Multi-Cell Uplink Interference Management: A Distributed Power Control Method

Abstract: This paper investigates a multi-cell uplink network, where the orthogonal frequency division multiplexing (OFDM) protocol is considered to mitigate the intra-cell interference. An optimization problem is formulated to maximize the user supporting ratio for the uplink multi-cell system by optimizing the transmit power. This paper adopts the user supporting ratio as the main performance metric. Our goal is to improve the user supporting ratio of each cell. Since the formulated optimization problem is non-convex, it cannot be solved by using traditional convex-based optimization methods. Thus, a distributed method with low complexity and a small amount of multi-cell interaction is proposed. Numerical results show that a notable performance gain achieved by our proposed scheme compared with the traditional one is without inter-cell interaction.

Keywords: uplink interference; multi-cell uplink network; non-cooperative game; interactive scheme

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1 Introduction

In 5G and Internet of Things (IoT) networks, the number and density of users have increased dramatically and data transmission has shown explosive growth, leading to an urgent need for greater capacity and higher spectrum efficiency (SE)[1 – 3], especially in the uplink transmission. For the uplink transmission, a cell user may suffer unacceptably high interference from other users in neighboring cells, who transmit signals over the same frequency band with it.

To pursue high SE and mitigate the inter-user interference, the orthogonal frequency division multiple access (OFDMA) protocol was proposed[4]. OFDMA divides the whole available channel frequency band into several sub-channels, so that multiple users can access over different sub-channels for data transmission simultaneously[5 – 7]. In OFDMA-based cellular systems, when the number of sub-channels is greater than or equal to the total number of users in all cells, the intra-cell interference can be ignored, since the sub-channels are orthogonal to each other[8].

However, in wireless cellular networks, due to the limited spectrum resource, different cells have to share the same spectrum resource. That is the users in different cells may transmit signals over the same sub-channel in an OFDMA-based cellular system so that the inter-cell interference (ICI) cannot be neglected, especially in the ultra-dense cellular system, where the radius of the cell is much smaller than traditional ones and the distance between the users from different cells is also smaller than traditional ones. Thus, in the ultra-dense cellular system, the inter-cell interference becomes the major factor of limiting the network capacity and users' achievable-information rates[9 – 10]. More importantly,

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as the demand for spectrum resource utilization continues to increase, the ICI issue is getting much worse[11].

As a matter of fact, the ICI is related to many factors including network topology, frequency reuse methods, multiple access schemes, and transmit power of users, among which the power control is shown to be the most significant way to migrate the ICI.

Moreover, in practical multi-cell networks, it is impossible to deploy a centralized power control algorithm due to the huge signaling overhead on collecting global network information from all users, so a lot of related work on multi-cell ICI suppression by designing distributed power control can be found in the literature[12–18]. In Ref. [12], an efficient power allocation approach in OFDMA cellular networks was proposed, which was based on the non-cooperative game theory. In Ref. [13], the distributed power control and subcarrier allocation problems in the multi-cell OFDMA system were studied, and the convergence rule and steady state characterization were analyzed with the potential game. In Ref. [14], a power control scheme was proposed to manage the LTE uplink interference, which was designed based on data-driven machine learning paradigms. In Ref. [15], two power control schemes were proposed by adjusting the maximum transmit power of femtocell users to suppress the cross-tier interference at a macro-cell base station (BS). In Ref. [16], a new interference cancellation scheme was presented for the uplink multi-channel environment to reduce error propagation with low backhaul use, and the scheme shares one real value scaler and hard symbols through backhaul to minimize residual interference variance. In Ref. [17], the user's unique interference-aware open-loop power control (IA-OPC) scheme was proposed, in which the incoming and outgoing line interference in the cell were taken into account. In Ref. [18], the energy efficiency maximization problem was investigated under uncertain channels, for which an optimal mobile relay selection algorithm and a robust distributed power control algorithm were proposed.

However, the aforementioned works on the distributed power control did not take into account information interaction, so the achieved performance is limited. As is known, more efficient strategies can be designed based on more information interacted among cells. This paper aims to design a new distributed power control method for OFDMA-based multi-cell networks by introducing proper inter-cell interaction. Note that proper inter-cell interaction means that the less interaction amount, the better. The contributions of this paper are summarized as follows.

1) An optimization problem is formulated to maximize the user supporting ratio for the uplink multi-cell systems by optimizing the transmit power, where the OFDM protocol is considered for mitigating the intra-cell interference. Different from existing works[12, 17], the goal of which was to improve the network throughput, this paper adopts the user supporting ratio as the main performance metric, which is described as the ratio between the number of users meeting the quality of service (QoS) threshold and the total number of users in the cell. If more users are supported, more profits can be gained by the communication network operators. Different from the existing work[19], which examined the exact downlink average capacity of multi-cell MIMO cellular network with co-channel interference, this paper aims to design a simple and low-complexity multi-cell uplink interference management method.

2) Since the formulated optimization problem is non-convex and we aim to design a distributed method with low complexity and a small amount of multi-cell interaction, the problem cannot be solved by using traditional convex-based optimization methods. Thus, an interactive power control scheme is proposed based on the non-cooperative game. In the presented scheme, a power control scheme based on a non-cooperative game is introduced, and the predicted transmit power obtained by the non-cooperative game is shared. Hence, it has low complexity and a small amount of multi-cell interaction. Numerical results show that a notable performance gain is achieved by our proposed scheme compared with the traditional one without inter-cell interaction. In our simulation, it shows that the user supporting ratio obtained by the interactive scheme based on the non-cooperative game is higher than that obtained by the non-interactive scheme.

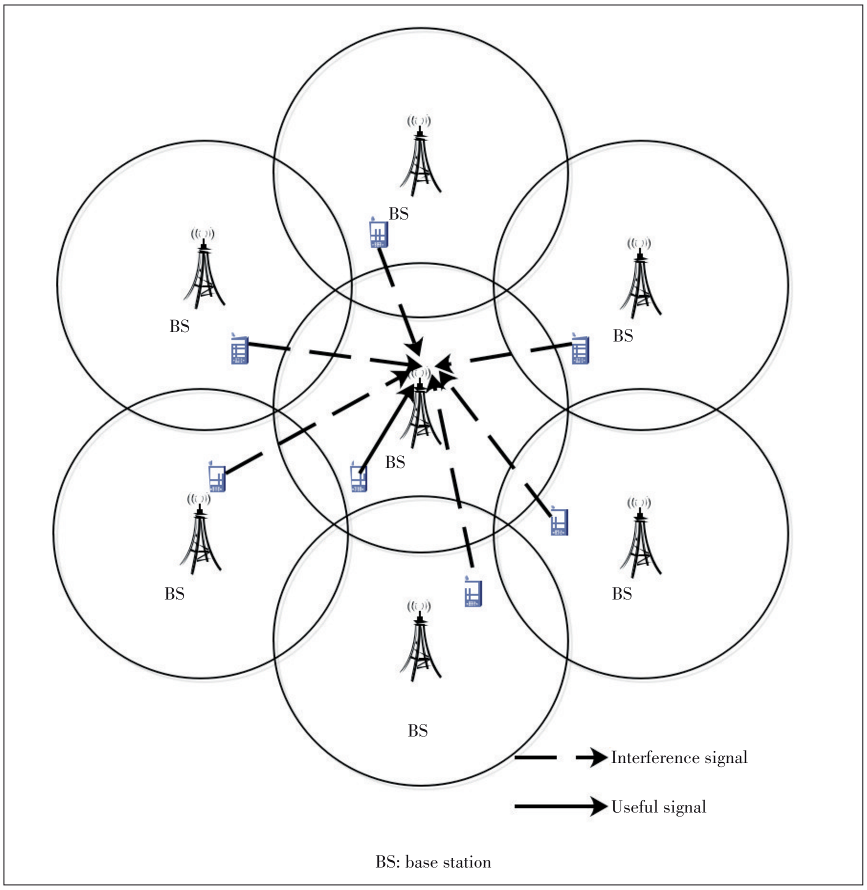
The rest of the paper is organized as follows. In Section 2, we present the system model and formulate the optimization problem. In Section 3, we present a distributed interactive uplink power control algorithm based on non-cooperative games. Section 4 proves the effectiveness of the proposed scheme via simulations. Section 5 summarizes the paper.

2 System Model

2.1 Network Model

We consider a multi-cell uplink transmission network, consisting of M cells/BSs, as shown in Fig. 1. In each cell, the number of users is N. Each BS in M cells performs uplink resource allocation to serve N randomly distributed users, with $m \in \{1,2,...,M\}$, and $n \in \{1,2,...,N\}$, where the OFDMA is used to avoid interference between users in the cell. In addition, due to limited spectrum resources, full spectrum multiplexing is used among multiple cells. Due to full frequency reuse among M cells, users in each cell suffer from co-channel interference imposed by frequency multiplexing users in other surrounding cells, where the radius of each cell is R, and the distance between adjacent base stations is D.

Assume that the total carrier number is C, and for fairness, carrier resources are evenly divided, so that N re-



▲**Figure 1. An illustration of a multi-cell uplink system**

source blocks (RBs) with the same number of sub-carriers are obtained. The size of each RB is $L = C/N$. Each user is randomly assigned with an RB, and each sub-carrier could only be exclusively allocated to one user in each cell. Let B denote the total bandwidth of the system. Then, the bandwidth of per sub-carrier is $B_s = B/C$.

Let $P_{m,n}$ denote the transmit power of the n-th user in the m-th cell. It is assumed that the BS can measure the channel quality from users in the cell to the BS in the uplink transmission. Therefore, the signal to interference plus noise ratio (SINR) of the n-th user's l-th subcarrier in the m-th cell is

$$\gamma_{m,n,l} = \frac{P_{m,n} h_{m,n,l}}{I_{m,n,l} + N_0}, \tag{1}$$

where $h_{m,n,l}$ is the channel power gain of the n-th user's l-th subcarrier in the m-th cell, N_0 is the power spectral density of additive white Gaussian noise (AWGN) on the subcarrier, and $I_{m,n,l}$ is the total interference received by the n-th user's l-th subcarrier in the m-th cell.

The expression of $I_{m,n,l}$ is given by

$$I_{m,n,l} = \sum_{i=1, i \neq m}^{M} \sum_{n=1}^{N} \alpha_{i,n,l} P_{i,n} h_{i,n,l}^{m}, \tag{2}$$

where $\alpha_{i,n,l}$ is a binary variable, and $\alpha_{i,n,l} = 1$ if the n-th user's l-th subcarrier in the i-th cell interferes with the l-th subcarrier in the m-th cell. Otherwise, $\alpha_{i,n,l} = 0$. $h_{i,n,l}^{m}$ represents the power gain from n-th user's l-th subcarrier in the i-th cell to m-th BS.

Let $R_{m,n}$ denote the achievable rate of the n-th user in the n-th cell. Therefore, the achievable rate of the n-th user over the allocated RB in the m-th cell is given by

$$R_{m,n} = \sum_{l=1} B_s \log(1 + \gamma_{m,n,l}). \tag{3}$$

2.2 Problem Formation

Assume that each user has an expected minimum rate requirement $R_{m,n}^{\mathrm{th}}$. If $R_{m,n} \geqslant R_{m,n}^{\mathrm{th}}$, the user can get the desired QoS. Otherwise, user's QoS requirement cannot be satisfied. In the following, $R_{m,n}^{\mathrm{th}}$ is defined as a QoS threshold to measure the QoS of the user. The goal is to maximize the user supporting ratio of each cell, which is defined as the ratio between the number of users meeting the QoS threshold and the total number of users in cell, i.e.,

$$p_m = \frac{N_m^{\mathrm{sat}}}{N}, \tag{4}$$

where N_m^{sat} denotes the number of users whose achievable rate meet $R_{m,n} \geqslant R_{m,n}^{\mathrm{th}}$ in the m-th cell.

Therefore, the user supporting ratio maximization can be mathematically expressed by

$$\begin{aligned} P_1: \quad & \max_{P_{m,n}} \; p_m \\ \text{s.t.} \quad & P_{\min} \leqslant P_{m,n} \leqslant P_{\max}, \\ & \forall m \in M, \forall n \in N, \end{aligned} \tag{5}$$

where $P_{\max}$ denotes the maximum transmit power of each user, and $P_{\min}$ denotes the minimum transmit power of each user.

The notations used in this paper are summarized in Table 1.

3 Proposed Solution

In this section, a distributed interference suppression method with low complexity and a small amount of multi-cell interaction is proposed to maximize the user supporting ratio of each cell. To reach the goal, the problem is defined as a non-cooperative game problem, and then a power interaction policy is proposed based on the power update formula obtained by the non-cooperative game.

▼Table 1. Summary of notations

Notation	Description
M	Number of BSs or cells
N	Number of users per cell
C	Total number of subcarriers
B	Total bandwidth
B_s	Bandwidth of per subcarrier
L	Number of subcarriers per user
$P_{m,n}$	Transmit power of the n-th user in the m-th cell
$P_{\max}$	Maximum transmit power of each user
$P_{\min}$	Minimum transmit power of each user
$R_{m,n}$	Achievable rate of the n-th user in the m-th cell
$R^{\text{th}}_{m,n}$	QoS threshold of the n-th user in the m-th cell
$\gamma_{m,n,l}$	SINR of the n-th user's l-th subcarrier in the m-th cell
$h_{m,n,l}$	Power gain of the n-th user's l-th subcarrier in the m-th cell
$h^{m}_{i,n,l}$	Power gain from n-th user's l-th subcarrier in the i-th co-frequency cell to m-th BS
$I_{m,n,l}$	Total interference received by the n-th user's l-th subcarrier in the m-th cell
N_0	Power spectral density of AWGN on the subcarrier
$\alpha_{i,n,l}$	A binary number
p_m	User supporting ratio of cell m

AWGN: additive white Gaussian noise
BS: base station
QoS: quality of service
SINR: signal to interference plus noise ratio

3.1 Formulation as Non-Cooperative Game

Let $G=\{P,A_m,U_m(\cdot)\}$ represent the power control game model of multi-cell non-cooperative game, where $P\in\{1,2,\ldots,M\}$ represents the set of users (i.e., participants) with co-frequency interference in each cell on the same subcarrier. That is, the cell index m is used to represent the user m within the cell. A_m represents the policy set of user m, $A_m=\{P_m|P_{\min}\leqslant P_m\leqslant P_{\max}\}$, and $U_m(\cdot)$ denotes the utility function for user m. Each user maximizes its utility value by adjusting the power. In order to achieve the goal, there may be malicious competition. Therefore, it is necessary to ensure that the system can obtain a steady-state solution, that is, the Nash equilibrium solution.

According to Ref. [20], the utility function based on the non-cooperative game model is defined as

$$U_m(P)=a_m\sqrt{\gamma_m-\gamma_m^{\text{th}}}-c_mP_m, \tag{6}$$

where γ_m^{th} is the SINR threshold of user m on a subcarrier. In Eq. (6), the first term considers the minimum SINR requirement of the user, and the second term represents the interference caused by the user to other users. Besides, a_m and c_m are system parameters.

3.2 Nash Equilibrium Solution

The second term of the utility function can be understood as the price paid by each user to improve SINR. In other words, users are not only restricted by power. In order to obtain the optimal solution, first of all, for convenience we have the following equation:

$$I_m=I_{m,n,l}+N_0. \tag{7}$$

Then, the gradient of the utility function $U_m(P)$ is calculated according to Eqs. (6) and (7), and we have

$$\frac{\partial U_m}{\partial P_m}=\frac{1}{2}a_m\left(\gamma_m-\gamma_m^{\text{th}}\right)^{-\frac{1}{2}}\frac{h_m}{I_m}-c_m. \tag{8}$$

Let $\frac{\partial U_m}{\partial P_m}=0$, we have

$$\gamma_m=\gamma_m^{\text{th}}+\left(\frac{a_mh_m}{2c_mI_m}\right)^2. \tag{9}$$

According to Eq. (1), we can obtain that

$$P_m=\frac{I_m}{h_m}\gamma_m^{\text{th}}+\beta_m\frac{h_m}{I_m}, \tag{10}$$

where $\beta_m=\left(\frac{a_m}{2c_m}\right)^2$.

According to Newton's iterative formula, we can obtain the following optimal power iterative formula:

$$P_m(k+1)=\frac{P_m(k)}{\gamma_m(k)}\gamma_m^{\text{th}}+\beta_m\frac{\gamma_m(k)}{P_m(k)}, \tag{11}$$

where k denotes the iterative number. According to Ref. [20], $\forall P\geqslant P'$, and then $I_m\geqslant I'_m$. When $I'_m\geqslant\sqrt{\beta_m/\gamma_m^{\text{th}}}$, the iterative expression Eq. (11) converges to a unique point.

3.3 Distributed Power Control Method

According to Eq. (11), the power of user n in cell m is calculated, denoted as $P^{\text{game}}_{m,n}$, namely, predictive power. BS in each cell calculates a ratio $r_{m,n}$ for each user, with $r_{m,n}>0$ as follows.

$$r_{m,n}=\frac{R_{m,n}}{R^{\text{th}}_{m,n}},\ \forall m,n. \tag{12}$$

The predicted power of users interacts between BSs. That is, the BS in cell m transmits a power $P^{\text{game}}_{m,n}$ to all BSs in other neighboring cells. The predicted power received by user n in cell m is stored in set S_p.

We define F as a binary variable. If half of the predicted power in set S_p is increased compared with the last time, $F=1$; otherwise, $F=0$. Then the current power of user n in cell m is set as follows,

Case 1: When $0<r_{m,n}<v_1$, then $P_{m,n}=P_{\min}$;

Case 2: When $v_1 \leqslant r_{m,n} < v_2$ and $F = 1$, then $P_{m,n} = \min \{ P^{\text{game}}_{m,n}, P'_{m,n} \}$, where $P'_{m,n} = P_{m,n} - (P_{m,n} - P_{\min}) \cdot (1 - r_{m,n})$. Moreover, when $v_1 \leqslant r_{m,n} < v_2$ and $F = 0$, then $P_{m,n} = P^{\text{game}}_{m,n}$;

Case 3: When $v_2 \leqslant r_{m,n} < 1$, then $P_{m,n} = \min \{ P_{\min}, P'_{m,n} \}$, where $P'_{m,n} = P_{m,n} + (P_{\max} - P_{m,n}) \cdot (1 - r_{m,n})$; where v_1 and v_2 is two constants, and $0 < v_1 < v_2 < 1$.

The problem of maximizing the number of users meeting the QoS threshold is actually non-convex, and the solution is very complicated, which means that it is difficult to converge to the global optimal solution. Therefore, the condition for ending the algorithm is set to converge or reach the maximum scheduling times.

4 Simulation Results

In this section, some simulation results are presented to verify the performance of our proposed scheduling scheme. The network scenario shown in Fig. 2 is simulated, where the number of cells/BSs is 7. The radius of each cell is R = 570 m, and the distance between the BSs is D = 950 m. For multi-cell OFDM systems, there is no intra-cell interference within each cell but the inter-cell interference cannot be neglected since different users from different cells may transmit signals over the same frequency band[22 – 23]. The more cell-edge users, the stronger the inter-cell interference. To explore the system power control scheme in severe inter-cell interference scenarios, in this paper, most users are densely distributed at the edge of each cell in the simulations. It is assumed that the edge area of the cell is from 380 to 570 m. Each cell has 190 users randomly and evenly distributed in the edge area and 10 users randomly and evenly distributed in the central area[1]. According to Ref. [21], the channel power gain is given by

$$h_{m,n,i} = -(-55.9 + 38 \cdot \log10(d_{m,n,i}) + (24.5 + 1.5 \cdot fc/925) \cdot \log10(fc)), \tag{13}$$

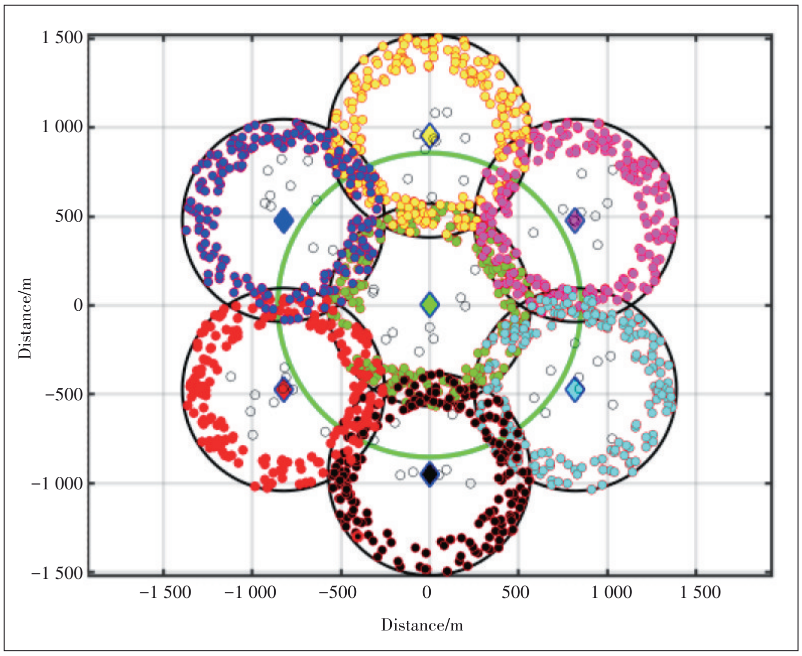
where $d_{m,n,i}$ denotes the distance between the n-th user in the m-th cell and the base station in the i-th cell, and fc is the center frequency point and is set as fc= 2 300 MHz.

The initial power of each user is 17 dBm. The total bandwidth of the system is 10 MHz, and the total number of subcarriers is 1 600. The bandwidth of a subcarrier is B = 1/160 MHz, and the number of carriers allocated to each user is L = 8. The noise power is $N_0 = -174$ dBm/Hz, and the maximum and minimum transmit power of the user is $P_{\max}$ = 23 dBm and $P_{\min}$ = 14 dBm. For the m-th cell, we define $r_m = (r_{m,1}, r_{m,2}, \ldots, r_{m,N})$. r_m is sorted in ascending order and then r'_m is obtained, where $r'_m = (r'_{m,1}, r'_{m,2}, \ldots, r'_{m,N})$. v_1 is set as $r'_{m,80}$, and v_2 is set as $r'_{m,140}$. That is, the rate for 40% of users is less than v_1 and 70% of users is less than v_2. The SINR threshold and the QoS threshold of each user are determined by the distance from the user to the BS and the initial power.

In this paper, it is assumed that if a cell user works on the same frequency band as the neighbor cell user and the distance between the neighbor cell user and the BS of the current cell is less than 1.5 R, it causes interference to the user of the current cell. In addition, since the central user is relatively far from the BS of the other cell, it is assumed that there is no interference from the central user.

The user supporting ratio of cell m after using our presented policy is referred to as cell m-After, with $m \in \{1,2,\ldots,M\}$. In order to verify the effectiveness of the proposed policy, the user supporting ratio of cell m without using our presented policy (called cell m-Before) is simulated as the benchmark method, with $m \in \{1,2,\ldots,M\}$.

Fig. 3 depicts the user supporting ratio of each cell versus scheduling times under a non-cooperative game scheme. It can be observed that the user supporting ratio of each cell gradually increases with the scheduling times and finally



▲**Figure 2. Simulation scene**

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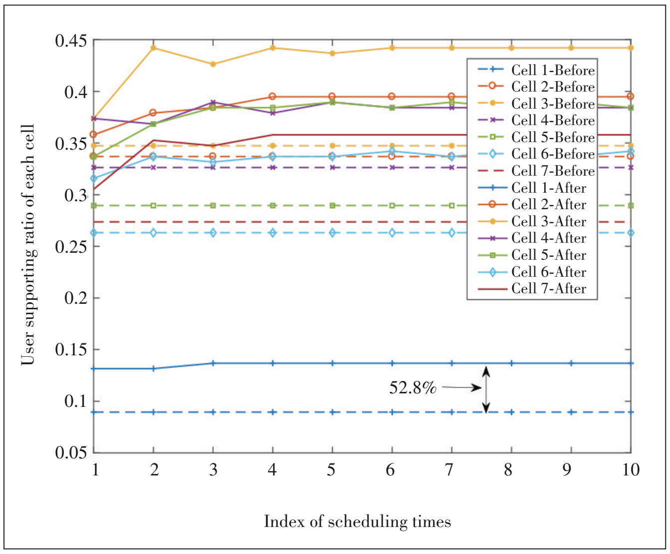
[1] When the numbers of users in the cells are different, the proposed algorithm can still work well, because the three cases in Section 3.3 can increase the number of users meeting the QoS requirement on each carrier, which means that the total number of users meeting the QoS requirement will also increase. When the numbers of users in the cells are different, inter-cell interference received on the same frequency band may change, because the values of v_1 and v_2 are adaptive and can be adjusted according to specific interference situations, the algorithm is still valid. Without loss of generality, the numbers of users in all cells are assumed to be the same in simulations.

tends to be flat. Taking the first cell as an example, compared with no scheduling policy, the user supporting ratio of the cell increases by 52.8%.

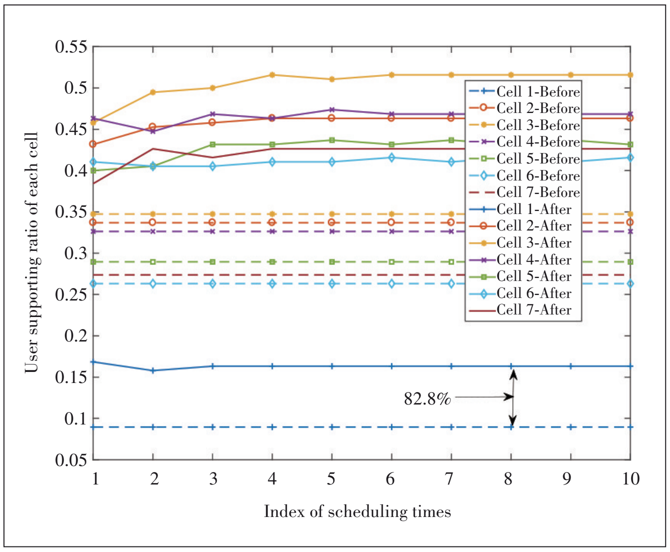
Fig. 4 plots the user supporting ratio of each cell versus scheduling times under an interactive scheme based on non-cooperative game. It can be observed that the user supporting ratio of each cell gradually increases with the scheduling times and finally tends to be flat. Taking the first cell as an example, the user supporting ratio of the cell is improved by 82.8% compared with the situation when no policy is used. In addition, the interaction scheme is improved by 30% compared with the non-interaction scheme. This is because when an interactive policy is adopted, some interfering users may choose to reduce transmit power, so that other interfering users may increase the communication rate.

Fig. 5 shows the average user supporting ratio of all cells versus scheduling times under the non-cooperative game scheme. One can see that the average user supporting ratio of all cells gradually increases with scheduling times and finally tends to be flat. The results with the non-cooperative game scheduling method are improved by 26.7% compared with those without the scheduling policy.

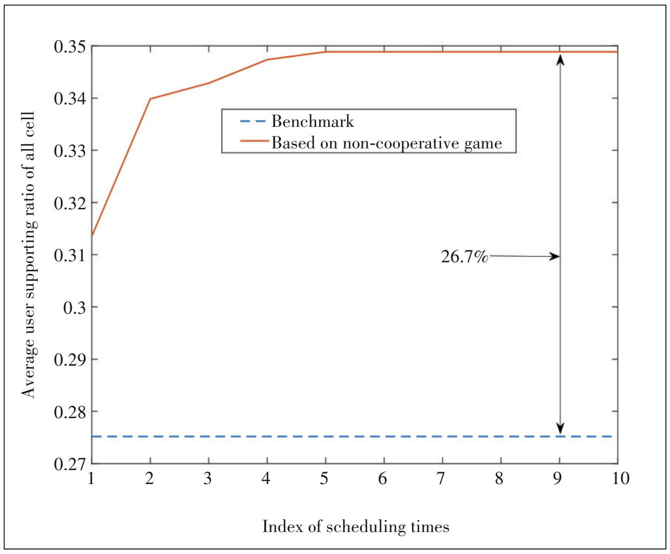
Fig. 6 shows the average user supporting ratio of all cells versus scheduling times under the interactive scheme based on the non-cooperative game. The average user supporting ratio under the proposed scheduling method based on non-cooperative game interaction is improved by 49.7% compared with the results without the scheduling policy. Be-



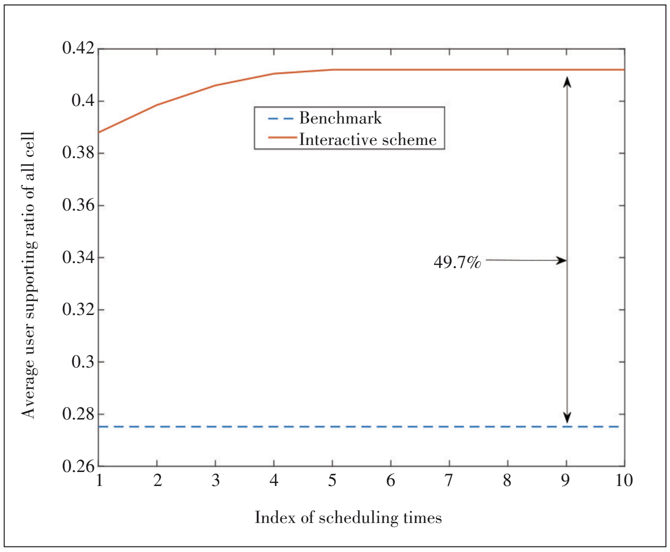
▲ **Figure 3. User supporting ratio of each cell under an interactive scheme based on non-cooperative game**



▲ **Figure 4. User supporting ratio of each cell under an interactive scheme based on non-cooperative game**



▲ **Figure 5. Average user supporting ratio of all cells under the non-cooperative game scheme**



▲ **Figure 6. Average user supporting ratio of all cells under the interactive scheme based on the non-cooperative game** sides, the interaction scheme is improved by 23% compared with the non-interaction scheme.

5 Conclusions

A distributed power control method with low complexity and a small amount of multi-cell interaction is presented in this paper. Different from the traditional work, our goal is to improve the user supporting ratio of each cell. For this purpose, first, a non-cooperative power control scheme is proposed, and then, an interactive power control scheme based on non-cooperative games is proposed. The simulation results show that our proposed scheme achieves a notable performance gain compared with the traditional method without inter-cell interaction.

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