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CoSFR: coordinated soft frequency reuse for OFDMA-based multi-cell networks with non-uniform user distribution

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Abstract Inter-cell interference coordination (ICIC) technology has been extensively studied to improve service quality of users near cell boundaries. Most ICIC schemes available make an assumption that users in the same cell are distributed uniformly. This is reasonable but incomplete. Mobility may result in users distributed non-uniformly, so this paper proposes a novel semi-static ICIC scheme, coordinated soft frequency reuse (CoSFR), for multi-cell networks with non-uniform user distribution. A finer cell partition structure with a tunable parameter r is proposed. With this structure, dedicated user classification rules and opportunistic scheduling strategies are designed for different cells. Assisted by a simple but efficient coordination scheme, a cell with overloaded cell-edge traffic, named aggressor cell, calls adjacent neighboring cells for help. Some reuse opportunities can be created after coordination and the aggressor cell can expand its cell-edge band to alleviate the overloaded state. No additional entity is required for being compatible with the flat network structure of LTE/LTE-Advanced. In addition, CoSFR can deal with the scenario that more than one cell suffering overloaded cell-edge traffic and it can also be applied to irregular cells with minimal modifications. Simulation results show that more than 97.4 % users are satisfied with their data rate. Average cell-edge user throughput is raised substantially and the outage probability declines significantly.

1 Introduction

High in flexibility and reliability, orthogonal frequency-division multiplex access (OFDMA) has been increasingly developed and deployed in a lot of mobile communication systems [1], such as the 3rd generation partnership project long term evolution (3GPP-LTE) [2], LTE-Advanced [3], and worldwide interoperability for microwave access (WiMAX) [4]. As universal frequency reuse is the pursuit of academia and industry, there is intense inter-cell interference (a.k.a. co-channel interference among different cells) in OFDMA-based multi-cell networks. It is a serious challenge and severely degrades the system performance, particularly users around boundaries of cells.

Frequency reuse-based interference avoidance has been identified as an effective and efficient inter-cell interference coordination (ICIC) solution [5]. It intends to improve the performance of users near cell borders while bring minimum loss of system performance. After several frequency reuse schemes are proposed by Huawei [6], Ericsson [7], Siemens [8], etc., ICIC has been studied extensively. A comprehensive survey on ICIC schemes in the downlink of OFDMA-based cellular networks can be found in [9]. ICIC schemes are categorized into two groups, static frequency reuse-based ones and dynamic cell coordination-based ones, by a new parameterized classification method. However, most ICIC solutions available make an assumption that users follow the uniform distribution which is reasonable but incomplete for practicality. User mobility will result in that users are distributed non-

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uniformly, so adaptive ICIC schemes are indispensable. Basic adaptivity has been mentioned when soft frequency reuse (SFR) is proposed in [6], while it is not enough. If users are populated near cell borders, the requirement of cell-edge user group may exceed the capacity of the major band and the system performance will be impaired. Therefore, more request for the adaptivity is brought forward to smooth away the problem.

Some literatures available have taken non-uniform user distribution into consideration. Researches in [10–13] claim two-level architectures to solve the adaptive resource allocation problem in such a multi-cell network. However, all of them need an additional higher level node to build an interference graph or to make coarse resource allocation decisions. The performance of low-complexity random beamforming transmission with user scheduling is analyzed in [14]. Authors show that the proposed scheme can achieve tremendous performance gain with a small amount of signaling overhead, especially when most users are near the cell boundary. Nonetheless, only dual-cell scenario is considered and the base station must have multiple antennas. An adaptive SFR scheme is proposed in [15] that two virtual users are introduced to represent user groups. The data rate requirements of virtual users are those of the sum of users in that group. This scheme can face up to uneven user distribution, while it still has two shortcomings: the virtual users are assumed at the worst-case position that it is too conservative; Although different cells may obtain varying amounts of resource, it keeps the restriction of standard SFR that major bands of adjacent cells must be orthogonal. Load distribution aware soft frequency reuse (LDA-SFR) [16] is an enhancement of the adaptive SFR scheme in [17], whereas it can only cope with slightly overloaded cell-edge traffic. LDA-SFR randomly assigns reusable subchannels to users and this is a waste of multi-user diversity gain. Another semi-dynamic ICIC scheme based on user grouping is presented in [18]. A cell is covered by three directional antennas and users are classified into several groups based on the handover information. Subchannel lists are kept for each group by static allocation and dynamic borrowing or leasing. A great deal of information exchanges are required for getting a leasing or returning agreement. Therefore, these schemes are not suitable to the OFDMA-based multi-cell networks with non-uniform user distribution.

In this paper, we propose a distributed semi-static ICIC scheme named coordinated soft frequency reuse (CoSFR) to solve the resource allocation problem when users are distributed non-uniformly, especially the majority of users are near cell borders. It inherits the conciseness and efficiency of standard SFR but also adopts some enhancements to cope with non-uniform user distribution. CoSFR permits cell-edge region of adjacent cells to reuse resources when

some cells suffer overloaded cell-edge traffic. This means the fundamental constraint of standard SFR that cells next to each other must keep their cell-edge bands orthogonal is relaxed. The contributions of this paper are summarized as follows:

- We propose a finer cell partition structure with a tunable parameter r. Inspired by the interference mitigation scheme for femtocell networks presented in [19] where some resource isolation users can be shifted to a transition zone, we find out that the cell-edge region can be further divided into vertex region and line region according to the interference environment.

- Different user classification rules and scheduling strategies are designed for cells with distinct traffic states. The details are described in Sect. 3. No matter which scheduler is selected, the base station will try to maximize the total throughput by opportunistic scheduling after users' minimum data rate requirements are guaranteed. If multiple antennas are installed at both transceivers and receivers, opportunistic scheduling may be combined with another promising technology for interference management, namely interference alignment [20].

- A simple but efficient coordination mechanism is proposed. With this coordination mechanism, some reuse opportunities can be created. It requires only little information exchange among cells and no extra entity is added. So CoSFR is compatible with the flat network structure of LTE/LTE-Advanced and it can be readily used in current practical systems.

- CoSFR can be easily applied to more than one cell suffering from overloaded cell-edge traffic. We also provide the way expanding CoSFR to cells with irregular shape with minor modifications.

The remainder of this paper is organized as follows. In Sect. 2, the multi-cell system model under consideration is described. A rate adaptive problem is formulated while it is NP-hard. Some special necessary definitions are given at the beginning of Sect. 3. We present the proposed CoSFR scheme in detail and a simple example is illustrated to demonstrate the necessity of CoSFR. Numerical simulation results and some discussions are shown in Sect. 4. Next, Sect. 5 addresses the extension of CoSFR and analyzes the signaling overhead and computational complexity. Finally, conclusions are drawn in Sect. 6.

2 System model

The downlink of a multi-cell OFDMA-based network with non-uniform user distribution is considered. There are K hexagonal cells in the system. A base station (eNodeB in

LTE/LTE-Advanced) with an omni-directional antenna is located at the center of a cell, denoted by $k \in \mathcal{K} = \{0, 1, \ldots, K-1\}$. Poisson point process [21–23] and fluid model [24, 25] are adopted to analyze the performance of frequency reuse schemes. Nevertheless, the traditional hexagonal model, Poisson point process model, and fluid model are all simplifications of reality. It is difficult to judge which one is the best. Cells with irregular shape is another important scenario as small cells come in. ICIC in multiple cells with irregular cell shape has been considered in [26–29], but most of them ignore the previous works of frequency planning, so much more computational complexity is brought. Although we assume the cell shape being a hexagon here, CoSFR is also able to meet irregular cells with minor modifications on user classification rules which is provided in Sect. 5.

A cell partition structure similar to [30] is adopted but with a tunable parameter r. As shown in Fig. 1 where $K = 7$, the radius of the circumscribed circle of the outer hexagon is R. A cell is divided into two parts, namely cell-center region and cell-edge region. We assume the cell-center region is also a hexagon with a circumscribed circle of radius R_{in}. This aims at providing reference points to facilitate subdividing. The cell-edge region is further divided into 12 pieces. $D_1, D_2, \ldots, D_6$ form the vertex region, while $D_a, D_b, \ldots, D_f$ make up the line region. It is easy to find out that the cell structure in [30] is just the special case that $r = \frac{(R - R_{in})}{2}$. Besides, when r equals 0, it becomes the sectored cell structure with omni-directional antenna mentioned in [16].
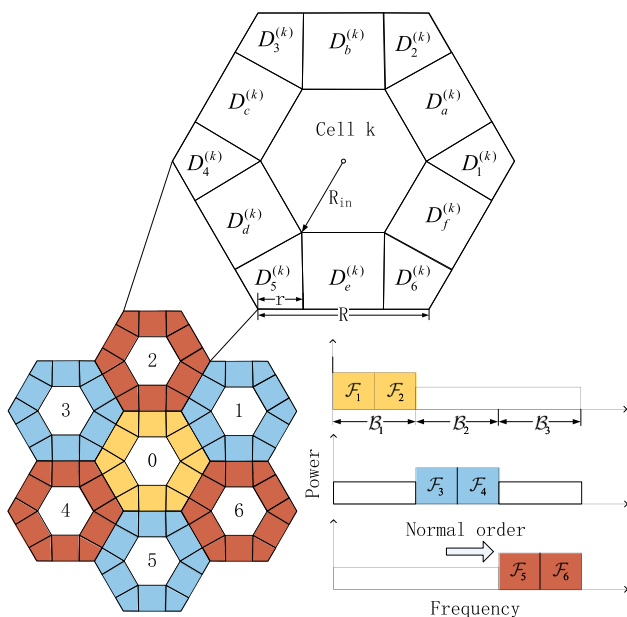
Users and frequency resources are two important compositions of the system. With a rational threshold, users are generally classified into two groups, namely cell-center user group and cell-edge user group, based on the received signal-to-interference-plus-noise ratio (SINR) or the geometrical distance to their serving base stations. Accordingly, the available resource is also partitioned. In LTE/LTE-Advanced, system band with bandwidth W is divided into several subcarriers, each of which is 15 kHz. Twelve localized or distributed subcarriers are grouped to form J subchannels, indexed by $j \in \mathcal{J}$ where $\mathcal{J} = \{1, 2, \ldots, J\}$. It means the number of available physical resource blocks (PRBs) for every cell in each slot is also J.[1] Fractional frequency reuse (FFR) and SFR are representative static ICIC schemes. The system bandwidth of FFR is divided into several non-overlapping parts, as shown in Fig. 2 where four parts for illustration. SFR trisects the system bandwidth, as depicted in Fig. 3. In a cell, the frequency band reserved for cell-edge user group is named major band, and that for cell-center user group is a minor band. Any overlapping between major bands of adjacent cells is forbidden, which is a fundamental restriction in standard SFR.

The system in this paper selects standard SFR as its ICIC scheme initially and keeps it in general. There are $N^{(k)}$ users (UE in LTE/LTE-Advanced) in cell k. Users in the same cell are classified into two groups, cell-center user group $\mathcal{N}_c$ and cell-edge user group $\mathcal{N}_e$, based on their geographical positions with a distance threshold.[2] They must satisfy $\mathcal{N} = \mathcal{N}_c \cup \mathcal{N}_e$ and $\mathcal{N}_c \cap \mathcal{N}_e = \emptyset$. Figure 1 shows system bandwidth partition, $\mathcal{B}_1 = \{1, 2, \ldots, J_1\}$, $\mathcal{B}_2 = \{J_1 + 1, J_1 + 2, \ldots, J_2\}$, and $\mathcal{B}_3 = \{J_2 + 1, J_2 + 2, \ldots, J\}$. Furthermore, a major band can be further divided into two sub-segments in CoSFR. Parameter α_i is defined as the ratio of the first sub-segment to its corresponding major band $\mathcal{B}_i$. For instance, $\mathcal{B}_3$ is bisected into $\mathcal{F}_5$ and $\mathcal{F}_6$ in Fig. 1. The value of α_3 is $|\mathcal{F}_5|/|\mathcal{B}_3|$, where $|\cdot|$ is the cardinality of set.

Let $X^{(k)}_{J \times N} = \left[x^{(k)}_{j,n} \right]$ be the scheduling matrix of cell k with

$$x^{(k)}_{j,n} = \begin{cases} 1, & \text{if cell-center user } n \text{ occupies PRB } j, \\ \beta, & \text{if cell-edge user } n \text{ occupies PRB } j, \\ 0, & \text{if PRB } j \text{ is idle,} \end{cases}$$

$$(1)$$

Fig. 1 CoSFR: coordinated soft frequency reuse

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[1] In this paper, we will use the notions subchannel and PRB interchangeably.

[2] User position information can be collected by GPS or other positioning systems. These information can be transmitted via the physical uplink control channel (PUCCH) defined in LTE.
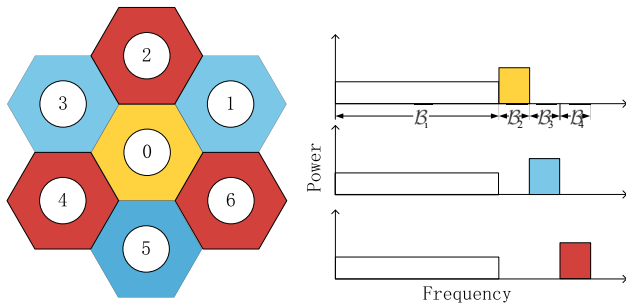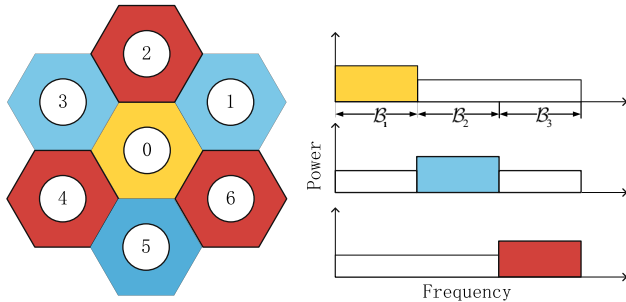
Fig. 2 FFR: fractional frequency reuse

Fig. 3 SFR: soft frequency reuse

where $\beta \geq 1$ is a tunable constant denoting the transmission power ratio between major band PRBs to minor band PRBs. Major band PRBs should be used with a relatively higher power while that of minor band PRBs is limited. The reason behind this is that cell-edge users are relatively farther from the serving base station so the propagation loss is large.

There is a debate over the necessity for fast power control in such a multi-cell system. In [31], the researchers point out that fast power control does not bring much performance improvement if adaptive modulation and coding (AMC) is adopted. While authors of [32] believe that most of ICIC schemes available ignore the importance of fast power control. In this paper, fast power control is not adopted, but transmission power in different region can be discrepant. It is in accordance with relative narrowband transmission power (RNTP) restriction adopted by the LTE/LTE-Advanced standard [33]. That restriction is utilized for eNodeBs to make promises about the resource usage of themselves in future several scheduling durations.

The instantaneous received SINR of user n in cell k using the jth PRB can be expressed as:

$$\gamma_{j,n}^{(k)} = \frac{x_{j,n}^{(k)} p_c^{(k)} g_{j,n}^{(k)}}{\sum\limits_{l \neq k, l \in \mathcal{K}} x_{j,n}^{(l)} p_c^{(l)} g_{j,n}^{(l)} + n_0 W/J}, \qquad (2)$$

where $p_c^{(l)}$ is the transmission power of a minor band PRB in cell l, and n_0 is the power spectral density of additive white Gaussian noise (AWGN). Let $g_{j,n}^{(l)}$ denote the channel

gain of PRB j from eNodeB l to user n in cell k. The wireless channels may suffer from path loss, shadow fading, and fast fading. Details about propagation characteristics of the wireless channel are discussed in [34]. However, [35] stresses that ICIC is a kind of non-frequency adaptive technology. It should work on time-scale of several hundred milliseconds and above. So we ignore short term changes in wireless channels caused by fast fading. Further, shadow fading makes it inaccurate to categorize users by their location. As a result, we can concentrate on the propagation path loss when dealing with the ICIC problem. Nevertheless, fast fading and shadow fading should be taken into consideration when PRBs are allocated in a cell to take advantage of multi-user diversity gain.

The effective data rate of user n occupying PRB j can be estimated with[3]

$$R_{j,n} = W_{PRB}\log_2(1 + \gamma_{j,n}/\Gamma), \qquad (3)$$

where $W_{PRB} = W/J$ is the bandwidth of a PRB, and $\Gamma = -\ln(5 \times \text{BER})/1.5$ is the SNR gap [36]. Note that a user may occupy more than one PRB to attain its aim. However, the error probability is usually dominated by the data streams with the lowest SINR [37]. This is beyond the scope of this paper. An indicator function is introduced:

$$y_{j,n} = \mathbf{1}(x_{j,n}) = \begin{cases} 1, & x_{j,n} \geq 1, \\ 0, & x_{j,n} = 0, \end{cases} \qquad (4)$$

so the resource allocation matrix is defined as $Y_{J \times N} = [y_{j,n}]$. The rate of user n can be expressed as

$$R_n = \sum_{j \in \mathcal{J}} y_{j,n} R_{j,n}, \qquad (5)$$

where R_n is the sum of throughput obtained by all PRBs assigned to user n. A user will be out of service if it cannot obtain enough PRBs to meet its minimum data rate requirement in time. We define the user outage probability P_{out} as the percentage of unsatisfied users.

Some literatures available concentrate on maximizing system throughput, whereas others would like to ensure fairness among users. It is worth noting the statement made in [35] that a user is unaware of resource allocation for other users so there is no notion of fairness. The main task of this work is to allocate PRBs reasonably in such a multi-cell network with non-uniform user distribution. It targets that users' demands are fulfilled meanwhile the system throughput is maximized. Mathematically, the multi-cell scheduling problem is formulated into a rate adaptive problem as follows:

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[3] Without misunderstanding, we omit the superscript k for simplicity.

$$\max_{y_{j,n}^{(k)}} \quad \sum_{k \in \mathcal{K}} \sum_{j \in \mathcal{J}} \sum_{n \in \mathcal{N}} y_{j,n}^{(k)} R_{j,n}^{(k)}, \tag{6a}$$

$$s.t. \quad R_n^{(k)} = \sum_{j \in \mathcal{J}} y_{j,n}^{(k)} R_{j,n}^{(k)} \geq R_{min}, \forall k, n, \tag{6b}$$

$$\sum_{n \in \mathcal{N}} y_{j,n}^{(k)} \leq 1, y_{j,n}^{(k)} \in \{0, 1\}, \forall k, j, \tag{6c}$$

$$\sum_{k \in \mathcal{K}_{adj}} y_{j,n}^{(k)} \leq J + \Delta J, n \in \mathcal{N}_e, \tag{6d}$$

where constraint (6b) reflects users' minimum data rate requirements.[4] Constraint (6c) ensures a PRB cannot be shared by users belong to the same cell so that intra-cell interference is avoided. Expression (6d) relaxes the orthogonality constraint of standard SFR that major bands of adjacent cells cannot overlap. $\mathcal{K}_{adj}$ is a set consisting of any 3 adjacent cells. ΔJ reflects the intention to reuse major band PRBs and the value should be set carefully. However, due to the coupling relationship among cells, it is difficult to determine the value of ΔJ. It is zero when there is no cell being cell-edge overloaded.

The multi-cell resource allocation with restrictions is essentially a three-dimensional (cell/user/PRB) assignment problem which is NP-hard [10]. The optimization problem formulated above is also a binary integer linear programming problem and the complexity to obtain the optimal solution is prohibitively high. Such a complicated problem consists of two subproblems, namely interference avoidance among multiple cells and resource allocation in a single cell. It is not difficult to find that these two subproblems corresponding to different time scales and their targets do not agree with each other usually. The first subproblem can be recognized as a large scale problem which should be tackled in long duration. Coordinate the constrained relationship with direct neighbors in order that as much as resource usage collisions between adjacent cells can be avoided. The second subproblem requires algorithms to implement frequently and every cell tends to make the best use of resource available. So we take both two subproblems into consideration and design different solutions in CoSFR scheme below.

3 Coordinated soft frequency reuse

For ease of description and understanding, some special necessary definitions used in this paper are introduced here.[5]

- *Dominant interference source*. Dominant interference source (DIS) set is recorded for every user at its serving

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[4] It deserves noting that users may have different demands.

[5] Additionally, we provide the list of used symbols in this section and onward in Table 1.

Table 1 List of symbols used

j	Index of PRBs
k	Cell index
n	User index
r	Tunable parameter for cell partition
R	Radius of circumscribed circle of outer hexagon
R_{in}	Radius of circumscribed circle of inner hexagon
J	Number of PRBs per cell
$\mathcal{B}_i$	System bandwidth partition i
$\mathcal{F}_i$	Sub-segment i divided from a partition
$\mathcal{J}_r$	Set of reusable PRBs
ΔJ	Number of reusable PRBs
K	Number of cells in the network
N	Number of users per cell
W	System bandwidth
$\mathcal{J}$	Set of PRBs available
$\mathcal{K}$	Set of cells in this multi-cell network
$\mathcal{N}$	Set of users
$\mathcal{N}_c, \mathcal{N}_e$	Set of cell-center, cell-edge users
$\mathcal{N}_s, \mathcal{N}_v$	Set of users in survivor, victim group
$\mathcal{N}_x, \mathcal{N}_l$	Set of users in vertex, line group
D	Area piece of cell-edge region
$\mathcal{T}$	Team defined in Sect. 3
$RP_l^{(k)}$	Related patch in cell k when l is the aggressor
p_c	Transmission power on a cell-center PRB
n_0	Power spectral density of AWGN
β	Trans. power ratio of cell-edge to cell-center
$\gamma_{j,n}$	SINR experienced by user n on PRB j
$x_{j,n}$	Scheduling state of PRB j to user n
$y_{j,n}$	Occupation indicator of PRB j by user n
$R_{j,n}$	Achievable rate on PRB j for user n
$g_{j,n}$	Channel gain seen by user n on PRB j
R_{min}	Minimum data rate requirement
P_{out}	User outage probability

base station. This concept is similar to the diversity set mentioned by [38] which is defined in the 802.16e standard. Yet a DIS set only contains the interference sources strong enough. We can assume a cell-edge user has at most two DISs.

- *Aggressor cell*. The cell-edge overloaded cell is regarded as an aggressor cell. The majority of resources will be allocated to its cell-edge region that it brings additional interference to neighboring cells.
- *Team*. A team is defined as the direct neighboring cells of an aggressor cell in which ones reserve the same major band. As shown in Fig. 1, cell 1, 3, and 5 form team $\mathcal{T}_1$. Likewise, cell 2, 4, and 6 make up team $\mathcal{T}_2$.
- *Vertex group* and *line group*. Cell-edge users in an aggressor cell are segregated into two groups according
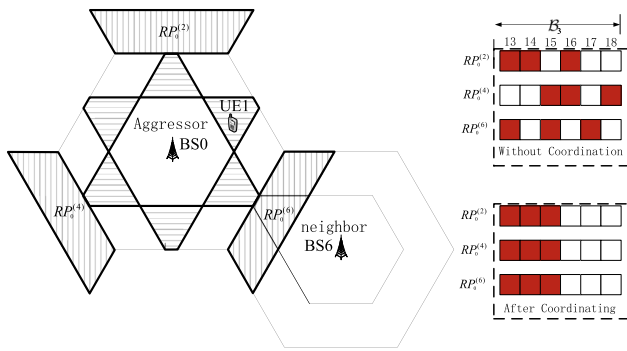
Fig. 4 A simple example showing the necessity of CoSFR

to the cardinality of their DIS sets. Users in the vertex region have 2 DISs and they make up the vertex group $\mathcal{N}_x$. Similarly, the line group $\mathcal{N}_l$ is composed by users in the line region which has only 1 DIS.

- *Survivor group* and *victim group*. Cell-edge users of a direct neighboring cell are further partitioned depending on whether the aggressor cell is one of DIS. If it is yes, then the user falls into the survivor group $\mathcal{N}_v$ because they will be protected specially, otherwise victim group $\mathcal{N}_s$.

- *Related patch*. The area that the survivor group located in is referred as the related patch. In Fig. 1, $D_4^{(1)}$, $D_5^{(1)}$, and $D_d^{(1)}$ form the related patch in cell 1, denoted by $RP_0^{(1)}$ where the subscript 0 indicates that cell 0 is the corresponding aggressor cell.

With these definitions above, we provide a simple example illustrated in Fig. 4 to demonstrate the necessity for such an ICIC scheme when users are distributed non-uniformly. BS0 plays the role of aggressor cell and the area with horizontal stripe is its line region. Suppose BS0 reserves $\mathcal{B}_1$ for its cell-edge region as Fig. 1 shown, while UE1 still desires more resources till PRBs in $\mathcal{B}_1$ have been allocated. So UE1 tries to reuse some PRBs in $\mathcal{B}_3$ reserved by team $\mathcal{T}_2$. If neighboring cells adjust their resource allocation collaboratively, some reuse opportunities can be created. As users in the survivor group need special protection, PRBs occupied by users in the related patches, namely $RP_0^{(2)}$, $RP_0^{(4)}$, and $RP_0^{(6)}$, should not be reused. These related patches are covered with vertical stripe. Therefore, the reusable PRBs list for UE1 can be expressed as:

$$\mathcal{J}_r = \mathcal{B}_3 \setminus \left\{ \varphi\left(RP_0^{(2)}\right) \bigcup \varphi\left(RP_0^{(4)}\right) \bigcup \varphi\left(RP_0^{(6)}\right) \right\}, \quad (7)$$

where $\varphi(\cdot)$ denotes PRBs occupied by users in the corresponding area. When the network operates without any coordination, the reusable PRBs list J_r is an empty set. Nevertheless, if these related patches can coordinate with each other to assign the same three PRBs to users, then we

get $J_r = \{16, 17, 18\}$ which means reuse opportunities have been created after coordinating.

A straightforward way to reach such an adjustment is that one of the cells with the heaviest related-patch traffic load notifies other cells in the same team its resource usage information. The rest cells in the same team try to adjust their PRBs allocation in accordance with the received information. Therefore, a simple but efficient CoSFR scheme with multiple intra-cell schedulers is proposed below.[6]

3.1 System initialization

The system is initialized by standard SFR and remains if there is not an aggressor cell. Every cell can allocate major band PRBs reserved for its cell-edge region to meet the minimum data rate requirements of cell-edge users. After these users satisfy their performance, the remainder of major band PRBs is available to cell-center users with a limitation on transmission power. It is just the basic adaptivity of standard SFR and this scheduling rule is then adopted by the normal intra-cell scheduler in the Sect. 4. However, the restriction of standard SFR that adjacent cells must utilize orthogonal major bands becomes a bottleneck when some cells undergo overloaded cell-edge traffic. More complex scheduling rules should be added to cope with this problem.

When a cell suffers cell-edge overloaded traffic, it would like to find opportunities to allocate its cell-edge users with the minor band and abolish the transmission power limitation on those PRBs. Namely, it becomes an aggressor cell. This cell monitors its load state and makes the decision that whether it should turn to its direct neighboring cells for help. It implies the aggressor cell is responsible for leading the coordination among cells to adjust resource allocation. The coordination process must go through two stages. Firstly, one of the two teams around is selected, and the help information is transmitted. Secondly, after reuse opportunities are provided by the selected team, the aggressor cell evaluates whether it is enough or not. If yes, the system maintains its status quo. Otherwise, the other team is also included in this coordination for additional reuse opportunities.

Let's consider an underfed cell-edge user UE1 in Fig. 4 who is located at $D_a^{(0)}$ of Fig. 1. Since cell 1 is a DIS, there are few of opportunities left if the cell-edge traffic load of cell 1 is at a high level. Furthermore, any resource allocation changes in cell 1 may affect the edge bandwidth extension of the aggressor cell. So It is reasonable to call three cells in $\mathcal{T}_2$ for help and to leave three direct

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[6] We assume there is only one aggressor cell here. The more complex scenario will be discussed later on.

neighboring cells in $\mathcal{T}_1$ alone. We attempt to solve the local problem in a single cell with help of multiple neighboring cells. Hence, involved cells are hoped as little as possible.

3.2 Resource usage coordination within a team

Once a cell receives the request from an aggressor cell for help, factorized intra-cell scheduler-A (FISA) is implemented unconditionally. In a cell with FISA, users are classified into three groups and served in the following order of priority: the survivor group $\mathcal{N}_s$, the victim group $\mathcal{N}_v$, and the cell-center group $\mathcal{N}_c$.

Users in the survivor group have the highest priority level, while the system just guarantees their minimum data rate requirements. This stems from the fact that the survivor group belongs to the cell-edge group which is relatively farther from the serving base station, so it makes a little contribution to system throughput. As depicted in Sect. 2, the major band $\mathcal{B}_i$ is further divided into two sub-segments. PRBs in the first part will be allocated to the survivor group and the best PRB-user pair is preferred. The percentage of the first sub-segment, α_i, is initialized with 0.5 and this parameter should be adjusted carefully. Since the number of PRBs is an integer, there are limited values that α_i can take. An example of FISA for cell 2 when cell 0 is the aggressor cell is described below as Algorithm 1. Lines 3–14 are resource allocation for the survivor group.

The victim group has medium priority. After all users in the survivor group are satisfied with their service quality, the remaining major band PRBs are assigned to users in the victim group. The system also prefers to the best PRB-user pair at this moment. If any cell-edge PRB is still idle after the minimum data rate requirements of users in the victim group are met, it will be supplemented to cell-center region. This process is related to line 15 of Algorithm 1.

The priority of the cell-center group is the lowest. Resource allocation for these users takes place in two phases. In the first phase, the system does its best to guarantee all cell-center users' minimum data rate requirements. In the second stage, it will maximize the system throughput by allocating PRBs to those users with the best channel quality. In Algorithm 1, line 16 and 17 describe these two phases, respectively.

When all PRBs have been assigned to users, the scheduling matrix, $X_{J \times N}$, is generated. The number of PRBs in the first sub-segment, cnt, has to be fed back to the aggressor cell. By the way, cells in a team must select the same scheduler with the purpose of creating reuse opportunities.

Algorithm 1 Factorized Intra-cell Scheduler-A

Require:

1: $\alpha_3 = 0.5, cnt = \alpha_3\,|\mathcal{B}_3|$

2: $\mathcal{N}_s = \{\text{cell-edge users in } RP_0^{(2)}\}, \mathcal{N}_v = \mathcal{N}_e \backslash \mathcal{N}_s$

Ensure:

3: $\mathcal{F}_5 = \{\text{the first } cnt \text{ PRBs in } \mathcal{B}_3\}, \mathcal{F}_6 = \mathcal{B}_3 \backslash \mathcal{F}_5$

4: **while** $\mathcal{N}_s \neq \emptyset$ **do**

5:    **if** $\mathcal{F}_5 = \emptyset$ **then**

6:       $cnt = cnt + 1$, GOTO line 4.

7:    **end if**

8:    $\{n^*, j^*\} = \arg\max_{n \in \mathcal{N}_s, j \in \mathcal{F}_5} R_{j,n}$

9:    **if** $R_{n^*} < R_{min}$ **then**

10:      $x_{j^*, n^*} = \beta, R_{n^*} = R_{n^*} + r_{j^*, n^*}, \mathcal{F}_5 = \mathcal{F}_5 \backslash \{j^*\}$

11:    **else**

12:      $\mathcal{N}_s = \mathcal{N}_s \backslash \{n^*\}$

13:    **end if**

14: **end while**

15: Actions like lines 4,8-14 above with $\mathcal{N}_s \rightarrow \mathcal{N}_v, \mathcal{F}_5 \rightarrow \mathcal{B}_3 = \{\mathcal{F}_5 \bigcup \mathcal{F}_6\}$.

16: Actions like lines 4,8-14 above with $\mathcal{N}_s \rightarrow \mathcal{N}_c, \beta \rightarrow 1, \mathcal{F}_5 \rightarrow \mathcal{B}_0 = \{\mathcal{B}_1 \bigcup \mathcal{B}_2 \bigcup \mathcal{B}_3\}$.

17: Assign the remaining PRBs in $\mathcal{B}_0$ to the cell-center users who can contribute the most to system throughput.

18: **Output** $X_{J \times N}^{(2)}, cnt$

3.3 Edge bandwidth extension in an aggressor cell

After receiving all the necessary feedback information from related neighboring cells, an aggressor cell can create reusable PRBs lists. Denote the feedback data come from cell i as $\mu^{(i)}$. In Fig. 4, cell 0 is the aggressor cell, so reusable PRBs in $\mathcal{B}_3$ are the last $\left(|\mathcal{B}_3| - \max\left(\mu^{(2)}, \mu^{(4)}, \mu^{(6)}\right)\right)$ ones. Users in $D_a^{(0)}$, $D_c^{(0)}$, and $D_e^{(0)}$ share this common list. The relationship between $\mu^{(i)}$ and the function $\varphi(\cdot)$ is:

$$\mu^{(i)} = \max\left(\varphi\left(RP_0^{(i)}\right), 0.5|\mathcal{B}_i|\right) \tag{8}$$

Similarly, it is easy to get the reusable list in $\mathcal{B}_2$, which are formed by the last $\left(|\mathcal{B}_2| - \max\left(\mu^{(1)}, \mu^{(3)}, \mu^{(5)}\right)\right)$ PRBs. This list is owned by users in $D_b^{(0)}$, $D_d^{(0)}$, and $D_f^{(0)}$. In addition, the total amount of reusable PRBs is just the parameter ΔJ in Eq. (6d). With these reusable PRBs lists, factorized intra-cell scheduler-B (FISB) can be used for extending the major band of an aggressor cell. In FISB, users are categorized into the vertex group $\mathcal{N}_x$, the line group $\mathcal{N}_l$, and the cell-center group $\mathcal{N}_c$. This is also the scheduling order of FISB. In Algorithm 2, we introduce the FISB of cell 0 for illustration.

The aggressor cell hands out its major band primarily. Users in the vertex group $\mathcal{N}_x$ have access to these PRBs with higher priority than those in the line group $\mathcal{N}_l$. The reason is that users in $\mathcal{N}_x$ are at inferior positions in facing complex interference. It seems that reserved major band PRBs are better than extended ones. If the reserved resource is not enough and it cannot meet minimum data rate requirements of some users in $\mathcal{N}_x$, these users will be abandoned (line 6–13). Conversely, idle PRBs of the major band will be assigned to users in $\mathcal{N}_l$ (line 14–16). After that, if any user in $\mathcal{N}_l$ still desires more PRBs, extending the major band is indispensable. The extension strategy for an aggressor cell is: selecting the best one in the reusable PRBs list and the user with the best channel quality on this PRB obtains it. The extension process will not stop until minimum data rate requirements of users in $\mathcal{N}_l$ are met or the reusable PRBs list becomes empty (line 17–29). After that, actions similar to line 16 and 17 in FISA are executed for assigning remainder PRBs to cell-center users (line 30).

Algorithm 2 Factorized Intra-cell Scheduler-B

Require:

1: $\mathcal{B}_1 = \{1, 2, \ldots, J_1\}, \mathcal{B}_2 = \{J_1+1, J_1+2, \ldots, J_2\}, \mathcal{B}_3 = \{J_2+1, J_2+2, \ldots, J\}$

2: $\mathcal{N}_x = \{\text{cell-edge users in vertex region}\}, \mathcal{N}_l = \mathcal{N}_e \backslash \mathcal{N}_x$

3: $\mathcal{J}_{r2} = $ the last $|\mathcal{B}_2| - \max(\mu^{(1)}, \mu^{(3)}, \mu^{(5)})$ PRBs in $\mathcal{B}_2$

4: $\mathcal{J}_{r3} = $ the last $|\mathcal{B}_3| - \max(\mu^{(2)}, \mu^{(4)}, \mu^{(6)})$ PRBs in $\mathcal{B}_3$

5: $\mathcal{B}_0 = \{\{\mathcal{B}_2 \backslash \mathcal{J}_{r2}\} \bigcup \{\mathcal{B}_3 \backslash \mathcal{J}_{r3}\}\}$

Ensure:

6: **while** $\mathcal{N}_x \neq \emptyset$ **do**

7: $\quad \{n^*, j^*\} = \arg\max_{n \in \mathcal{N}_x, j \in \mathcal{B}_1} R_{j,n}$

8: $\quad$ **if** $R_{n^*} < R_{min}$ **then**

9: $\quad\quad x_{j^*, n^*} = \beta, R_{n^*} = R_{n^*} + r_{j^*, n^*}, \mathcal{B}_1 = \mathcal{B}_1 \backslash \{j^*\}$

10: $\quad$ **else**

11: $\quad\quad \mathcal{N}_x = \mathcal{N}_x \backslash \{n^*\}$

12: $\quad$ **end if**

13: **end while**

14: **if** $\mathcal{B}_1 \neq \emptyset$ **then**

15: $\quad$ Assign remainder PRBs in $\mathcal{B}_1$ to users in $\mathcal{N}_l$ just like what have been done on $\mathcal{N}_x$.

16: **end if**

17: **if** $\mathcal{N}_l \neq \emptyset$ **then**

18: $\quad \mathcal{N}_{la} = \{\text{users in } \mathcal{N}_l \text{ that cell 1, or 3, or 5 is DIS}\}$

19: $\quad \mathcal{N}_{lb} = \{\text{users in } \mathcal{N}_l \text{ that cell 2, or 4, or 6 is DIS}\}$

20: **end if**

21: **while** $\mathcal{N}_{la} \neq \emptyset$ & $\mathcal{J}_{r3} \neq \emptyset$ **do**

22: $\quad \{n^*, j^*\} = \arg\max_{n \in \mathcal{N}_{la}, j \in \mathcal{J}_{r3}} R_{j,n}$

23: $\quad$ **if** $R_{n^*} < R_{min}$ **then**

24: $\quad\quad x_{j^*, n^*} = \beta, R_{n^*} = R_{n^*} + r_{j^*, n^*}, \mathcal{J}_{r3} = \mathcal{J}_{r3} \backslash \{j^*\}$

25: $\quad$ **else**

26: $\quad\quad \mathcal{N}_{la} = \mathcal{N}_{la} \backslash \{n^*\}$

27: $\quad$ **end if**

28: **end while**

29: Actions similar to line 20-27 above with $\mathcal{N}_{la} \to \mathcal{N}_{lb}, \mathcal{J}_{r3} \to \mathcal{J}_{r2}$

30: Actions like line 16 and 17 in FISA with $\mathcal{B}_0 = \{\mathcal{B}_0 \bigcup \mathcal{J}_{r2} \bigcup \mathcal{J}_{r3}\}$

31: **Output:** $X_{J \times N}^{(0)}$

Table 2 Simulation parameters

Parameter	Value
Network topology	19 Hexagonal cells, wrap around
Carrier frequency	2 GHz
System bandwidth	10 MHz
Base station antenna	Omni-directional antenna
BS transmit power	46 dBm
Trans. power ratio β	9 dB
Number of PRBs	48 for PDSCH, 2 for PDCCH
Cell radius R	500 m
Center radius R_{in}	350 m
r in Fig. 1	200 m
Number of users	30 per cell
Min. distance to BS	35 m
Path loss	L = 128.1+37.6log10(d), d in km
Shadow fading	Log. normal with 8 dB std. dev.
Thermal noise	−174 dBm/Hz
Noise figure	5 dB
Target BER	10^{-6}
Min. data rate	64 kbps

4 Numerical results and discussions

The simulation study is performed using MATLAB and simulation parameters are given in Table 2. We assume both the transmission power ratio and the cell-center radius are fixed. Analysis and optimization on these two parameters have been presented in [39–41] and references therein. Although 19 hexagonal cells are considered, only users located in the centering seven cells are calculated because they are suffering full inter-cell interference. The number of users in the aggressor cell is kept 30, but the cell-edge user amount varies from 16 to 28. Assuming the system has perfect channel state information of the desired signal and merely path loss of the interference channel. In practice, this decreases the cost of channel state information collection and improves the robustness to channel uncertainty. Numerical results are collected from 200 simulation drops and every drop is held 500 TTIs.

Performance of the proposed CoSFR is compared with other reference schemes available, such as reuse 1, standard SFR, LDA-SFR, and another variation of CoSFR.[7] Reuse 1 represents a scheme without any interference coordination. Standard SFR works with basic adaptivity and the normal intra-cell scheduler mentioned in system initialization of Sect. 3. LDA-SFR is merely the scheme in [16] without the cell-center bandwidth compensation

algorithm, which is a variation of standard SFR. Additional simple coordination scheme which is analogous to CoSFR, named SimCoor, is to demonstrate the importance of both coordination among cells and intra-cell schedulers. The neighboring cells received a request for help will select PRBs one by one from the beginning of their major bands, depicted as the normal order in Fig. 1. While edge bandwidth extension for the aggressor cell begins at the last one in the reusable PRBs list. All of these five schemes considered can realize universal frequency reuse and we try to allocate all available PRBs to users. Assuming users fall in the same service class with the minimum data rate requirement of 64 kbps. So the number of users is regarded as an approximate measure of the traffic load.

A cell is partitioned into cell-center region and cell-edge region and users are randomly located in the corresponding region. We set the tunable parameter r equals $(R - R_{in})$ and observe the difference of signal strength between two neighboring cells. Figure 5 shows the signal intensity difference between cell 0 and cell 1. UE1 and UE2 are almost on the same contour and cell 1 should be recorded into their DIS sets. The position of UE3 is good enough so it is free from strong interference of cell 1. Pay particular attention to the contour passing through the vertex of the inner hexagon. It shows r should be increased so that enough cell-edge users are included into the survivor group to avoid strong inter-cell interference. Hence, we reset $r = \frac{4(R-R_{in})}{3}$ in the simulations below. Note that too large an r is also not the solution because some reuse opportunities will be deprived in the aggressor cell.

The average user throughput of cell 0 is shown in Fig. 6. Obviously, performance of reuse 1 is the worst one since there is no any interference coordination. It can be observed that the more cell-edge users in the aggressor cell, the lower average user throughput is obtained. This is
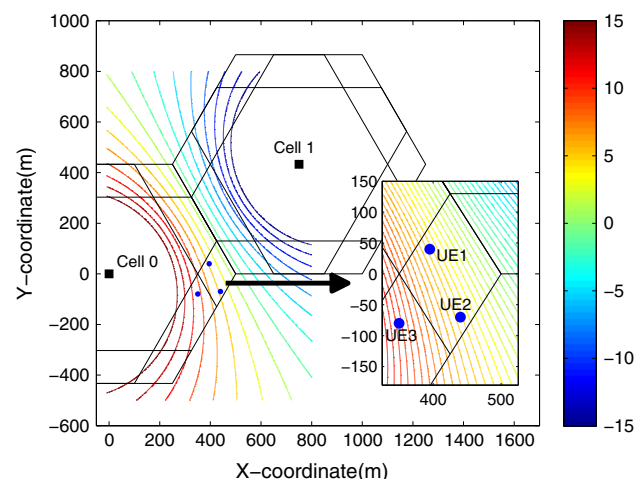

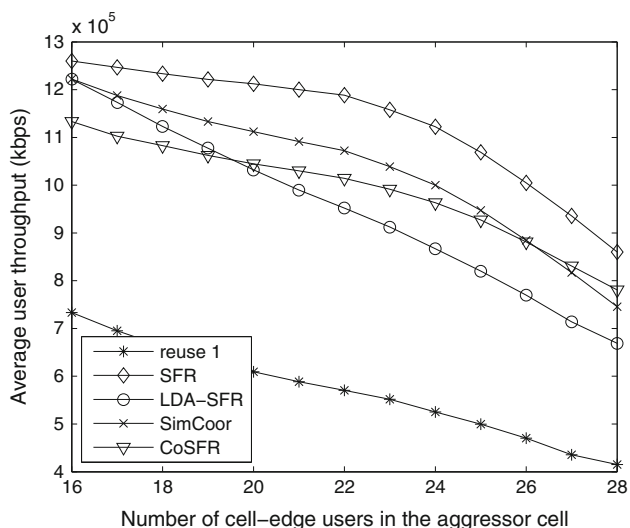**Fig. 5** Signal intensity difference between two cells

Fig. 6 Average user throughput in cell 0

because we assume users are distributed non-uniformly and most users are located far away from the base station. Standard SFR is the best since LDA-SFR, SimCoor, and CoSFR are variations based on standard SFR. Complex resource usage restrictions are added to standard SFR and thus some performance losses are brought.

The average throughput of cell-center users and that of cell-edge users in the aggressor cell 0 are demonstrated in Figs. 7 and 8, respectively. No matter which scheme is applied, the average cell-center user throughput always increases with the number of cell-edge users in the aggressor cell. This benefits from opportunistic scheduling after users' minimum data rate requirements are achieved. CoSFR can raise average cell-edge user throughput at least
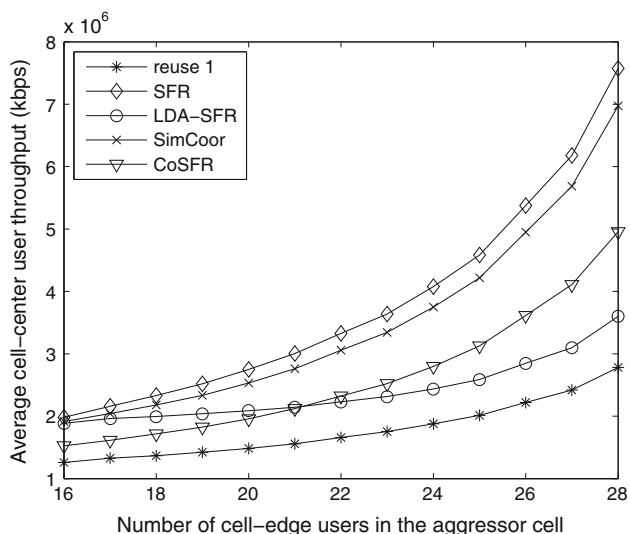

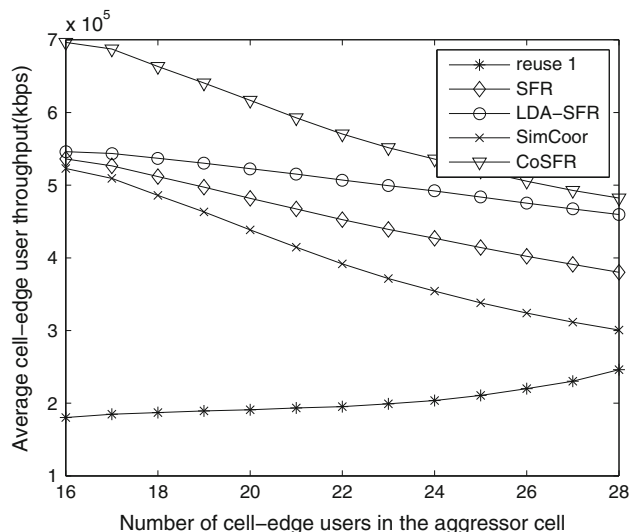Fig. 7 Average cell-center user throughput in cell 0

Fig. 8 Average cell-edge user throughput in cell 0

by 100 kbps than standard SFR at the expense of cell-center users. When there are more than 21 cell-edge users, CoSFR is better than LDA-SFR in all respects. Except reuse 1, the weakest coordination scheme in the average cell-edge user throughput is SimCoor. It applies too much restrictions resulting loss of multi-user diversity gain. In addition, average cell-edge throughput of reuse 1 also increases with the number of cell-edge users in the aggressor cell which is not agree with others. This is explained by the fact that although most users located near the cell boundary, there is no user classification in reuse 1 scheme. It looks like the leakage of benefit resulting from opportunistic scheduling.

Our chief concern is the outage probability of users. CoSFR aims at guaranteeing quality of service (QoS) and maximizing the system throughput at the same time. As shown in Fig. 9, LDA-SFR alleviates the cell-edge over-loaded state to some extent, but a fair number of users are dissatisfied with their rate. CoSFR can keep the outage probability low and the metric increases slowly with the increase of cell-edge user number. By comparison with LDA-SFR, the outage probability decreases by 4.8 % at most. Yet the gain of SimCoor is just so insignificant than standard SFR. This reflects the importance of reasonable intra-cell schedulers. CoSFR and SimCoor have the similar coordination mechanism but different scheduling strategies. The performance of them is far away from each other.

What needs to be stressed is that the QoS guarantee for users in the aggressor cell is at the expense of its neigh-boring cells. Without loss of generality, the outage proba-bility of all users in the centering seven cells is presented in Fig. 10. Obviously, the result shows that CoSFR is the best
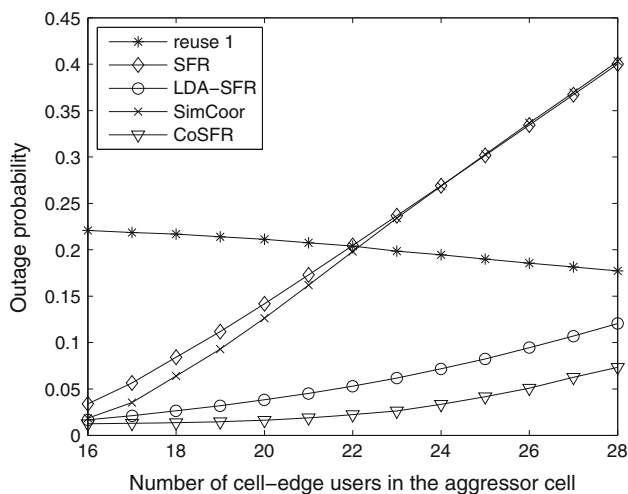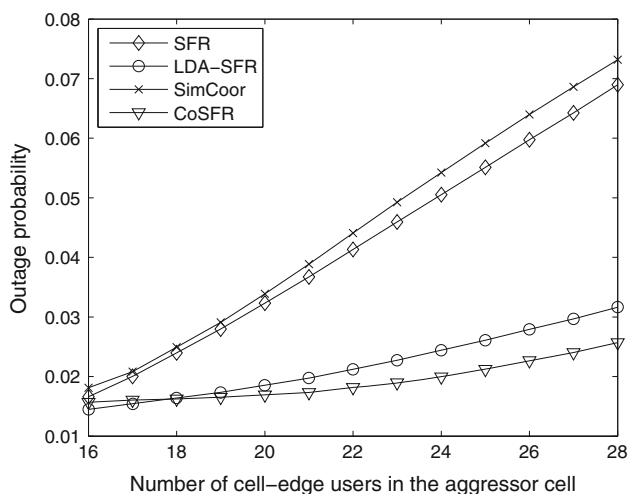
Fig. 9 Outage probability of users in cell 0

Fig. 10 Outage probability of users in the centering seven cells

one to serve the vast majority of users. When the number of cell-edge users in aggressor cell is less than 24, the outage probability is no more than 2 %. As the state gets worse, more than 97.4 % users in the system are pleased with the service. This means that CoSFR is always worthwhile seen from the perspective of system if there is a cell being cell-edge overloaded. However, when the number of cell-edge users is less than 18, the outage probability of CoSFR is worse than LDA-SFR. This is stemmed from the fact that CoSFR coordinates the direct neighboring cells to create more reuse opportunities. Whereas, coordination of these cells may degrades some users in them, and the gain obtained by the aggressor cell is so little. In addition, it is better to keep standard SFR in charge to cope with the general case. Another aspect of CoSFR requires comment. The minimum data rate requirements of users may be

substantially higher than 64 kbps. In this case, the trigger timing of switching from standard SFR to CoSFR should be optimized carefully. This is also one of our future works.

5 Extension and complexity analysis

5.1 Further extensions

CoSFR can be easily applied to more than one cell suffering from overloaded cell-edge traffic. Take an example of two cells here. In Fig. 1, supposing cell 1 and cell 5 are cell-edge overloaded and cell 0 is one of their common neighbors. So there are two related patches in cell 0 simultaneously, namely $RP_1^{(0)}$ and $RP_5^{(0)}$. Considering $\mathcal{B}_1$ has been bisected into $\mathcal{F}_1$ and $\mathcal{F}_2$, we can apply different sub-segment sequences for multiple related patches. If $RP_1^{(0)}$ selects the permutation $\mathcal{F}_1\mathcal{F}_2$, then another one, $\mathcal{F}_2\mathcal{F}_1$ is left for $RP_5^{(0)}$. It is important to emphasize that the related patches must be disjoint, so CoSFR can deal with the case that at most three cell-edge overloaded cells sharing a common neighbor.[8] It also requires to subdivide the major band into three or more sub-segments for providing enough sub-segment sequences. Furthermore, only information corresponding to the aggressor cell is fed back.

CoSFR can also be used in cells with irregular shape with some modifications. It is difficult to estimate the interference environment with users' location information when the cell shape is irregular. LTE has adopted cell-specific reference signal (RS) for channel estimation and scheduling. In such a case, we can assume users are able to identify interference sources by estimating these orthogonal cell-specific RS. Then the DIS set for a user can be determined. According to the celebrated four color theorem [42], the preferred reuse factor of cell-edge region should be four, so a user may have at most three DISs.

5.2 Signaling overhead comparison

Signaling overheads of LDA-SFR presented in [16] and the proposed scheme CoSFR are discussed here. Both CoSFR and LDA-SFR are coordinated semi-static interference coordination schemes, therefore information exchanges are indispensable. The required information can be exchanged among cells over the X2 interface in LTE/LTE-Advanced, which is primarily used for handover management.

In LDA-SFR, the cell-edge region is sectored although an omni-directional antenna is equipped. The resource usage information of cell-edge region should be transmitted

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[8] When the aggressor cells are also direct neighbors, the system should turn to other load balance technologies for help.

from direct neighboring cells to the aggressor cell. In addition, PRBs occupied by cell-edge users nearby the closest edge of the aggressor cell must be marked specially. With these information, six reusable sets and a database recording the reused PRBs are maintained.

As for CoSFR, only the number of PRBs occupied by users located in the related patch is fed back. Two reusable PRBs lists are created for the six pieces in the line region. At the same time, neighboring cells in a team select their schedulers collaboratively, so more reuse opportunities are offered to remit the cell-edge overloaded state even it is severe. As a result, exchanged information of CoSFR is much less than LDA-SFR.

5.3 Complexity analysis

In a cell serving N users with J PRBs, there are N^J possibilities allocating all PRBs to users. It means the exhaustive search for the optimum has an exponential complexity of $\mathcal{O}(N^J)$. Since N and J are on the order of several tens in general, the computational complexity of exhaustive search for K cells network is almost an astronomical amount.

To the centralized method in [43], its objective function is similar to expression (6a) and we assume transmission power are fixed here. If a user can only obtain a PRB, the computational complexity of this centralized method is $\mathcal{O}(J^2N)$. When the system allows a user to occupy multiple PRBs, the computational complexity becomes $\mathcal{O}(J2^JN)$.

In CoSFR, different intra-cell schedulers have been adopted by cells with distinct user distributions. However, it is easy to verify that both FISA and FISB are upper-bounded by complexity $\mathcal{O}(JN)$. In FISA, users are classified into survivor group, victim group, and cell-center group. An extreme scenario is the case that all users belong to the cell-center group. As mentioned in Sect. 3, Resource allocation for cell-center users contains two phases. In the first phase, allocating a PRB needs at most N comparisons, so this phase is upper-bounded by $\mathcal{O}(JN)$. The second phase is simple than the former one because it does not need users exclusion. Hence the overall complexity of FISA in such an extreme scenario is $\mathcal{O}(JN)$. In general, denoting the number of PRBs occupied by the survivor group and the victim group as J_s and J_v. Then resource allocation for each group is just a simplification of the extreme scenario above. The number of PRBs occupied by these three groups are J_s, $J/3 - J_s$, and $J - J_s - J_v$. It is obvious that the computational complexity of these three parts are no more than $\mathcal{O}(JN)$. The overall complexity of FISA is upper-bounded by $\mathcal{O}(JN)$. Analysis for FISB comes to a similar conclusion. Therefore the computational complexity of CoSFR is $\mathcal{O}(JN)$.

6 Conclusions

In this paper, a novel semi-static ICIC scheme called CoSFR is proposed for multi-cell OFDMA-based networks with non-uniform user distribution. The system throughput is maximized while users' minimum data rate requirements are met. The major restriction of standard SFR, cells next to each other must utilize orthogonal major bands in their cell-edge regions, is relaxed. The cell-edge overloaded state of an aggressor cell is mitigated by extending its major band after coordinating with its direct neighbors. Each cell in the system has access to launch such a coordination, which looks like that one for all and all for one. The coordination scheme is simple but efficient and no extra entity is added so it can be readily used in practical systems. Simulation results demonstrate that CoSFR improves cell-edge user throughput effectively without so much system performance losses. The outage probability declines significantly and most users in the network are satisfied with their service quality.

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