A Performance Study of Fractional Frequency Reuse in OFDMA Networks

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***Abstract*—Long Term Evolution (LTE) technology is considered as the most possible candidate for next generation mobile communications. LTE networks offer high capacity and are specified and designed to accommodate small, high performance, power-efficient end-user devices. One limiting factor that influences LTE performance is the interference from neighbor cells, the so called Inter-Cell Interference (ICI). Fractional Frequency Reuse (FFR) has been proposed as a technique to overcome this problem, since it can efficiently utilize the available frequency spectrum. This paper analyzes the FFR scheme and proposes a dynamic FFR mechanism that selects the optimal frequency allocation based on the cell total throughput and user satisfaction. In detail, the mechanism divides the cell into two regions (inner and outer) and selects the optimal size as well as the optimal frequency allocation between these regions with main target to maximize the overall throughput and user satisfaction. The mechanism is evaluated through several simulation scenarios that incorporate users’ mobility.**

Keywords-fractional frequency reuse; optimization; orthogonal frequency division multiple access; orthogonal frequency division multiple access

I. INTRODUCTION

Orthogonal Frequency Division Multiple Access (OFDMA) is a promising technique being proposed for the next generation mobile networks. The available network spectrum is split into a number of parallel orthogonal narrowband subcarriers. These can be independently assigned to different users in a cell. Several techniques with different degrees of complexity can be considered for out-of-cell interference mitigation in OFDMA systems. Most of these techniques involve transmitting in any given cell over a portion of the spectrum that is smaller than the entire available bandwidth, while neighboring cells employ a different portion of the spectrum.

Based on the above, one of the key characteristics of a cellular network is the ability to reuse frequencies in order to increase both capacity and coverage. Fractional Frequency Reuse (FFR) is discussed in OFDMA-based networks, such as the Long Term Evolution (LTE), to overcome the Co-Channel Interference (CCI) problems [1]. In FFR the cell space is divided into two regions: inner, which is close to the Base Station (BS) and outer, which is situated to the borders of the cell. The whole frequency band is divided into several sub-bands, and each one is differently assigned to inner and outer region of the cell respectively. As a result of FFR, intra-cell interference is eliminated, and inter-cell interference is substantially reduced [2]. At the same time the system throughput is enhanced. Various reuse factors and interference mitigation levels can be achieved by adjusting either the bandwidth proportion assigned to each region or the transmission power of each band.

In detail, OFDMA FFR, for interference mitigation, divides frequency and time resources into several resource sets (sub-bands). Typically, each resource set is reserved for a certain reuse factor and is associated with a particular transmission power profile. FFR schemes can be considered both in uplink and downlink channels, but typically they are considered in the downlink. This can be explained due to the reduction of the complexity and the less required information. The use of FFR in cellular networks leads to natural tradeoffs between enhancement in coverage and rate for the users found in outer region and overall throughput and spectral efficiency.

By utilizing interference avoidance schemes, the system tries to avoid collisions between the same frequencies used in neighbor cells. This can be done either in a static way by allocating different frequencies to neighbor cells (also referred to as Frequency Reuse Factor (FRF) greater than one), or in a dynamic way, with an intelligent scheduler taking care of the collisions. Considering the signaling overhead and the complexity to implement the intelligent scheduler, only the static method is widely adopted in practical network deployments.

The advantages of FFR schemes have triggered the research interest. The authors of [3] studied the performance of FFR for 3GPP / 3GPP2 OFDMA systems and included system level simulations in their analysis, while the author of [4] and [5] has studied the FFR in an IEEE 802.16 based system. In these works, the author proposed an interference coordination system, which focuses on the users’ scheduling. Moreover, two new algorithms, Fractional Time Reuse (FTR) and Fractional Time and Frequency Reuse (FTFR), are proposed in [6] to cater for reduced capacity in the cell border area because of FFR. In [7], the authors estimate the capacity and the simulation with homogeneous traffic load among cells shows that the Soft Frequency Reuse (SFR) scheme is a good

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candidate to enhance the cell edge throughput, without sacrificing the average cell throughput. Furthermore in [8], the authors describe a complete technical proposal for a Mobile Broadband Wireless Access (MBWA) system that meets the requirements for the IEEE 802.20 standard. Both TDD and FDD technologies are included, since there is much in common between the two approaches. The authors in [9] focus on the evaluation of two main types of FFR deployments - Strict FFR and Soft Frequency Reuse (SFR) - using a Poisson point process to model the base station locations. Under reasonable special cases for modern cellular networks, the results of the paper, reduce to simple closed-form expressions, which provide insight into system design guidelines and the relative merits of Strict FFR, SFR, universal reuse, and fixed frequency reuse. Finally, the work in [10] proposes a wireless topology based on FFR in order to optimize the SINR of multi-cell deployments within an aircraft. The results show that this approach can increase the cell-edge SINR in approximately 6dB with respect to a multi-cell deployment lacking FFR.

This paper proposes a dynamic FFR mechanism that selects the optimal frequency allocation based on the total throughput and users' satisfaction. Particularly, the mechanism divides the cell into two regions (inner and outer) and selects the optimal size as well as the optimal frequency allocation between these regions with main target to maximize the overall throughput and user satisfaction. Therefore, the per-user throughput, the total throughput and user satisfaction metric are calculated in periodic time intervals and at each time interval, the FFR scheme that maximizes the above parameters is selected.

The rest of this paper is structured as follows: Basic theoretical background regarding FFR is explained in Section II. Section III describes the procedure used for the calculation of throughput and user satisfaction, while in Section IV we describe the system model and the mechanism overview. The evaluation of the mechanism and the simulation results are presented in Section V. Finally, the conclusions and some ideas for future work are shown in Section VI.

II. Fractional Frequency Reuse

In FFR, in order to ensure that the mutual interference between users and BSs remains below a harmful level, adjacent cells use different frequencies. In fact, a set of different frequencies are used for each cluster of adjacent cells. Cluster patterns and the corresponding frequencies are reused in a regular pattern over the entire service area. The closest distance between the centers of two cells using the same frequency (in different clusters) is determined by the choice of the cluster size and the layout of the cell cluster. This distance is called the frequency reuse distance.

One of the main objectives of LTE is to achieve high spectral efficiency, meaning the use of the whole of the system's bandwidth in all cells. This approach is called Frequency Reuse 1 and is considered as the simplest scheme: all sub-bands of the available bandwidth are allocated to each cell. In Frequency Reuse 3, the system bandwidth is divided into 3 equal sub-bands; each one of these is allocated to cells in a manner that no other surrounding cell is using the same sub-band. Full frequency reuse in each cell can exempt the necessity of advance frequency planning among different cells, and the frequency reuse patterns can be dynamically adapted on a frame-by-frame basis in each cell. In this work we study a sub-case of these approaches which we analyze below.

Firstly we define an LTE multi-cellular network. Our main objective is to apply FFR in order to improve the Signal to Interference plus Noise Ratio (SINR) and throughput and simultaneously reduce CCI. An indicative architecture and frequency band allocation are depicted in Figure 1. If the central BS is considered (blue color), it can be assumed that most interference is caused by the six direct neighbors.

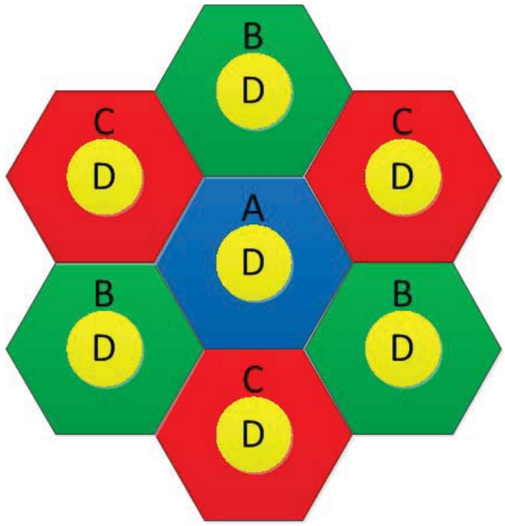

Figure 1. Proposed frequency band allocation.

For example, suppose we have a certain area that consists of 7 cells (Figure 1), and there are four resource sets. Each cell of the architecture is divided into two regions; inner and outer region. The total available bandwidth of the system is split into four uneven spectrums (or resource sets), denoted by A (blue), B (green) C (red) and D (yellow). Spectrums A, B, and C have equal bandwidth and are allocated in outer regions with Frequency Reuse 3. On the other hand, spectrum D is allocated in all inner regions with Frequency Reuse 1. The frequency resources in all inner regions are universally used, since the inner region users are less exposed to inter-cell interference. The specific FFR scheme is used in our simulations and can eliminate the intra-cell interference and greatly reduce the inter-cell interference.

III. Calculation of Throughput and User Satisfaction

In this section we describe the theoretical approach to calculate the SINR, throughput and user satisfaction factor. We assume that the overall network is composed of N adjacent cells. Each cell contains a number of users seeking to share a group of subcarriers. We distinguish the case where a user is found in the inner or in the outer region of the cell. In a typical OFDMA cellular network, for a user x who is served by a base station b on subcarrier n, the related SINR is given by the following equation [11]:

$$SINR_{x,n} = \frac{G_{b,x} \cdot P_{b,n} \cdot h_{b,x,n}}{\sigma_n{}^2 + \sum_{j=1}^{k} G_{j,x} \cdot P_{j,n} \cdot h_{j,x,n}} \quad (1)$$

In (1), $G_{b,x}$ refers to the path loss associated with the channel between user x and base station b, $P_{b,n}$ is the transmit power of the base station on subcarrier n, $h_{b,x,n}$ is the exponentially distributed channel fast fading power and $\sigma_n{}^2$ is the noise power of the Additive White Gaussian Noise (AWGN) channel. Symbols k and j refer to the set of all the interfering BSs (i.e. BSs that are using the same sub-band as user x). In detail, j is the cell index and k the number of co-channel cells. In our analysis, we assume that equal transmit power is applied, $P_{b,n}=P$ for all BSs and the interference of users is negligible. The coefficient $h_{b,x,n}$ is replaced by its mean value ($h_{b,x,n} = 1$) in equation (1).

The interference that occurs comes from disjoint sets of downlinks in the inner and outer region. A transmission in an inner cell region that is assigned specific frequency band causes interference only to inner users of other cells that are assigned the same band. Furthermore, it is necessary to distinguish two categories of BSs. The first consists of all interfering BSs transmitting to inner cell users on the same sub-band as user x and the second consists of all interfering BSs transmitting to cell-edge users on the same sub-band as user x.

After the SINR estimation, we proceed with the throughput calculation. The capacity of user x on subcarrier n can be calculated by the following equation [12]:

$$C_{x,n} = \Delta f \cdot \log_2(1 + SINR_{x,n}) \quad (2)$$

where, Δf refers to the available bandwidth for each subcarrier divided by the number of users that share the specific subcarrier. Moreover, the throughput of the user x can be expressed as follows:

$$T_x = \sum_n \beta_{x,n} \cdot C_{x,n} \quad (3)$$

where, $\beta_{x,n}$ represents the subcarrier assigned to user x. When $\beta_{x,n} = 1$, the subcarrier n is assigned to user x. Otherwise, $\beta_{x,n} = 0$.

Moreover, in order to evaluate the performance of our experiments we define the relative throughput of a user compared to the throughput of the users around him. This metric is called User Satisfaction (US) and it is calculated as the sum of the users' throughput divided by the product of the maximum user's throughput and the number of users (X). This metric physically presents how close the user's throughput is to the maximum throughput in the area. Specifically:

$$US = \frac{\sum_{x=1}^{X} T_x}{\max\_user\_throughput \cdot X} \quad (4)$$

US ranges between 0 and 1. When US approaches 1, all users in the corresponding cell experience similar throughput, while when US approaches 0, there are big variations in the throughput achieved by the users in the cell.

IV. System Model And Mechanism Overview

The mechanism assumes a topology that consists of a grid of cells and a number of multicast users that are uniformly distributed.

In order to find the optimal FFR scheme, the mechanism divides each cell into two regions and calculates the total throughput and US for the following 26 Frequency Allocations (FA), assuming Frequency Reuse 1 and 3 for the inner and the outer region respectively:

- FA1: All (25) subcarriers are allocated in inner region.
  No subcarriers are allocated in outer region.
- FA2: 24 subcarriers are allocated in inner region.
  1/3 subcarriers allocated in outer region.
- …
- FA25: 1 subcarrier allocated in inner region.
  24/3 subcarriers allocated in outer region.
- FA26: No subcarriers allocated in inner region.
  25/3 subcarriers allocated in outer region.

For each FA, the mechanism calculates the per-user throughput, the cell total throughput and US. This procedure is repeated for successive inner cell radius (0 to R, where R is the cell radius). After the above calculations, the mechanism selects the optimal FFR scheme that maximizes the cell total throughput and US.

This procedure is repeated periodically in order to take into account user's mobility in the topology. Therefore, the per-user throughput, the cell total throughput and US are calculated in periodic time intervals (the exact time is beyond the scope of this paper) and at each time interval, the FFR scheme that maximizes the above parameters is selected. This periodic process is called adaptation.

The pseudo-code of the mechanism is illustrated below. The complexity and the running time of the algorithm are proportional to the number of users multiplied by the number of cells in the topology, i.e. O(#users*#cells).

```
% Algorithm
generate_network_cell_&_users()          % define topology and user
                                         % distribution
for r = 0:R                              % inner cell radius
        for n = 0:N                      % inner cell subcarriers
                for x = 1:X              % users
                calculate_sinr(x)        % based on equation (1)
                calculate_capacity(x)    % based on equation (2)
                calculate_throughput(x)% based on equation (3)
                end
        calculate_total_throughput(r,n)
        calculate_user_satisfaction(r,n)  % based on equation (4)
        end
end
select_ffr_for_max_total_throughput()    % select r,n values that
                                         % maximize the cell total
                                         % throughput
calculate_ffr_for_max_user_satisfaction()  % select r,n values
                                         % that maximize the US
perform_adaptation_process()  % periodically repeat the above
                              % procedure in order to take
                              % into account user's mobility
```

V. Performance Evaluation

A. Simulation Parameters

The simulation parameters that are necessary for the conduction of the experiment are presented in Table I. In detail, we consider a system with 10MHz of bandwidth (i.e. LTE) divided into 25 subcarriers each having a bandwidth of 375 KHz. The scenario assumed is urban macro which exists in dense urban areas served by macro-cells. Path loss is calculated according to Cost-Hata Model [13] and the correlation distance of the shadowing is set to 40m [12].

TABLE I. Simulation parameters

Parameter	Units	Value
System bandwidth	MHz	10
Subcarriers		25
Subcarriers' bandwidth	KHz	375
Carrier frequency	MHz	2000
Cell Radius	m	250
Correlation distance	m	40
Channel model		3GPP Typical Urban
Users' speed	km/h	3
Path loss	dB	Cost 231 Hata Model
BS transmit power	dBm	46
Power Noise Density	dbm/Hz	-174

B. Optimal FFR Scheme based on Cell Total Throughput

The first simulation experiment presents a mobility scenario and shows the output of the mechanism when selecting the FFR scheme that maximizes the cell total throughput. The examined topology consists of 16 cells and 360 uniformly distributed users (Figure 2). Our experiment focuses on one cell of the topology (second row and third column), which is highlighted in Figure 2. This cell contains 21 users.Figure 2 presents the initial topology and user distribution. During the experiment that lasts for 215 sec, the users of the examined cell are moving randomly inside the cell with speed 3km/h and it is assured that all of them remain into the cell's area (ensuring that their number will remain constant).

Figure 3 presents the cell total throughput against the time, while the mechanism maximizes the cell total throughput ("Throughput with adaptation" curve). For comparison purposes, the graph also shows how the throughput changes if the adaptation process does not take place ("Throughput without adaptation" curve). We remind that during the adaptation process, the mechanism updates the frequency allocation (FA) and inner cell radius in order to take into account the users' mobility. On the other hand, the case without adaptation assumes that the FA and inner cell radius are calculated once (for the initial user distribution) and remain constant during the scenario.

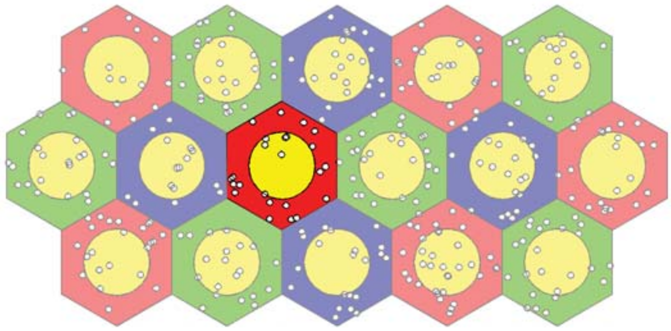

Figure 2. Initial user distribution.

During the first 20 seconds of the experiment, the two curves coincide. This happens because in this small time interval the users have covered a small distance and consequently the FA and the inner cell radius that were calculated in the beginning of the experiment remain the optimal. For the time interval 20 sec until the end of the experiment, the total throughput with adaptation shows better performance than without adaptation. Indeed, during this time interval the users have covered a large distance and have moved away from their initial position. Therefore, the initial FA and inner cell area are not the most efficient. The adaptation process assures that the FA and inner cell area will be re-calculated in order to take into account the changes in users' distribution. This process leads to improved values of cell total throughput.

Figure 3 also includes the representation of US with and without adaptation. The two curves coincide for the time intervals 0-20 sec and 65-110 sec, since the throughput values during these intervals are similar. On the other hand, from 20-65 sec and from 110 sec until the end of the experiment, the US without adaptation remains higher than the US with adaptation. Even if this appears as an advantage, a more careful examination of Figure 3 shows that it is not. Indeed, the case without adaptation leads to high values of US because the cell total throughput is close to zero and consequently all users experience almost the same throughput, which is however very close to zero. On the other hand, if the adaption process is applied the US metric is lower which means that there are "high throughput" users and "low throughput" users in the cell.

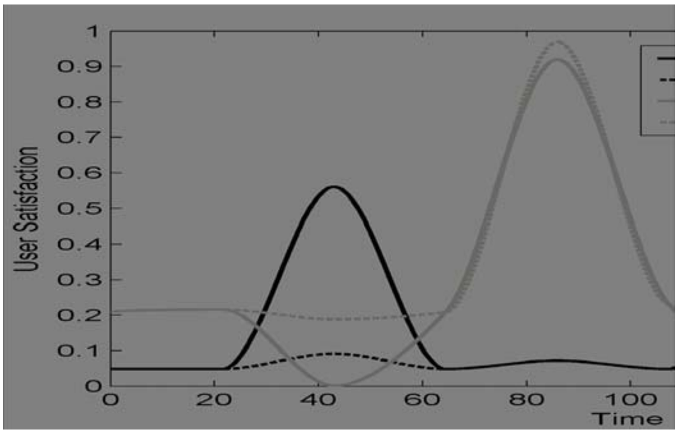

Figure 3. User satisfaction and cell total throughput based on throughput maximization.

C. *Optimal FFR Scheme based on User Satisfaction*

The US metric, has been introduced in order to overcome the unfairness in bandwidth allocation among the users in different regions of the cell. Therefore, a high US value ensures that all users in a cell will experience similar values of throughput. This experiment presents the operation of the mechanism when selecting the FFR scheme that maximizes the US. The topology and user distribution are the same with the previous experiment.

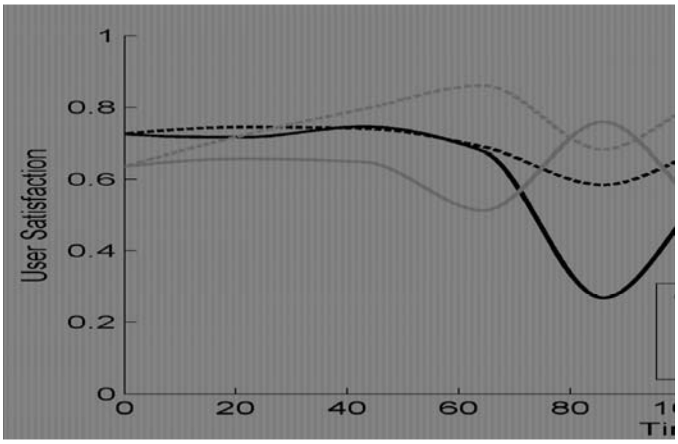

Figure 4. User satisfaction and cell total throughput based on user satisfaction maximization.

In Figure 4, the "US with adaptation" curve shows how the US changes with time while the mechanism applies the adaptation process in order to maximize the US metric. Depending on the users' location, the mechanism scans and updates the optimal FA and inner cell radius. In addition, the "US without adaptation" curve has been added in order to show the effectiveness of the adaptation process. Indeed, during the experiment the values of US with adaptation are always higher than the corresponding values when adaptation is not applied.

In the same figure we have included the corresponding curves for the total cell throughput. In general, the adaptation case leads to increased (and fairer) values of total throughput.

D. *Comparison of the Approaches*

This section makes a direct comparison between two approaches that the mechanism follows in order to select the optimal FFR scheme: the approach that is based on cell total throughput maximization and on US maximization.

In order to compare these two approaches we examine the minimum, maximum and average per-user throughput that each approach achieves (Figure 5), and how the subcarriers' allocation and the inner cell radius changes with time (Figure 6). These results correspond to the mobility scenario that was presented in the previous sections.

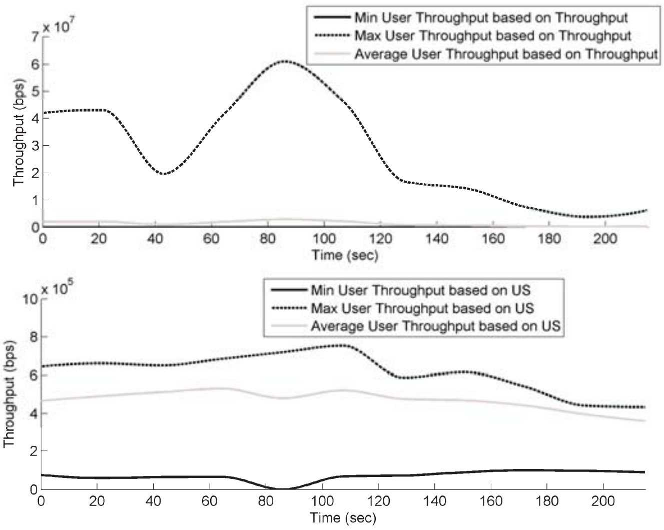

Figure 5. Minimum, maximum and average user throughput vs. time for the two approaches when adaptation is applied (up: based on cell total throughput, down: based on user satisfaction).

According to Figure 5, the average user throughput with the approach that maximizes the cell total throughput is very close to the minimum user throughput, which equals to zero during the whole experiment. This actually means that most of the users experience low or zero throughput, while only a few users have high throughput values.

In most cases, the specific approach allocates all the available bandwidth in the inner cell region (see Figure 6 where all the 25 subcarriers are allocated in the inner cell area) and serves the users that are found in this area. On the other hand the users that are located in the outer cell region have throughput equal to zero. Even though this approach leads to higher cell total throughput, it is obvious that it introduces unfairness to the bandwidth that is allocated between the inner and outer cell regions.

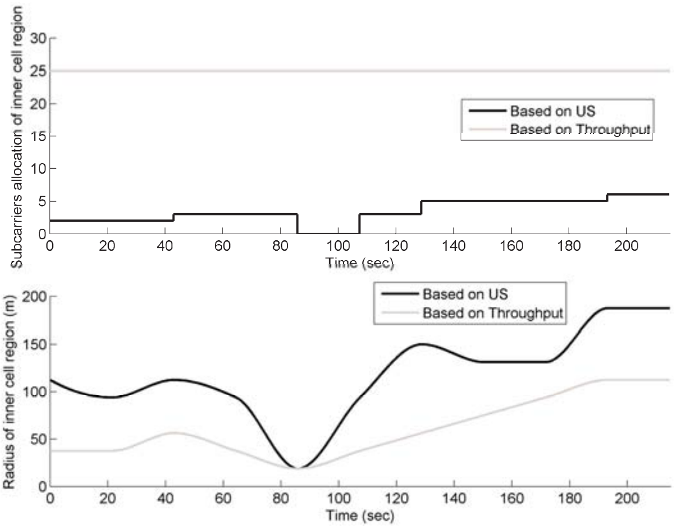

Figure 6. Subcarriers' allocation and inner cell radius vs. time for the two approaches when adaptation is applied.

As Figure 5 depicts, the approach that maximizes the US ensures that the average user throughput remains close to the maximum user throughput achieved. Therefore, most of the users have throughput similar to the maximum one. To sum up, this approach may lead to lower cell total throughput (see Figure 3 and Figure 4), however it allocates the available bandwidth between that inner and the outer region of the cell in a more fair way (see Figure 6).

VI. CONCLUSIONS AND FUTURE WORK

In this paper we proposed an interference management FFR mechanism that calculates the per-user SINR, capacity and throughput. After the above calculations, the mechanism selects the optimal FFR scheme that either maximizes the cell total throughput or the US metric. In order to take into account user's mobility in the topology, the mechanism performs an adaptation process, i.e. repeats this procedure periodically. During the adaptation process, the per-user throughput, the cell total throughput and US are re-calculated in periodic time intervals ensuring that at each time interval, the FFR scheme that maximizes the above parameters is selected. According to the simulation results, this adaptation process leads to improved performance and to increased total cell throughput and user satisfaction.

The step that follows this work could be an extension of the mechanism in order to optimize the scanning process and minimize its complexity. Indeed, assuming pedestrian users, it is expected that the new users' position will be near to the initial ones. Therefore, it is expected to have small changes in the optimal frequency allocation and the optimal radius of the inner cell area. In brief, the extended mechanism could reduce the scanning procedure so as to take into account the "expected" frequency allocation and "expected" inner cell radius.

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