LETTER

Multi-Cell Cooperation with Fairness Constraint in the Downlink OFDMA Cellular Networks*

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SUMMARY In this letter, we study cell cooperation in the downlink OFDMA cellular networks. The proposed cooperation scheme is based on fractional frequency reuse (FFR), where a cooperation group consists of three sector antennas from three adjacent cells and the subchannels of each cooperation group are allocated coordinately to users. Simulation results demonstrate the effectiveness of the proposed schemes in terms of throughput and fairness.

key words: *multi-cell cooperation, OFDMA, FFR, ICI coordination, fairness*

1. Introduction

As an advanced physical layer technology, OFDMA has been proposed by 3GPP LTE (3rd Generation Partnership Project Long Term Evolution) to be the multiple access technique for the downlink in B3G (Beyond 3rd Generation) systems [1]. In the OFDMA-based cellular system, the subchannels used within a cell are orthogonal to each other such that the interference can be avoided. However, the users on the border of the cell not only receive signals from the serving base station (BS), but also suffer severe inter cell interference (ICI) from the neighboring cells which use the same set of subchannels. The so called ICI will degenerate the system performance and must be mitigated.

In 3GPP LTE, three approaches have been proposed to mitigate the so-called ICI, i.e., ICI randomization, ICI coordination, and ICI cancelation. Among the three approaches, ICI coordination is comparatively easier to be realized and can be used in various wide band traffics [2]. The basic idea behind ICI coordination is exploiting FFR technique to separate the interfering source as far as possible while increasing spectral efficiency as much as possible [3], [4]. FFR relies on partitioning the total available frequency resource into two sets and dividing a cell into two concentric region, namely, interior region and exterior region. One set of the frequency is used by users in the interior region of all cells with a frequency reuse factor (FRF) of 1. While the other set of frequency is used by users in the exterior zone with a FRF less than 1. As far as we know there are two frequency partitioning patterns, namely, joint and disjoint [5]. In this letter, disjoint frequency partitioning scheme is used for easy power control.

As a promising technique which can improve spectral efficiency and enlarge coverage, cooperative communication [6] has attracted increasing interest in recent years. For single-cell scenario, ICI is not considered in resource allocation with fairness constraint [7]. However for multi-cell scenario, mobile terminals (MTs) located near the cell boundary will receive bad service due to shadowing path loss and heavy ICI. Hence cooperative transmission among two or more BSs for cell-edge MTs in OFDMA cellular systems is worthy of being investigated. In [8], cooperation between two BSs in MIMO system was studied. However, fairness and OFDMA were not considered. Although an virtual cell frequency reuse scheme was proposed to improve the capacity of cell-edge users in [9], cooperation among BSs and FFR were not investigated. In [10], the authors proposed a cooperative scheme based on distributed subcarrier and power allocation at the source and relays. In [11], a fairness-aware cooperation method for the downlink CDMA cellular networks was proposed to improve the throughput of cell-edge users. However, there is no frequency partitioning problem and the only work that is needed is distributing power among users in different time slots.

In this letter, we propose a new multi-cell cooperation strategy using FFR for the downlink OFDMA networks. The goal is to maximize the total throughput and guarantee the fairness of all cell-edge users via cooperation among multiple BSs.

2. System Model

The multi-cell OFDMA systems considered in this letter is shown in Fig. 1(a). Each cell is divided into two concentric regions, i.e., cell-center region and cell-edge region. Subsequently, the cell-edge region is sectorized into three sectors. A BS is located in the center of each cell and each BS has one omnidirectional antenna and three sector antennas (SAs). The omnidirectional antenna is used to serve the cell-center area. While each SA is a directional antenna roughly covering a 120-degree of sectorized cell-edge region. Correspondingly, the available frequency spectrum are also statically partitioned into two disjoint groups (Fig. 1(b)), i.e.,

Manuscript received July 14, 2009.
Manuscript revised December 22, 2009.

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*This work is supported by the NSFC No. 60572157, No. 60972031, and SEU SKL for Mobile Communications No. W200907.

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DOI: 10.1587/transcom.E93.B.1653

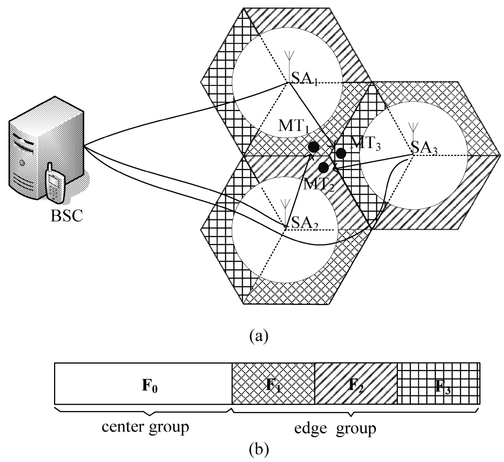

Fig. 1 The BSs cooperation and frequency reuse pattern.

center subcarrier group and edge subcarrier group. The former one, e.g., F_0 as denoted in Fig. 1(b) is used in cell-center area of all cells, while the latter one which consists of F_1, F_2, and F_3 is exclusively used by three sectors of each cell. Besides, Base Station Controller (BSC) is employed to control multiple BSs and allocate subcarrier and power to different MTs.

As denoted in Fig. 1(a), a cooperation group consists of SA_1, SA_2, and SA_3 from three adjacent BSs. The area served by one cooperation group is called a virtual cell. For the MTs located in the virtual cell, the incoming data is first routed to the corresponding BSC and then is distributed to different BSs, depending on the location of the served MTs. The transmission between BSC and BSs is assumed to be perfect. This may be achieved by using high-speed wired backbone or directional radio links. Additionally, the frequency reuse pattern described in [12] is adopted. In other words, the reuse factor is 1 in the cell-center, while 3 at the cell edge.

3. Multi-Cell Cooperation Scheme

In this section, we formulate the multi-cell cooperative transmission scheme as an optimization problem and propose a suboptimal solution to the optimization problem.

3.1 Problem Formulation

In the conventional OFDMA cellular systems, each SA only transmits to the MTs within its serving sector, no matter how bad the subchannels from SA to MTs are. Since MTs are located near the cell boundary, some of them may be better served by the SAs in other cells. For example, as illustrated in Fig. 1, MT_1, MT_2, and MT_3 are located in a virtual cell. Suppose that subchannel groups $\mathbb{F}_1$, $\mathbb{F}_2$, and $\mathbb{F}_3$ belong to SA_1, SA_2, and SA_3, respectively. When noncooperation mode is used, MT_1, MT_2, and MT_3 can only be always served by a subset of $\mathbb{F}_1$, $\mathbb{F}_2$, and $\mathbb{F}_3$, respectively. However, when cooperation scheme is adopted, the serving subchannels for each MTs may be any subchannels of $\mathbb{F}_1$, $\mathbb{F}_2$, and $\mathbb{F}_3$. For example, in one time slot, MT_1 is served by the subchannels of $\mathbb{F}_1$ and $\mathbb{F}_2$. However in the next time slot, MT_1 may be served by other subchannels belong to $\mathbb{F}_2$ and $\mathbb{F}_3$. Since the wireless channel is time-variant, the appropriate subchannels are assigned to MT_1 according to the instantaneous channel power gain. So do MT_2 and MT_3. Thus, all MTs are assigned better subchannels and hence higher data rate can be obtained.

Let P_{SA}, $P_{k,m}(n)$, and $G_{k,m}(n)$ denote the total transmission power of each SA, the transmit power and channel power gain of subchannel n from SA_k to the serving MT_m, respectively. Thus the Signal-to-Noise and Interference Ratio (SINR) at the receiver of user m on subcarrier n can be written as

$$SINR_{k,m}(n) = \frac{P_{k,m}(n)G_{k,m}(n)}{\sum_{i=1}^{I} P_{i,m}(n)G_{i,m}(n) + N_0 B}, \tag{1}$$

where I is the number of interfering SA, $G_{i,m}(n)$ is the channel power gain of subchannel n from the ith interfering SA to user m, N_0 is the noise power spectral density which is assumed to be same for all subcarriers and users, and B is bandwidth of each subcarrier, respectively. Thus the transmission rate of subchannel n from the kth SA to user m is

$$R_{k,m}(n) = B \log_2 \left(1 + SINR_{k,m}(n)\right). \tag{2}$$

Consequently, the sum transmission rate from SA_k to user m can be written as

$$R_{k,m} = \sum_{n=1}^{N} \rho_{k,m}(n) R_{k,m}(n), \tag{3}$$

where N is the total number of subchannels available to SA_k and $\rho_{k,m}(n) \in \{0, 1\}$ is an indicator which denotes whether or not subcarrier n is used by user m. If subchannel n of SA_k is used by user m, then $\rho_{k,m}(n) = 1$. Otherwise, $\rho_{k,m}(n) = 0$. Suppose that there are M users in a virtual cell, the total throughput of one virtual cell can be given by

$$R = \sum_{k=1}^{3} \sum_{m=1}^{M} R_{k,m}. \tag{4}$$

The objective of multi-cell cooperation is to maximize the sum-rate of all cell-edge users, in other words, maximize the total throughput of all SAs of a cooperation group, under the constraints of distributed total transmission power and subchannel occupation. Hence, the optimization problem can be formulated as

$$\max_{\rho,P} R, \tag{5}$$

subject to

$$C1 : \sum_{m=1}^{M} \sum_{n=1}^{N} P_{k,m}(n) \leqslant P_{SA_k}, \tag{6}$$

$$P_{k,m}(n) \geq 0, \text{for all } k, m, n,$$

$$C2 : \sum_{k=1}^{3} \sum_{m=1}^{M} \rho_{k,m}(n) = 1, \forall n,$$

$$C3 : \sum_{k=1}^{3} \sum_{n=1}^{N} \rho_{k,m}(n) \leqslant N_m, \forall m,$$

$$\rho_{k,m}(n) \in \{0, 1\}, \text{for all } k, m, \text{ and } n.$$

Constraint $C1$ indicates that the transmission power of each SA is limited to be P_{SA}, $C2$ denotes that each subchannel can only be occupied by at most one users, and $C3$ indicates that the total number of subchannels occupied by user m is not greater than N_m. Extremely, each user can get equal number of subchannels when $N_m = N/M$ is integer.

In order to obtain the optimal solution to (5), subchannel and power allocation among multiple cells should be considered jointly. It is a nonlinear programming problem which is very hard to solve. A suboptimal but very efficient algorithm is proposed in the following.

3.2 Suboptimal Solution

Suppose that BSC knows the instantaneous channel state information of all subchannels, the proposed multi-cell cooperation scheme can be implemented in two steps, namely, subchannel allocation in single cell and power allocation among multiple cells. Subchannel allocation procedure can be described briefly in the following steps

- *Step1. Initialization: set $R_{k,m}(n)$ to be 0, for all m, k, and n.*
- *Step2. For each subchannel of every SA, calculate the SINR of all users according to (1) under the assumption of equal power allocation among all subchannels.*
- *Step3. The BSC selects the users with the highest SINRs, and determine the combination of SAs and MTs.*
- *Step4. Set the channel power gain of the selected subchannels to be zero, which denotes that these subchannels have been used.*
- *Step5. Count the number of subchannels occupied by each user. If user m has gotten N_m subchannels, stop assign subchannels to it. Otherwise, go to step 1.*

Based on the determined subchannel allocation in single cell, the power distribution among multiple cells can be performed to further enhance the cell capacity. One generally used method is the noncooperative game [13].

4. Numerical Results and Discussion

In this section, simulation results are presented to demonstrate the performance of the proposed cell cooperation scheme. We use a 7-cell simulation model in which the center cell acts as the objective cell and the other 6 surrounding cells act as interfering sources. Each cell has three sector and users are randomly located near the cell edge. The optimal radius of interior cell region is equal to 2/3 of the cell radius and so the cell edge is the annular region with width of 1/3 cell radius. The channel power gain of each subchannel is given as the product of path loss, shadowing and fast fading component. Simulations' parameters are listed in the following:

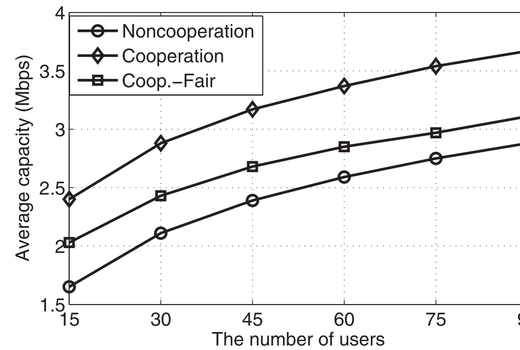

Fig. 2 Sum capacity vs. the number of users.

- The radius of each cell is 1 km.
- The total bandwidth for each sector is 1 MHz and the available subchannels of each SA is 64. Hence, the bandwidth of each subchannel is 15.625 kHz.
- The path-loss is modeled as a modified Hata Urban propagation model $PL = 38.4 + 35.0 * \log_{10}(d)$, in dB, where d (in meters) is the distance between transmitter and receiver.
- The shadowing component follows lognormal distribution with a mean value of 0 dB and a standard deviation of 7 dB.
- The fast fading component is modeled as a 6-path Rayleigh fading model.
- The noise power spectral density is -174 dBm/Hz.
- The total transmit power of each SA is 1 W and the fairness constraint, i.e., the number of subchannels allocated to the mth MT is $N_m = \lceil N/M \rceil$.

All the experiment results are averaged over 10000 independent trials.

Figure 2 compares the throughput of different transmission schemes according to variable number of users. It can be found that the proposed cooperation scheme without and with fairness constraint, i.e., Cooperation and Coop.-Fair, increasingly outperforms the Noncooperation method with the increase of the number of users. This improvement in throughput comes from multiuser diversity gain. Suppose that there are M_1, M_2, and M_3 users associate with SA_1, SA_2, and SA_3, respectively. For Noncooperation scheme, SA_1, SA_2, and SA_3 separately transmit to three set of users. Thus the total transmission rate is $R_{M_1} + R_{M_2} + R_{M_3}$. However for cooperation scheme, each SA can transmit to any of the $M_1 + M_2 + M_3$ users according to the instantaneous SINRs at the receivers. Hence the number of effective users for each SA is increased. Consequently, the transmission rate of cooperation scheme is $R_{M_1+M_2+M_3} + R_{M_1+M_2+M_3} + R_{M_1+M_2+M_3}$. As indicated in [11], cooperation scheme enhances multiuser diversity gain by virtually increasing the effective number

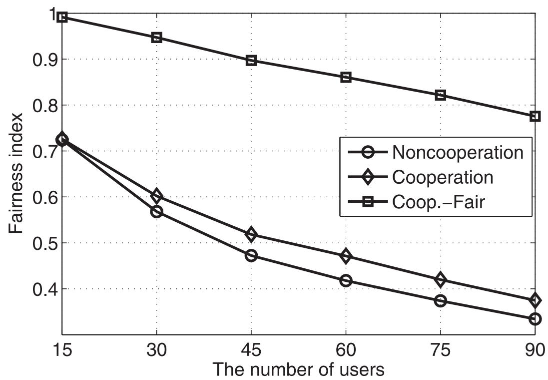

Fig. 3 Fairness index vs. the number of users.

of users for each SA.

Figure 3 illustrates the fairness comparison of different transmission schemes. There are several fairness metrics which are used to measure wether users are receiving a fair share of system resource. In this letter, Jain's fairness index [14] is used to identify the fairness of different schemes. The Jain's fairness index is defined as

$$F = \frac{\left(\sum_{m=1}^{M} N_m\right)^2}{M \sum_{m=1}^{M} N_m^2}, \tag{7}$$

where M is the number of MTs and N_m is the number of subchannels allocated to MT m. It can be found from Fig. 3 that the proposed Coop.-Fair scheme outperforms both Noncooperation and cooperation schemes without fairness constraint in terms of Jain's fairness.

5. Conclusion

In this letter, a multi-cell cooperation scheme has been proposed to maximize the sum-rate of cell-edge users in downlink OFDMA cellular systems. Based on fractional frequency reuse, a virtual cell is constructed and resource are allocated cooperatively to users located in the virtual cell. Through the cooperation among multiple BSs, the cell capacity can be improved greatly. Moreover, the fairness constraint is also considered to enhance the fairness of subchannel occupation in this letter.

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