Uplink Coordinated Scheduling Based on Resource Sorting

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***Abstract*—Uplink Inter-Cell Interference (ICI) and interference fluctuation degrades the uplink throughput of LTE/LTE-Advanced systems seriously. To deal with these problems, a coordinated scheduling method with resource sorting is proposed. In the proposed method, the uplink interference fluctuation is resisted by exploiting resource sorting and limiting the ICI generated by a given user to a predefined range. Meanwhile, the resources are allocated by differentiating the users' ability to bear the interference. Simulation results show that the proposed method outperforms traditional ICIC schemes, such as Fractional Frequency Reuse, fractional Transmit Power Control (TPC), and overload indicator based TPC.**

I. Introduction

Single Carrier Frequency Division Multiple Access (SC-FDMA) is a modified form of Orthogonal FDMA (OFDMA), which has been adopted as uplink multiple access method by Long Term Evolution (LTE) system [1]. Besides the ability to reduce the Peak-to-Average Power Ratio (PAPR) of OFDM signals, SC-FDMA can also eliminate intra-cell interference for users in the same cell. However, SC-FDMA is as sensitive to Inter-Cell Interference (ICI) as OFDMA, so the ICI leads the cell-edge users' throughput to be seriously degraded.

Moreover, since the uplink interference comes from the users whose position is unfixed, and the interfering user assigned on a given Physical Resource Block (PRB) may vary at each scheduling period for each cell, the uplink interference across the transmission bandwidth is fluctuant, and changes dynamically along with the time. The unwanted interference fluctuation affects the efficiency of channel-based Radio Resource Management (RRM), such as Adaptive Modulation and Coding (AMC) and channel-based scheduling, and so on. For example, suppose AMC selects the Modulation and Coding Scheme (MCS) for each user according to the estimated Signal to Interference plus Noise Ratio (SINR) at previous scheduling period, the raise of actual ICI will increase the error probability of the data transmission.

Theoretically, the uplink ICI and interference fluctuation can be tackled by global optimal scheduling over the entire network. Whereas, it is impractical to exchange the Channel State Information (CSI) of all users via backhaul links with limited capacity and large latency. Therefore, suboptimal ICI mitigation techniques, which make scheduling decisions by one cell or cell cluster independently, are being investigated by different standardization bodies and forums that are focusing on forthcoming cellular systems [2-3].

Among various ICI mitigation methods, ICI Coordination (ICIC) is considered as an effective method to deal with ICI at present. Generally, the ICIC methods for LTE uplink systems can be categorized into two kinds, which are resource rearrangement and power control [4]. A typical method of resource rearrangement is Fractional Frequency Reuse (FFR) [5], which is based on the concept of mitigating the ICI by utilizing non-overlapping resource at cell-edge areas. Different from resource rearrangement, fractional Transmit Power Control (TPC) mitigates the ICI by limiting the transmit power of users at different areas [6]. However, these traditional ICIC schemes can merely mitigate ICI without considering the uplink interference fluctuation [7-9].

In order to inform the variation of ICI dynamically, TPC based on Overload Indicator (OI) is adopted in LTE [10]. However, since OI-based TPC intends to reduce the transmit power of users at cell-edge area which usually causes high ICI, the cell-edge throughput is apt to be reduced unexpectedly. Coordinated scheduling (CS) is proposed in LTE-Advanced to improve the cell-edge throughput further [11]. With CS, scheduling decisions are made with coordination among multiple cells. In [12], multi-cell coordinated scheduling method based on multiple levels of OI threshold was proposed. In [13], three methods based on FFR were utilized to reduce the uplink interference fluctuation. However, non-overlapping frequency allocation is used at cell-edge areas, and the cell spectrum efficiency of all mentioned above are low.

In this paper, an uplink coordinated scheduling method named as Uplink Coordinated Scheduling Based on Resource Sorting (UCSRS), is proposed to deal with the ICI and interference fluctuation simultaneously. In UCSRS, resource sorting and ordered scheduling are used to keep the ICI suffered by the users stable. Meanwhile, the range of interference fluctuation in adjacent cells is weakened by limiting the ICI generated by a given user. Furthermore, the difference of users' ability to bear the interference is utilized to prevent the SINR on some PRBs from being too low to provide service. Therefore, the effects of ICI and interference fluctuation can be weakened

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effectively by UCSRS.

The remainder of this paper is organized as follows. Firstly, the system model and interference analysis are given in section II. In section III, the introduction of resource sorting is followed by the coordinated scheduling method UCSRS. System level simulation and analysis are given in section IV. And section V concludes the paper.

II. System Model and Interference Analysis

In this section, system model is introduced at first. And then, the characteristics of uplink ICI and interference fluctuation are analyzed.

A. System Model

In this subsection, we consider the uplink system consisting of M users in each cell. The minimum scheduling unit is PRB, which is adopted in LTE. The total available bandwidth can be divided into S PRBs, and one PRB can only be assigned to a single user. To determine the optimal pair of user and PRB for each cell, the problem of system level utility maximization can be formulated as [14],

$$\max \sum_i \sum_{m=1}^{M} U_{i,m}(R_{i,m}); \quad R_{i,m} = \sum_{s=1}^{S} r_{i,m,s}\beta_{i,m,s}$$
$$\beta_{i,m,s} = \begin{cases} 0, \; if\ PRB \text{ s } is\ not\ allocated\ to\ user \text{ m} \\ 1, \; if\ PRB \text{ s } is\ allocated\ to\ user \text{ m} \end{cases} \tag{1}$$

where $U_{i,m}(R_{i,m})$is the utility function defined as an increasing function of user's achievable data rate $R_{i,m}$. Note that some classical scheduling methods, such as Proportional Fair (PF), Round Robin (RR) and so on, can be implemented by using specific utility function U [15]. $R_{i,m}$ is achievable data rate of user m in cell i, and $r_{i,m,s}$ is the achievable data rate on PRB s seen by user m in cell i. Generally, $r_{i,m,s}$ can be denoted as,

$$r_{i,m,s} = f\left(\log_2\left(1 + \frac{1.5}{-\ln(5BER)} SINR_{i,m,s}\right)\right) \tag{2}$$

Where $f(\bullet)$ is determined by the selected MCS for the user. BER is the target bit-error rate. Moreover, the $SINR_{i,m,s}$ on PRB s seen by user m in cell i can be expressed as,

$$SINR_{i,m,s} = \frac{P_{i,m,s}H_{i,m,s}}{\sum_{i\neq j} P_{j,\bar{m},s}H_{i,\bar{m},s} + N_{i,m,s}} \tag{3}$$

where $H_{i,m,s}$ is the path gain between user m and BS of cell i on PRB s. The parameter H includes the effects of distance-based path loss, shadowing, fading, and antenna gains. $N_{i,m,s}$ is the thermal noise power. $P_{i,m,s}$ is the transmit power of user m served by cell i on PRB s. Moreover, the users' transmit power on each PRB is assumed to be equivalent, and can be determined by the method of open-loop fractional TPC, which is shown as [6],

$$P_{i,m} = \min\{P_{max}(m), 10\log_{10}(L_{i,m}) + P_0 + \alpha PL_{i,m}\} \tag{4}$$

In (4), $P_{i,m}$ is the total transmit power of user on all allocated PRBs. $L_{i,m}$ is the number of PRBs that can be used by user m. $PL_{i,m}$ is the average path loss expressed in dB. α is a cell specific path loss compensation factor, and the range of α is $0 \leq \alpha \leq 1$. When $\alpha = 1$, the path loss of a user is fully compensated. P_0 is a cell-specific or user-specific parameter, it is calculated to guarantee that the target SINR can be achieved with the maximum transmit power P_{max}.

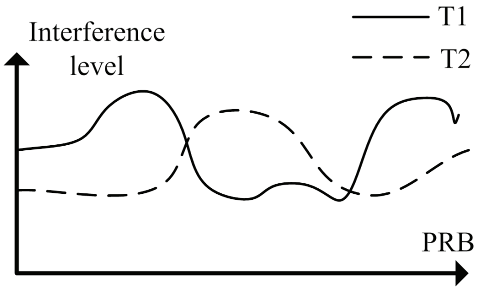

Fig. 1. Interference fluctuation

According to (2)-(4), every user's achievable data rate is affected by the transmit power of other users and scheduling decisions of other cells. In order to solve the problem formulated in (1), global optimal scheduling over the entire network is needed to maximize the system level utility function. However, since the backhaul links between different BSs have limited capacity and large latency, global optimal scheduling is impractical to be implemented in realistic network. Therefore, the scheduling needs to be executed by one cell or cell cluster independently to obtain a suboptimal solution. However, the independent scheduling causes uplink interference fluctuation that decreases the efficiency of AMC and channel-based scheduling.

B. Analysis of Uplink Interference Fluctuation

In uplink, the interference sources are users of adjacent cells. According to (3), the level of interference on a PRB mainly depends on the transmit power of interfering users and the path gain between interfering users and the BS of interfered cells. Moreover, a specific PRB may be allocated to different users at different Transmit Time Interval (TTI). Therefore, the user's transmit power on a PRB may be changed, and the interference is prone to be fluctuant at each TTI. As is shown in Fig.1, T1 and T2 are two TTIs, and there is obvious discrepancy in the interference level.

Unfortunately, the Modulation and Coding Scheme (MCS) for a user is determined based on the estimated SINR, so it is difficult to select the exact MCS for each TTI. For example, the estimated ICI at T1 is assumed with I_1, and the MCS selected according to I_1 for a given user is MCS5. However, the actual ICI level at T2 is I_2, and $I_2 > I_1$. If the given user uses MCS5 to transmit data at T2, the effective throughput will be decreased. Therefore, the merits of Adaptive Modulation and Coding (AMC) can't be achieved, and the efficiency of channel-based scheduling is limited.

III. Uplink Coordinated Scheduling Based on Resource Sorting

In this section, resource sorting is introduced to deal with the interference fluctuation at first. Based on resource sorting, UCSRS is shown to mitigate the negative effects of uplink ICI and interference fluctuation effectively.

A. Resource Sorting

Since a user mainly interferes with two cells which are adjacent to its serving cell, three adjacent cells are grouped into a cluster. And then, the available resources are divided into three PRB groups which are listed as,

$$PRB_{all} = \{PG_1, PG_2, PG_3\} \tag{5}$$

where PRB_{all} is all the available resource for a cell, and the first PRB group is denoted as PG_1. Furthermore, the process of scheduling for each cell is divided into three phases, which is shown in Fig.2. In each phase, one of the PRB groups for each cell is re-scheduled, and the users served on the other PRB groups are kept unchanged. Moreover, the PRB groups needed to be re-scheduled for adjacent cells in each phase are orthogonal, so the interference suffered by users on PRBs that will be re-scheduled is kept stable. As is shown in Fig.2, cell 1, cell 2 and cell 3 are assumed to be adjacent cells. The PRB group PG_1 for cell 1 is re-scheduled in phase 1, while the users served on PG_2 and PG_3 for cell 1 are kept unchanged in the phase. In addition, the users served on PG_1 for cell 2 and cell 3 are all kept unchanged, so the interference suffered by users on PG_1 for cell 1 is stable.

As is shown in phase1 of Fig.2, although the resource sorting can keep the interference suffered by users on PG_1 for cell 1 stable, it cannot guarantee the interference suffered by users on PG_1 for cell 2 or 3 stable simultaneously. Suppose the transmit power of users that will be allocated on PRB s for cell 1 is $P_{i,m,s}$, and the Interference suffered by users on PRB s for cell 2 or 3 are denoted as I_1 and I_2 respectively. In order to weaken the interference fluctuation on PRB s for cell 2 or 3, $P_{i,m,s}$ should satisfy the constraint as,

$$(1-\rho)I_{ave} \leq P_{i,m,s}H_{j,m,s} \leq (1+\rho)I_{ave} \tag{6}$$

where $I_{ave} = (I_1+I_2)/2$. $\rho(0 \leq \rho \leq 1)$ is the fluctuation factor. When the interference fluctuation is resisted by exploiting resource sorting and limiting the ICI generated by a given user to a predefined range, the scheduling decisions of a cell make little effects on the achievable data rate of users in other cells. Thus, a sub-optimal solution can be used to solve the problem formulated in (1) by maximizing single cell aggregated utility function expressed as,

$$\begin{aligned} &\max \sum_{m=1}^{M} U_{i,m}(R_{i,m}); \quad R_{i,m} = \sum_{s=1}^{S} r_{i,m,s}\beta_{i,m,s} \\ &\beta_{i,m,s} = \begin{cases} 0, \ if\ PRB \text{ s } is\ not\ allocated\ to\ user \text{ m} \\ 1, \ if\ PRB \text{ s } is\ allocated\ to\ user \text{ m} \end{cases} \end{aligned} \tag{7}$$

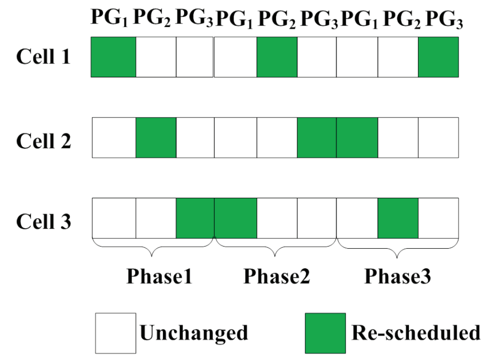

Fig. 2. Resource sorting of adjacent cells

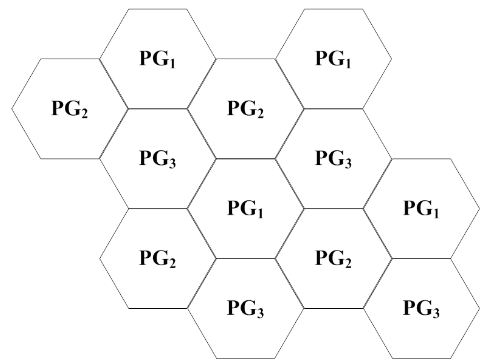

Fig. 3. Example of resource assignment in a single phase

B. UCSRS

Besides the interference fluctuation, the ICI level is also an important factor needed to be considered. Suppose the target SINR of two users are the same, and the first user is closer to the serving BS. Because the transmit power of the first user used to compensate the path loss is lower than that of the second user, then the remaining power of the first user can be used to resist more interference from adjacent cells. Therefore, in order to prevent the SINR of some PRBs from being too low to provide service, the user sets correspond to a given PRB need to be selected before scheduling. For example, the PRBs with high ICI ought to be allocated to cell-center users.

Assume the corresponding user set for PRB s is $\Omega_{i,s}$, the optimal user ought to be allocated on the PRB s is expressed as [14],

$$\begin{aligned} &(i,m,s) = arg \max_{m\in\Omega_{i,s}} (Q_{i,m,s}) \\ &Q_{i,m,s} = r_{i,m,s}\frac{\partial U_{i,m,s}}{\partial r_{i,m,s}} \end{aligned} \tag{8}$$

where (i,m,s) denotes the PRB s allocated to user m in cell i.

On basis of the above analysis, a coordinated scheduling method, named as UCSRS is shown to weaken the effects of ICI and interference fluctuation simultaneously. The detailed process of UCSRS is shown as below,

1 Initialization

1) All cells in the network are partitioned into multiple cell clusters, and each cluster is composed of three adjacent cells.
2) Users in each cell are partitioned into two user sets, which are cell-center user set CCU_i and cell-edge user set CEU_i respectively. The sum of cell-center and cell-edge users can be denoted as $User\_all_i$.
3) Set the Interference over Thermal (IoT) threshold as IoT_{thresh} to differentiate the users' ability to bear the interference.
4) According to the principles in Fig.2, divide the available resource of a cell into three PRB groups, and the process of scheduling is partitioned into three phases. An example of resource assignment for adjacent cells in a single phase is shown in Fig.3.

2 Coordinated scheduling

1) According to pre-defined ordering of scheduling in Fig.2, obtain the available PRB group for each cell in a single phase.
2) For each PRB s of cell i in each phase, measure the IoT on the PRB, and the value of IoT is expressed as $IoT_{i,s}$.
3) If $IoT_{i,s} > IoT_{thresh}$, the candidate user set for the PRB is CCU_i; Else, the candidate user set is $User\_all_i$.
4) For each user m in the candidate user set, calculate the transmit power $P_{i,m,s}$ on the PRB s according to (4).
5) If $P_{i,m,s}$ cannot satisfy the constraint in (6), delete the user m from the candidate user set.
6) Calculate $Q_{i,m,s}$ for each user in the candidate user set, and allocate the PRB s to the user m according to (8).
7) Repeat the process of 2) - 6) until all of PRBs are allocated.

In the process of UCSRS, the interference fluctuation is weakened by resource sorting and limiting the ICI to a pre-defined range expressed in (6). Thus, and the accuracy of AMC can be achieved and the efficiency of channel-based scheduling can be improved. Furthermore, the PRBs with high ICI are allocated to the cell-center users. Therefore, the average SINR of users can be increased, and the cell spectrum efficiency can be improved.

IV. Simulation Results

System level simulation is used to evaluate the performance of the UCSRS. The major system level simulation parameters are listed in Table.1 [11].

The reference schemes are FFR, fractional TPC, and OI based TPC. For fractional TPC, open-loop power control is adopted, the path loss compensation factor is set to 0.6, and the cell-specific parameter P_0 is assumed as -60. The fluctuation factor ρ for UCSRS is 0.1. In addition, the Cumulated Distribution Function (CDF) curves of user throughput, 5% CDF of user throughput and average user throughput are adopted to compare the performance of different ICIC schemes.

As is shown in Fig.4, the CDF curves of user throughput with different ICIC methods are given. For any value of user throughput, the corresponding CDF of UCSRS is less than that of other methods, especially when the user throughput is below 0.1Mbps. For example, nearly 80% users' throughput is less than 0.1Mbps with FFR or fractional TPC. While for UCSRS, only 20% users' throughput is less than 0.1Mbps. This is mainly because the UCSRS allocates the PRBs that suffer high ICI to the cell-center users, and the SINR of each user will not be too low to provide service.

The comparison of 5% CDF of user throughput, which is also seen as cell-edge user throughput is shown in Fig.5. It can be seen that the cell-edge user throughput of FFR is greater than that of fractional TPC and OI based TPC, since the FFR assigns non-overlapping resource to cell-edge areas of adjacent cells. Moreover, compared with the FFR, UCSRS improved the cell-edge user throughput about 55%. This is mainly because UCSRS is apt to allocate the PRBs that suffer low interference to the cell-edge users, and it can weaken the

TABLE I
SIMULATION PARAMETERS

Parameters	Values
Cellular layout	Hexagonal grid , 57 cells / 19 sites
Carrier frequency	2GHz
System bandwidth	10MHz
Number of PRBs	50
Antenna pattern	Tri-sector antenna
Inter-site distance	1732m
Maximum power at UE	24dBm
Path loss	128.1+37.6log10(d)(dB), d in km
Shadowing factor variance	8dB
Correlation of distance	50m
Fading channel	Extended Typical Urban (ETU)
UE distribution	Union random distribution
IoT threshold	10dB
Traffic Model	Full Buffer
Scheduling scheme	RR
Thermal Noise	-174dBm/Hz

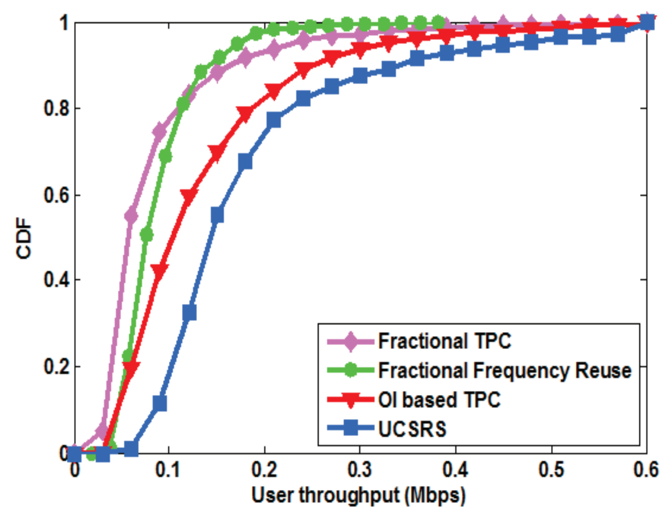

Fig. 4. CDF of user throughput

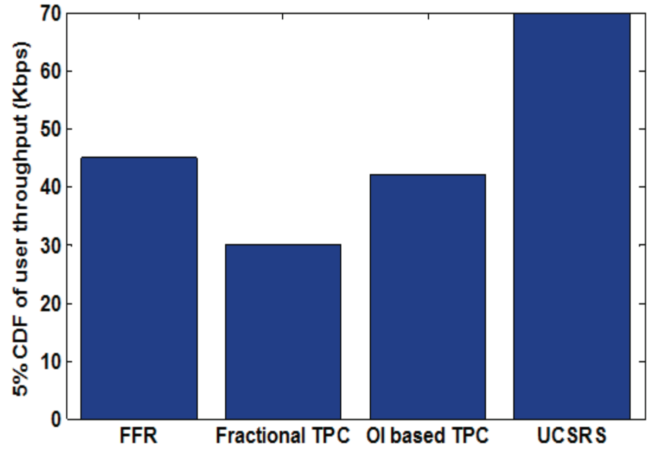

Fig. 5. Comparison of 5% CDF of user throughput

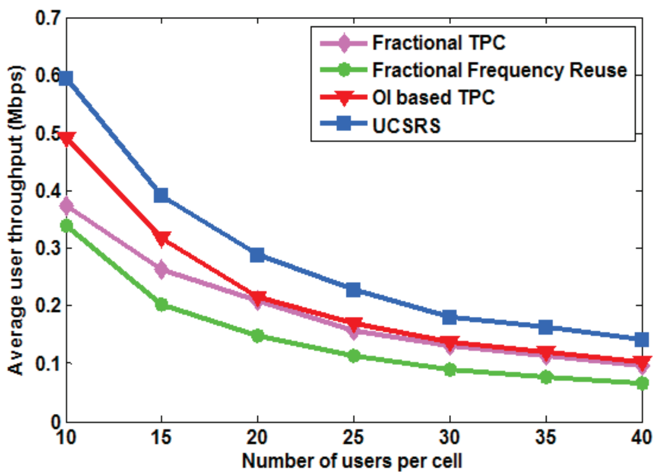

Fig. 6. Average user throughput Vs number of users per cell

interference fluctuation to improve the efficiency of AMC and channel-based scheduling.

Fig.6 shows the average user throughput with different number of users per cell. When the number of users per cell increases, the number of PRBs that can be allocated to a single user decreases, so that the average user throughput is decreasing along with the increment of users per cell, as is shown in Fig.6. In addition, the average user throughput of UCSRS is greater than that of the reference ICIC methods. For example, when there are 25 users per cell, the average user throughput of UCSRS is about 0.28Mbps, while the values for FFR, fractional TPC and OI based TPC are 0.15Mbps, 0.19 Mbps and 0.2Mbps respectively. These results demonstrate that the spectrum efficiency can be increased further by weakening the uplink interference fluctuation.

Furthermore, the scheduling decisions are made by each cell independently with the pre-defined cell cluster and scheduling order, so UCSRS only needs to exchange the ICI level on each PRB among multiple cells. Therefore, UCSRS is easy to be implemented in realistic network.

V. Conclusion

In this paper, Uplink Coordinated Scheduling based on Resource Sorting (UCSRS) is proposed to deal with the ICI and interference fluctuation, which seriously degrade the spectrum efficiency in uplink systems. In UCSRS, interference fluctuation is weakened by resource sorting and limiting the ICI according to the fluctuation factor ρ. Moreover, the effects of ICI are mitigated by allocating the PRBs that suffer high interference to cell-center users, so the average SINR of users can be effectively improved. Simulation results demonstrate that UCSRS significantly outperforms FFR, fractional TPC and OI based TPC in terms of cell-edge user throughput and average user throughput.

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