Evaluating ICIC Performance in LTE-A Systems

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***Abstract*—LTE-A technology incorporates Inter-Cell Interference Coordination (ICIC) methods in order to enhance performance and mitigate interference. These methods include frequency allocation techniques that allow neighboring cells and femtocells in heterogeneous networks, to coordinately share and reuse available spectral resources, in order to avoid performance degradation for interference suffering cell-edge users. In this paper we evaluate the performance of the ICIC methods in LTE-A multi-cell systems using a simulation framework integrating several frequency reuse techniques and providing a user-friendly graphical presentation of the results. The optimal frequency reuse configuration for the examined network instance is also determined, based on overall performance and fairness index metrics.**

I. Introduction

Several Frequency Reuse (FR) schemes have been discussed for OFDMA-based networks such as Long Term Evolution-Advanced (LTE-A), each one of different efficiency and complexity, to achieve the conflicted goals of utilizing efficiently the limited and expensive radio spectrum, and mitigating interference effects on network performance. Used as methods for Inter-Cell Interference Coordination (ICIC), three are the basic FR schemes: the Integer FR (IFR), the Fractional FR (FFR) and the Soft FR (SFR). In all these schemes the whole frequency band is divided into several sub-bands. The network is then divided in areas that may utilize all or part of the sub-bands depending on the scheme implemented. The most common IFR implementations are of reuse factor 1 and 3. In the first case (IFR1), all cells may use the entire frequency spectrum. In the second case (IFR3) adjacent cells use different sub-bands, while in FFR and SFR the cell space is divided even further, distinguishing the reuse factor achieved in inner areas from the one in outer areas.

The discussion on these subjects has been large and continuous. An evaluation of various FR schemes including IFR and FFR is presented in [1] for cellular OFDMA networks where FFR with appropriate settings of inner region radius and power ratio is shown to provide the best performance when a scheduler fair in throughput is assumed.An optimization mechanism for FFR configuration is presented in [2] to achieve better system performance based on dynamic cluster sizing and frequency allocation. Soft FR was introduced and discussed in [3].A comparison between the latter scheme and the strict FFR in [4], attributes better overall throughput and cell-edge SINR for FFR but better balance in terms of spectral efficiency and interference reduction for SFR. Two variations of FFR are presented in [5] that compensate for the reduced capacity experienced by cell-edge users in standard FFR. Tools for reproducing LTE-A systems with inter-cell interference mitigation schemes include the thorough Vienna LTE Simulators [6] with FFR implementation capabilities and LTE-sim of [7] that encompasses IFR schemes of factor 1, 3, and 4.

In this paper we evaluate all LTE-A main ICIC schemes using a software framework [8], which simulates LTE-A multi-cell topologies and evaluates the performance of the resulting deployments. Different FR techniques have been integrated, specifically IFR1, IFR3, FFR and SFR. For FFR and SFR cases, an optimization mechanism is triggered, in order to configure the optimal parameters of frequency sub-bands allocation and division areas sizing. The optimization is decided upon maximizing total throughput and/or fairness index. Finally, we discuss the results and compare the outcomes of different configurations. It is important to mention that, there is no similar platform offering similar simulation capabilities.

The rest of this paper is structured as follows: the system model and theoretical analysis are presented in Section II. In Section III we present the performance evaluation results and, finally, in Section IV we reach our conclusions and suggest possible future steps of this work.

II. System Model

In this section the model used for the performance evaluation is described, as well as our optimization technique.

A. Frequency Reuse Schemes

Fig. 1 shows the most notable frequency allocation schemes, namely: IFR, FFR and SFR. IFR1 provides the simplest form where all sub-bands are used by all cells without distinction. Its main advantage is the reuse factor of 1, at cost, though, of severe co-channel interference effects, especially at the borders of the cell. IFR of factor 3 allocates different sub-bands for adjacent cells as shown in Fig. 1.

A more complex but balanced approach is considered in FFR. In this scheme the cell area is divided in two regions: the inner one, which is close to the Base Station (BS) and outer one, which is situated to the borders of the cell. The part of the frequency band dedicated to the cell centre users is common for every cell of the network, achieving a reuse factor of 1. The rest is divided in three sub-bands that are allocated to the outer regions of the cells identically to the IFR3 distribution, achieving a reuse factor of 3.

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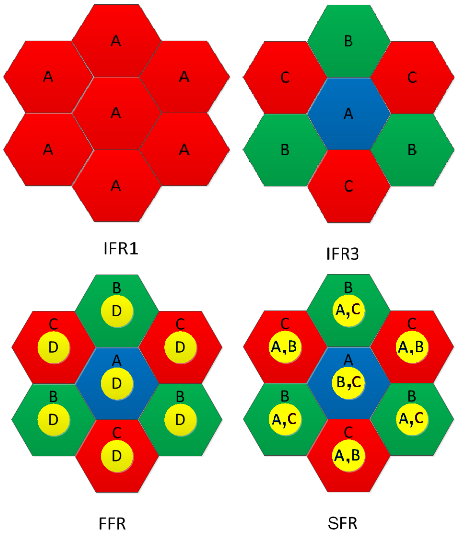

Fig. 1: Frequency reuse schemes.

SFR utilizes frequency similarly to FFR but allows inner areas of the cell to share sub-bands of edge users of adjacent cells. It is best suited for situations where spectrum utilization is of major significance, and small increase in interference compared to FFR can be tolerated. Thus, a power control factor $b \geq 1$ is adapted to define the ratio of different areas' power levels. More formally:

$$b = \frac{P_{edg}}{P_{cen}} \tag{1}$$

where P_{cen} and P_{edg} denote the BS transmit power for a cell-centre and a cell-edge user, respectively. The exact value of b is often based on heuristic results, though values of 2 or 4 are usually adapted for typical analysis [4].

B. Modeling Evaluation

In order to evaluate the performance of the simulated networks we use three different metrics. The first is the theoretical average throughput of the network, based on the calculation of per-user SINR and considering path loss, according to the model described by 3GPP [9]. Since extreme individual performance could affect the average outcome leading to misinterpretation of the resultsthe second metric is defined as the relative throughput of a user compared to the throughput of the other users. This metric is called Fairness Index (*FI*) [10] and it is calculated as the square sum of the users' throughput divided by the product of the sum of squared users' throughput and the number of users (*X*). It represents the deviation of users throughput in the area, thus expressing the fairness of provided services across different areas of the cells.

$$FI = \frac{\left(\sum_{x=1}^{X} T_x\right)^2}{\sum_{x=1}^{X} (T_x)^2 * X} \tag{2}$$

FI ranges between $\frac{1}{X}$ and 1. When FI approaches 1, all users in the corresponding cell experience similar throughput, while values approaching $\frac{1}{X}$ mean that there are big variations in the throughput achieved by the users in the cell.

However, since seeking optimized configurations, as subsequently described, to maximize FI metric may lead to low user throughput, we introduce a third metric called weighted throughput, in order to achieve both user fairness and good overall throughput. Weighted throughput (*WT*) is defined as:

$$WT = FI * Throughput \tag{3}$$

C. FFR, SFR Optimization

FFR and SFR optimization assumes a number of multicast users that are uniformly distributed. It uses exhaustive search to decide the proper parameters for frequency allocation and cell division. For FFR, the mechanism divides each cell into two regions and calculates the total throughput, the FI and the WI for the following Frequency Allocations (FA), assuming FR 1 and 3 for the inner and the outer region respectively:

- FA_0: All (N) Resource Blocks (RBs) are allocated in inner region. No RBs are allocated in outer region. N depends on bandwidth as chosen by user.
- FA_1: $N-1$ RBs are allocated in inner region. $1/3$ RBs allocated in outer region.
- ...
- FA_{N-1}: 1 RBs allocated in inner region. $N-1/3$ RBs allocated in outer region.
- FA_N: No RBs allocated in inner region. $N/3$ RBs allocated in outer region.

For each FA, the mechanism calculates the per-user throughput, the mean throughput, the FI and WT. This procedure is repeated for successive inner cell radius sizes, ranging from 0 to R, where R is the cell radius. Finally, the mechanism selects the optimal FFR that maximize the mean throughput, fairness index or weighted throughput. The above process is applied periodically for updated frequency and sector distribution.

The process followed for the SFR case is mostly the same. The main difference is the distinction of exterior and interior areas of the cell regarding power control. A value of $b = 2$ is chosen here for the power control factor b for a balanced approach between achieved SINR and relative spectral efficiency as shown in [4].

III. Performance Evaluation

In this section, we provide information on the simulation framework and the parameters of the used network model. Afterwards, we present several experimental results obtained.

A. Simulation Framework & Parameters

The developed framework receives user input to configure the size of the network and the number of present users, the bandwidth that is available, the modulation and the FR scheme. It simulates user activity and random mobility inside the network and calculates overall cells' throughput and the degree of fair resource allocation. It is implemented in MATLAB [8].

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TABLE I: Simulation Parameters

Parameter	Value					
Cell Radius	250 m					
Bandwidth (MHz)	20	15	10	5	3	1.4
Modulation Mode	64QAM		16QAM		QPSK	
Subcarriers bandwidth	15 KHz					
Carrier frequency	2 GHz					
Correlation distance	40 m					
Channel model	3GPP Typical Urban					
Path loss	Cost 231 Hata Model					
BS transmit power	46 dBm					
White noise power density	-174 dBm/Hz					

Table I summarizes the network parameter values used during the simulation. The topology consists of multiple adjacent macro sites of radius 250m and macro BS TX power of 46db, wherein arbitrary number of users are distributed. System bandwidth and resource blocks follow LTE specifications. The scenario deployed is urban canyon macro. Path losses are calculated according to Cost-Hata Model and the correlation distance of the shadowing is set to 40m [11].

For the needs of results' presentation, a 9-cell network with 200 randomly generated users was considered. Mobile users were moving at random chosen speeds and direction for a time frame that covered 120sec approximately. Channel bandwidth was set at 20MHz and the modulation used was 64QAM.

B. Experimental Results

1) IFR3: Fig. 2a displays an overview of the entire network's performance, providing the average throughput and fairness index accomplished throughout the entire site, when IFR3 allocation is applied. One can see the somewhat complementary nature of the two graphs since the largest values for throughput may suggest many users closer to the BS achieving unbalanced performance, affecting downwards the fairness index, and vice versa. For a more explicit approach, Fig. 2b focuses on the throughput exhibited by each cell of the network distinctively, and the throughput experienced by users individually. Since the first depends on the density and mobility of users, the above figure is a starting point for the inter-cell coordination between macro BS, as used in dynamic ICIC capable systems such as LTE-A. On the other hand, the latter provides the throughput experienced by individual users for a random chosen cell of the site, to avoid overlooking extended individual poor performance due to satisfying maximum or average indexes. The lower values represent users located at the edge of the cell suffering significant path loss, while the higher ones represent those closer to the centre.

2) SFR, FFR: For SFR and FFR, we first present the results of the optimization process for the same network topology described above. Fig. 3 displays the cell area division and resource allocation values (the latter for FFR exclusively) that were found to accomplish the maximum throughput, FI and weighted throughput. It is interesting to note that to maximize throughput, the allocation of the entire bandwidth to a single

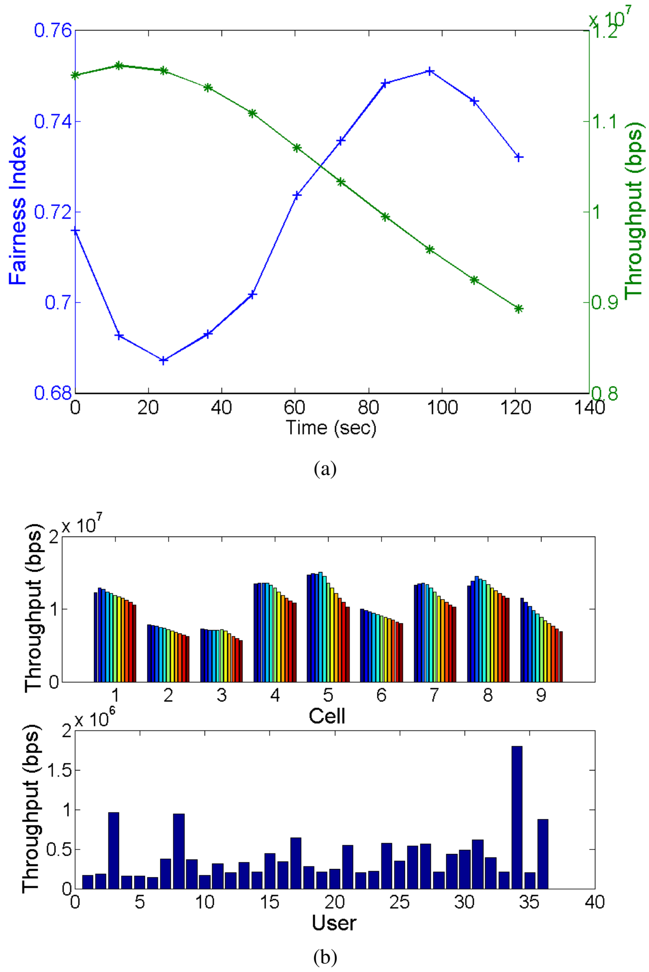

Fig. 2: IFR3: (a) overall throughput and fairness index, (b) throughput per cell and per user.

area is required. Although this would lead to optimal average throughput, the outer area users would not have access to service. Thus, FI or weighted throughput would constitute a fairer and more realistic overall solution. Regarding the inner area radius, a value of zero is needed, which is actually the IFR3 approach. Again, a more balanced result is accomplished when optimization for FI and weighted throughput is selected.

After applying all three above configurations, the results for FFR and SFR are displayed in Fig. 4 and Fig. 5, respectively. The cost in throughput in favor of fairer service distribution is obvious in Fig. 4a and 5a, where the overall throughput subject to the different optimal metrics is shown. Since SFR frequency allocation is fixed, optimization process depends solely on the area division, so smaller differences between the metrics are exhibited. Fig. 4b and 5b show the best and worst throughput experienced by a user in the network. The chasm is smaller in SFR, mostly due to power control method encompassed, which reduces the best case value.

3) Comparison: The comparison between the different ICIC approaches is given via accumulated results to showcase

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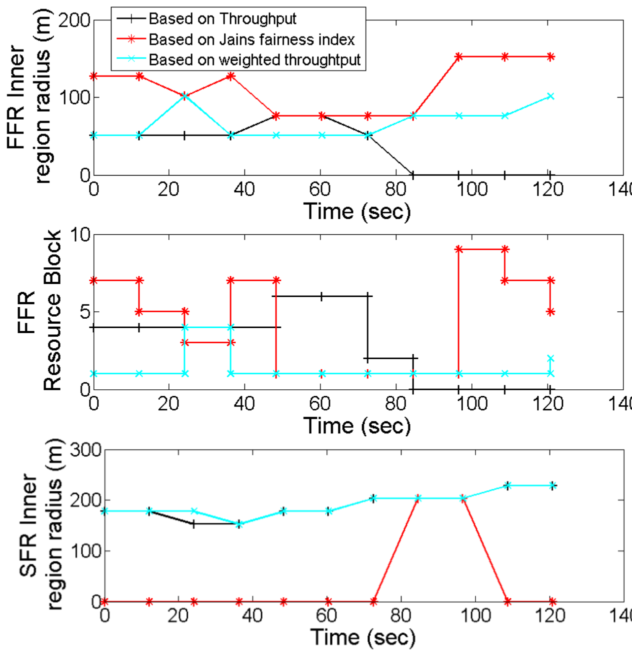
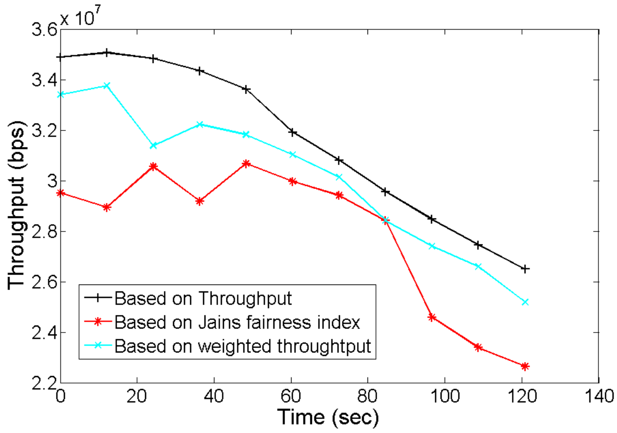


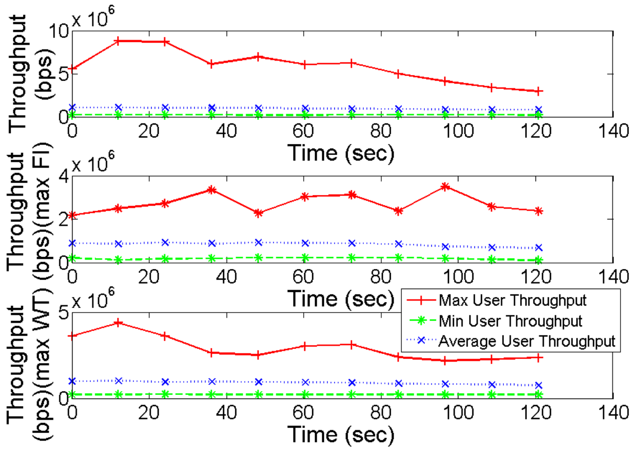
Fig. 3: Optimal resource and area allocation for each performance metric.

the trade-offs regarding the choice of the selected interference mitigation scheme, between the different aspects of network performance and resource utilization. As seen in Fig. 6a, IFR1 exhibits the worst performance regarding overall throughput, while IFR3 the best one as a result of exclusive frequency allocating. On the other hand, SFR and FFR provide a settlement between the two. Since the optimization process based on overall throughput for FFR led to IFR3, the two lines would normally coincide. Instead, the weighted throughput is chosen to be depicted for FFR, for a fairer approach as mentioned above. Additionally, SFR may seem that it performs poorly, but it should be noted that beside the added interference in SFR case, part of the difference with FFR is attributed to reduced transmit power for the cell-centre users which is not actually perceived as performance degradation by users. For a clear view on that matter, Fig. 6b shows the throughput achieved throughout the network for cell-centre and cell-edge users, distinctively, mostly highlighting the impact of interference on cell-edge users, where the power levels are similar and the performance is critical.

To conclude, the main motivation for adapting a certain allocation scheme, depends on the custom defined parameters, such as tolerable interference levels, overall and cell-edge performance goal, transmit power levels and the achieved spectral efficiency. Thus, the above results offered a behaviour analysis of each case, as well as attempted to showcase the simulator's capability to extract the trade-offs that are involved in seeking the optimal selection, between the different aspects of network performance and resource utilizing.



(a)



(b)

Fig. 4: FFR performance: (a) overall network throughput, (b) min, max and average user throughput.

IV. Conclusions & Future Work

In this paper, we presented a performance evaluation of ICIC main schemes in LTE-A systems, IFR, FFR and SFR. This evaluation has been made with the aid of a simulation framework that estimates the performance experienced by users in custom size and occupancy networks. Throughput and service distribution fairness are measured, with the latter representing the balance of quality in offered services within an area. An algorithm is employed seeking the optimal size and frequency configuration of the schemes. User mobility is simulated, and periodical recalculation is applied to ensure the optimal adaptation.

Results showed high variation in network's performance depending on the metric decided to give priority to. Cell-edge performance enhancement yields worse overall performance sacrificing spectral efficiency. Optimization for WT index provides a good compromise solution. Moreover, we found that the gain of searching for the optimal configuration of the ICIC integrated (radius, frequency allocation) proved to be quite substantial.

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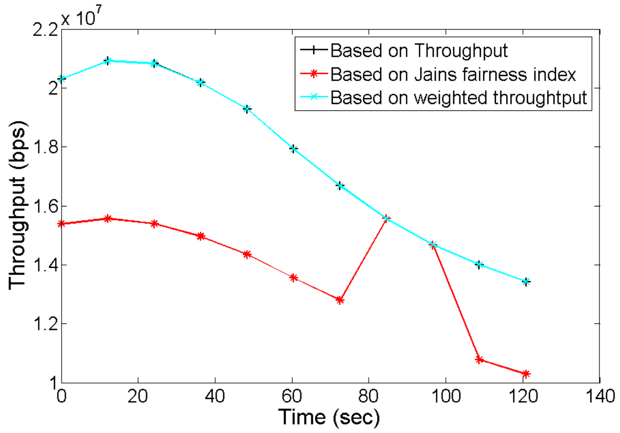
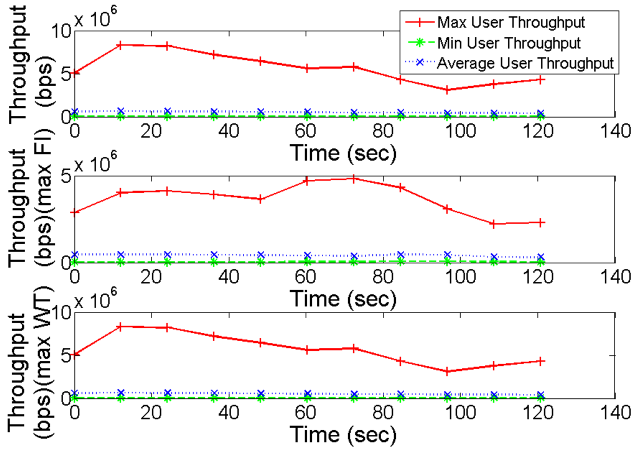
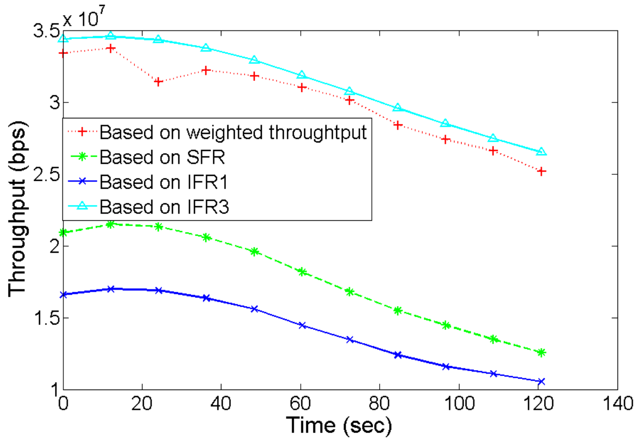


(a)

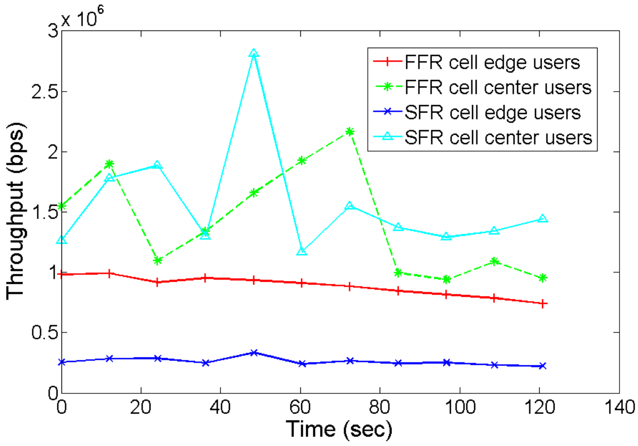


(b)

Fig. 5: SFR performance: (a) overall network throughput, (b) min, max and average user throughput.



(a)



(b)

Fig. 6: Throughput comparison between schemes: (a) for entire network, (b) by distinguishing cell-edge from cell-centre users.

Future research could elaborate on adding the capability of dynamic ICIC with coordinated eNBs or including different frequency or cell divisions such as adaptive SFR scheme. The simulation framework is available through [8] and can be used to evaluate ICIC behavior or for its further development.

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