Interference Management in LTE Femtocell Systems Using an Adaptive Frequency Reuse Scheme

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***Abstract*—Long Term Evolution (LTE) has developed a new technology in order to enhance indoor coverage. This new technology is called femtocells and is achieved with the use of access points installed by home users. However, interference problem between the femtocell and the macrocell decreases the system's capacity and as a result users' throughput. In this paper we study the interference mitigation techniques in femtocell/macrocell networks and we propose a frequency reuse mechanism that leads to increased overall system performance. In particular, the mechanism aims to maximize throughput via a variety of combinations between inner cell radius and frequency allocation to the macrocell. Additionally, a position minded frequency allocation to the femtocells targets to further optimize the total throughput of the cell.**

Keywords- frequency reuse; interference mitigation; long term evolution; femtocell;

I. Introduction

In modern societies the demand for higher data rates is quite intense and users expect to achieve comparable data rates in both wired and mobile networks. This has triggered the design and development of new data-minded cellular standards of which the Third Generation Partnership Project's (3GPP's) Long Term Evolution (LTE) appears to be the most promising candidate. The LTE is technologically based on Orthogonal Frequency Division Multiple Access (OFDMA) to achieve higher data rates and enhanced spectral efficiency. Knowing that radio spectrum is limited and becoming insufficient nowadays, it is inevitable to use precious spectrum resource wisely. One of the efficient ways of spectrum resource utilization is to apply Frequency Reuse, however if same sub-carriers are used by different users among adjacent cells, Co-Channel Interference (CCI) problem occurs especially for cell edge users. Appropriate inter-cell interference coordination technique should be required to enhance the system capacity [1].

The LTE has developed a femtocell for indoor coverage extension. Femtocells, also called home base stations (BSs) or Home Node-Bs (HNBs), are short-range low-cost low-power BSs installed by the consumer that work in the licensed frequency bands and they are connected to broadband Internet backhaul [2], [3]. A femtocell allows service providers to extend service coverage indoors, especially where access would otherwise be limited or unavailable. Therefore, the subscriber is satisfied with higher data rates and reliability and simultaneously the operator reduces the amount of traffic on expensive macrocell network.

Femtocells and macrocells could suffer severe CCI from each other if cell planning or spectrum management is not appropriately considered. Operating femtocells on a dedicated frequency band is a simple solution, but the frequency resources are not utilized effectively. Co-channel model is suitable for practical deployment and overcomes the problem of misuse, but the CCI problem should be solved. In [4] an extensive analysis of the different interference scenarios is provided considering closed access for OFDMA technologies while in [5], a proposal for interference avoidance is based on Dynamic Frequency Planning (DFP) in a survey conducted in a WiMAX network integrating femtocells. Frequency is dynamically assigned, considering user bandwidth demand, aiming to decrease interferences and therefore improve the network capacity. However the centralized approach of this solution is against the femtocell technology where the HNBs are supposed to be powered up and managed by a personal owner. The authors of [6] study various frequency reuse schemes in the OFDMA based network, such as the LTE, to overcome the CCI problems. Whole frequency band is divided into several sub-bands and each sub-band is allocated in the cells in different ways so as to mitigate interference. Fractional Frequency Reuse (FFR) and Two Level Power Control (TLPC) schemes with appropriate settings of inner region radius and power ratio provide the best performance when a scheduler fair in throughput is assumed. As a result, intra-cell interference is removed, and inter-cell interference is substantially reduced. Finally, the authors of work [7] propose a mechanism for optimal FFR scheme selection based on the mean user throughput or user satisfaction. This survey is conducted in a cellular network that does not support the existence of femtocells, however the use of user satisfaction as a metric of evaluation appears to be very interesting.

In this paper, a frequency reuse selection mechanism is proposed, aiming to reduce cross-tier CCI between macrocells and femtocells. Each macrocell is divided into inner and outer region and frequency is allocated with reuse factor 1 and reuse factor 3 respectively. The frequency band that will be used in each region is calculated for every possible combination of inner cell radius and subcarrier allocation. For femtocells, frequency allocation is done according to the femtocells's

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position in the network. Each femtocell chooses a frequency band which is different from the sub-band already used for the macrocell located in the same area and this frequency allocation is expected to further improve network's performance. The mechanism computes the total throughput of the cell and user satisfaction for each pair of radius an frequency and finally selects the optimal frequency allocation scheme. Inner cell radius and the number of subcarriers to be allocated in each region are selected so as to maximize the value of user satisfaction. A method to evaluate the proposed scheme is via the estimation of the adjacent cell interference. For the calculation of the desired results an analytical model analysis is used, that takes into account the path loss and propagation in order to estimate the SINR and therefore the adjacent cell interference due to femtocells. Finally, those results are compared with other frequency reuse schemes.

The remaining of this paper is structured as follows. The proposed network model is described in Section II. Section III analyzes the simulation mechanism. Section IV presents the equations which will be used for the implementation of the proposed scheme and Section V gives performance evaluation and comparison of the proposed method with other frequency reuse schemes. Finally, Section VI includes the conclusions of this study and ideas for future work.

II. Proposed Network Model

The primary goal of this survey is to enhance throughput for both femto and macro users. One way to achieve this is to mitigate interference with frequency reuse schemes.

To this direction FFR is applied to each macrocell of the topology, as shown in Figure 1, in order to reduce interference between adjacent cells and enhance throughput.

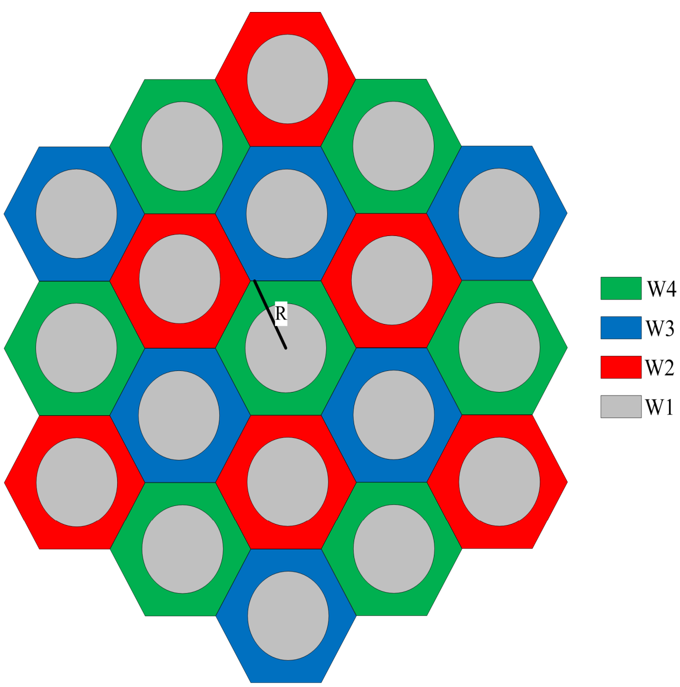

Figure 1. Frequency band allocation using FFR with reuse factor 3.

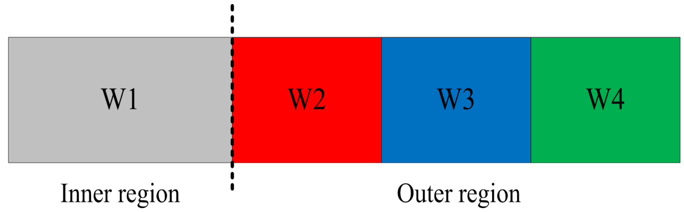

Figure 2. Frequency band division.

Each hexagonal cell of radius R is divided into inner (gray color) and outer region (colors red, green and blue). One part of the available frequency band is dedicated to the cell centre users with reuse factor of 1 (frequency band W1), while the rest of the spectrum is equally divided in three sub-bands and assigned to the cell edge users with reuse factor of 3 (frequency bands W2, W3 and W4). The frequency band division is depicted in Figure 2.

If a femtocell is located in the outer region of a macrocell, then the sub-band used for the inner region can be reused for the femto users. On the contrary, a femtocell dropped in the inner region cannot reuse the sub-band which was assigned to the cell edge users of the macrocell. The reason is the transmit power of the BS in each case. Inner cell users are closer to the BS, which means that lower transmit power is required. On the other hand, the BS should transmit in maximum power in order to satisfy cell edge users. For example, according to Figure 1, if a femtocell is operating in the outer region of the central cell (colored with gray and green) it can use not only sub-bands W3 and W2 (red and blue that are assigned to the outer regions of the adjacent cells) but also sub-band W1 (gray) even if it is already used in this macrocell. Under these conditions, the interference from the macrocell to the femtocell and vice versa will be reduced.

III. Mechanism Description

The mechanism receives as input the macrocell environment dimensioning, the number of femtocells and their positions as well as other characteristics of the network such as the macrocell and femtocell BS transmission power. Consequently it calculates the received power from serving as well as from the interfering cells and based on these values and by taking into account the white Gaussian noise, the mechanism is able to make an estimation of the SINR and throughput at any given position of the examined LTE network. Finally, user satisfaction for each cell is calculated via the values of throughput of each user.

The mechanism follows the approach presented below:

- Calculate inner cell radius

Given the macrocells' characteristics, different radiuses from 0 to R are examined in order to find the best dimensions of the inner cell that optimizes user satisfaction for the cell users.

- Find the optimum frequency band division

The aim of this step is to calculate user satisfaction for every possible combination of spectrum division. The available spectrum will be allocated to the users according to the combination that maximizes user satisfaction. There are two disjoint sets of subcarriers. Set I that contains the subcarriers of the inner region and set O that contains the subcarriers of the outer region. There are totally 26 different cases and every time the frequency band that is allocated to the outer region is equally divided between W1, W2 and W3. Initially, set I is an empty set and all the subcarriers are contained in set O, which means that all the subcarriers are allocated to the outer region and each one of W1, W2 and W3 equals to 25/3. In each one of the following cases one subcarrier is removed from set O and is added to set I. Finally, in the 26th case, set I consists of 25 subcarriers and set O is an empty set.

- Allocate frequency band to the femtocells

In this step frequency is allocated to the femtocells with the process presented in Section II.

The The pseudo-code that follows presents briefly the general idea of the mechanism.

```
create_topolgy() %defines cells and drops femtocells and users
for r = 0: R %inner cell radius
  for f = 0: 25 %frequency band division
    allocate frequency band for macrocells
    if r > = distance_femto %femtocell belongs to inner cell
      allocate frequency band for femtocell
    else %femtocell belongs to outer cell
      allocate frequency band for femtocell
    end
    for u = 1 : U %all users
      sinr = calculate_sinr(u)
      capacity = calculate_capacity(u)
      throughput = calculate_ throughput(u)
    end
    US = calculate_user_satisfaction(r, f)
  end
end
define_FFR(max_ user_satisfaction)
```

IV. Analysis Of Mechanism

This section presents the simulation model that will be used in our analysis. It estimates the cross-tier interference and the throughput in every point of the LTE network integrating femtocells and macrocells. Based on the proposed network scheme the model takes into account the path loss and propagation models in order to estimate the SINR and therefore the adjacent cell interference of the integrated LTE network.

In order to evaluate the performance of a link we can use either block error ratio (BLER) or throughput. In this paper we will continue our analysis with the help of throughput performance. To formulate the equation for the system throughput, first of all we will need an equation for the SINR calculation. The received SINR for a macro user i on a subcarrier n can be expressed as [8] :

$$SINR_{i,n} = \frac{P_{M,n} G_{i,M,n}}{N_0 \Delta f + \sum_{M'} P_{M',n} G_{i,M',n} + \sum_{F} P_{F,n} G_{i,F,n}} \qquad (1)$$

where, $P_{M,n}$ and $P_{M',n}$ is transmit power of serving macrocell M and neighboring macrocell M' on subcarrier n, respectively. $G_{i,M,n}$ is channel gain between macro user i and serving macrocell M on subcarrier n and $G_{i,M',n}$ corresponds to channel gain from neighboring macrocell M'. Transmit power of neighboring femtocell F on subcarrier n is denoted by $P_{F,n}$ and $G_{i,F,n}$ represents channel gain between macro user i and neighboring femtocell F on subcarrier n. Finally, N_0 is white noise power spectral density and Δf is subcarrier spacing.

In case of a femto user f, the received SINR on a subcarrier n can be similarly given by [8] :

$$SINR_{f,n} = \frac{P_{F,n} G_{f,F,n}}{N_0 \Delta f + \sum_{M} P_{M,n} G_{f,M,n} + \sum_{F'} P_{F',n} G_{f,F',n}} \qquad (2)$$

where, F' is the set of interfering femtocells.

The channel gain G is dominantly affected by path loss, which is different for macro users and femto users. The path loss between a macro BS and a User Equipment (UE) is modeled as [9] :

$$PL = 15.3 + 37.6 \log_{10}(d) + L_{ow} \qquad (3)$$

For the case of an outdoor user, L_{ow} is set to 0. The path loss between a femto BS and a UE in the same house is given by the following equation [9] :

$$PL = 38.46 + 20 \log_{10}(d) + 0.7 d_{2D,indoor} + 18.3 n^{((n+2)/(n+1) - 0.46)} + qL_{iw} \qquad (4)$$

and in the case that the UE is not in the same house, path loss is given by [9] :

$$PL = \max(15.3 + 37.6 \log_{10}(d), 38.46 + 20 \log_{10}(d)) + 0.7 d_{2D,indoor} + 18.3 n^{((n+2)/(n+1) - 0.46)} + qL_{iw} + L_{ow1} + L_{ow2} \qquad (5)$$

For the case of an outdoor user, L_{ow2} is set to 0.

In the equations of path loss, d is the distance between the transmitter (Tx) and the receiver (Rx) in meters and L_{ow} and L_{iw} corresponds to penetration loss of an outdoor and indoor wall respectively which are set to L_{ow} = 20 dB and L_{iw} = 5 dB. Especially for path loss between a femto BS and a user, n is the number of penetrated floors, q is the number of walls separating apartments between the femto BS and the UE and the term $0,7d_{2D,indoor}$ takes account of penetration loss due to walls inside an apartment with $d_{2D,indoor}$ representing the distance inside the house.

So, the channel gain can be expressed as follows [8] :

$$G = 10^{-PL/10} \qquad (6)$$

Additionally, for the throughput calculation, we use the capacity of a user *i* on a specific subcarrier *n*, which can be estimated via the SINR from the following equation [8] :

$$C_{i,n} = W \cdot \log_2(1 + aSINR_{i,n}) \quad (7)$$

where W is the available bandwidth for subcarrier n divided by the number of users that share the specific subcarrier and α is a constant for a target bit error rate (BER) defined by $\alpha = -1.5 / \ln(5BER)$. Here we set BER to 10^{-6}.

So the expression of the total throughput of the serving macrocell M is [8] :

$$T_M = \sum_i \sum_n p_{i,n} C_{i,n} \quad (8)$$

where $p_{i,n}$ is an assignment index variable with $p_{i,n} = 1$ implying that subcarrier n is assigned to user i and $p_{i,n} = 0$ otherwise. In the specific paper the study is done for LTE systems, which means that each subcarrier can be only occupied by one user in the same cell in each time slot. Supposing that N_i is the number of users in a macrocell, this implies that:

$$\sum_{i=1}^{N_i} p_{i,n} = 1 \quad (9)$$

The expressions for the capacity (equation (7)) and the total throughput (equations (8) and (9)) are similar in the case of a femto user.

In [7] the term User Satisfaction (US) is introduced. The authors have proved that US guarantees slight differences in users' throughput values. US physically presents how close the user's throughput is to the maximum throughput of a user dropped in the same cell. When US approaches 1, all users in the cell experience similar throughput. On the contrary, when there is big difference in the throughput achieved by the users in the cell, US value approaches to 0. US can be expressed as [7] :

$$US = \frac{\sum_{i=1}^{U} T_i}{max\_user\_throughput \cdot U} \quad (10)$$

where U is the total number of users in the specific cell, T_i is the throughput of each user (either macro or femto user) and *max_user_throughput* is the maximum throughput value achieved by a user in this cell.

The mathematical analysis presented previously will be the basis for the implementation of the simulation mechanism that will help us to evaluate the solution proposed for the scenarios which will be examined in this paper.

V. PERFORMANCE EVALUATION

A. Scenarios Presentation

The simulation parameters that will be used for the experiment are listed in Table I.

The transmit power of the femto BS is 20 mW and the macro BS transmits for the edge region with 22 W and for the centre zone with 15 W. Furthermore we consider a system with 10 MHz of bandwidth divided into 25 subcarriers of 375 kHz of bandwidth and 15 kHz of subcarrier spacing. A fixed number of 100 femtocells randomly located in the network area is used only for the calculation of the optimum parameters for the proposed scheme. In the experiments for the comparison with other frequency reuse schemes varying number of femtocells from 0 to 5 femtocells per macrocell were used.

TABLE I. SIMULATION PARAMETERS

Parameters	**Values**	
	Macro	***Femto***
Number of cells	19	100
Radius	250 m	20 m
BS transmit power	15, 22 W	20 mW
Bandwidth	10 MHz	
Subcarriers	25	
Subcarriers' bandwidth	375 kHz	
Subcarrier spacing	15 kHz	
Carrier frequency	2 GHz	
Channel model	3GPP Typical Urban	
Power Noise Density	-174 dBm / Hz	

The following scenarios will be used as a means to evaluate the proposed scheme presented previously:

- In the same network topology Integer Frequency Reuse (IFR) with reuse factor 1 is applied which means that all the available bandwidth is used in each macrocell. Furthermore, each femtocell uses the same frequency band.

The available spectrum is divided into 3 equal sub-bands and IFR with reuse factor 3 is applied to the macrocells of the network. As a result, each macrocell uses a sub-band which is different from all the neighboring macrocells. Frequency allocation to the femtocells is done according to their position, which means that each HNB can only transmit in the two sub-bands that are not used by the macrocell where the femtocell belongs.

B. *Numerical Evaluation and Comparison*

This section presents the operation of the mechanism and the application of the proposed FFR scheme with the values that maximize user satisfaction. Figure 3 depicts the network topology presented previously and particularly the central cell (colored with green outer region). Users and femtocells are distributed uniformly in the topology and optimal inner cell radius and subcarrier allocation is calculated via the experiment.

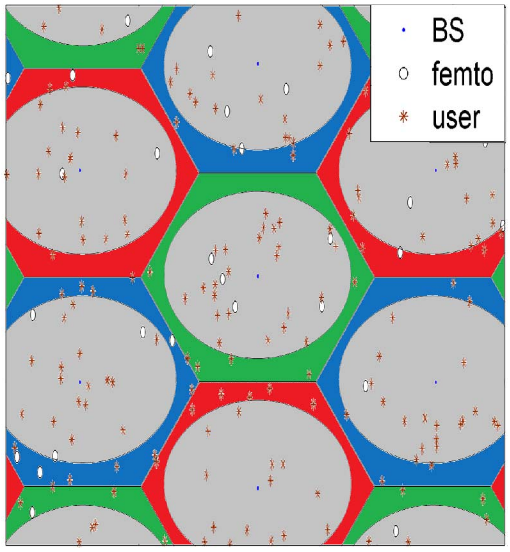

Figure 3. Network Topology with the application of FFR for optimal radius.

In the central cell there are 30 users and 5 femtocells randomly located. With the proposed mechanism the inner cell radius that maximizes user satisfaction was calculated and equals to 175m which means that all the femtocells and 24 users belong to the inner region while the remaining 6 users were dropped in the outer region of the cell.

Figure 4 depicts US while the number of subcarriers allocated to the inner cell varies from 0 to 25 for the optimum inner cell radius presented in Figure 3.

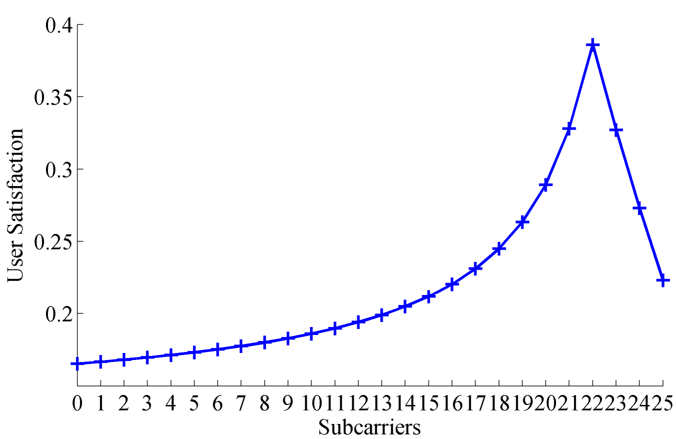

Figure 4. User Satisfaction vs subcarriers allocated to inner region for optimal inner radius.

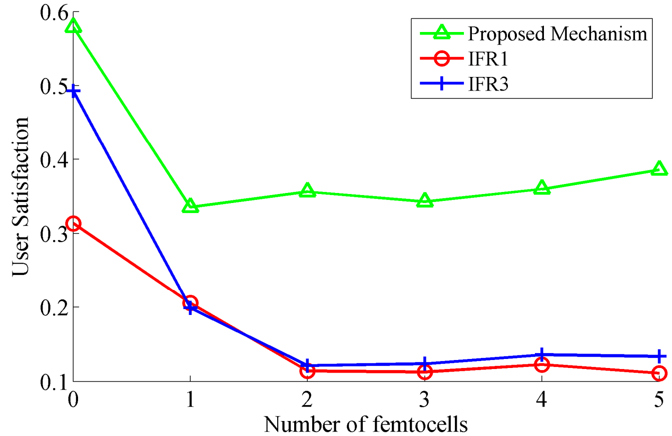

Figure 5. User satisfaction vs number of femtocells.

The conclusion of Figure 3 and Figure 4 is that the maximum value of user satisfaction which is 0.3859 was achieved for inner cell radius 175m while allocating 22 subcarriers for the inner region and the remaining 3 for cell edge users which corresponds to 8.25 MHz and 1.125 MHz respectively. As the number of subcarriers allocated to the inner cell increases, user satisfaction increases too and maximizes for 22. This is rational and can be explained by the fact that almost all the users belong to the inner region, which means that the majority of the subcarriers should be allocated to the cell centre.

Figure 5 shows how US changes as number of femtocells per macrocell increases from 0 to 5. In order to evaluate the proposed mechanism we present a comparison with IFR with reuse factor 1 (IFR1) and IFR with reuse factor 3 (IFR3).

According to Figure 5, the cases of IFR1 and IFR3 achieve similar values of user satisfaction and about three times smaller than the proposed scheme when there are more than 1 femtocells. This is very important because it indicates that there is fairness among all the users and the resources are distributed in a way that everyone will have throughput values with little variation from the maximum one. The sudden drop of user satisfaction in the case of IFR1 and IFR3 when the first femtocell appears indicates the absence of an algorithm that will distribute appropriately the resources among the users. As soon as there are femto users, big part of the available bandwidth is allocated to them leading to disproportionate values of throughput and reducing user satisfaction.

Figure 6 illustrates another comparison between the proposed scheme and the cases of IFR1 and IFR3. The assumption is again that the number of femtocells varies from 0 to 5, although this time throughput values are plotted. In each case is calculated the minimum (min) and maximum (max) value of throughput of a user as well as the average value of throughput for all the users being served by the same cell. Through this experiment we aim to prove once again the fairness of the proposed mechanism. For that reason Figure 6 focuses to an overall comparison of all the cases and less attention is paid to the values of throughput in each case separately.

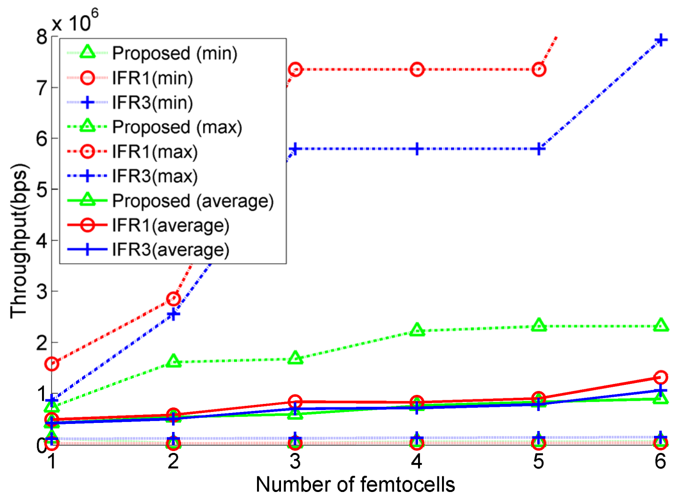

Figure 6. Throughput vs number of femtocells.

The most valuable observation from Figure 6 is that the average values of throughput of the proposed mechanism are close enough to the minimum and maximum value of this technique. This slight difference indicates that all the users experience values of throughput with little variance. This is exactly what was expected, because using US as a metric for the application of the FFR, all the users are served with comparable quality. On the contrary, the cases of IFR1 and IFR3 have average values of throughput close enough to the worst case, however the values of maximum throughput are extremely high giving a sense of injustice in the way that the users are treated.

In the experimental process the characteristics of the FFR scheme to be applied were selected using US. The value of inner cell radius and the distribution of subcarriers were those that maximized US. The reason is that US allocates frequency in a way that enables all the users to achieve comparable values of throughput. Figure 7 presents the comparison of user throughput for two different metrics. In each case throughput for every user is calculated based on maximum US or maximum total cell throughput. It should be highlighted that users 3, 4, 7, 10, 26 and 29 are femto users while the rest of them are macro users.

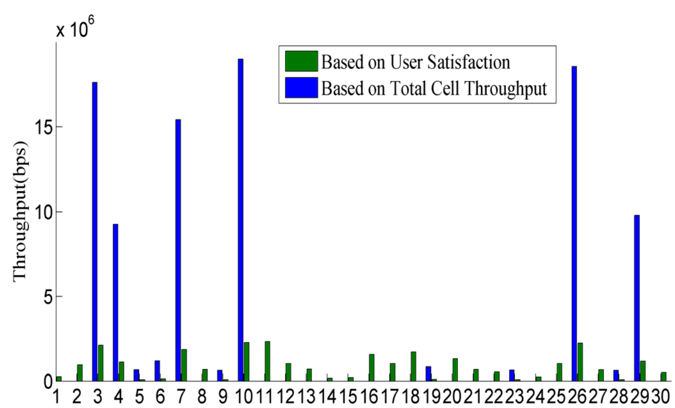

Figure 7. Per user throughput based on User Satisfaction and Total Cell Throughput.

It is worth noting that user throughput is lower when US is the metric, however high values of throughput are sacrificed in order to serve the users in a more fair way. On the contrary, applying FFR in a way that maximizes total cell throughput leads to an unfair distribution of the available resources. The biggest part of the available bandwidth is allocated to the femto users and as a result they achieve big throughput values - almost ten times bigger than the macro users - which maximizes total cell throughput. Additionally, Figure 7 shows that when total cell throughput is used as a metric, there are users that are not served at all. These are the users that belong to the cell centre. As soon as inner cell increases and includes all the femtocells, all the subcarriers are allocated to the outer cell. In this occasion there is the maximum profit for a femto user. On the contrary, using user satisfaction as a metric reassures not only to serve the inner cell users, but also with similar values of throughput with the cell edge and the femto users.

VI. CONCLUSIONS AND FUTURE WORK

The research in this paper focused in the mitigation of the interference in LTE networks that integrate femtocell overlay. Our technique is based on the idea of frequency reuse in order to reduce SINR and achieve higher values of throughput. The proposed mechanism selects the optimum values for the application of the FFR based on the maximization of user satisfaction. Our mechanism seems to be far more effective when it comes to fairness even though it seems to be worse concerning total cell throughput. For further evaluation we present the comparison when maximization of total cell throughput is used as a metric and scenarios where different frequency reuse schemes are applied.

An interesting suggestion for future work could be the import of more variables in the proposed model, aiming to provide more realistic scenarios. For example, we could take care of the case that the user is served by a femtocell that belongs to another apartment, adding more factors in the path loss equations. Additionally we could generalize the proposed mechanism in order to support users' mobility. However this implies the reduction of complexity in the computations in order to become feasible the extraction of results from such a complicated model.

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