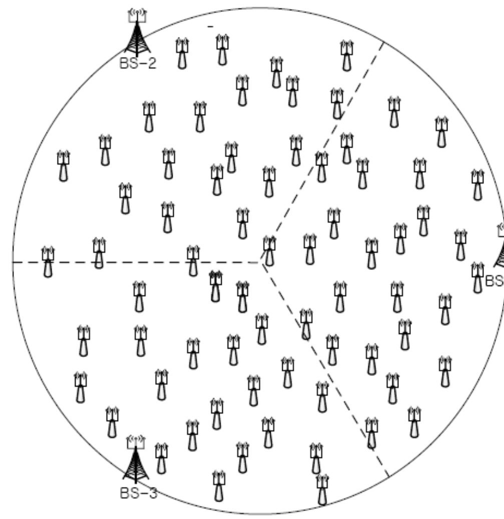

Fig. 1. System setup for simulation.

equal phase distance, and users are uniformly distributed within unit circle. Path loss was calculated with $d^{-3.5}$ where d is the distance between the user and the BS. For simplicity, shadowing is not considered while short-term fading is generated independently over each link. The maximum power for each MS is set to be $0.01P_{DL}$ which is a conventional power setup in a cellular system. We also denote downlink SNR at the cell edge as $SNR=P_{DL}/\sigma_n^2$. For each time slot, power control schemes were applied to M users per each cell with randomly generated locations. To characterize the average performance of the proposed schemes, the performance is averaged out over 500 different drops of users.

To optimize the performance of the proposed power control, several parameters are required to be optimized. In Fig-2. we study the convergence speed of the proposed algorithm where the threshold of sum effective interference power was fixed to be 10, SNR was set to be 30dB, the number of receive antennas per BS was 4, and the initial transmit power level of each MS was maximum. It is observed that in most cases, it achieves almost the best performance with two iterations, which happens to remove the complexity for iterating the algorithm and signaling overhead. To investigate further the convergence property of the proposed algorithm with maximum power initialization, power allocation with iterations for a realization of user drop shown in Fig. 3 was shown in Table 1. MMSE receive beamforming at the BS is assumed for this simulation. As shown in Table 1. full power allocation and zero power allocation at the first iterations are kept with iterations. MSs with those power allocation are found to be closely or far located from each serving BS in Fig. 3. MSs with non-zero and non-maximum power allocation at the first iteration have minor change in power allocation with iterations as shown in Table 1. Similar results could be often find with other realization of MS drops even though they were not shown here. In the view of sum rate, MSs closely located to the serving BS may contribute much to the sum rate. Thus correct decision of MSs with full power allocation may be of the very importance, which is done at the first iteration. At the same time, correct removal of possibly interfering MS with very marginal rate contribution will be of another importance. Thus, single iteration with maximum power initialization is likely to have a practical importance in terms of signaling overhead.

Number of required iterations may vary depending on the channel and system conditions. To evaluate the convergence property more objectively and statistically, histograms of required number of iterations for convergence isshown in Fig-4. System setup is setup for call cases except that M varies. Here, "convergence" is treated as the first iteration where the throughput change between consecutive iterations normalized by current throughput is less than 1%. It is observed that convergence occurs within 5 iterations in most cases regardless of M. As M gets bigger, the average number of iteration seems to be decreasing. It is conjectured that this happens due to averaging effect of the number of receive antenna and number of interfering users.

To consider the worst case interference, we consider the initial power allocation as the maximum transmit power allocation for each MS. Since the proposed algorithm does not guarantee independence of the initial condition, we compared the performance of the maximum initial power allocation to the maximum system throughput among power allocations starting with 1000 different random initial power allocations in

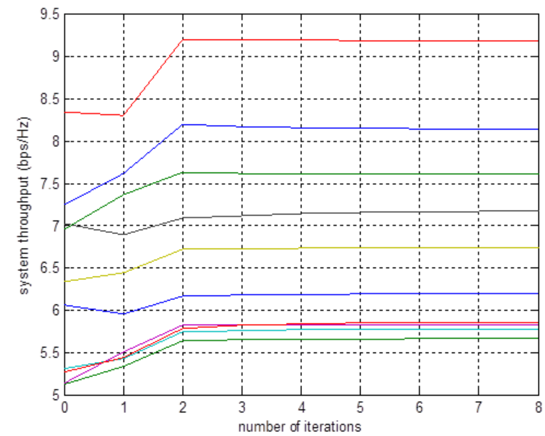

Fig. 2. Convergence of the proposed power control scheme with MMSE beamforming for 10 realizations

Table 1. Power allocation with iterations (3 BSs, and 4 MSs for each BS)

iteration	0	1	2	8
power allocation	10 10 10 10 10 10 10 10 10 10 10 10	0 10 0 10 10 10 4.97 10 10 6.95 10 3.34	0 10 0 10 10 10 3.61 10 10 8.72 10 3.34	0 10 0 10 10 10 3.48 10 10 8.89 10 3.34

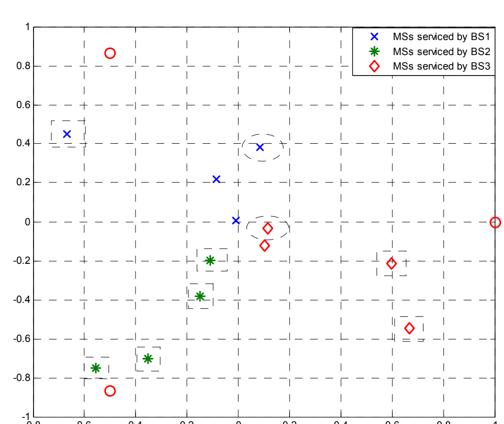

Fig .3. A sample realization of MS drops in simulation (three solid circles are BSs. MSs in the dotted circle have zero power allocation while MS in the dotted rectangle have full power allocation)

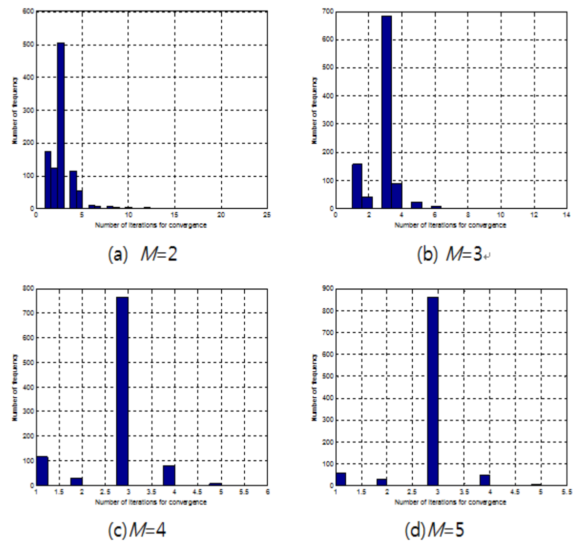

Fig. 4. Histograms of the required number of iterations for convergence of the proposed power control scheme with MMSE beamforming for different number of M

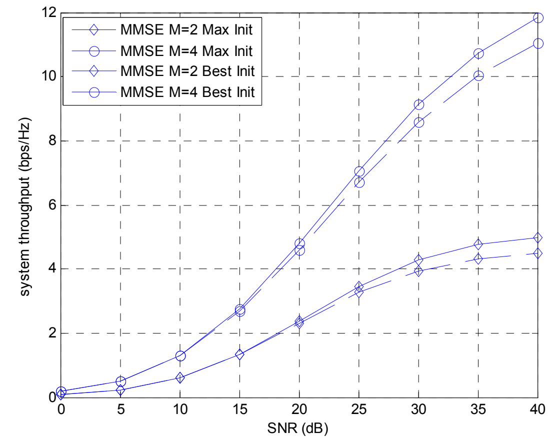

Fig. 5. Comparison of the system throughputs of the initial maximum power allocation and the best initial random power allocation

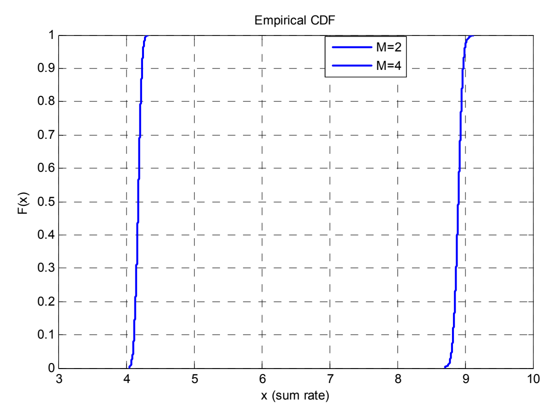

Fig. 6. CDF of the sum throughput with different initializations

Fig-5 where weighted sum interference threshold was set to be maximum transmit power for the MS, the number of iteration was one, and only MMSE beamforming is considered. It can be seen that initial maximum power allocation results in marginal performance degradation in most cases. i.e. at most 10% throughput degradation compared to selecting the best one among 1000 random initializations. To investigate effect of initialization on the performance more thoroughly, cumulative distribution function (CDF) of the system throughput with different initializations is shown in Fig.6. For a fixed random initialization, average system throughput over 500 drops was calculated. For 1000 different initializations, CDF was calculated for M =2 and M=4 when SNR = 30dB. The threshold of sum effective interference power and exponent factor were fixed to be 10 and 0.5 respectively. As expected from Fig. 5, Fig. 6 confirms that difference between the maximum system throughput and minimum one is less than 10%. From this result, it can be conjectured that the proposed algorithm is robust to an initialization.

With the same parameter setup used in generating Fig-5, the effects of different exponents of the inverse downlink SINR in an added constraint are investigated in Fig-7. It can be observed that the best exponents is close to 0.

The proposed PC can allocate the power in consideration of both the intra-cell and other cell interference, which have more degree of freedom of power allocation within total effective interference constraint. As we explained earlier, even thought the proposed algorithm is guaranteed to converge, convergence to the optimal point is never guaranteed. To find out the efficiency of the proposed algorithm by comparing it to the optimal power control, a simple system with two BSs with two receive antennas are considered. Comparing results are shown in Fig.8. Optimal power is selected through brute-force search over 10000 randomly generated power vectors satisfying total interference power constraint where exponent in (9) was set to be 0, and total interference power was set to be . As shown in the figure, performances of both the proposed and optimal power control are almost same in low SNRs, since performance in power limited region is likely to depend on maximum power. However, in high SNR region, even though performance of the proposed algorithm is inferior to the optimal power control, it shows marginal performance degradation.

Based on the numerical results in paragraphs, exponent u and number of iterations are set to be 0 and 1. Initial maximum power allocation is always applied in the following simulation. To find out the best possible performance, with $0.01 \times P_{\max,b,m}$ step, the performance with different total effective interference power thresholds are evaluated up to $\sum_{m=1}^{M} P_{\max,b,m}$. The performances of the MMSE beamforming with the proposed power allocation scheme are compared in Fig-9. While the system throughput of the maximum power allocation is saturated to some value with increasing SNR, the performance of the MMSE beamforming with proposed power control scheme keeps being improved. At low SNRs, since thermal noise is dominant factor in performance, the best power allocation is observed to be maximum power allocation. The average sum transmit power for properly selected effective sum interference power threshold decreases with

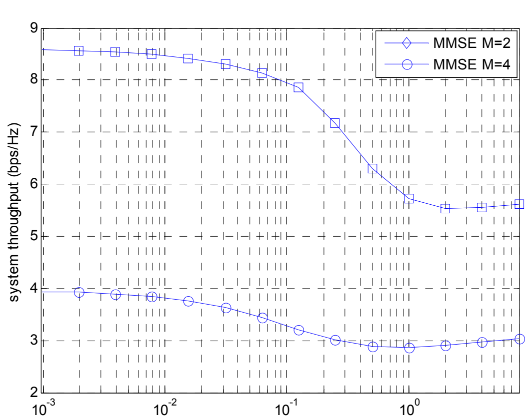

Fig. 7. Effect of the exponent factor.

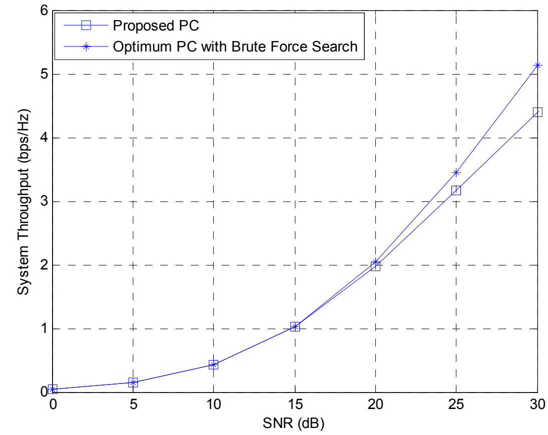

Fig. 8. System throughput comparison of the proposed power control schemes with optimum power control

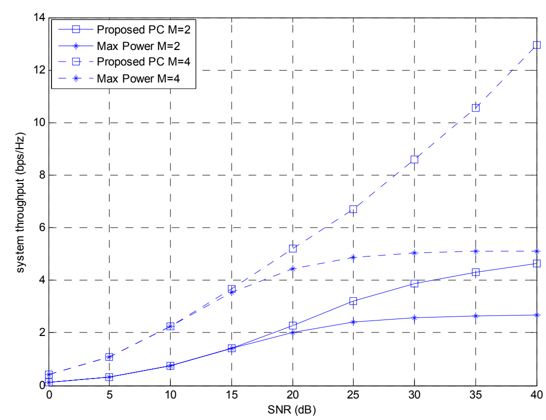

Fig. 9. System throughput comparison of the proposed power control schemes with MMSE receive beamforming.

increasing SNRs. Specifically, average sum transmit power with MMSE beamforming for $M=4$ at $SNR=40dB$ is about 15% of the sum maximum transmit power, which makes other cell interference control effective.

Ⅴ. Conclusions

In this paper, an uplink power control scheme for the multi-cell network was proposed. Unlike the conventional game theoretic approach introducing a penalty term in a utility function to improve performance by preventing selfish behavior, an additional constraint on the total effective interference power is incorporated into the utility function. Since utility is nonconvex, inertia in an iterative power update was added to guarantee the convergence. Simulation results show that the proposed power allocation with initial maximum transmit power setup can perform better without iteration than with iteration in most cases.

There are still many open issues associated with the proposed power control. To be employed in a practical system, channel adaptive threshold shall be developed, effect of the channel estimation error can be considered, and more rigorous analysis of the proposed power allocation may be made, which are left for future research.

Appendix-A

Removing dependency on current power allocation from $\zeta_{b,m}(n)$ makes the optimization problem a convex one with three constraints, min power constraint, max power constraint, and weighted sum power constraint. The Lagrangian on this constrained problem can be expressed as

$$\begin{aligned} L = & \sum_{m=1}^{M} \log(1+x_{b,m}\zeta_{b,m}(n)) + \sum_{m=1}^{M} a_m x_{b,m} \\ & - \sum_{m=1}^{M} b_m (x_{b,m} - P_{\max,b,m}) \\ & - c(\sum_{m=1}^{M} x_{b,m} \bar{q}_{b,m}^{u} - \chi_T) \end{aligned} \quad (10)$$

where a_m, b_m, and c are Lagrangian multiplies associated with constraints. The KKT condition on this problem can be arranged as

$$\begin{aligned} & \frac{\zeta_{b,m}(n)}{1+x_{b,m}\zeta_{b,m}(n)} + a_m - b_m - c\bar{q}_{b,m}^{u} = 0 \quad (11) \\ & a_m \geq 0, a_m x_{b,m} = 0 \\ & b_m \geq 0, b_m (x_{b,m} - P_{\max,b,m}) = 0 \\ & c \geq 0, c(\sum_{m=1}^{M} x_{b,m} \bar{q}_{b,m}^{u} - \chi_T) = 0 \end{aligned}$$

If $\sum_{m=1}^{M} P_{\max,b,m} \bar{q}_{b,m}^{u} < \chi_T$, $a=0, b \geq 0$, $c=0$, which results in $x_{b,m} = P_{\max,b,m}$ for $\forall m$. If not, the following case can be considered to determine the power level. If $x_{b,m}=0$, $a \geq 0, b=0, c \geq 0$ with which the first order derivative condition results in $c \geq \zeta_{b,m} q_{b,m}^{u}$. If $0 < x_{b,m} < P_{\max,b,m}$, $b=0$, $a=0$, $c \geq 0$, which provides $x_{b,m} = (q_{b,m}^{u} c^{-1} - \zeta_{b,m}^{-1})$. If $x_{b,m} = P_{\max,b,m}$, $a=0, b \geq 0, c \geq 0$ with which the first order derivative condition results in $c \leq \frac{q_{b,m}^{u}\zeta_{b,m}}{1+P_{\max,b,m}\zeta_{b,m}}$. In summary, if $\sum_{m=1}^{M} P_{\max,b,m} \bar{q}_{b,m}^{u} < \chi_T$, the solution can be written as

$$x_{b,m} = \begin{cases} 0, & \text{if } A \& B \\ \frac{q_{b,m}^{u}}{c} - \frac{1}{\zeta_{b,m}(n)}, & \text{if } (\sim A) \& B \& C \\ P_{\max,b,m}, & else \end{cases} \quad (12)$$

where A denotes the condition, $c > \zeta_{b,m}(n) q_{b,m}^{u}$, B does $\sum_{m=1}^{M} P_{\max,b,m} \bar{q}_{b,m}^{u} < \chi_T$, C does $\frac{\zeta_{b,m}(n) q_{b,m}^{u}}{1+P_{\max,b,m}\zeta_{b,m}(n)} < c$, $\sim$ does logical not, and c is chosen such that it can satisfy $\sum_{m=1}^{M} \bar{q}_{b,m}^{u} \left[\frac{q_{b,m}^{u}}{c} - \frac{1}{\zeta_{b,m}(n)} \right]_0^{P_{\max,b,m}} = \chi_T$. If $\sum_{m=1}^{M} P_{\max,b,m} \bar{q}_{b,m}^{u} \geq \chi_T$, $x_{b,m} = P_{\max,b,m}$ for $\forall m$.

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