Performance Analysis of Soft Frequency Reuse Schemes for a Multi-Cell LTE-Advanced System with Carrier Aggregation*

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***Abstract*— Carrier aggregation is one of the promising features that expands the bandwidth of the Long Term Evolution-Advanced (LTE-A) system through aggregating multiple carriers to support high data rate up to 1 Gbit/s. When considering a multi-cell scenario, an appropriate resource allocation method that takes the inter-cell interference into account should be used. We investigate different soft frequency reuse (SFR) schemes and address an important issue which is how they should be applied in the presence of multiple carriers. Particularly, we propose two novel methods for performing the resource partitioning process: Local partitioning (LP) that divides each carrier individually between cell-center and cell-edge users, and Global partitioning (GP) in which dividing is at the level of the aggregate bandwidth. Simulation results demonstrate that the LP method performs better when most of users are LTE-A-capable terminals, whereas if the majority is for the legacy LTE Release 8 terminals then the GP method is advantageous. Furthermore, we show that using the transportation problem based resource allocation is a simple and yet flexible method that can be tuned to match the investigated SFR schemes and the proposed LP and GP resource partitioning methods.**

Keywords- Carrier aggregation; resource allocation; transportation problem; soft frequency reuse; inter-cell interference coordination

I. INTRODUCTION

To cope with the increased users uptake of the new wireless communication services, the Third Generation Partnership Project (3GPP) has introduced the Carrier Aggregation (CA) concept as one of the Long Term Evolution-Advanced (LTE-A) features in order to fulfill the 4th Generation (4G) requirements [1]. The CA technology allows the aggregation of multiple LTE-supported carriers, known as component carriers (CCs), to form a larger carrier. This aggregation should be in a backward compatible way such that both LTE-A capable user equipment (UE) and legacy LTE release 8 (Rel-8) UE are served simultaneously.

One of the limiting factors that affect the performance of the cellular LTE orthogonal frequency division multiplexing (OFDM) system is the inter-cell interference (ICI) [2] between users in different cells being served in the same physical resource block (PRB). Although the aggressive spectrum reuse (reuse-1) achieves the highest system capacity, it causes the largest degradation in signal-to-interference-plus-noise ratio (SINR) due to ICI, especially at the cell edge. This causes the difference to widen between the performance of cell-center and cell-edge users. Several interference management solutions are made [3] to improve the cell edge throughput including the frequency reuse concept which reduces the interference levels significantly at the expense of the reduction in the available bandwidth. To strike a balance between the need of a high system throughput and sufficient cell-edge spectral efficiency, the concept of fractional frequency reuse (FFR) is presented. Using this concept, some of the available PRBs are assigned to the cell-center users, whereas the rest are divided between the edge users of the adjacent cells.

The FFR schemes are extensively discussed in the literature, we provide herein a sample of some of the most relevant works. In [4], the authors compare different FFR schemes in OFDMA-based networks and show that the soft-frequency-reuse (SFR) achieves higher spectrum efficiency than the partial-frequency-reuse (PFR). An FFR scheme is introduced in [5] that divides the resources of the cell-center and the cell-edge region not only by frequency sub-bands but also by time slots. The performance of SFR in LTE networks under different load and power setups is discussed in [6].

In the presence of multiple carriers and users with different capabilities, CA is not only deployed as a capacity-boosting technique, but it can also be used as a coordination scheme to improve the cell-edge efficiency and alleviate the interference from neighboring cells. The contribution of this paper is twofold: (1) we investigate the appropriate SFR based coordination scheme in a multi-cell LTE-A system operating with CA for different users' type conditions and partitioning methods. In particular, we propose and compare two methods of partitioning the available resources. One method performs the partitioning on each CC separately (local partitioning (LP)) whereas the other considers the whole aggregated bandwidth as one segment and perform the partitioning over it (Global Partitioning (GP)); (2) we introduce the masking concept in the transportation problem based scheduler (originally

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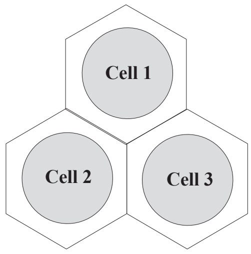

Figure 1. Three-cell layout

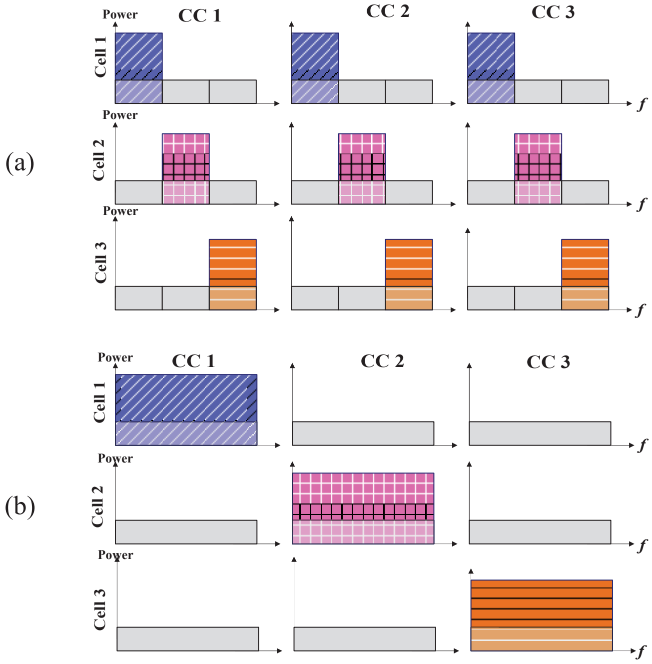

Figure 2. SFR-1 partitioning and the corresponding power levels (a) Local partitioning (b) Global partitioning

introduced in [7]), which is a simple method to easily adjust the scheme to different partitioning methods. To our knowledge, the performance of SFR schemes with CA is not investigated in the literature.

The rest of this paper is organized as follows. In section II, we describe the system model and the applied SFR schemes. The multi-cell transportation problem based resource allocation scheme is presented in section III. Then, section IV provides the performance evaluation. Finally, section V concludes the paper.

II. System Model

A. System Model of a Multi-Cell System

We consider an LTE-A system consists of N cells and operates in Frequency-Division Duplex (FDD) mode, where we are interested in the downlink transmission with L CCs. Each CC has V PRBs, where the PRB is the smallest unit of allocation. Each cell in the system is comprised of an enhanced NodeB (eNB) that serves a number of U UEs randomly dropped in the layout (including LTE-A UEs and Rel-8 UEs). Each UE requests a constant number of bytes (according to an arbitrary traffic model) each subframe of 1 millisecond. LTE-A UEs are assumed to be able to use the whole set of CCs. Rel-8 UEs are capable of connecting to a single CC only, and therefore we use a Round Robin (RR) load balancing to distribute their load across CCs.

In a CA-enabled system, the user may be allocated resource blocks across different CCs. Since reporting the Channel Quality Indicator (CQI) per-PRB over all CCs would cause a large signaling overhead for the UE uplink channel, 3GPP has defined a sub-band which is a number of PRBs grouped together. In order to reduce signaling overhead, the CQI index will be reported in terms of sub-bands (SBs) and one CQI value is reported representing their average channel state. This index has an integer value ranging from 1 to 15, each corresponding to a certain SINR range. The higher the SINR value, the higher the CQI index [10].

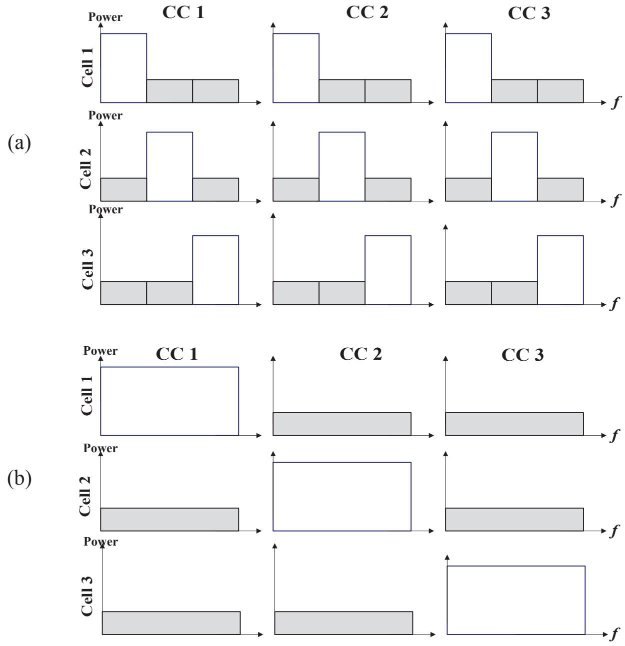

Figure 3. SFR-2 partitioning and the corresponding power levels (a) Local partitioning (b) Global partitioning

TABLE I. TRANSPORTATION PROBLEM PARAMETERS

Parameter	Description
S	Number of supply nodes.
D	Number of demand nodes.
s_i	Number of available units at supply node i, i ∈ {1, 2, …, S}.
d_j	Number of needed units at demand node j, j ∈ {1, 2, …, D}.
$c_{i,j}$	Cost of shipping one unit from supply node i to demand node j.
$x_{i,j}$	Number of assigned units from supply node i to demand node j.

B. Soft Frequency Reuse Schemes

Fractional frequency reuse is a frequency planning technique in which the available spectrum is partitioned into multiple portions; each portion is reserved for the use of a specific part of the cell in a coordinated way such that the ICI is reduced.

In this paper, we consider two soft frequency reuse (SFR) schemes, although both of them are commonly defined as SFR, their realizations are different. The first definition of SFR [8], denoted herein as SFR-1, divides the spectrum into *N* parts (for a reuse pattern of *N* cells). Each cell in the pattern uses one of these parts with high power in the cell-edge and uses the remaining parts in the cell-center with reduced power. Since our model inherently has multiple CCs, we propose two configurations to partition the resources. We define the first configuration as local partitioning (LP) in which we consider each CC individually. Hence, each CC will be partitioned separately into multiple parts according to the reuse pattern. An example for three CCs is depicted in Fig. 2-a for the cells layout of Fig. 1. We define the second configuration as the global partitioning (GP) in which the spectrum formed by the whole CCs is considered as one portion while partitioned. Fig. 2-b depicts this configuration for the previous example. As shown, SFR-1 scheme gives cell-center UEs access to all resources with reduced power, so it is equivalent to a reuse factor of 1 in the cell-center. However, cell-edge UEs are scheduled in one third of the bandwidth only, therefore resulting in a reuse-3 in the cell-edge. The second definition of the SFR [9], denoted herein as SFR-2, is different from SFR-1 in that the cell-edge portion is not used in the cell-center. Thus, there is orthogonality between the resources used by cell-center and cell-edge users within a certain cell, which guarantees improving of the cell-edge spectral efficiency as one portion is fully dedicated to their usage. The configuration of this scheme is depicted in Fig. 3-a and Fig. 3-b for the LP and GP cases, respectively. We define a parameter called the *power ratio*$= P_e/P_c$ where P_e is the total power of the cell-edge portion and P_c is total power of the cell-center portion.

III. MULTI-CELL RESOURCE ALLOCATION USING THE TRANSPORTATION PROBLEM

We formulate the multi-cell resource allocation problem as a transportation problem. The goal of the optimization problem is to efficiently allocate the resources to users and minimize the ICI.

A. Transportation Problem

A transportation problem aims at minimizing the total cost of shipping of units from supply nodes to demand nodes such that the needs of each demand node is satisfied whilst each supply node serves within its capacity. The transportation problem parameters are listed in Table I.

A transportation problem can be efficiently solved as linear programming (LP) optimization problem if it is balanced, i.e., the total number of units in the supply nodes equals the total number of units in the demand nodes, and it is formulated as follows:

$$\min_{X} \sum_{i=1}^{S} \sum_{j=1}^{D} x_{i,j} c_{i,j} \tag{1}$$

subject to

$$\sum_{i=1}^{S} s_i = \sum_{j=1}^{D} d_j$$

$$\sum_{i=1}^{S} x_{i,j} = d_j \quad , \quad \forall j$$

$$\sum_{j=1}^{D} x_{i,j} = s_i \quad , \quad \forall i$$

$$x_{i,j} \geq 0 \quad , \forall i, \forall j.$$

B. Mapping of the Resource Allocation Problem to a Transportation Problem

A supply node is represented by an SB which is formed by a group of PRBs. Hence, these PRBs represent the supply units. The downlink UEs with pending traffic demand at a certain subframe will represent the demand nodes. The demand at each node is represented by the number of PRBs required to satisfy the UEs pending traffic. As the pending traffic demand is expressed in terms of bytes, it needs to be mapped to a number of PRBs using the UEs average wide-band channel state [7].

We set the objective of the optimization problem as to maximize the proportional fairness (PF) of the system. Therefore, the cost of assigning a resource to a UE is defined as the negative of the PF metric, so that a higher PF metric lead to a lower assignment cost, as follows:

$$c_{i.j} = -\frac{R_{i.j}}{\bar{R}_j} \tag{2}$$

where $c_{i.j}$ is the cost of assigning one unit from SB i to user j, $R_{i.j}$ is the instantaneous rate of user j in the SB i and $\bar{R}_j$ is the historical total average rate for user j in the previous allocations over all CCs.

If the total demand is greater than the available resources, a dummy supply node will be added to balance the problem, containing a number of units equal to the shortage in supply. The cost of assignment from this node will be higher than the normal range of costs to increase the opportunity for users to be served from real supply nodes. Resources allocated from this dummy supply are not counted in the calculation of users' rate.

As some users in the system are Rel-8 users capable of connecting to only one CC at a time, the cost of shipping from other CCs to these users is set to a high value α. This ensures that these users will be allocated resources only from the selected CC. This introduces a great advantage of using the transportation problem which is masking. Masking of a number of sources for a certain user is done by simply setting costs from these sources to a high value, denoted herein as α. This makes it easy to manage who to serve and from which source. For example, if a UE in the cell-edge is allowed to be served only from a certain portion, we simply set high cost values between this UE and all sources (SBs) except in that portion. Fig. 4 illustrates an example of the masking concept, assuming the system has two CCs and each CC is divided into two portions, one for the center and the other for the edge. In the first case, since the user is an LTE-A user, he is capable of connecting to both CCs but being a cell-center UE allows him to be allocated only from the first portion of each CC so the sources from the other portion is masked. The second case is the same but for a cell-edge user. In the third case, the user is a Rel-8 UE who is connected to the first CC only so the whole sources in the second CC is masked whereas only the first portion of the first CC is available as the user is in the cell-center. The fourth case is similar but for a cell-edge Rel-8 user.

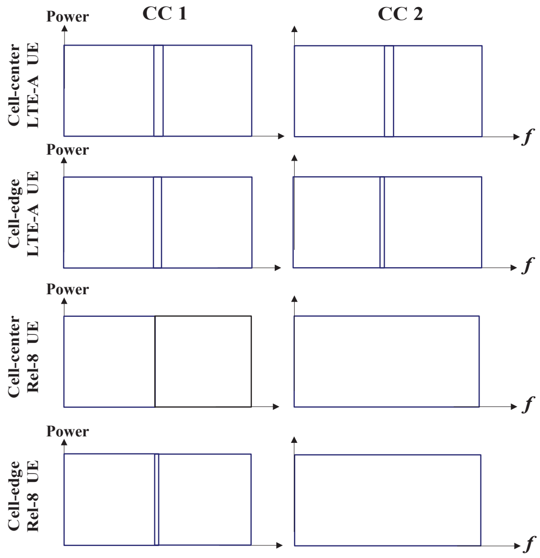

Figure 4. Example for the masking concept

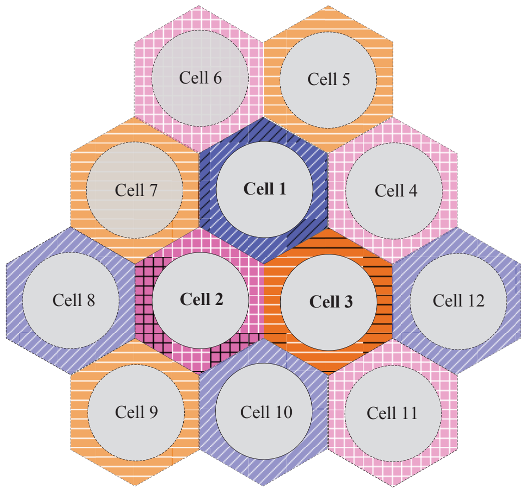

Figure 5. Cells layuot

Note that we are interested in obtaining the solution with minimum total cost rather than the value of the total cost itself. The exact values of α is not of a particular importance in the problem as long as it prevents assignment from the masked resources.

The transportation problem is then solved using the Vogel Approximation Method (VAM) which is a sub-optimal but efficient method that solves the problem in a much shorter time than the simplex method for optimal solution [7].

IV. PERFORMANCE EVALUATION

We study the performance of different SFR schemes using system level simulations. We use the WINNER II C2 channel model as specified in [11]. We consider a multi-cell scenario, in which we perform the dynamic resource allocation process on the scheduled cells concurrently on each subframe. Unsatisfied demand in a certain subframe is accumulated to the demand of the next subframe. The main parameters used in the simulations are summarized in Table II. The cells layout is depicted in Fig. 5, all cells are scheduled, however, only the three interior cells are used to calculate the throughput whereas the cells in the outer tier are used only to generate ICI on the interior cells. The transportation problem is solved on each cell in a distributed manner. The users report the CQI values corresponding to their current SINR levels [10]. The interference is calculated from the allocation of the previous subframe assuming the difference in the allocation is not significant which is reasonable if all PRBs are used and no power control is implemented.

TABLE II. SIMULATION PARAMETERS

Parameter	Value/description
Layout scenario	Hexagonal grid with 3 interior cells, and 9 outer cells. Typical urban scenario [11]
Shadowing	Log-normal [11]
Carrier aggregation pattern	3 × 10 MHz non-contiguous CCs
Site-to-site distance	500 m
Max. BS Tx power/CC	46 dBm
Number of PRBs per CC	50 PRB, each containing 12 subcarriers
Sub-frame duration	1 ms
Simulation time	1000 subframes
Traffic model	CBR (100 Mbps/cell)
Thermal noise spectral density	-174 dBm/Hz
CQI reporting resolution	3 PRBs/sub-band

Each cell contains 10 UEs distributed randomly in the cell area. Without loss of generality, we assume that 4 UEs are located in the cell-edge whereas the rest are in the cell-center. This is done on purpose to illustrate the effect of the proposed scheme in improving the cell-edge throughput. A UE is considered as a cell-edge one if its distance from the center is more than 70% of the cell radius. The traffic demand for users is generated in terms of a constant bit rate (CBR) application. A constant rate of 100 Mbps is offered in each cell, thus each user requires 10 Mbps.

We investigate the performance of the SFR-1 and SFR-2 schemes, each with the local and global partitioning configurations. Hence, we denote them as LP-SFR-1, LP-SFR-2, GP-SFR-1 and GP-SFR-2. We use the geometric average of rates as in [12], expressed as:

$$\hat{R} = \left(\prod_{j=1}^{U} \bar{R}_j\right)^{\frac{1}{U}} = \exp\left(\frac{1}{U}\sum_{j=1}^{U} \ln(\bar{R}_j)\right) \quad (3)$$

since it is a good measure of system rate utility as it is defined as sum of the log the users rate (the geometric average is then the exponent of the utility). In Fig. 6, the geometric average UE throughput versus the cell-edge UE throughput is compared for the four schemes against reuse-1 scheme. The power ratio is varied from 5 to 15 with a step of 3. The experiment is repeated three times under different percentage of LTE-A UEs and Rel-8 UEs (0%, 50%, and 100% LTE-A users). It is shown that, in all cases, the different SFR schemes perform better in terms of cell-edge throughput at the expense of geometric average throughput decrease due to the lower utilization of resources caused by using fractional reuse planning, these two effects increase as the power ratio increases, since increasing the cell-edge power decreases the power dedicated to the cell-center to keep the total power constant within a CC. The SFR-2 always achieves better cell-edge throughput than the SFR-1 scheme but with higher degradation in the geometric average throughput. This difference is due to the orthogonality in dividing the cell-center and cell-edge resources in the SFR-2 scheme which restrict the high power spectrum portion to cell-edge users only, thus increasing their throughput to the detriment of decreasing the cell-center and average throughput.

When all users are LTE-A users, the LP schemes perform better than the GP schemes. Nevertheless, this preference vanishes as the percentage of LTE-A users decreases. On the contrary, when all users are Rel-8 users, the GP schemes perform better. The explanation of this behavior is as follows, when all users are LTE-A, all of them are able to connect to the whole CCs. Therefore, using the LP schemes will enable both cell-edge and cell-center users to be scheduled on the whole bandwidth and take advantage of the frequency diversity, in particular, all of them will be able to access one third or two thirds of the available bandwidth as they are supposed to. But using the GP schemes in this case will limit some users from using some of the CCs in which they are technically able to connect to them. Conversely, if all users are Rel-8 users, they are able to connect to a single CC only regardless of being in the cell-center or cell-edge, therefore, a GP scheme will be better for them, as it will allow any user to benefit from the entire of his CC whereas an LP scheme will allow him to be scheduled only on a portion of his single CC. It is worth mentioning that there will be no difference between GP-SFR-1 and GP-SFR-2 in the case of 0% LTE-A users, as all users are connected to a single CC so cell-center users are restricted to their CC and cannot be scheduled on cell-edge resources.

Fig. 7 illustrates the system behavior under different offered load conditions. It is shown that although the geometric average throughput increases significantly in all cases, due to the load increase, the edge UE throughput decreases with increasing the offered load in SFR-1 schemes in which the center users have access to the edge resources along with their dedicated resources. In this case, increasing the load makes the edge resources more vulnerable to be assigned to cell-center users, and hence the edge throughput decreases. On the contrary, as portion of the bandwidth is dedicated to cell-edge UEs in the SFR-2 schemes, the edge performance is guaranteed and thus throughput increases with increasing the offered load. It is shown also that in the case of reuse-

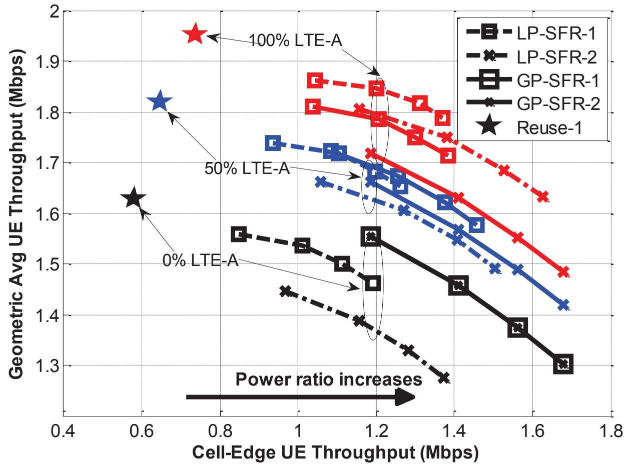

Figure 6. Average geometric throughput versus cell-edge throughput for different SFR schemes against reuse-1 scheme

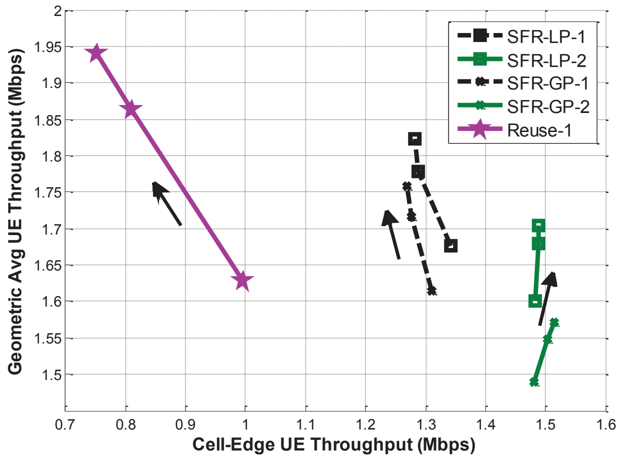

Figure 7. Performance under different load conditions of 20, 30 and 100 Mbps per cell for the different SFR schemes with a constant power ratio of 10.

1 scheme, the cell-edge throughput decreases with increasing load as high traffic leads to high ICI, which affects the cell-edge performance considerably.

The performance is then investigated while varying the percentage of LTE-A users in the system at a constant power ratio of ten. Fig. 8 and Fig. 9 show the average cell-edge UE throughput and the average cell-center UE throughput, respectively, for the different schemes. It is shown that at lower percentage of LTE-A users, GP schemes give better edge throughput. But when the LTE-A percentage increases, LP schemes achieve almost the same edge throughput and with higher center throughput.

V. Conclusions

In this paper, the performance of different soft-frequency-reuse (SFR) based inter-cell interference coordination schemes are studied for a multi-cell multi-carrier LTE-A system. Two schemes are investigated with two different proposed partitioning configurations, local partitioning (LP) and global partitioning (GP). Simulation results show that the second SFR method performs better in terms of the cell-edge throughput at the expense of higher geometric average throughput degradation. The LP method applies the partitioning on each CC individually and its performance is better when most of the users are LTE-A. If most of the users are Rel-8, the GP method, which performs the partitioning globally on the entire bandwidth, is better. Furthermore, the proposed scheduling scheme can be easily adjusted by simply changing the transportation problem cost values to adapt the network to any of the SFR schemes whenever the users' conditions change.

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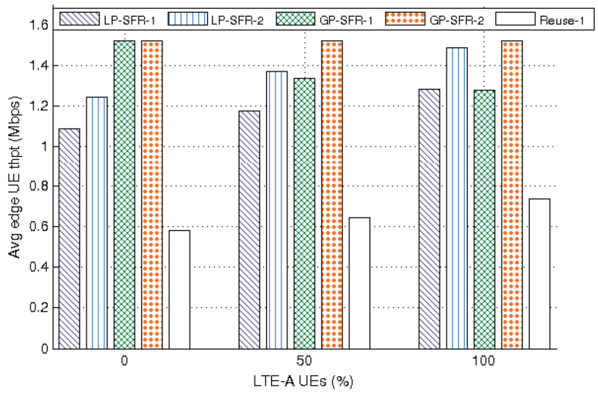

Figure 8. Average cell-edge UE throughput for different schemes against the percentage of LTE-A users

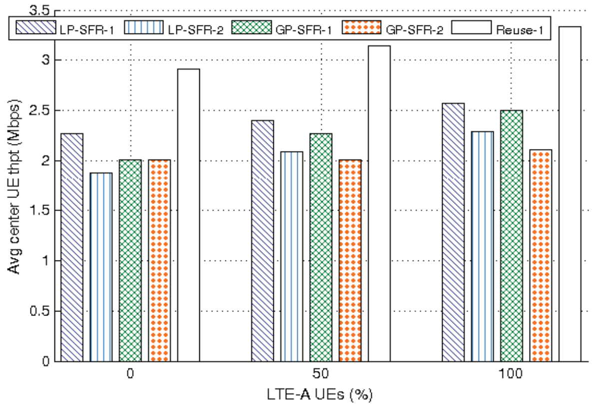

Figure 9. Average cell-center UE throughput for different schemes against the percentage of LTE-A users

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