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Downlink cooperative beamforming for MIMO cellular systems

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Abstract: In downlink cellular systems using beams, the multiple users in multiple cells should cooperate to generate beams to improve the spectrum efficiency. A mathematical model for the multi-cell multi-user downlink transmission is established, and the gradients of the variables including beamforming filters, receiving filters and transmitting power are calculated. Then, a gradient-project-based cooperative beamforming scheme is proposed in which each user iteratively adjusts beamforming variables in the direction of the gradients and projects onto feasible spaces. The information exchange protocol needed to support the scheme is also described. Simulation results show that the proposed scheme can achieve an average spectral efficiency of about 5 bit/(s · Hz · cell). The results show that cooperative beamforming can improve the spectrum efficiency of the cellular systems.

Key words: cellular system; mutiple-input mutiple-output (MIMO); cooperative beamforming; spectral efficiency

Multiple-input multiple-output (MIMO) has shown great potential for providing high spectral efficiency in isolated single link without co-channel interference. However, when MIMO is used in cellular systems, the co-channel interference can seriously degrade the overall capacity. This paper studies the method to improve the spectral efficiency of the downlinks of MIMO cellular systems. In particular, we investigate the idea of cooperative beamforming, in which users select and adjust their transmitting and receiving filters in a coordinated manner.

Many methods have been proposed in the literature to deal with the interference. These methods can be classified into two categories. The first category aims at avoiding or reducing the interference. The representative methods in this category are power control, dynamic channel allocation and soft frequency reuse. The second category aims at using signal processing to cancel or reduce the interference. The representative methods in this category are interference zero-forcing, interference coordination, interference cancellation, dirty-paper coding, and the recent interference alignment. This paper proposes a cooperative beamforming based interference coordination method, which belongs to the second category.

The typical interference coordination methods can be found in Refs. [1 – 5]. However, these methods have problems. First, some methods assume a single antenna and omit the receiver design problem or assume that the antenna number is very great. Secondly, some methods heavily rely on the uplink-downlink channel duality which does not always hold. Thirdly, some methods do not consider the distributed implementation of the proposed algorithms. To deal with these unresolved problems, this paper proposes a novel gradient-project-based cooperative beamforming method, and describes the needed information exchange protocol. Simulation results show that the proposed method can achieve good spectral efficiency performance.

1 System Assumptions and Problem Formulations

Consider downlink transmission in multi-cell multi-user MIMO cellular systems. Assume that there are B cells (or bases) and K users, where each base has M antennas, and each user has N antennas and L independent data streams. Assume that the system bandwidth is W Hz, which is divided into S subcarriers. Consider stream (s, k, l), which is the l-th $(1\leqslant l\leqslant L)$ data stream of the k-th $(1\leqslant k\leqslant K)$ user on the s-th $(1\leqslant s\leqslant S)$ subcarrier. As shown in Fig. 1(a), let $d_{s,k,l,t}$ be the data bit of stream (s, k, l) in slot t, $p_{s,k,l,t}$ the allocated power, and $\boldsymbol{g}_{s,k,l,t}$ the $M\times 1$ transmitting vector (or beamformer). Then the transmitted signal of user k in slot t is $\boldsymbol{s}_{s,k,t} = \sum_l \boldsymbol{g}_{s,k,l,t} p_{s,k,l,t}^{1/2} d_{s,k,l,t}$, where $\| \boldsymbol{g}_{s,k,l,t} \| = 1$ and $p_{s,k,l,t}$ satisfies $\sum_s \sum_{k:\, b(k)=n} \sum_l p_{s,k,l,t} \leqslant P$ for each base n and slot t, where P is the maximum base transmitting power and $b(k)$ is the serving cell of user k.

Let $\boldsymbol{H}_{s,b,k,t}$ the $N\times M$ channel matrix between base b and user k on subcarrier s in slot t. Assuming that all the users can reuse the same time-frequency radio resource, then the received signal of user k is $\boldsymbol{r}_{s,k,t} = \boldsymbol{H}_{s,b(k),k,t} \boldsymbol{s}_{s,k,t} + \sum_{j\neq k} \boldsymbol{H}_{s,b(j),k,t} \boldsymbol{s}_{s,j,t} + \boldsymbol{z}_{s,k,t}$, where $\boldsymbol{z}_{s,k,t}$ is noise with covariance

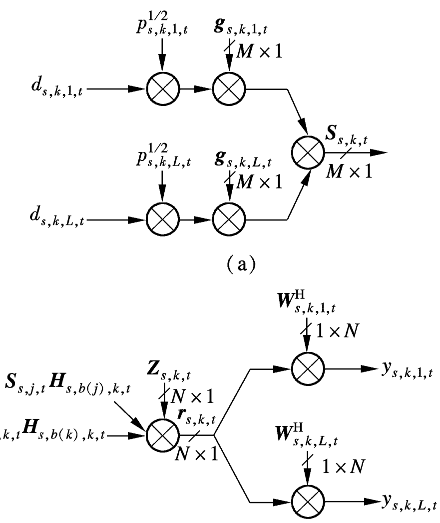

Fig. 1 The link level transmission model. (a) Transmitter; (b) Receiver

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$\boldsymbol{R}_{z,s,k}$. Assume $\boldsymbol{R}_{z,s,k} = (W/S)\eta_0 \boldsymbol{I}_N$, where η_0 is the noise power spectrum density and $\boldsymbol{I}_N$ is the $N \times N$ identity matrix. As shown in Fig. 1(b), assume that $\boldsymbol{w}_{s,k,l,t}$ is the $N \times 1$ receiving vector of stream (s, k, l), and then the signal after processing is $y_{s,k,l,t} = \boldsymbol{w}^{\mathrm{H}}_{s,k,l,t}\boldsymbol{r}_{s,k,t}$, where $\| \boldsymbol{w}_{s,k,l,t} \| = 1$.

Assuming that $d_{s,k,l,t}$ is independently generated with unit-variance, the signal-interference-noise-ratio (SINR) of stream (s, k, l) in slot t is

$$x_{s,k,l,t} = \frac{p_{s,k,l,t} \left| \boldsymbol{w}^{\mathrm{H}}_{s,k,l,t} \boldsymbol{H}_{s,b(k),k,t}\, \boldsymbol{g}_{s,k,l,t} \right|^2}{\sum\limits_{(j,i) \neq (k,l)} p_{s,j,i,t} \left| \boldsymbol{w}^{\mathrm{H}}_{s,k,l,t} \boldsymbol{H}_{s,b(j),k,t}\, \boldsymbol{g}_{s,j,i,t} \right|^2 + \boldsymbol{w}^{\mathrm{H}}_{s,k,l,t} \boldsymbol{R}_{z,s,k} \boldsymbol{w}_{s,k,l,t}} \tag{1}$$

Therefore, the achieved throughput of stream (s, k, l) in slot t is

$$r_{s,k,l,t} = \frac{W}{S} \log_2 (1 + x_{s,k,l,t}) \tag{2}$$

Let $R_{s,k,l,t}$ be the average throughput of stream (s, k, l) until slot t, which is updated according to $R_{s,k,l,t} = (1 - e_{\mathrm{R}}) R_{s,k,l,t-1} + e_{\mathrm{R}} r_{s,k,l,t}$ where e_{R} is the weight factor. Assume $e_{\mathrm{R}} = 0.01$ in this paper. Then the average throughput of user k until slot t is

$$R_{k,t} = \sum_{s=1}^{S} \sum_{l=1}^{L} \boldsymbol{R}_{s,k,l,t} \tag{3}$$

Assume that the utility is $f_k(R_{k,t})$, where $f_k(\cdot)$ is a continuously differentiable scalar function. Therefore, the multi-cell multi-user downlink transmission problem is how to solve the following optimization problem in each slot t:

$$\max f = \sum_{k=1}^{K} f_k(R_{k,t}) \tag{4}$$

s. t.

$$\sum_{s=1}^{S} \sum_{k:\, b(k) = n} \sum_{l=1}^{L} p_{s,k,l,t} \leqslant P \qquad 1 \leqslant n \leqslant B$$

$$\| \boldsymbol{g}_{s,k,l,t} \| = \| \boldsymbol{w}_{s,k,l,t} \| = 1 \qquad 1 \leqslant s \leqslant S; 1 \leqslant k \leqslant K; 1 \leqslant l \leqslant L$$

where $R_{k,t}$ is specified by Eqs. (1) to (3).

2 Proposed Scheme

The problem in Eq. (4) has three types of variables $\{\boldsymbol{g}_{s,k,l,t}\}$, $\{\boldsymbol{w}_{s,k,l,t}\}$, and $\{p_{s,k,l,t}\}$. Take $\boldsymbol{g}_{s,k,l,t}$, the transmitting vector of stream (s, k, l) in slot t, as an example to explain the idea. The basic idea of the proposed scheme is that, if we move $\boldsymbol{g}_{s,k,l,t}$ along the direction of gradient $[\partial f / \partial \boldsymbol{g}_{s,k,l,t}]$; i. e., set $\boldsymbol{g}_{s,k,l,t+1} \propto \boldsymbol{g}_{s,k,l,t} + \alpha_{\mathrm{g}} [\partial f / \partial \boldsymbol{g}_{s,k,l,t}]$ where α_{g} is the step, the utility can be improved. Furthermore, the vector $\boldsymbol{g}_{s,k,l,t+1}$ must satisfy the constraint $\| \boldsymbol{g}_{s,k,l,t+1} \| = 1$.

Therefore, we can propose the cooperative beamforming algorithm, in which each stream (s, k, l) executes the following steps at the beginning of each slot $(t+1)$:

1) Collect needed information (see section 3 for details);

2) The transmitter adjusts $\tilde{\boldsymbol{g}}_{s,k,l,t+1} = \boldsymbol{g}_{s,k,l,t} + \alpha_{\mathrm{g}} [\partial f / \partial \boldsymbol{g}_{s,k,l,t}]$ where α_{g} is the step, and then sets $\boldsymbol{g}_{s,k,l,t+1} = \tilde{\boldsymbol{g}}_{s,k,l,t+1} / \| \tilde{\boldsymbol{g}}_{s,k,l,t+1} \|$.

3) The receiver adjusts $\tilde{\boldsymbol{w}}_{s,k,l,t+1} = \boldsymbol{w}_{s,k,l,t} + \alpha_w \partial f / \partial \boldsymbol{w}_{s,k,l,t}$ where α_w is the step, and then sets $\boldsymbol{w}_{s,k,l,t+1} = \boldsymbol{w}_{s,k,l,t+1} / \| \tilde{\boldsymbol{w}}_{s,k,l,t+1} \|$.

4) The transmitter adjusts the power $\tilde{p}_{s,k,l,t+1} = p_{s,k,l,t} + \alpha_p \partial f / \partial p_{s,k,l,t}$ where α_p is the step, and then sets $p_{s,k,l,t+1} = \left(\tilde{p}_{s,k,l,t+1} \Big/ \sum\limits_{s=1}^{S} \sum\limits_{j:\, b(j) = b(k)} \sum\limits_{i=1}^{L} \tilde{p}_{s,j,i,t+1} \right) P$.

5) Let $t = t + 1$, and return to step 1).

The gradients used in the above steps can be calculated as

$$\begin{aligned} \frac{\partial f}{\partial \boldsymbol{g}_{s,k,l,t}} = {} & f'_{s,k,l,t} \frac{x_{s,k,l,t}}{G_{s,(k,l),(k,l),t}} \boldsymbol{H}^{\mathrm{H}}_{s,b(k),k,t} \boldsymbol{w}_{s,k,l,t}\, \boldsymbol{w}^{\mathrm{H}}_{s,k,l,t} \boldsymbol{H}_{s,b(k),k,t} \boldsymbol{g}_{s,k,l,t} - {} \\ & \sum_{(j,i) \neq (k,l)} f'_{s,j,i,t} \frac{p_{s,k,l,t} x^2_{s,j,i,t}}{p_{s,j,i,t} G_{s,(j,i),(j,i),t}} \boldsymbol{H}^{\mathrm{H}}_{s,b(k),k,t} \boldsymbol{w}_{s,k,l,t} \boldsymbol{w}^{\mathrm{H}}_{s,k,l,t} \boldsymbol{H}_{s,b(k),k,t} \boldsymbol{g}_{g,k,l,t} \end{aligned} \tag{5}$$

$$\begin{aligned} \frac{\partial f}{\partial \boldsymbol{w}_{s,k,l,t}} = {} & f'_{s,k,l,t} \frac{x_{s,k,l,t}}{G_{s,(k,l),(k,l),t}} \boldsymbol{H}_{s,b(k),k,t}\, \boldsymbol{g}_{s,k,l,t}\, \boldsymbol{g}^{\mathrm{H}}_{s,k,l,t}\, \boldsymbol{H}^{\mathrm{H}}_{s,b(k),k,t}\, \boldsymbol{w}_{s,k,l,t} - \sum_{(j,i) \neq (k,l)} f'_{s,k,l,t} \frac{p_{s,j,i,t}\, x^2_{s,k,l,t}}{p_{s,k,l,t}\, G_{s,(k,l),(k,l),t}} \cdot \\ & \boldsymbol{H}_{s,b(j),k,t}\, \boldsymbol{g}_{s,j,i,t}\, \boldsymbol{g}^{\mathrm{H}}_{s,j,i,t}\, \boldsymbol{H}^{\mathrm{H}}_{s,b(j),k,t} \boldsymbol{w}_{s,k,l,t} - f'_{s,k,l,t} \frac{x^2_{s,k,l,t}}{p_{s,k,l,t} G_{s,(k,l),(k,l),t}} \boldsymbol{R}_{z,s,k}\, \boldsymbol{w}_{s,k,l,t} \end{aligned} \tag{6}$$

$$\frac{\partial f}{\partial p_{s,k,l,t}} = f'_{s,k,l,t} \frac{x_{s,k,l,t}}{p_{s,k,l,t}} - \sum_{(j,i) \neq (k,l)} f'_{s,j,i,t} \frac{x_{s,j,i,t}\, G_{s,(j,i),(k,l),t}}{p_{s,j,i,t}\, G_{s,(j,i),(j,i),t}} \tag{7}$$

where $G_{s,(k,l),(j,i),t} = \left| \boldsymbol{w}^{\mathrm{H}}_{s,k,l,t}\, \boldsymbol{H}_{s,b(j),k,t} \boldsymbol{g}_{s,j,i,t} \right|^2$ and $f'_{s,k,l,t} = \partial f_k / \partial x_{s,k,l,t}$. By the terminology of optimization, the proposed scheme is gradient-project-based[6]. According to the well known results in Refs. [6-8], the gradient project method can be convergent to a stationary (although not necessarily the optimal) solution, which can also be validated by the simulation results reported in section 4.

3 Information Exchange Protocol

In step 1), each stream should collect needed information. Therefore, what types of information are needed to support the proposed algorithm and will be exchanged between neighboring bases?

First, examine the information needed by step 2). In step 2), each stream (s, k, l) calculates the gradient in Eq. (5). Therefore, step 2) needs the knowledge of $x_{s,k,l,t}$, $p_{s,k,l,t}$, $G_{s,(k,l),(k,l),t}$, and $\boldsymbol{u}_{s,k,l,t} = \boldsymbol{w}^{\mathrm{H}}_{s,k,l,t}\, \boldsymbol{H}_{s,b(k),k,t}$ of stream (s, k, l), and needs the knowledge of $x_{s,j,i,t}$, $p_{s,j,i,t}$, $G_{s,(j,i),(j,i),t}$, and $\boldsymbol{u}_{s,k,j,i,t} = \boldsymbol{w}^{\mathrm{H}}_{s,j,i,t}\, \boldsymbol{H}_{s,b(k),j,t}$ of all the interfering streams (s, j, i), as shown in Fig. 2(a). Therefore, the gradient $\partial f / \partial g_{s,k,l,t}$ in step 2) can be calculated as

$$\left(f'_{s,k,l,t}\frac{x_{s,k,l,t}}{G_{s,(k,l),(k,l),t}}\boldsymbol{u}^{\mathrm{H}}_{s,k,l,t}\boldsymbol{u}_{s,k,l,t}-\sum_{(j,i)\neq(k,l)}f'_{s,j,i,t}\frac{p_{s,k,l,t}\,x^2_{s,j,i,t}}{p_{s,j,i,t}G_{s,(j,i),(j,i),t}}\boldsymbol{u}^{\mathrm{H}}_{s,k,j,i,t}\boldsymbol{u}_{s,k,j,i,t}\right)\boldsymbol{g}_{s,k,l,t}$$

Next, examine the information needed by step 3). In step 3), each stream (s, k, l) calculates the gradient in Eq. (6). Therefore, step 3) needs the knowledge of $x_{s,k,l,t}$, $p_{s,k,l,t}$, $G_{s,(k,l),(k,l),t}$, and $\boldsymbol{v}_{s,k,l,t}=\boldsymbol{w}^{\mathrm{H}}_{s,k,l,t}\boldsymbol{H}_{s,b(k),k,t}$ of stream (s, k, l), and needs the knowledge of $p_{s,j,i,t}$ and $\boldsymbol{v}_{s,k,j,i,t}=\boldsymbol{w}^{\mathrm{H}}_{s,j,i,t}\boldsymbol{H}_{s,b(k),j,t}$ of all the interfering streams (s, j, i), as shown in Fig. 2(b). Therefore, the gradient $\partial f/\partial \boldsymbol{w}_{s,k,l,t}$ in step 3) can be calculated as

$$\left(\boldsymbol{v}_{s,k,l,t}\boldsymbol{v}^{\mathrm{H}}_{s,k,l,t}-\frac{x_{s,k,l,t}}{p_{s,k,l,t}}\sum_{(j,i)\neq(k,l)}p_{s,j,i,t}\boldsymbol{v}_{s,k,j,i,t}\boldsymbol{v}^{\mathrm{H}}_{s,k,j,i,t}-\frac{x_{s,k,l,t}}{p_{s,k,l,t}}\boldsymbol{R}_{z,s,k}\right)\boldsymbol{w}_{s,k,l,t}$$

Finally, examine the information needed by step 4). In step 4), each stream (s, k, l) calculates the gradient in Eq. (7). Therefore, step 4) needs the knowledge of $x_{s,k,l,t}$ and $p_{s,k,l,t}$ of stream (s, k, l), and needs the knowledge of $x_{s,j,i,t}$, $p_{s,j,i,t}$, $G_{s,(j,i),(j,i),t}$, and $G_{s,(j,i),(k,l),t}$, as shown in Fig. 2(c).

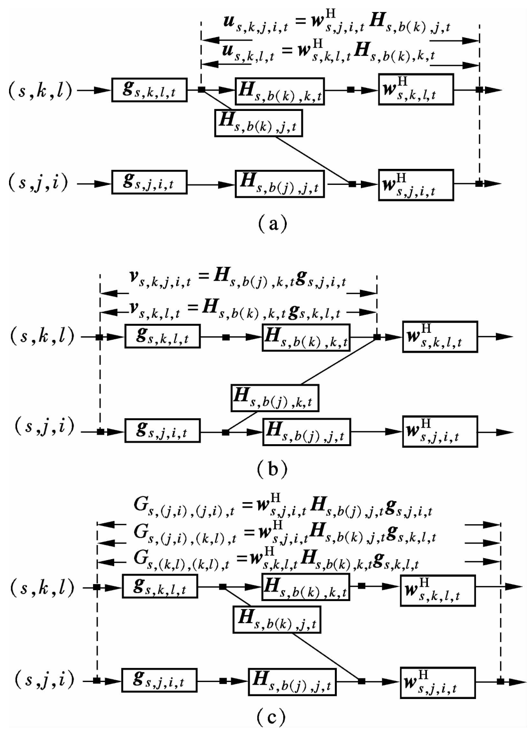

Fig. 2 Information exchange. (a) Step 2); (b) Step 3); (c) Step 4)

Therefore, the information exchange protocol should work as follows. For each slot, each stream (s, k, l) collects $x_{s,k,l,t}$, $p_{s,k,l,t}$, $G_{s,(k,l),(k,l),t}$, $\boldsymbol{u}_{s,k,l,t}$, and $\boldsymbol{v}_{s,k,l,t}$ itself, and $x_{s,j,i,t}$, $p_{s,j,i,t}$, $G_{s,(j,i),(j,i),t}$, $\boldsymbol{u}_{s,k,j,i,t}$, $\boldsymbol{v}_{s,k,j,i,t}$, and $G_{s,(j,i),(k,l),t}$ of all interfering streams (s, j, i). Furthermore, if the stream (s, k, l) and (s, j, i) are in the same cell, the information exchange is easy; if in different cells, the information exchange will be on line connecting neighboring bases.

4 Simulation Results

Consider a cellular system with $B=7$ cells and $K=20$ users and all the users are uniformly distributed in the covered area. Assume that the radius of a cell is 250 m, each base has $M=4$ antennas, each user has $N=2$ antennas and $L=2$ data streams to send. The system bandwidth is $W=10$ MHz and is divided into $S=10$ subcarriers. The maximum base transmitting power is $P=10$ W, and the noise power spectrum density is $\eta_0=-174$ dBm/Hz.

Assume that the channel matrix $\boldsymbol{H}_{s,b,k,t}=\mathrm{PL}_{s,b,k}\boldsymbol{H}_t$, where $\mathrm{PL}_{s,b,k}=d^{-4}$ models the path loss and d is the distance between base b and user k in meters, and $\boldsymbol{H}_t$ models the fast fading and all elements are independent identically distributed (i. i. d.) complex normal random variables with zero mean and unit variance. Furthermore, to model the correlation between the fast fading matrices in consecutive slots, we assume $\boldsymbol{H}_{t+1}=(1-e_{\mathrm{H}})\boldsymbol{H}_t+e_{\mathrm{H}}\boldsymbol{H}_{\mathrm{new}}$, where e_{H} ranges from 0 to 1, and $\boldsymbol{H}_{\mathrm{new}}$ is an independent random matrix with all the elements i. i. d. complex normal random variables with zero mean and unit variance.

When implementing the proposed scheme, we assume that the step $\alpha_{\mathrm{g}}=\alpha_{\mathrm{w}}=\alpha_{\mathrm{p}}=0.5$ and the correlation factor $e_{\mathrm{H}}=1$, select the utility function is $f_k(x)=\log(x)$ and the corresponding derivative is $f'_{s,k,l,t}=\partial f_k/\partial x_{s,k,l,t}=(1/R_{s,k,l,t})e_{\mathrm{R}}/(1+x_{s,k,l,t})$, and select the initial point randomly. Furthermore, in the algorithm proposed in section 2, each slot contains one iteration. However, to improve the performance, each slot can contain more iterations. We assume that the number of iterations in each slot is $\mathrm{rnd}_{\max}=2$. The simulation results are plotted in Fig. 3(a). As shown by the curves in the figure, the proposed scheme is convergent, and can achieve an average spectral efficiency of about 5 bit/(s · Hz · cell). For comparison, it can be noted that the average spectral efficiency requirement of ITU for IMT-advanced is about 2.6 bit/(s · Hz · cell) [9].

First, consider the performance of the proposed scheme with different e_{H}. Let e_{H} be 0.1, 0.3, 0.5, 1, and keep other parameters the same as those in Fig. 3(a), where $e_{\mathrm{H}}=0.1$ corresponds to the slow-changing channel case, and $e_{\mathrm{H}}=1$ corresponds to the fast-changing channel case. We run simulations for each e_{H} and plot the simulation results in Fig. 3(b). Simulation results show that if the channel change is slow, the iterative algorithm can exploit the channel transmission capacity and improve the average spectral efficiency. Specifically, for $e_{\mathrm{H}}=1$, the performance is about 5 bit/(s · Hz · cell); for $e_{\mathrm{H}}=0.1$, the performance is improved to about 7 bit/(s · Hz · cell). The main reason is that the iterative algorithm needs time to converge. Therefore, if the channel change is fast, the channel condition will change before the convergence of the algorithm; on the other hand, if the channel change is slow, the algorithm will converge before the channel condition changes.

Secondly, consider the performance of the proposed scheme with different $\mathrm{rnd}_{\max}$. Let $\mathrm{rnd}_{\max}$ be 1, 2, 3, 4, and keep other parameters the same as those in Fig. 3(a), where $\mathrm{rnd}_{\max}=1$ means each slot contains one iteration, and $\mathrm{rnd}_{\max}=4$ means each slot contains four iterations. We run simulations for each e_{H}, and plot the simulation results in Fig. 3

(c). Simulation results show that, the more iteration numbers per slot, the better the average spectral efficiency performance. Specifically, for $rnd_{max} = 1$, the performance is about 3.5 bit/(s · Hz · cell), but for $rnd_{max} = 4$, the performance can be improved to about 6.2 bit/(s · Hz · cell).

Finally, consider the performance of the proposed scheme with different steps. Let step ($\alpha_g = \alpha_w = \alpha_p$) be 0.1, 0.3, 0.5, 0.7, and 0.9, and keep other parameters the same as those in Fig. 3(a). We run simulations for each e_H, and plot the simulation results in Fig. 3(d). Simulation results show that the average spectral efficiency performance under different steps is different. However, the difference is not great. Therefore, if the step is selected in a reasonable range, the average spectral efficiency performance is acceptable.

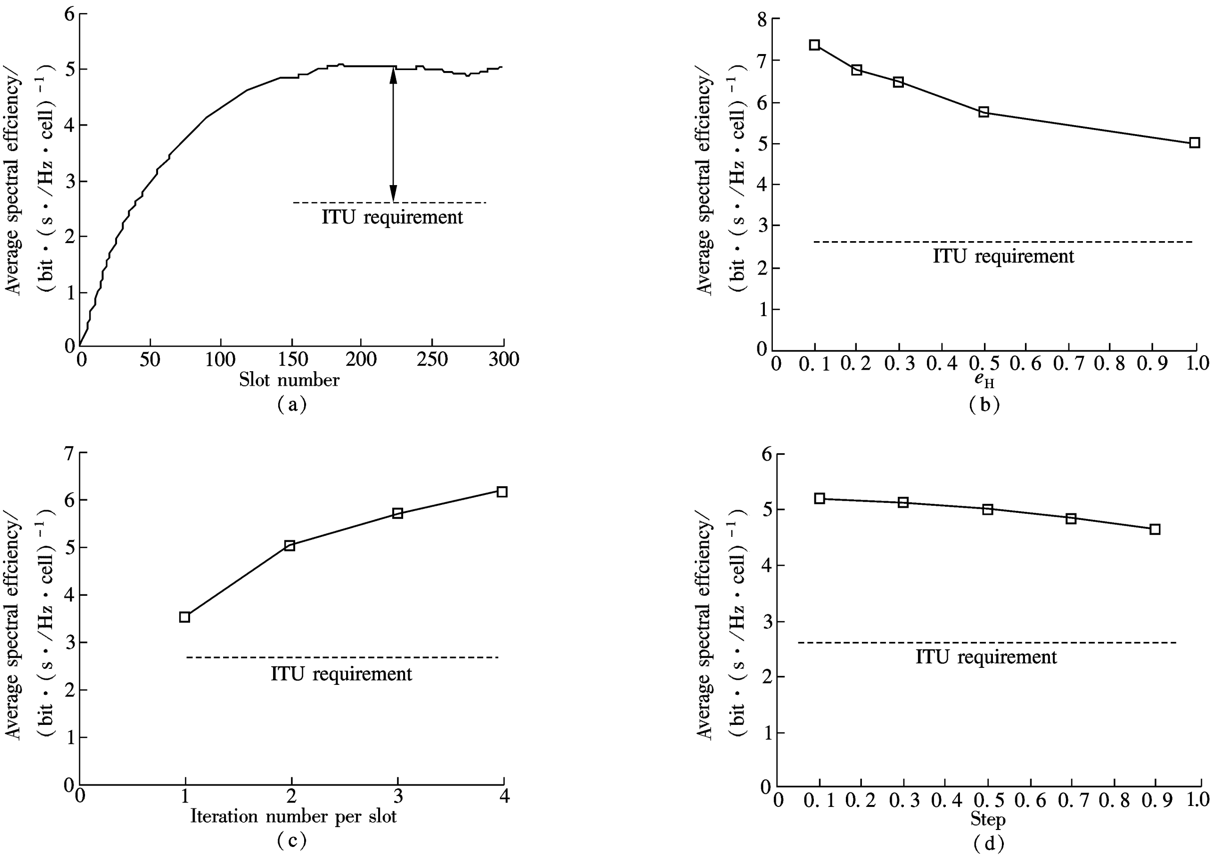

Fig. 3 Average spectral efficiency. (a) Basic; (b) e_H; (c) rnd_{max}; (d) Step

5 Conclusion

This paper studies the multi-cell multi-user downlink transmission problem and proposes a novel cooperative beamforming scheme. First, the mathematical model for multi-cell multi-user MIMO downlink transmission is established, and then a gradient-project-based cooperative beamforming scheme and the information exchange protocol are designed. Simulation results show that the proposed scheme can achieve an average spectral efficiency of about 5 bit/(s · Hz · cell).

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多天线蜂窝系统中的下行协作波束成型传输

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摘要：在使用波束成型传输数据的蜂窝系统中，为提高下行链路的频谱效率，需要多小区多用户之间协作地产生波束. 以多小区多用户下行链路的数学模型为基础，计算了各用户波束发送滤波器、接收滤波器、发送功率三类变量的梯度，使这些变量不断沿梯度方向调整并投影至可行空间，从而提出了一种基于梯度投影的多小区多用户下行协作波束成型传输方案，并分析了该方案需要在相邻小区基站间交互的信息. 仿真结果表明，该方案在典型场景与参数配置下可达到约 5 bit/(s · Hz · cell) 的平均频谱效率性能. 因此，多小区多用户之间的有效协作有助于提高蜂窝系统频谱效率性能.

关键词：蜂窝系统；多输入多输出；协作预编码；频谱效率

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