Cooperative resource management and power allocation for multiuser OFDMA networks

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Abstract: Mobile network operators are facing the challenge to increase network capacity and satisfy the growth in data traffic demands. In this context, long-term evolution (LTE) networks, LTE-advanced networks, and future mobile networks of the fifth generation seek to maximise spectrum profitability by choosing the frequency reuse-1 model. Owing to this frequency usage model, advanced radio resource management and power allocation schemes are required to avoid the negative impact of interference on system performance. Some of these schemes modify resource allocation between network cells, while others adjust both resource and power allocation. In this study, the authors introduce a cooperative distributed interference management algorithm, where resource and power allocation decisions are jointly made by each cell in collaboration with its neighbouring cells. Objectives sought are: increasing user satisfaction, improving system throughput, and increasing energy efficiency. The proposed technique is compared with the frequency reuse-1 model and to other state-of-the-art techniques under uniform and non-uniform user distributions and for different network loads. They address scenarios where throughput demands are homogeneous and non-homogeneous between network cells. System-level simulation results demonstrate that their technique succeeds in achieving the desired objectives under various user distributions and throughput demands.

1 Introduction

The increasingly growing demand for mobile broadband communications and the proliferation of mobile applications and services have led to the dense deployment of mobile networks with aggressive frequency reuse patterns. In fact, the long-term evolution (LTE) [1] of universal mobile terrestrial radio access System allows using all the available spectrum according to the frequency reuse-1 model. While trying to improve system throughput and increase spectrum profitability, mobile network operators find themselves constrained by inter-cell interference (ICI) problems. ICI reduces signal-to-interference and noise ratio (SINR), and has a negative impact on system performance. Another important concern for mobile network operators is minimising signalling traffic required to coordinate resource and power allocation between LTE/LTE-advanced (LTE-A) base stations, also called evolved-NodeBs (eNodeBs).

Third-generation partnership project (3GPP) has chosen orthogonal frequency division multiple access (OFDMA) technique for the downlink of the radio interface [2]. The smallest resource unit to be allocated to a user equipment (UE) is called resource block (RB). At each eNodeB, the scheduler allocates the available RBs for active UEs every transmit time interval (TTI), also called scheduling period (1 ms). There is no intra-cell interference problems, since each RB is allocated to only one UE within the same cell [3].

Several ICI coordination (ICIC) techniques are conceived to mitigate the negative impact of ICI on system performance. We classify them into static and dynamic techniques. For instance, fractional frequency reuse (FFR) and soft frequency reuse (SFR) [4] apply pre-planned frequency and power allocation strategies between eNodeBs of the same cluster. No adjustments are made, even when traffic demands are not uniformly distributed among LTE cells. Dynamic ICIC techniques are capable of responding to time-varying traffic demands in the network by modifying RB attribution, power allocation or both on a smaller time scale.

Although static ICIC techniques such as FFR and SFR reduce ICI in comparison with the frequency reuse-1 model, these schemes do not adjust resource allocation according to UEs distribution, satisfaction, or throughput demands. Therefore, there is a need to introduce novel ICIC schemes that overcome the limitations of the static schemes. The resource and power allocation is therefore dynamically adjusted according to UE distribution or throughput demands. This dynamic adjustment may be locally done by each cell, without any collaboration with the neighbouring cells, but at the risk of causing harmful interference to the neighbours when modifying the local transmission power allocation. In this work, we make use of the collaboration between the adjacent cells to propose dynamic ICIC schemes capable of optimising the resource and power allocation without any side effects in terms of interference.

In this paper, we introduce a cooperative ICIC technique that exploits communications between adjacent eNodeBs to reduce ICI problems in multiuser OFDMA networks such as LTE/LTE-A networks. Our technique aims at improving system throughput, UE satisfaction, and energy efficiency under various UE distributions and network loads. We define a satisfaction function as well as satisfaction throughput thresholds for each cell in the simulated network. The time scale of the proposed technique is higher than the scheduling period, since it sets RB and power allocation restrictions for the scheduler of each eNodeB. It also adjusts RB distribution between cell-centre and cell-edge zones for each LTE cell. Our technique is compared with the frequency reuse-1 model, FFR, SFR, and other ICIC techniques. System-level simulation results show that the proposed technique achieves significant improvements under various UE distributions and network loads.

The rest of this paper is organised as follows: in Section 2, we describe existing ICIC techniques. System model is reported in Section 3, while details about our proposed ICIC algorithm are given in Section 4. System-level simulator and simulation parameters are described in Section 5 and simulation results are reported in Section 6. Conclusion is given in Section 7.
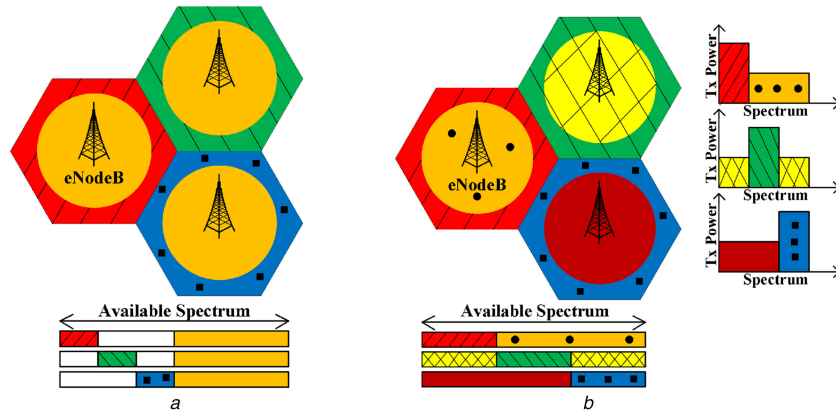
Fig. 1 *FFR and SFR techniques*
(a) FFR technique, *(b)* SFR technique

2 ICIC approaches

The frequency reuse-N model [5] mitigates ICI. However, the spectral efficiency is reduced, since only $1/N$ of the available spectrum is used in each cell. The frequency reuse-1 model [6] increases spectral efficiency and network capacity due to dense usage of the available RBs in the network. However, ICI problems have a negative impact on UE throughput, especially for UEs located at the edge of the cell.

FFR is a static ICIC technique, where restrictions on RB usage [7] are made to protect cell-edge UEs. FFR assumes that UEs of the cell-centre zone do not receive high-power interfering signals from the neighbouring cells. Nevertheless, UEs in cell-edge zone are close to the cell boundary and receive strong ICI. After creating two zones per cell, FFR divides the available spectrum into a few non-overlapping frequency sub-bands [8]. Cell-centre and cell-edge UEs from the same cell operate over different frequency sub-bands. Cell-edge UEs of the neighbouring cells also operate over non-overlapping frequency sub-bands as shown in Fig. 1*a*

SFR [9] protects cell-edge UEs by reducing the transmission power allocated to their interfering RBs in the cell-centre zones of the neighbouring cells. SFR's resource and power allocation for a cluster of three adjacent LTE cells are illustrated in Fig. 1*b*. SFR succeeds in mitigating ICI without largely sacrificing spectral efficiency [10]. Restrictions on RB and power allocations for both FFR and SFR techniques are statically made in each cell, and no modifications are made even when network load increases, or when UEs are not uniformly distributed between cell zones.

Both FFR and SFR are static ICIC techniques *i.e.*, the resource and power allocation of the whole system is statically applied as planned in advance. No adjustment is made in response to the varying network load or non-uniform UEs throughput demands. In this context, our proposed cooperative ICIC approach makes use of the collaboration between the neighbouring eNodeBs to overcome the limitations of FFR and SFR. The main idea is to dynamically adjust the resource and power allocation strategies in a collaborative manner and based on UEs' needs.

Several dynamic ICIC techniques are introduced [11–13]; some of them adjust frequency and power allocation in each cell locally, without any cooperation between eNodeBs. For instance, the heuristic power control algorithm introduced in [14] is an autonomous dynamic ICIC technique. The downlink transmission power allocated to each RB is dynamically adjusted (increased or decreased) depending on the received narrowband channel quality indication (CQI) feedback. Power allocation decisions are made locally by the scheduler of each cell and without any information exchange with the neighbouring cells. Another approach proposed in [15] locally adjusts the spectrum distribution between the cell-centre and cell-edge zones of the same cell without modifying the downlink transmission power allocated to the RBs. Hence, the spectrum allocation is dynamically adjusted in response to UE throughput demands in each zone, without causing additional interference to the neighbours, and without any collaboration between the adjacent cells. Nevertheless, these two approaches do not adjust IC spectrum allocation since the decisions made only

respond to local UE throughput and satisfaction demands. On one hand, our cooperative approach proposed in this paper makes use of the collaboration between eNodeBs to adjust IC power allocation in a coordinated manner, i.e. without increasing interference, on the network (or cluster) scale. On the other hand, it adjusts the local resource distribution between the different zones of each cell in response to the local UEs throughput demands on the cell scale.

In [16], a distributed potential game is proposed to maximise a utility function, and the convergence of this game is proven since a unique Nash equilibrium exists. However, there is neither guarantee on the time nor on the number of iterations required for convergence. In fact, this approach is not adequate for scenarios where UEs distribution or throughput demands are rapidly changing over time. The scalability of the proposed solution is another limiting factor. Other techniques depend on the signalling exchange between neighbouring eNodeBs. For example, Rengarajan *et al.* of [17] describe an ICIC technique that responds to network dynamics, through exchange of interference-related information among neighbouring cells. It is a dynamic cooperative FFR-based ICIC technique. Other ICIC techniques require the existence of a management entity to control RB and power allocation over the entire network. They are known as centralised techniques, and they are characterised by a heavy signalling burden and high complexity. For instance, in [18], a centralised entity collects information about RB usage and ICI from a set of eNodeBs, then it sends its decisions to the network schedulers. Moreover, coordinated multi-point (CoMP) [19, 20] creates a framework of transmission and reception methods using multiple geographically distributed antennas. Real-time information about RB allocation and interference status are exchanged among eNodeBs through X2 interface. For instance, Zhang *et al.* of [21] propose an interference mitigation scheme for heterogeneous Cloud small cell networks based on CoMP strategies, and they, namely focus on joint transmission. In fact, ICI is mitigated by coordinating the transmissions of the adjacent small cells. The coordination of the small cells requires the existence of a centralised controller in the Cloud. On the contrary, using our proposed approach, the IC spectrum coordination is done without the need for a centralised controller.

Compared to the cognitive radio networks such as cognitive femtocells [22, 23] that exploit the RBs when they are unused by the macrocells, our approach addresses the worst-case scenario. In fact, we seek minimising interference via a distributed low-complexity approach while using the entire spectrum in every cell. The classification of ICIC techniques is summarised in Table 1.

3 System model

ICIC techniques proposed for multi-user orthogonal frequency division multiple access (OFDMA) [24] networks, divide each cell into cell-centre and cell-edge zones. The former contains UEs close to the serving eNodeB, whereas the latter contains UEs located near the cell boundary. This geographical classification assumes

that cell-centre UEs are characterised by high SINR values, and that cell-edge UEs have lower SINR. However, we have cell-centre UEs suffering from interference or fading problems, as well as cell-edge UEs with good radio conditions due to shadow fading.

ICIC approaches such as the one proposed in [25] require the knowledge of the exact position of each active UE in the network, which results in an additional information exchange and processing load. In our work, we classify UEs according to their radio conditions. Instead of using geographical positions, we perform UE classification according to mean wideband SINR, since it reflects the useful signal power to the received interference. An SINR threshold ($SINR_{threshold}$) is set to classify UEs: when mean SINR of an UE is higher than the predefined $SINR_{threshold}$, it is considered as a good radio (GR) conditions UE; otherwise, it is considered as a bad radio (BR) conditions UE. GR UEs are commonly known as cell-centre UEs and BR UEs as cell-edge UEs.

Our classification is more accurate than the traditional approach: UEs suffering from ICI are classified as BR UEs, even if they are close to the serving eNodeB. Moreover, it does not require any localisation information. For practical implementations, the eNodeB classifies the active UEs into GR and BR UEs according to the received wideband CQI feedback. In fact, the wideband CQI is a discrete integer [26] that reflects the average channel quality of a given UE across the entire cell bandwidth. Once the CQI feedback is received by the eNodeB, it decides whether the concerned UE is a GR UE, i.e. in case the received CQI is greater than a predefined threshold; otherwise, the UE is classified as a BR UE. We note that the eNodeB is not aware of the instantaneous UE radio conditions, since the received wideband CQI feedbacks are periodically transmitted with a period that ranges from 2 to 320 ms [27]. In fact, the 3GPP does not specify an exact period for CQI reporting. Instead, 3GPP provides a mapping between the received values and a predefined performance. In our simulations, we consider the minimum CQI reporting period in order to get more accurate and efficient resource and power allocation decisions.

Let K denote the set of active UEs, I denotes the set of LTE/LTE-A eNodeBs, and N is the set of RBs available in each cell. We consider an UE k attached to cell i and allocated RB n. The corresponding SINR is given by:

$$\text{SINR}_{k,n}^i = \frac{P_n^i \cdot G_{k,n}^i}{\sum_{j \neq i} P_n^j \cdot G_{k,n}^j + P_{TN}}, \qquad (1)$$

where P_n^i is the downlink transmission power allocated by cell i for the RB n, $G_{k,n}^i$ is channel gain for UE k served by eNodeB i on RB n, and P_{TN} is the thermal noise power on the considered RB. Channel gain includes all key fading components, i.e. path loss, shadowing and multipath that UE k experiences on RB n. Indexes i and j refer to the serving and the interfering cells, respectively.

Let $R_{k,n}^i$ denote the achievable rate on RB n for user k in the cell i, then:

$$R_{k,n}^i = f(\text{SINR}_{k,n}^i). \qquad (2)$$

where $f(.)$ is the adaptive modulation and coding function that maps SINR to rate. Table 2 shows the mapping of SINR values to data rates [28]. Note that in our simulations, the single antenna transmission scheme is used, which is the transmission mode 1 as specified by 3GPP [27]. In our work, we consider an LTE/LTE-A network of several adjacent hexagonal cells. Each cell is equipped with 120° directional transmit antennas with an azimuth offset of 30°, where the azimuth offset angle is the angle difference between the target and the interference antennas in the horizontal plane. The frequency reuse-1 model is used to serve UEs existing within each cell.

LTE/LTE-A networks require the transmission of UE feedback in order to adapt transmission to current channel conditions. In this context, CQI is a 4 bit value sent from UE to eNodeB [27] that reflects the level of SINR of a given frequency band in downlink channels. It indicates the highest modulation and coding scheme that guarantees a block error rate lower than 10% for physical downlink-shared channel transmissions. Several reporting modes are supported: for example, wideband CQI feedbacks reflect the average channel quality across the entire cell bandwidth, while specific reports require the transmission of one CQI per configured sub-band (narrowband CQI feedbacks).

We consider elastic traffic sessions such as file transfer, web traffic, and email, since these are the traditional data services in mobile networks [29]. Then, we define the satisfaction function for each UE k at time t, $S_k(t)$, as a function of the achievable throughput for this UE, $R_k(t)$, and it is given by [29]:

$$S_k(t) = 1 - \exp\left(-\frac{R_k(t)}{R_S}\right), \qquad (3)$$

where R_S is the satisfaction throughput for the considered UE. When UE throughput equals R_S, its corresponding satisfaction function equals 2/3; therefore, R_S is the mean throughput beyond which UE satisfaction exceeds 2/3. The satisfaction with respect to R_k has a concave shape. On the one hand, the satisfaction dramatically decreases when UE throughput is below R_S. In fact, the elastic sessions do not require sophisticated quality of service guarantees; however, UE satisfaction is greatly reduced when the achieved throughput is below the satisfaction threshold R_S. On the other hand, it slowly increases as the throughput exceeds R_S, since UE throughput demands for its elastic sessions are already satisfied. The satisfaction of an LTE/LTE-A cell i having K_i UEs is given by

$$S^i(t) = \frac{\sum_{k=1}^{K_i} S_k(t)}{K_i}. \qquad (4)$$

LTE/LTE-A cells are hexagonal, and each cell exchanges signalling messages with its six neighbouring cells. The cell i calculates mean satisfaction function $\overline{S}$ for the considered cluster C that contains K_C UEs:

$$\overline{S} = \frac{\sum_{k=1}^{K_C} S_k(t)}{K_C}. \qquad (5)$$

Table 1 Classes of ICIC techniques

ICIC class	Description	Examples
static frequency reuse based	static RB and power allocation	FFR, SFR [4, 7]
autonomous	local decisions on RB and power allocation	[12, 14, 15]
coordinated	cooperation between neighbouring eNodeBs	[13, 16, 17]
centralised	centralised control entity	[19–21]

Table 2 SINR–data rate mapping table

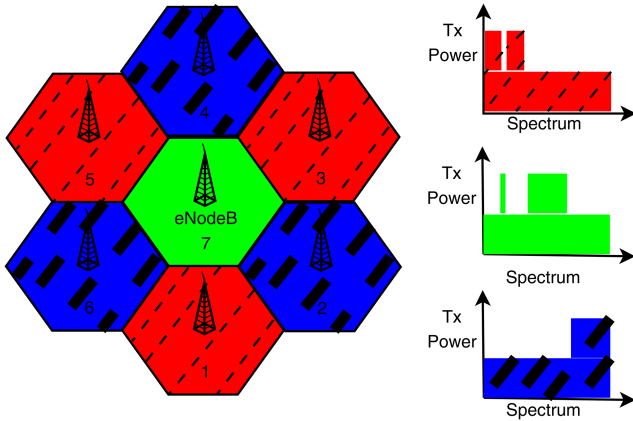| Minimum SINR, dB	Modulation and coding scheme,	Data rate kbit/s
1.7	quadrature phase shift keying (QPSK)(1/2)	168
3.7	QPSK(2/3)	224
4.5	QPSK(3/4)	252
7.2	16 quadrature amplitude modulation (QAM)(1/2)	336
9.5	16QAM(2/3)	448
10.7	16QAM(3/4)	504
14.8	64QAM(2/3)	672
16.1	64QAM(3/4)	756

Fig. 2 *LTE network of seven adjacent cells*

4 Cooperative ICIC technique

We introduce a cooperative ICIC technique for multiuser OFDMA networks, where adjacent eNodeBs collaborate in order to reduce ICI problems. It is a distributed technique that requires cooperation between adjacent eNodeBs to adjust RB and power allocation. Initially, RB and power distribution between the different cells are performed according to the SFR scheme. Thus, the frequency reuse-1 model is chosen to maximise spectral efficiency. Decentralised cooperative interference mitigation schemes are adequate for medium-sized and big-sized networks, where the centralised schemes face severe limitations in terms of signalling and processing load.

Our technique makes use of the signalling messages exchanged between neighbouring eNodeBs over X2 interface. Each cell has local information, concerning SINR of its active UEs, as well as their achievable throughputs and their satisfaction. It also requests information about UE satisfaction from the neighbouring cells. Therefore, adjacent eNodeBs adjust power allocation to the different RBs, in order to reduce ICI and to improve UE satisfaction in a collaborative manner.

As explained in previous sections, an LTE/LTE-A cell is divided into two zones, according to UEs wideband SINR values: GR and BR zones. Initially, one third of the available spectrum in each cell is kept for BR UEs, and the maximum downlink transmission power (P_{max}) is allocated to each RB used in this zone. The remaining bandwidth is used at a lower transmission power (P_{GR}) in the GR zone. BR UEs of adjacent cells operate on different frequency sub-bands, and they receive low-power interfering signals from their neighbouring cells. ICIC algorithm intervention period is chosen to be higher than scheduling period (1 ms) and CQI feedback reception delay, so the scheduler of each eNodeB has enough time to investigate the impact of RB and power allocation changes on UEs throughput. Each cell performs periodically, every T TTIs, where $T \geq \max(1\,\text{TTI}, \text{CQI feedback delay})$, the following actions:

(1) Classify the available RBs according to mean narrowband CQI feedback values.
(2) Collect information about mean throughput per UE in the neighbouring cells.
(3) Request information about RB and power distribution from all the neighbouring cells.
(4) Send *Stop* messages to the neighbouring cells.
(5) Calculate the local cell satisfaction $S^i(t)$.
(6) Calculate mean satisfaction for the neighbouring cells $\overline{S}(t)$.
(7) When unsatisfied, increase the downlink transmission power allocated to the worst low-power RB, and ask the neighbouring cells transmitting at high power to reduce their downlink transmission power allocated to this RB.
(8) When satisfied, keep the same RB and power distribution.
(9) Send *Release* messages to the neighbouring cells.
(10) Locally adjust RB allocation between GR and BR zones of the current cell according to throughput demands in each zone.

Our proposed technique exploits the fact that adjacent eNodeBs can exchange information related to UE throughput in each cell. When a given cell decides to perform the cooperative ICIC procedure, it sends *Stop* messages to its neighbouring cells to avoid any potential conflict that might occur when adjacent cells take simultaneous power allocation decisions. Since the X2 interface between adjacent eNodeBs is bidirectional, the *Stop* messages contain a time stamp, that allows to avoid any potential deadlock that might occur if two eNodeBs send simultaneous *Stop* messages to each other. Every eNodeB calculates the mean satisfaction for its active UEs, as well as mean satisfaction for UEs in the neighbouring cells. We tolerate a slight difference (Δ_S^i) between the satisfaction of the local cell and mean satisfaction per cell to reduce the number of interventions performed by each cell. When power adjustments are done, a *Release* message is sent to the neighbouring cells, and RB distribution between GR and BR zones is locally made according to throughput demands in each zone.

The distributed algorithm operates at the scheduler of each eNodeB as shown in Algorithm 1 (see, Fig. 2). $\overline{R}_i(t)$ denotes the mean throughput per UE in cell i; I is the number of cells in the neighbouring cells pool I. P_n^i is the downlink transmission power allocated by cell i to the RB n. P_{max} is the power allocated to a BR RB, while P_{GR} is the downlink power per GR RB. $\overline{R}_{GR}$ and $\overline{R}_{BR}$ denote the mean throughputs per GR and BR zones, respectively. After receiving narrowband CQI feedbacks from the UEs, eNodeB calculates mean CQI per RB. The coefficient γ equals 0.5, and it is used to emphasise the last received CQI feedback value, $CQI_n(t)$. eNodeB classifies the available RBs according to mean CQI values, then it sends signalling messages to its neighbours, so that downlink transmission power allocated to the different RBs is kept the same.

Our algorithm is in linear complexity in the number of available RBs, which outperform other exhaustive search and NP-hard integer programming algorithms. It consists of two phases: in the first phase, adjacent eNodeBs exchange the necessary information required to coordinate power allocation among neighbouring cells, whereas in the second phase, each cell locally modifies RB distribution between the different zones. After setting restrictions on power allocation with its neighbours, each cell adjusts RB allocation between GR and BR zones according to UE throughput demands in each zone. The objective behind second phase is to dynamically respond to throughput demands within each cell, even when UE distributions are not homogeneous among GR and BR zones.

Fig. 3 shows a cluster of seven adjacent hexagonal LTE/LTE-A cells. We assume that the central cell (eNodeB 7) has the highest traffic load, and seeks to improve its mean UE satisfaction. After exchanging the necessary signalling messages with its neighbouring cells, eNodeB 7 increases the downlink transmission power allocated to a portion of the available bandwidth that was originally used at a low transmission power. It also orders the concerned neighbouring cells (eNodeBs 1, 3, and 5) to reduce their downlink transmission power allocated to this portion of the spectrum. Therefore, eNodeB 7 reduces ICI and improves mean UE satisfaction via collaborative power allocation decisions. Moreover, it autonomously adjusts resource allocation between cell-centre and cell-edge zones based on throughput demands in each zone.

5 Simulation parameters

An LTE downlink system level simulator [30] is chosen as simulation platform. The original version of the simulator includes the frequency reuse-1 model as well as FFR technique. To compare our technique with the frequency reuse-1 model and other reference ICIC techniques, we integrated SFR scheme within the simulator. We also adjusted the power allocation scheme, so that the power mask can be modified according to the used technique. Finally, we integrated our proposed cooperative distributed ICIC algorithm. The simulated network includes seven adjacent hexagonal LTE/LTE-A cells, with a 5 MHz operating bandwidth. Since the total bandwidth per RB equals 180 kHz, we have 25 RBs

1: Initially, RBs are distributed according to SFR
2: All UEs send CQI feedbacks to the eNodeB
3: Δ_{th} = 512 kbit/s
4: **for each** $RB \in RB\_pool$ **do**
5: $\quad CQI_n^i(t) = \dfrac{\sum_{k=1}^{K} CQI_n^k(t)}{K}$
6: $\quad \overline{CQI_n^i}(t) = \gamma \times \overline{CQI_n^i}(t-1) + (1 - \gamma) \times CQI_n(t)$
7: **end for**
8: Every T TTIs:
9: Cell i sends *Stop* messages to its neighbors
10: $S_k(t) = 1 - exp(-\frac{R_k(t)}{R_S})$
11: $S^i(t) = \dfrac{\sum_{k=1}^{K_i} S_k(t)}{K_i}$
12: $\overline{S}(t) = \dfrac{\sum_{k=1}^{K_C} S_k(t)}{K_C}$
13: **if** $(S^i(t) < (1 - \Delta_S^i) \times \overline{S}(t))$ **then**
14: $\quad$ Select the low power RB n with the lowest $\overline{CQI_n^i}(t)$, where $1 \leq n \leq N$
15: $\quad P_n^i \leftarrow P_{max}$
16: $\quad P_n^j \leftarrow P_{GR}; \forall j \in \mathbf{I}$
17: **else**
18: $\quad$ Keep the same power allocation mask
19: **end if**
20: Send *Release* messages to the neighboring cells
21: **if** $(\overline{R}_{GR} - \overline{R}_{BR} > \Delta_{th})$ **then**
22: $\quad$ Select RB n with the highest $\overline{CQI_n^i}(t)$ from GR zone, where $1 \leq n \leq N$
23: $\quad$ Allocate this RB to the BR zone
24: **else if** $(\overline{R}_{BR} - \overline{R}_{GR} > \Delta_{th})$ **then**
25: $\quad$ Select RB n with the lowest $\overline{CQI_n^i}(t)$ from BR zone, where $1 \leq n \leq N$
26: $\quad$ Allocate this RB to the GR zone
27: **else**
28: $\quad$ Keep the same RB distribution
29: **end if**

Fig. 3 *Cooperative ICIC*

available in each cell. Traffic model is full buffer; thus, the available spectrum is permanently used to serve active UEs. With the full buffer model, the maximum ICI is generated since all the available spectrum is simultaneously used in the adjacent cells. Thus, we place ourselves in a worst-case scenario. Simulation parameters are given in Table 3.

6 Simulation results

6.1 Tolerated satisfaction ratio

We simulate an LTE/LTE-A network having seven adjacent hexagonal cells, where each cell is serving 10 UEs. Simulation time is 350 TTIs (350 ms). The throughput satisfaction threshold (R_S) is not the same for all the UEs across the network. In fact, for the UEs of the middle cell, i.e. the cell located in the centre of the simulated cluster of seven adjacent cells, the throughput satisfaction threshold is four times greater than that of the UEs in the other cells. This reflects a scenario, where UEs throughput demands are not the same across the network. In other words, it is required to provide higher throughputs for the UEs of the central cell, since their satisfaction throughput threshold exceeds that of the other UEs.

First, we study the impact of the tolerated satisfaction ratio Δ_S, which is a percentage of the mean satisfaction value, on the central cell satisfaction and mean satisfaction for the entire network. Simulations are repeated 100 times, and satisfaction versus time for central cell UEs and for all UEs versus time are reported in Figs. 4 and 5, respectively. The objective of this paper is to find the most adequate value of Δ_S, i.e. the value that maximises system satisfaction.

For tolerated satisfaction ratios higher than 20%, power allocations over the different RBs are kept the same, since all the

cells achieve an acceptable satisfaction compared with mean satisfaction per UE. However, when Δ_S equals 1%, satisfaction for central cell UEs is increased, while mean satisfaction per UE is slightly decreased with time. When the tolerated satisfaction is lower than $0.01 \times \overline{S}$, the central cell decides to increase transmission power allocated to some RBs (that were already used with a lower transmission power), and it orders all its neighbours to reduce the downlink power allocated to these RBs. Satisfaction for central cell UEs is increased in comparison with the remaining cases, where no power adjustments are performed. For the remaining cells, satisfaction is decreased, since power reduction will reduce the achievable throughput. Thus, mean satisfaction per UE in the entire network is slightly reduced. When Δ_S is set to 1%, we maximise the satisfaction of the whole system.

In the following, the tolerated satisfaction ratio Δ_S equals 1%. Hence, when the mean satisfaction per UE exceeds by 1% the satisfaction of a cell, it decides to launch a cooperative ICIC procedure with its neighbours in order to adjust power allocation and improve the satisfaction of its UEs. We compare our proposed cooperative ICIC technique with the frequency reuse-1 model, FFR, SFR, an adaptive ICIC technique given in [12], and an autonomous ICIC technique introduced in [15], where power allocations for the different RBs are not modified among adjacent eNodeBs. Nevertheless, periodic interventions are made by the scheduler of each eNodeB, locally, in order to find out whether GR or BR users are unsatisfied. RB distribution between cell zones is adjusted according to UEs throughput demands in each zone.

The adaptive ICIC technique [12] operates as follows:

• UEs are divided into cell-edge and cell-centre UE groups.
• RB and power allocation to the cell-edge group is performed. After that, the RB and power allocation to the cell-centre group is performed.
• The RBs and power allocation to cell-edge UEs are performed using a waterfilling-based power allocation algorithm, so that all the cell-edge UEs satisfy the predetermined target throughput.
• Problem constraints are related to the minimum throughput per UE, and to the maximum downlink transmission power.
• Each cell solves its own optimisation problem with minimal exchange of information between the cells.

6.2 Throughput cumulative distribution function

Under the same simulation conditions, we study the impact of each technique on throughput CDF for all UEs existing in the network. Throughput CDF is shown in Fig. 6.

Although FFR succeeds in reducing ICI, especially for BR UEs, restrictions on RB usage between the different zones of each cell will reduce the amount of available spectrum dedicated for the existing UEs. Thus, FFR shows a lower percentage of UEs having throughputs higher than 512 kbit/s in comparison with reuse-1, SFR, autonomous, and cooperative ICIC techniques. In fact, throughput CDF for FFR reaches the maximum value of dissatisfaction before that of reuse-1, SFR, autonomous, and cooperative ICIC techniques. SFR improves the frequency reuse-1 model by reducing the percentage of UEs with throughputs lower than 1 Mbit/s. Our cooperative ICIC technique shows the highest percentage of UEs having high throughputs, and it reaches its maximum value of dissatisfaction for the same throughput as for reuse-1. We also note that the adaptive ICIC technique does not succeed in reducing the percentage of UEs characterised by low throughput values, since its CDF curve shows the highest values for throughputs less than 0.5 Mbit/s. In fact, this technique does not take ICI problems into account, and resource allocation is performed in a manner that improves spectral efficiency. Therefore, BR UEs throughput decreases and more RBs are allocated to GR UEs in order to maximise system throughput.

6.3 Satisfaction cumulative distribution function

For the same simulated scenario, we show satisfaction cumulative distribution function (CDF)for all the compared techniques. Satisfaction function ranges from 0 (minimum satisfaction) to 1

Table 3 Simulation parameters

Parameter	Value	Description
cell geometry	hexagonal	a cell is served by an eNodeB
inter-eNodeB distance	500 m	urban area
operating bandwidth	5 MHz	—
number of RBs (N)	25	in the 5 MHz bandwidth
transmission frequency	2 GHz	—
sub-carrier frequency	15 kHz	1 RB = 12 sub-carriers
total bandwidth per RB	180 kHz	12×15 kHz
TTI	1 ms	transmit time interval
pathloss model	TS 25.814	same as in HSDPA
thermal noise density	-174 dBm/Hz	—
feedback delay	3 ms	3 TTIs
scheduler	round robin	—
traffic model	full buffer	—
eNodeB maximum power (P)	20 W	43 dBm
maximum RB power ($P_{\max}$)	0.8 W	$\frac{P}{N}$
SINR threshold	3	UE classification
SFR power ratio (α)	0.25	$P_{GR} = \frac{P_{\max}}{4}$
SFR power per GR RB	0.2 W	$P_{GR} = \alpha \times P_{\max}$
SFR power per BR RB	0.8 W	$P_{BR} = P_{\max}$
intervention period (T)	25 TTIs	$T \geq \max(1\,\text{TTI}, \text{feedback delay})$
Δ_{th}	512 kbit/s	satisfaction per zone
throughput threshold R_S	512 kbit/s	UEs in the centre cell
	128 kbit/s	UEs in other cells

TS: Time Slot, HSDPA: High Speed Downlink Packet Access
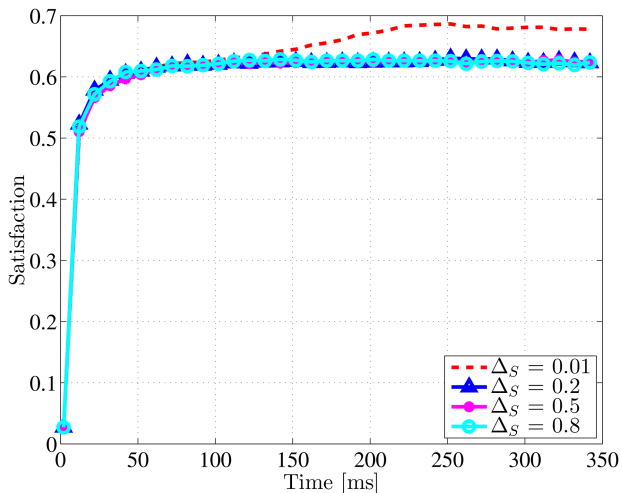
Fig. 4 *Central cell satisfaction versus time*

(maximum satisfaction). Satisfaction CDF for the performed simulations are shown in Fig. 7.

According to these results, adaptive ICIC always shows the highest percentage of UEs with low satisfaction values. The frequency reuse-1 model, SFR, and autonomous ICIC techniques have approximately the same satisfaction CDFs, and our proposed cooperative ICIC technique has the best satisfaction CDF in comparison with the other techniques. For instance, when cooperative ICIC is applied, only 10% of UEs have a satisfaction below 0.9, whereas 30% of the active UEs have their satisfaction below 0.9 for the adaptive ICIC technique. Therefore, our technique improves UE satisfaction by adjusting power allocation over RBs used simultaneously in adjacent LTE cells.

6.4 Unsatisfied UEs versus network load

For an LTE network of seven adjacent LTE cells, with 25 RBs available in each cell, we study the impact of network load (number of UEs per eNodeB) on the percentage of unsatisfied UEs in the network. The percentage of satisfied UEs at 63% denotes the percentage of UEs characterised by a mean throughput higher than the satisfaction throughput threshold R_S. When an UE has its throughput equal to R_S, the satisfaction function equals 2/3. We investigate the percentage of UEs that are unsatisfied at 63%, i.e. the number of UEs characterised by a throughput lower than R_S, among all the active UEs in the network. Fig. 8 shows the percentage of unsatisfied UEs at 63% versus the number of UEs per eNodeB.

For very low network load scenarios such as two or five UEs per eNodeB the frequency reuse-1 model and all the other ICIC techniques have approximately the same percentage of unsatisfied UEs. However, when the number of UEs per eNodeB increases, throughput demands become more difficult to satisfy, especially with the increased ICI. FFR has always the highest percentage of unsatisfied UEs, which increases with network load. Unsatisfied UEs with SFR technique are comparable with those with the frequency reuse-1 model. Moreover, their percentage decreases when network load increases. Our proposed cooperative ICIC technique shows the lowest percentage of unsatisfied UEs regardless of the number of UEs per eNodeB. It adjusts power allocation over the available RBs for each cell in a collaborative manner, which reduces the number of UEs with low satisfaction values.

6.5 Energy efficiency versus UE distribution

The energy efficiency is defined as the ratio between the total system throughput and the total downlink transmission power allocated to the available resources. It is given by:

$$\text{energy efficiency} = \frac{\sum_{k=1}^{K} R_k \,(\text{bit/s})}{\sum_{i=1}^{I} \sum_{n=1}^{N} P_n^i \,(\text{W})}. \qquad (6)$$

We investigate the impact of UE distribution on the performance of the compared ICIC techniques. We generate scenarios with different UE distributions by controlling the percentage of GR UEs among all the existing UEs in each cell. For every UE distribution scenario, simulations are repeated 50 times, and mean energy efficiency values are shown in Fig. 9.

According to these results, the frequency reuse-1 model shows always the lowest energy efficiency among all the compared techniques. In fact, when the maximum downlink transmission power is permanently allocated to all the available RBs, power consumption increases, ICI increases and the achievable throughput is reduced, especially for BR UEs. When using FFR, a fraction of the available spectrum is not used in each cell; therefore, no downlink transmission power is allocated to the unused frequency sub-band. Power consumption is reduced, while also improving SINR for BR UEs. For these reasons, FFR improves energy efficiency when compared with the frequency reuse-1 model. We also note that the adaptive ICIC technique is a compromise between the frequency reuse-1 model and FFR technique in terms of energy efficiency, since it succeeds in improving system performance in comparison with the frequency reuse-1 model.

Our cooperative ICIC technique shows an energy efficiency comparable with that of SFR. When there is more BR UEs in the network (the percentage of GR UEs is low), ICIC algorithm increases downlink transmission power allocated to selected RBs to increase BR UEs satisfaction. Thus, total power consumption increases, and energy efficiency is slightly lower than that of SFR. However, it shows the highest energy efficiency when the majority of UEs is GR UEs.
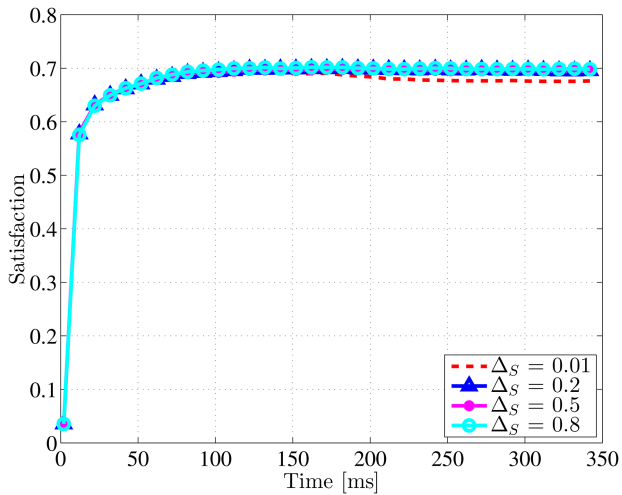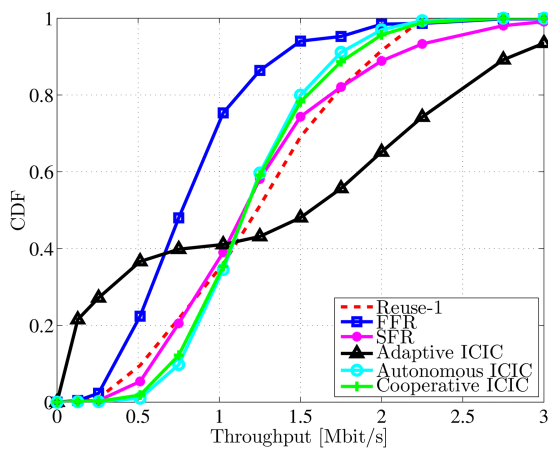
Fig. 5 *Mean satisfaction versus time*
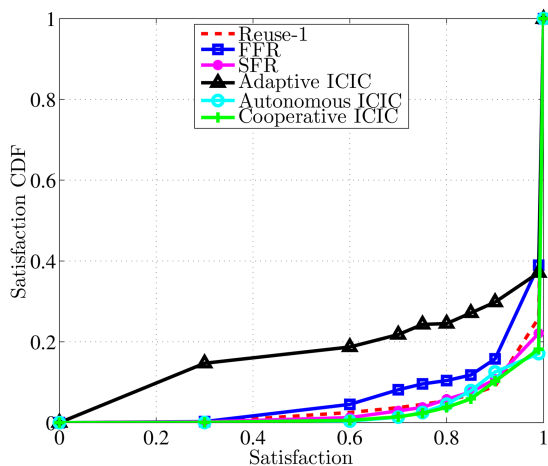

Fig. 6 *Throughput cumulative distribution function*

Fig. 7 *Satisfaction CDF*

Fig. 8 *Unsatisfied UEs at 63% versus network load*

Fig. 9 *Energy efficiency versus UE distribution*

adequate for large-sized networks. The cooperative ICIC techniques are, therefore, a compromise between centralised and autonomous approaches.

In this paper, we introduced a cooperative distributed ICIC technique where communications between adjacent eNodeBs are required to adjust RB and power allocation. Our algorithm consists of two phases: in the first phase, signalling messages are exchanged to get the necessary information about UE satisfaction and power allocation in the neighbouring cells. Decisions concerning transmission power adjustments are made in a collaborative manner during this phase. In the second phase, the scheduler of each eNodeB locally adjusts restrictions on RB distribution between cell zones according to UE demands per zone. Simulation results show that our technique improves energy efficiency, enhances throughput CDF, and reduces the percentage of unsatisfied UEs, when compared with the frequency reuse-1 model, FFR, SFR, adaptive ICIC, and non-cooperative ICIC techniques.

7 Conclusion

Dense frequency reuse model is used in multiuser OFDMA networks such as LTE/LTE-A networks to increase spectral efficiency and to improve network capacity. However, the resulting ICI problems have a negative impact on UE throughput and system performance. ICIC techniques are proposed to improve UE throughput, without largely sacrificing spectral efficiency. They include static techniques such as FFR and SFR, autonomous techniques, cooperative techniques, and centralised techniques. Centralised resource and power allocation techniques are adequate for small-sized networks, since they generate a large amount of signalling overhead. Autonomous resource allocation schemes do not generate an additional signalling overhead. Thus, they are
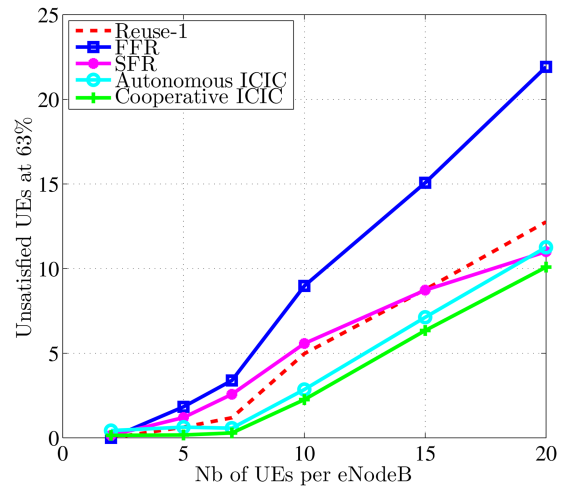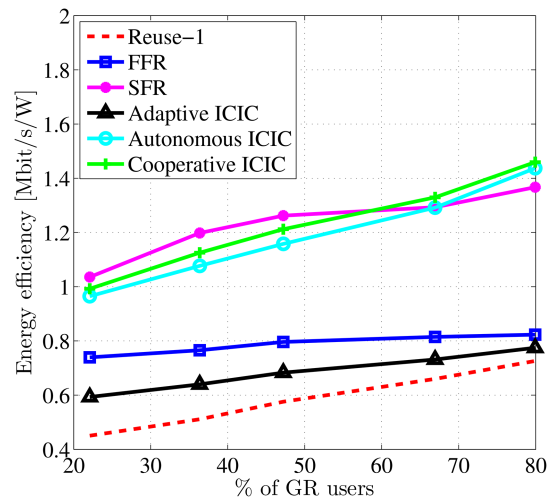
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