Fractional Frequency Reuse in Integrated Femtocell/Macrocell Environments

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Abstract. Femtocells have a strong potential for increasing the efficiency, cell coverage and network capacity of next-generation mobile networks. In Long Term Evolution technology, the adaptation of Fractional Frequency Reuse techniques has been proposed in order to overcome the co-channel interference and augment the total throughput of the network. In this work, we propose a Fractional Frequency Reuse method that on the one hand calculates the optimal inner region radius and frequency allocation of a macrocell and on the other hand assigns frequency resources to the femtocells in order to mitigate the co-channel interference. We apply this method in an integrated femtocell/macrocell environment and evaluate it based on the optimization of three metrics, depending on the network operator's needs.

Keywords: Fractional frequency reuse, channel interference, throughput.

1 Introduction

The integrated femtocell/macrocell environments comprise of a conventional cellular network overlaid with shorter-range self-configurable base stations (BS), called femtocells [1]. These kinds of networks offer an efficient way to improve cellular system capacity. The limiting factor in such networks is the interference between macrocells and femtocells that can suffocate the capacity due to the near-far problem. This means that femtocells should use a different frequency channel than the one of the potentially nearby high-power macrocell users (MUs). Fractional Frequency Reuse (FFR) techniques are discussed in Long Term Evolution (LTE) networks to overcome the Co-Channel Interference (CCI) problems, i.e., interference from transmitters located in neighbor cells with the same frequency bands as the reference cell of interest, and Inter-Cell Interference (ICI) problems, i.e., interference from neighboring cells. In FFR techniques the cell space is divided into two regions: inner, which is close to the macrocell BS and outer, which is situated to the cell borders.

There are several published related works that concern FFR techniques for interference mitigation in femtocell/macrocell deployments. In [2], the authors propose a scheme that adapts radio frequency parameters taking into account all the user and channel conditions. Furthermore in [3], a hybrid frequency assignment framework is introduced for femtocells and different scenarios of femtocell CCI are

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analyzed. The authors of [4] propose a frequency planning mechanism, in which femtocells choose the frequency sub-bands that will not be used in the sub-region of a macrocell using FFR in an integrated macrocell/femtocell network. Work in [5] proposes a novel frequency partitioning method, in which both sub-channels for inner cell region and sub-channels for outer region are allowed to be used in the inner region of cells while sub-channels for outer region are defined differently from cell to cell to reduce CCI. Another FFR scheme is introduced in [6], by noting that the inner and the outer regions can be served in a different way, not only in terms of frequency sub-bands but also in terms of time slots. This scheme is extended further in [7], by employing the concept of making cell sectors. Finally, the authors of [8] propose an interference avoidance scheme for LTE downlink using dynamic inter-cell coordination, facilitated through the interface between neighboring LTE BS.

Although these works provide very useful ideas regarding FFR techniques, they do not offer methods that take into consideration real parameters from the network operator's side nor do they optimize the network conditions according to them. In this paper, we focus on the downlink process of an integrated femtocell/macrocell environment by evaluating several metrics related to the fairness of the network resources. We propose an FFR method that calculates the optimal inner region radius and bandwidth allocation as well as assigns the proper frequency resources to the overlaid femtocells in order to reduce the total interference. The proposed method is evaluated for three different approaches. The 1st approach finds the optimal inner region radius and frequency allocation based on the maximization of the network's total throughput, the 2nd one based on the Jain's Fairness Index and the 3rd one based on a new metric, which is called weighted throughput. This metric aims to make a trade-off between the total cell throughput values and the per-user throughput values that occur from the two previous approaches, so as higher cell throughput are achieved simultaneously with similar per-user throughput values. The proposed FFR method aims to enhance the total cell throughput and allocate the network resources in a fair way among the MUs and femtocell users (FUs).

The paper is organized as follows. Section 2 introduces the downlink interference scenarios and the proposed frequency allocation scheme. Section 3 presents the theoretical approach of the proposed FFR method. The evaluation of the proposed method is presented in Section 4 and the final conclusions and proposals for future work are drawn up in Section 5.

2 Frequency Allocation in Femtocell/Macrocell Environments

In FFR the whole frequency band is divided into several sub-bands, and each one is exclusively assigned to inner and outer region of the cell respectively. In order to ensure that the mutual interference between users and BSs remains below a harmful level, adjacent cells use different frequencies. The interference scenarios that appear in such integrated femtocell/macrocell environments during the downlink session are described in Fig. 1. In more detail, the interference caused to a FU by a macrocell BS (Scenario 1), the interference caused to a MU by a femtocell BS (Scenario 2) and the interference caused to a FU by a neighboring femtocell BS (Scenario 3) are depicted.

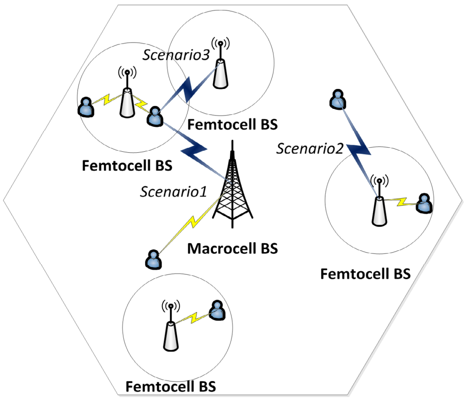

Fig. 1. Downlink interference scenarios in an integrated femtocell/macrocell environment

In order to mitigate these kinds of interference, we apply a specific frequency allocation scheme for the MUs and FUs. As shown in Fig. 2, each cell of the architecture is divided into inner and outer region. The total available bandwidth of the system is split into four uneven spectrums (or resource sets), denoted by yellow (A), blue (B), red (C) and green (D) colors. All the MUs that are located in the inner region of each cell, are assigned sub-band A. The MUs located in the outer region will be assigned one of the rest sub-bands (B, C or D). If a FU is located in the outer region of a cell, then the sub-band used for the inner region plus the sub-bands that are used in the outer region of the neighboring cells can be reused. According to this allocation, each femtocell BS adopts an effective frequency assignment, assuring that MUs/FUs use different frequencies and the CCI is reduced.

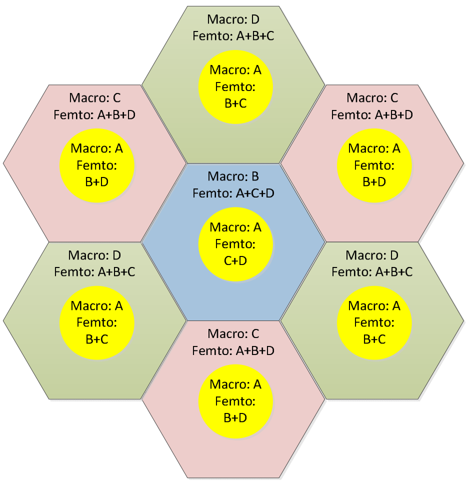

Fig. 2. Proposed frequency allocation for an integrated femtocell/macrocell environment

3 Theoretical Approach and Method Description

In this section we describe the theoretical approach for calculating the metrics that are related to the proposed FFR method: Signal Interference to Noise Ratio (SINR), cell total throughput, Jain's Fairness Index (JI) and Weighted Throughput (WT). Then, we introduce the proposed FFR method by presenting its pseudo-code.

3.1 Calculation of Metrics

We assume that the overall network is composed of N adjacent cells. Each cell contains a number of users (either MUs or FUs) seeking to share a group of subcarriers. The macrocell BSs are located at the center of each cell. Femtocell BSs are uniformly distributed in the topology. Moreover, we consider that the MUs are outdoor users whereas the FUs are located indoors. We use the path loss suburban model described in [9], for the calculation of the path loss between an outdoor MU and a macro BS (with frequency of 2GHz):

$$PL_{MU}[dB] = 15.3 + 37.6\log_{10}(d[m]) + S^{out} \tag{1}$$

where d is the distance between the transmitter and the receiver and S^{out} factor represents the outdoor shadowing which is characterized by the Gaussian distribution with zero mean and standard deviation. In the same way, we calculate the path loss between an indoor FU and a femto BS:

$$PL_{FU}[dB] = 38.46 + 20\log_{10}(d[m]) + 0.7d_{2D,indoor} + 18.3n^{((n+2)/(n+1)-0.46)} \tag{2}$$

where n is the number of penetrated floors and in case of a single-floor house, the last term equals to zero. The term $0.7d_{2D,indoor}$ takes into account the penetration loss by the walls inside a house with $d_{2D,indoor}$ representing the distance in the house. So now we can define the channel gain as [8]:

$$G = 10^{-\frac{PL}{10}} \tag{3}$$

The downlink SINR that a user receives depends on the interference of the cells that include the user within their range. For the case of MU m on subcarrier n, we consider both the impact of the adjacent macrocells and overlaid femtocells. So the SINR for this case is defined as [8]:

$$SINR_{m,n} = \frac{G_{M,m,n} \cdot P_{M,n}}{\sigma_n{}^2 + \sum\limits_{neigM} G_{m,neigM,n} \cdot P_{neigM,n} + \sum\limits_{F} G_{m,F,n} \cdot P_{F,n}} \tag{4}$$

where $P_{X,n}$ is the transmit power of the serving BS X on subcarrier n (X can be either the macrocell M or the neighboring macrocell $neigM$ or the femtocell F). The term $G_{x,X,n}$ refers to the channel gain between user x and the serving cell X (where x can be an MU or a FU and X his serving BS). It is calculated from (1) for the MU and from (2) for the FU. Finally, the term σ_n^2 is the power of the Additive White Gaussian Noise (AWGN). Consequently, the expression for the SINR of a FU is expressed as follows, taking into account the interference caused by neighboring femtocells (*neigF*) and the macrocells that use the same frequency bands:

$$SINR_{f,n} = \frac{G_{F,f,n} \cdot P_{F,n}}{\sigma_n^2 + \sum_{neigF} G_{f,neigF,n} \cdot P_{neigF,n} + \sum_{M} G_{f,M,n} \cdot P_{M,n}} \tag{5}$$

After the SINR estimation, we proceed to the throughput calculation. The capacity of user x on subcarrier n can be calculated by the following [10]:

$$C_{x,n} = \Delta f \cdot \log_2(1 + aSINR_{x,n}) \tag{6}$$

where, Δf refers to the subcarrier spacing. The constant term α is connected with the target bit error rate (*BER*) as follows $\alpha = -1.5/\ln(5BER)$. Moreover, the overall throughput of a serving macrocell can be expressed as follows [4]:

$$T_M = \sum_m \sum_n \beta_{m,n} \cdot C_{m,n} \tag{7}$$

where, $\beta_{m,n}$ represents the subcarrier assignment to MU m. When $\beta_{m,n}=1$, the subcarrier n is assigned to MU m. Otherwise, $\beta_{m,n}=0$. A similar expression can be derived for FUs. To obtain a metric of fairness for the proposed FFR method we use the JI metric, firstly introduced in [11]. Assuming the allocated throughput for user i is x_i, then JI is defined as:

$$JI = \frac{\left(\sum_{i=1}^{\#users} x_i\right)^2}{\#users \cdot \sum_{i=1}^{users} x_i^2} \tag{8}$$

This metric is very interesting for the evaluation of the proposed method due to its properties. It is scale-independent, applicable for different number of users and it is bounded between [0, 1], where 0 means “total unfairness” and 1 means “total fairness” in terms of throughput division among the users. In the following section, we are going to prove that the optimization of the throughput favors the users that are located next to the BS whereas the optimization of JI assigns similar per-user throughput values but the total cell throughput remains quite low. In order to make a trade-off between the achieved total cell throughput and the per-user throughput values that occur from the previous approaches, we introduce one more named WT and we define it as:

$$WT_x = JI_x \cdot T_x \tag{9}$$

where *x* is the corresponding user (either FU or MU), which we calculate the metric for. By introducing this metric, we aim not only at the low variance of the per-user throughput values but also at higher values of the cell total throughput.

3.2 Proposed FFR Method

The proposed FFR method receives as input the integrated femtocell/macrocell environment with all its parameters (i.e., the number of femtocells, macrocells, FUs, MUs, and their positions in the deployment). In order to find the optimal FFR scheme, the method divides each cell into two regions (inner and outer) and scans all the inner region radiuses and frequency allocations. The frequency allocation is examined in terms of resource blocks (RBs), the minimum allocation unit in LTE both for protocol side and system resource allocation [9]. For each RB, the method calculates the per-user throughput, the cell total throughput, JI and WT. This procedure is repeated for successive inner region radiuses (0 to *R*, where *R* is the cell radius). After the above calculations, the method chooses the optimal FFR scheme that maximizes the cell total throughput, the JI and the WT. The pseudo-code that follows describes the main idea of the proposed FFR method.

```
% Pseudo-code for the proposed FFR method
generate_network();
generate_MUs();
generate_FUs();
for r=0:R                  %scan all the radiuses
   for b=0:50              %scan all the RBs
      allocate_RBs();      %according to Fig. 2
      for x=1:X %for all users
          calculate_sinr(x);
          calculate_capacity(x);
         calculate_througput(x);
      end
      calculate_total_througput(r,b);
      calculate_JI(r,b);
      calculate_WT(r,b);
   end
end
select_optimal_radius&rb_throuputApproach();  %1st
                                              % approach
select_optimal_radius&rb_JIApproach();          %2nd
                                              % approach
select_optimal_radius&rb_WTApproach();          %3rd
                                              % approach
```

4 Performance Evaluation

4.1 Simulation Parameters

The simulation parameters for the examined system that are necessary for the conduction of the experiments are presented in Table 1. We consider a topology of 16 cells sites with 360 uniformly distributed users and 90 uniformly distributed femtocells (Fig. 3). Our experiments focus on one cell of the topology (second row and third column). This cell contains 7 femtocells, 5 FUs and 22 MUs.

Table 1. Simulation parameters

Parameter	Units	Value
System bandwidth	MHz	10
Resource Blocks (RB)		50
Carrier frequency	MHz	2000
Macrocell / Femtocell Radius	m	250 / 40
Correlation distance	m	40
Channel model		3GPP Typical Urban
Path loss	dB	Suburban deployment
Macrocell BS transmit power	W	20
Femtocell BS transmit power	mW	20
Power Noise Density	dbm/Hz	-174
Intersite Distance	m	500

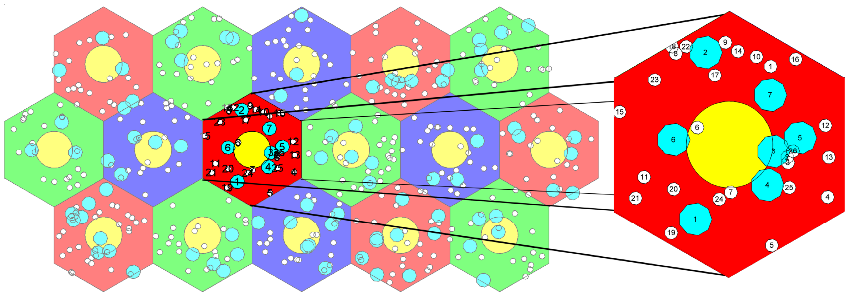

Fig. 3. Multicell integrated femtocell/macrocell environment

4.2 Operation of the Proposed FFR Method

Selection of Optimal Inner Region Radius and RB

The first experiment shows how the proposed FFR method chooses the optimal inner region radius and frequency allocation for the three approaches. Fig. 4 depicts the selection of the optimal inner region radius whereas Fig. 5 shows how each metric change while the number of RBs allocated to the inner region varies from 0 to 50.

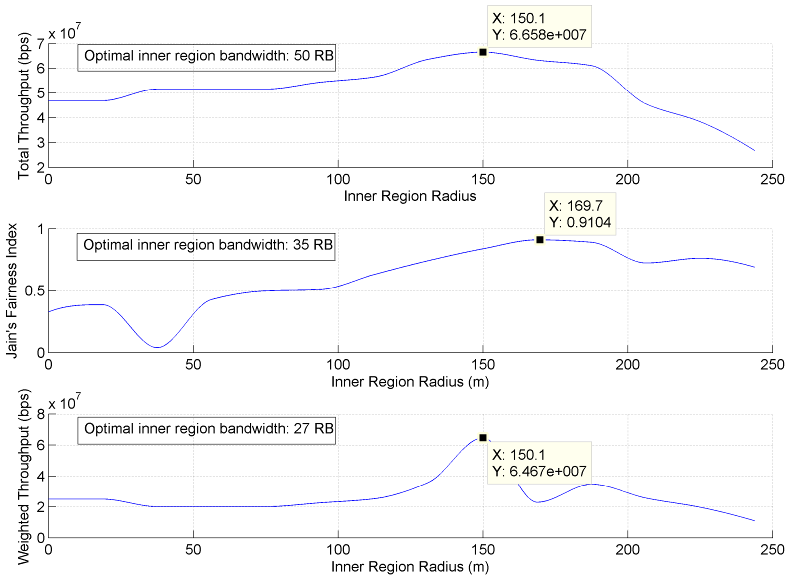

Fig. 4. Selection of optimal inner region radius

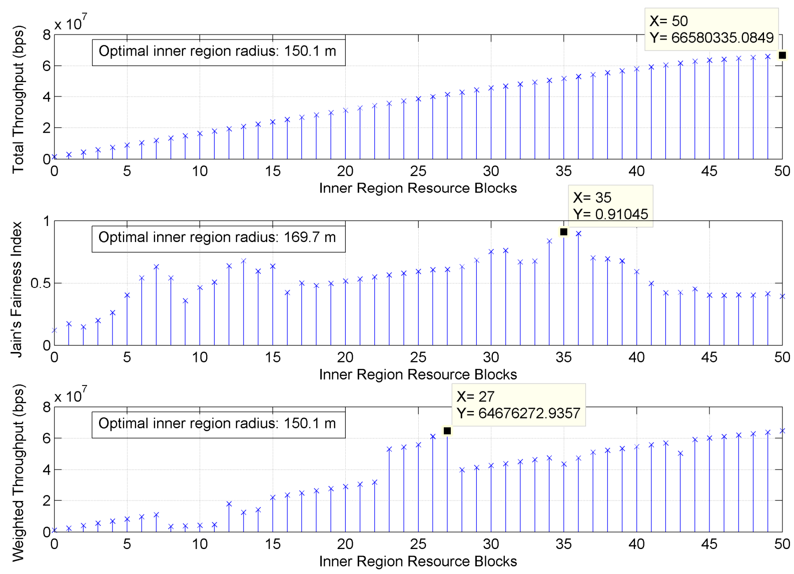

Fig. 5. Selection of optimal inner region RB

In both figures, we mark the optimal combination of inner region radius and RB for each approach. In the 1st approach, the maximum value of the cell total throughput is 66.58Mbps (150.1m radius and 50 RBs). This means that the method assigns all the

RBs to the inner region due to the fact that almost all the users are located in the inner region. In the 2nd approach, the JI is maximized (0.9104) for 169.7m radius and 35 RBs. Finally, the 3rd approach maximizes the WT (64.67Mbps) for 150.1m radius and 27 RBs.

Per-User throughput for Each Approach

After demonstrating the operation of the proposed FFR method for the three approaches, we examine the per-user throughput achieved by each one of the approaches. In Fig. 6 we depict the per-user throughput of an environment consisting of 5FUs (users 5, 6, 12, 15 and 22) and 22MUs for the three approaches. The 1st approach that chooses the optimal inner region radius and RB based on the total throughput, leads to an unfair distribution of the available frequency resources. It is remarkable, that in this case the users are treated in two different ways; there are users that achieve very high throughput values whereas there are others with quite low values. This is rational, because the 1st approach assigns all the available bandwidth to the inner region and the users of the outer region are not served. Consequently the femtocells BS of the outer region are allocated with the biggest bandwidth part whereas the ones located in the inner region achieve quite low values (Fig. 2). That is the reason why FU 22, covered by femtocell 2 (Fig. 3) achieves the highest throughput value (24.198 Mbps). For this approach the average user throughput equals to 2.466Mbps and the minimum throughput value is 1.905Kbps.

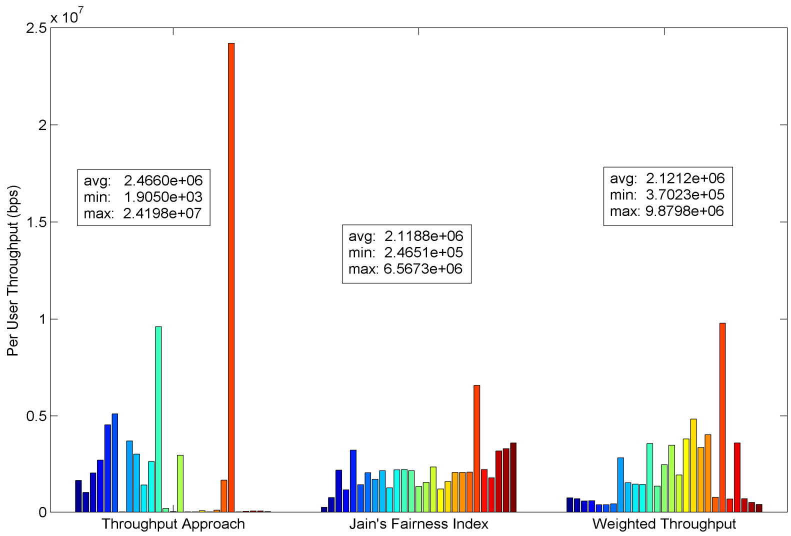

Fig. 6. Per-user throughput for each approach

In the 2nd approach, the FFR method finds the optimal inner region radius and frequency allocation based on the JI. We can observe that this approach allocates the frequency resources in a way that allows all users to have similar throughput values. The average throughput value equals to 2.1188Mbps, when the maximum is

6.5673Mbps and the minimum is 0.24651Mbps. So, this approach not only assures the serving of inner region users but also the ones located in the outer region. However, the total cell throughput is lower compared to the 1st approach. This is the reason why we have introduced WT approach where the throughput values are ranged between the ones occurred by the previous approaches. In this case the average per-user throughput is 2.1212Mbps, whereas the maximum equals to 9.8798Mbps and the minimum to 0.37023Mbps. To sum up, this approach makes a trade-off between the previous two, because it ensures both high cell total throughput and similar per-user throughput values among FUs and MUs.

Scalable Number of Femtocells

For this part of the experimental evaluation, we assume an integrated femtocell/macrocell environment consisting of a scalable number of femtocells. Fig. 7 shows how the cell total throughput changes as the number of femtocells per macrocell increases from 1 to 7, for each one of the three approaches. Moreover, Fig. 8 presents the combination of inner region radius and RBs for each added femtocell. According to this figures, for the 1st approach the maximum value (66.581Mbps) is achieved when the 6th femtocell is added to the environment (for 151.2m radius and 50RBs). The throughput value when the 7th femtocell is added to the environment is quite close to the maximum one. For the 2nd approach, the highest achieved throughput value equals to 52.622Mbps for 169.5m inner region radius and 33 RBs (6th femtocell). Finally, for the 3rd approach, the maximum total throughput (59.675Mbps) is succeeded when the 6th femtocell is added to the topology, for 150.9m radius and 25RBs.

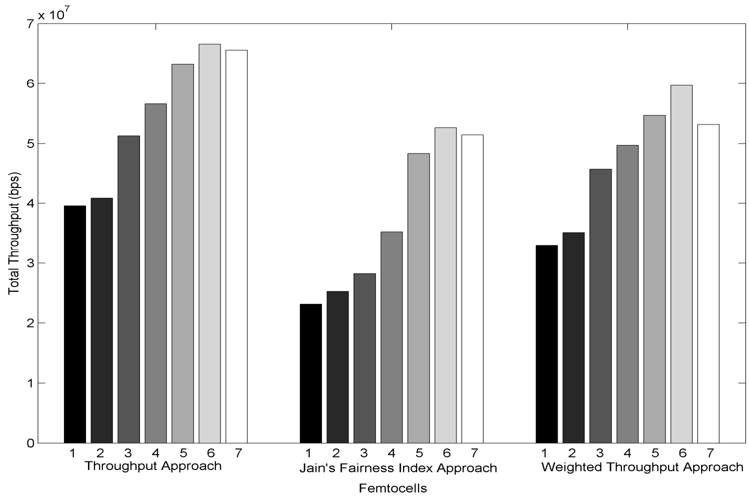

Fig. 7. Total throughout for each femtocell added to the topology

The proposed FFR method adapts as we add femtocells to the integrated femtocell/macrocell environment. As Fig. 8 shows, while the FFR method finds the optimal inner region radius and RBs based on WT, the inner region radius and RBs remain in similar values since the addition of the 4th femtocell. It is worth noting, that in this case, the method can succeed satisfying total cell throughput values without the need of altering the inner region radius and frequency allocation of the examined environment which is a demanding task by the network operator's side. So, we conclude that this approach seems the most efficient from the network operator's side.

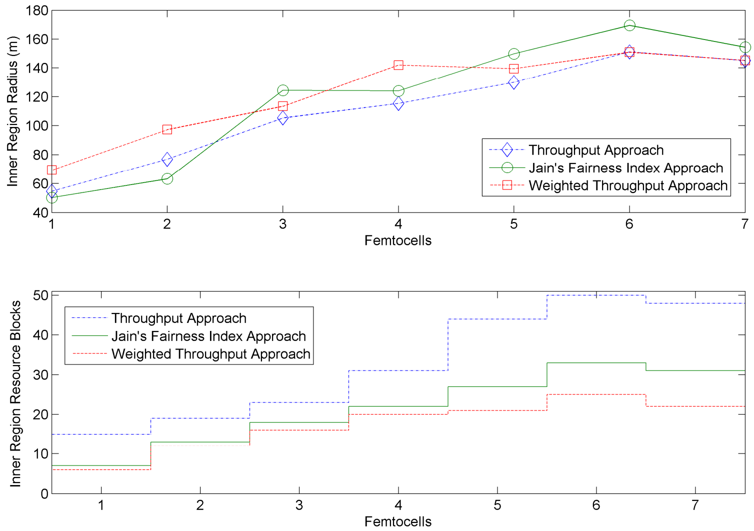

Fig. 8. Inner region radius and RBs for each femtocell

5 Conclusions and Future Work

In this paper we proposed an FFR method that calculates the optimal inner region radius and frequency allocation based on three different metrics: the cell total throughput, JI and a newly introduced metric called WT. Moreover, we described a potential frequency allocation scheme for both femtocell and macrocell BS so as the total network interference is reduced. The application of the FFR method based on WT makes a trade-off between the other two approaches, due to the fact that it increases the cell total throughput and decreases the variance of per-user throughput values.

A potential future step for this work is to integrate several realistic network parameters in the proposed method and evaluate it in real conditions. Also, we can create a dynamic frequency allocation scheme instead of the proposed static one, for the frequency assignment.

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