Performance Evaluation of Static Frequency Reuse Techniques for OFDMA Cellular Networks

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***Abstract*—The use of orthogonal frequency division multiple access (OFDMA) in Long Term Evolution (LTE) and WiMax cellular systems mitigates downlink intra-cell interference by the use of sub-carriers that are orthogonal to each other. Inter-cell interference, however, limits the downlink performance of cellular systems. In order to mitigate inter-cell interference, various techniques have been proposed. This paper examines one group of these techniques, static frequency reuse. We present a comprehensive comparison of Reuse-1, Reuse-3, fractional frequency reuse (FFR), and soft frequency reuse (SFR), with varying input parameters, such as inner radius and power ratios. System simulation is used to evaluate the overall system performance in terms of throughput and SINR are evaluated. In addition to the overall system performance, cell-edge user performance, whose performance is severely limited by interference from neighboring cells, for each technique is also evaluated.**

I. Introduction

Emerging wireless mobile systems, such as the 3GPP Long Term Evolution (LTE) and Mobile WiMax aim at providing higher data rate and enhanced spectral efficiency. To achieve that goal, they use orthogonal frequency division multiple access (OFDMA) in their downlink air interfaces [1]. OFDMA offers a high spectral efficiency and a scalable bandwidth for cellular systems. It uses orthogonal frequency division multiplexing (OFDM), which is a multi-carrier modulation scheme that divides a frequency band into a group of mutually orthogonal narrow band sub-carriers whose bandwidth is smaller than the coherence bandwidth of the channel.

The spectrum that is available for cellular systems is limited. Therefore, some form of mechanism is needed to use the available resource wisely and enhance the system capacity. One technique is to use the same frequency band in all the cells in a given cellular system. This is called frequency-reuse one approach (Reuse-1), since a band is reused over and over again across the cells. By using the same bands in different cells, the available spectrum can be reused, thereby improving spectral efficiency. The sub-carriers' orthogonality in OFDMA mitigates any inter-carrier interference among the sub-carriers. However, when using a Reuse-1 scheme, co-channel interference (ICI) or inter-cell interference (ICI) will be incurred in adjacent cells that share the same spectrum. The ICI decreases the signal to interference and noise ratio (SINR), which causes a decrease in the spectral efficiency and data rate of the system[2]. Hence, the need for interference mitigation schemes.

The frequency collision in these cells results in severe inter-cell interference in the cell-edge users [3] (i.e., users located in the boundaries of a cell). To alleviate this problem, different interference mitigation techniques have been studied. The 3GPP categorizes these interference mitigation techniques for LTE into three: inter-cell interference randomization, inter-cell interference cancellation, and inter-cell interference coordination/avoidance [4]. Inter-cell interference randomization techniques randomize interfering signals by cell-specific scrambling, interleaving and frequency hoping to suppress interference and achieve frequency diversity gain. Inter-cell interference cancellation techniques perform interference mitigation by either detecting and subtracting interfering signals from the desired signal or by employing multi-user detection at the receiver to select the desired signal. In inter-cell interference avoidance techniques the principle of coordinating resource allocation between cells to avoid interference and improve SINR and data rates is applied.

In this work, we consider inter-cell interference coordination/avoidance techniques. These techniques require some form of coordination between different cells to restrict/allow resources in order to improve SINR and coverage [4]. Various inter-cell coordination techniques have been studied in the past. These techniques generally fall into two categories: static/dynamic , or centralized/distributed techniques [5].

In static inter-cell interference coordination/avoidance techniques, allocated resource and power levels of transmitter for base stations are fixed. In the dynamic schemes, on the other hand, the resources are adaptively allocated and power levels adjustments are made depending on the channel condition and capacity demand of the cells. In centralized inter-cell interference coordination schemes a centralized entity assigns resources to users while in distributed schemes cells based on the exchange of information from other cells assign resources to users in a distributed manner. Each of the above mentioned techniques have advantages and disadvantages, a discussion of which is beyond the scope of this paper.

Static inter-cell interference avoidance schemes are studied in this paper. Since the allocation of resources in the static schemes is fixed regardless of change in user distribution or channel condition, it is impossible to build resilient cellular network structures which can be re-configurable adapting to their environment. By adjusting different parameters adaptively, a resilient network can be deployed. However, for that,

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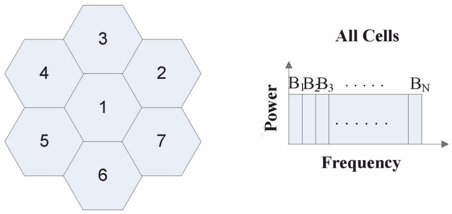

Fig. 1. Reuse-1 scheme deployment. In this scheme all the cells transmit on all available sub-carriers in the spectrum with the same power.

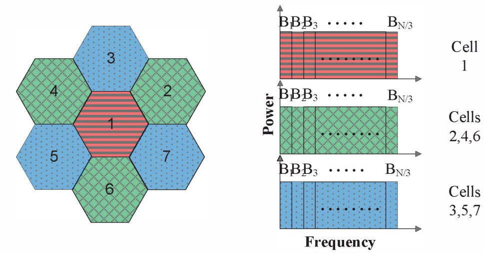

Fig. 2. Reuse-3 scheme. In this scheme no neighboring cells use the same spectrum.

a better understanding of the tradeoffs between the different approaches as their settings are varied is needed. Therefore, in this paper, we present a comprehensive assessemnt of static interference schemes, and evaluate the cell-edge, cell-center, and overall performance of the system in terms of the SINR, and spectral efficiency by adjusting different input parameters.

This paper is organized as follows. In section II the static inter-cell interference avoidance schemes are presented. In section III the cellular system model and the performance evaluation metrics used in this work are described. Simulation results and analysis are presented in section IV while section V presents the conclusion.

II. Background

A hexagonal multi-cell OFDMA cellular network is considered in this paper. Each cell has a base station placed at the center of the cell serving a set of users within each cell. The smallest resource allocated for a user is called a resource block (RB). Each resource block consists of 12 sub-carriers. The sub-carrier spacing is 15kHz making the bandwidth of each RB 180kHz. In this section of the paper, $B_i (i = 1, 2, 3, ...)$ represent the RBs for a given cell.

A. *Reuse-*1

In next generation cellular networks, spectral efficiency is given a high emphasis because these networks aim at providing high data rates for users,[6]. It is well known that frequency is scarce and effective utilization of resources is important in cellular systems. The simplest approach to use the available spectrum in a cellular OFDMA system is the frequency reuse one (Reuse-1) approach. In this approach the entire bandwidth is reused in multiple cells. Upon deployment of the cellular network, all base stations are allowed to use the same cellular spectrum. Fig. 1 illustrates a Reuse-1 approach. In the 7 cell layout shown in Fig. 1, all cells use the entire available band with equal power levels in their sub-carriers for their down link. In other words, all RBs in the cellular spectrum are available to all cells to be allocated to users.

It is known that using a frequency one approach targets higher system capacity and spectrum efficiency by reusing the scarce resource in all cells. However, it is predictable that Reuse-1 causes considerable inter-cell interference when adjacent cells allocate the same frequency. This interference greatly limits the capacity and spectral efficiency of users by significantly reducing the SINR of users, especially that are located at the edge of cells.

B. *Reuse-n*

The simplest approach used to address this inter-cell interference problem that occurs when Reuse-1 is applied is the frequency reuse-n (Reuse-n) approach. In this approach neighboring cells use different spectrum to avoid interference to users in their respective cells. The available bandwidth is split into n orthogonal sub-bands and each cell transmits on non interfering sub-bands. This ensures that the spectrum is reused at distant cells. n is called the frequency reuse factor and can be written as $n = i^2 + ij + j^2$, for $i, j \in \mathbb{N}$. One example of Reuse-n is the Reuse-3. In Reuse-3, the whole frequency band is divided into three equal and orthogonal sub-bands, as shown in Fig. 2. The band is divided into three and allocated to the three groups. Accordingly, the total number of resource blocks per cell is N/3 where N is the number of total resource blocks available for the system. B_1, B_2,...,$B_{N/3}$ represent the resource blocks in each cell.

Reuse-n scheme provides improved inter-cell interference by avoiding using the same frequency bands in adjacent cells. By increasing the reuse factor, interference can be further reduced. However, interference avoidance comes at the expense of bandwidth [7]. In this scheme, each cell will have only a fraction of the available spectrum, resulting in a reduction in the number of resource blocks provided for users in each cell. This in turn will reduce the capacity and spectral efficiency of the system.

C. *Fractional Frequency Reuse (FFR)*

It is inferred from the above discussion that while the Reuse-n scheme solves the problem of interference, it is not bandwidth efficient [8],[9]. Fractional frequency reuse, originally proposed in [10], partitions the whole spectrum into two parts; namely, one with reuse factor 1, and one with reuse factor n, usually $n = 3$. The key idea behind FFR is to employ a reuse factor of unity for cell-center regions and a reuse factor of 3 for cell-edge regions. An example of FFR scheme is shown in Fig. 3.

In Fig. 3, the cellular service area of every cell is split into a center zone and edge zone (the center zone is the shown in circle). Correspondingly, the total spectrum is split into two regions, the center part where only users in the center zone are allowed to use, and the edge part, where only users in the edge zone are allowed to use. The total edge spectrum

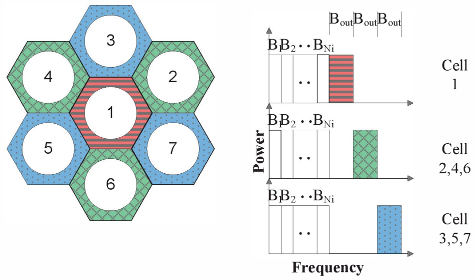

Fig. 3. FFR scheme. In FFR, the reuse factor for interior users is 1 and the reuse factor for exterior users is 3.

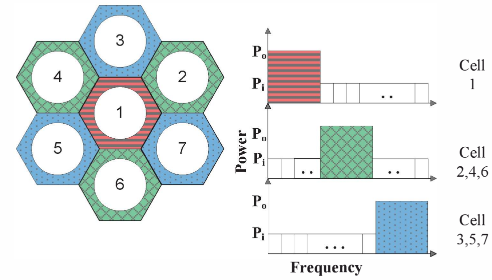

Fig. 4. SFR scheme. In this scheme inner RBs transmit with a higher transmit power than RBs used for cell-edge users.

is further divided into three parts, corresponding to Reuse-3. B_1, B_2,...,B_{Ni} represent the resource blocks available for each center zone (inner region), where Ni is the total number of inner RBs. For the outer region, B_{out} represents the total number of RBs for each outer region in a cell. Therefore, the total number of outer RBs for the seven cell system presented in Fig.2 is equal to $3B_{out}$.

As a result of splitting the spectrum for inner and outer regions of a cell so that interior users do not share any spectrum with exterior users, significant inter-cell interference reduction, particularly for cell-edge users, is achieved [11]. However, the spectrum is underutilized in FFR since the cell-edge user can only use part of the total spectrum [8]. In addition, the implementation of a reuse factor at a cell edge results in lower system throughput [12].

D. Soft Frequency Reuse (SFR)

Similarly to FFR, the basic idea of soft frequency reuse (SFR) is to apply Reuse-1 at the inner cell region and a higher frequency reuse (Reuse-n) at the outer or edge cell region. Unlike FFR, however, SFR reduces inter-cell interference without reducing spectrum efficiency [13].

SFR splits the available band and RBs into two regions: cell-edge or outer band and cell-center or inner band. Correspondingly, users in a cell are grouped into two classes. The users closer to the center of the cell are grouped into cell-center or inner users, and the users close to the edge of the cell are grouped together and are called cell-edge or outer users. The cell-edge users are restricted to use only the cell-edge band. The cell-center users have exclusive access to the cell-edge band, and with lower priority, they have access to the cell-edge band.

Fig. 4 illustrates a SFR deployment. In the figure, the cell is divided into two zones; a center zone where all of the spectrum is available and a cell-edge zone where only a portion of the spectrum is available. The cell-edge band is transmitted with a higher power level whereas the cell-center band is transmitted with a reduced power level.

III. SYSTEM MODEL AND ASSUMPTIONS

A. The LTE Downlink

LTE uses OFDMA on the downlink and Single-carrier frequency division multiple access (SC-FDMA) on the uplink. In this work, we focus on the LTE downlink. For a given bandwidth, the bandwidth is split into sub-carriers, each having a smaller bandwidth also known as sub-carrier spacing $\triangle f = 15$kHz. A resource block (RB) is the smallest resource assigned by a scheduler of a base station (eNodeB). An RB consists of 12 sub-carriers, therefore it has a total size of $W = 180$kHz in the frequency domain and $0.5ms$ in the time domain. The more RBs a user gets, the higher the bit-rate. A scheduling mechanism decides how many RBs a user gets at a given time.

The total number of RBs available for a given cell, N_c varies according to the scheme used. If N denotes the total RBs of an OFDMA system, then for Reuse-1 , $N_c = N$. For Reuse-n, $N_c = N/n$.

In FFR and SFR, the differentiation between inner and outer cell users is very important. One method to separate the two is to use their geographic location as a reference. Based on a user's distance from the center of a cell, if the distance is greater than a threshold radius, then user is an outer cell user (cell-edge user), if not, an inner cell user. Another method to differentiate between inner and outer users uses a geometry factor (SINR). Based on the measurement of a user's SINR, if the SINR is greater than a certain threshold, then the user is an inner cell user, if not a cell-edge user. For this work, we use distance to differentiate between the two. The number of RBs is proportional to the inner radius of a cell for FFR and SFR. The inner radius is used to distinguish between cell-center users and cell-edge users, and is given as $r_{in} = \alpha R$, where R is the radius of the cell, and α is ratio of the inner radius and the cell radius ($0 < \alpha < 1$). Consequently, from [14], the number of inner and outer RBs for FFR can be determined as $N_{in} = N(\frac{r_{in}}{R})^2$, and $N_{edge} = \frac{N-N_{in}}{n}$, where, n is the reuse factor (usually $n = 3$). Similarly for systems employing SFR, $N_{in} = N(\frac{r_{in}}{R})^2$, and $N_{edge} = N - N_{in}$.

However, from the simulation results performed, it is understood that the value of α^2 or $(\frac{r_{in}}{R})^2$ which affects the number of RBs has a direct influence on the overall performance of the system, since spectral efficiency is proportional to the bandwidth. Therefore, in this work, instead of multiplying the total number of RBs with the square of the ratio of inner radius to cell radius (α), it is multiplied by the ratio of α and an optimization parameter γ. Accordingly, for FFR $N_{in} = N(\frac{\alpha}{\gamma})^2$, where $\alpha \leq \gamma \leq 1$, and $N_{edge} = \frac{N-N_{in}}{n}$. For

SFR, $N_{in} = N(\frac{\alpha}{\gamma})^2$, and $N_{edge} = N - N_{in}$.

B. Channel Model

We consider a cellular system with C base stations, each serving U number of users. The signal to interference noise ration (SINR) of the received signal at user u using a RB b can be expressed as

$$SINR_{u,b} = \frac{P_b^s \cdot G_b^s}{N_0 + \sum_{i \in IC} P_b^i \cdot G_b^i} \quad (1)$$

where P_b^s denotes the transmitted power by serving cell s on RB b, and P_b^i denotes the transmitted power by interfering cell i. IC is the set of all interfering cells in the cellular network. N_0 represents the thermal noise power, and G_b^s and G_b^i represent channel gain between user u and the serving base station and interfering base stations respectively. The channel gain is composed of the path loss between the base station and u and is given as $PL[dB] = 128.1 + 37.6\log_{10}(d)$, where d is the distance, measured in kilometers, between a user and the center of the serving or interfering cell [15].

where d is the distance, measured in kilometers, between a user and the center of the serving or interfering cell.

The number of interfering cells differ depending on the type of scheme used. In Reuse-1, every cell can access the available resource. Therefore, interference occurs when the same RB is assigned to users in adjacent cells. In systems employing Reuse-n, adjacent cells do not interfere with each other. Instead, interference occurs when the same RB is assigned to users in non-adjacent cells which share the same spectrum with the cell (For example, in Fig. 2, cell-3 could interfere with cell-7, if they allocate their users the same RB). In FFR, interference occurs between adjacent cells when the cells allocate the same RB for their inner users. The interference for cell-edge users follows the same principle as Reuse-n scheme.

In practical LTE systems, channel state information (CSI) is used and adaptive coding and modulation (ACM) is applied in determining the throughput. For this work, however, we use Shannon's equation to calculate user throughput and it is given as

$$T_{u,b} = W \cdot \log_2(1 + SINR_{u,b}) \quad (2)$$

where $T_{u,b}$ is the throughput of user u on RB b, W is the bandwidth of b, and $SINR_{u,b}$ is the SINR of user u on b. The overall system throughput can be expressed as

$$T_{total} = \sum_{u=1}^{U} \sum_{b=1}^{B} T_{u,b} \quad (3)$$

where U is the total number of users in the system, and B is the total number of resource blocks.

Depending on the frequency reuse scheme used, power allocated to each RB differs. For Reuse-1, all RBs share equal power, meaning $P_t = P_{total}/N$, where N is the total number of RBs, and P_{total} is total transmitting power. The power is evenly distributed among RBs. For Reuse-n, the total number of RBs available in a cell is $N_c = N/n$, and the transmitted power on each RB is given as $P_t = P_{total}/N_c$.

For FFR, the total number of RBs available in a cell is the sum of inner RBs (N_{in}) and edge RBs (N_{edge}), $N_c = N_{in} + N_{edge}$. Transmitted power on each RB is given as $P_t = P_{total}/N_c$. As discussed in the previous section, in SFR, edge or outer RBs and center or inner RBs transmit at different power levels. If the power on edge RBs is denoted as P_{edge}, and the power on inner RBs is denoted as P_{in}, then each can be calculated as

$$P_{edge} = \frac{nP_{total}}{N(1 + \beta(n-1))}$$
$$P_{in} = \beta P_{edge} \quad (4)$$

where n is the reuse factor, and β is defined as the power ratio. The power ration β has a range $0 < \beta \leq 1$. If $\beta = 1$, the scheme becomes a Reuse-1 scheme where all the RBs, inner and outer, transmit using the same power level.

IV. Simulation results

A. Simulation Settings and Parameters

In this work an LTE based cellular system is simulated. The simulation follows the LTE downlink described in section III. A 19 cell system layout is simulated with users randomly distributed in each cell. Each cell is assumed to have a base station with an omnidirectional antenna at the center of a cell. This can easily be extended to a sectorized cell layout, but since the purpose of this paper is to demonstrate the performance of different schemes, we focus only on the omnidirectional setting. The radius of each of the hexagonal cells is R = 2 km. The inner radius for FFR and SFR schemes is given as αR, where alpha takes values from 0 to 1 as discussed in section III. The total bandwidth of the system is 10 MHz. The spectrum is divided into 50 RBs each having a bandwidth of 180 KHz. The total transmit power is set to 43 dBm. There are 608 users randomly placed over the 19 cell system.

B. Results

Previous studies have used a reference cell to evaluate different frequency reuse schemes. In this work, however, we consider all the cells in a hexagonal layout, and evaluate the overall system throughput and SINR of the four schemes discussed in section II.

Fig. 5 presents results for the average overall system user throughput as a function of the ratio of inner radius to cell radius (α) for Reuse-1, Reuse-3, FFR, and SFR. The number of RBs in each cell for Reuse-1 was set to 50 and for Reuse-3 it was set to one third of 50 (approximately 17). For FFR and SFR, the parameter γ was set to $\gamma = 0.8$, the higher α value, the higher the number of inner RBs. Four values of $alpha$ are considered; 0.4, 0.5, 0.6, and 0.7. For SFR, the power ratio β is set to 0.1.

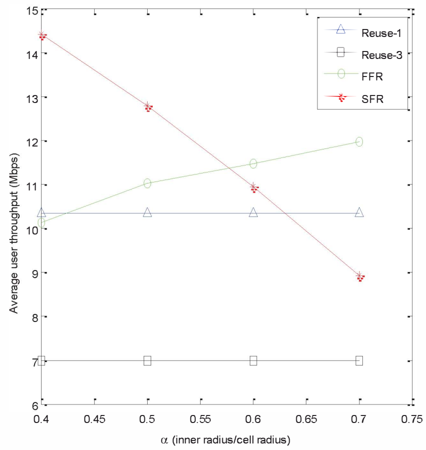

Fig. 5. Average user throughput for Reuse-1, Reuse-3, FFR, and SFR, with $\gamma = 0.8$, and SFR power ratio $\beta = 0.1$ as a function of α

The scheduling method used for all of the four schemes is Round Robin (RR) scheduling algorithm, where users take turns using RBs over a period of time (frame).

For each α value, the average user throughput for the cellular system is computed and presented in Fig. 5. It can be seen that SFR provides higher throughput for smaller α values, where FFR provides higher throughput for larger alpha values. In the case of SFR, the throughput decreases rapidly as α increases. That is because as the ratio increases, the number of inner users increases leading to an increase in interference for cell-edge users between adjacent cells. Similarly, the SINR for inner cell users decreases as the ratio increases.

Again, from Fig. 5, when α equals 0.7, the overall system throughput for SFR is even worse than for Reuse-1. It can be inferred that for smaller inner radius to cell radius ratio, system performance can be significantly enhanced by using SFR.

Fig. 5 also shows that performance in terms of system throughput increases for FFR as α increases. That is because as α increases, the number of inner RBs increase and the increase in resource could mitigate the resource shortage by the increase in inner cell area, which increases the number of inner cell users. Another result to notice from the figure is the performance of the Reuse-3 scheme. This scheme avoids interference at best by using a reuse factor of 3. However, since the entire cell uses just a third of the available RBs, its efficiency is very low. Reuse-1, on the other hand, uses the entire set of RBs. Nevertheless, the sever interference caused by reusing the available spectrum degrades the performance.

To see the effect of the change in parameter γ on the performance of FFR and SFR, a simulation is performed by keeping α constant at 0.4, and varying the value of γ. Fig. 6 and 7 present the results. For FFR and SFR, the average user throughput decreases rapidly as γ increases. The inner to cell radius ratio is kept constant, meaning the increase in γ decreases the number of inner RBs. At $\gamma = 0.4$, all the available RBs are given to inner users, since $\gamma = \alpha$. In Fig. 6 we can see that as γ increases the inner cell user throughput decreases because the number of inner RBs is reduced. However, from Fig. 7, it can be shown that the increase in γ results in the increase in cell-edge user throughput. This is because of the increase in the number of outer RBs. Throughput for Reuse-1, and Reuse-3 remains constant as γ does not have any impact on the RB allocation for the two schemes.

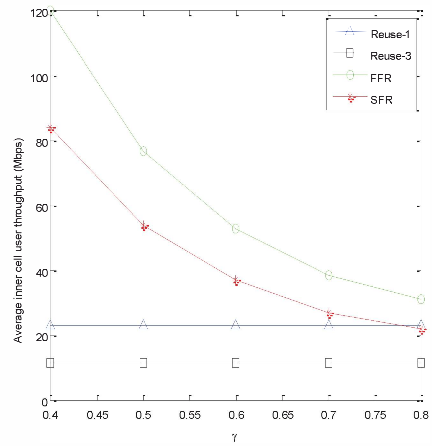

Fig. 6. Average inner cell user throughput for Reuse-1, Reuse-3, FFR, and SFR, with $\alpha = 0.4$, and SFR power ratio $\beta = 0.1$ as a function of γ

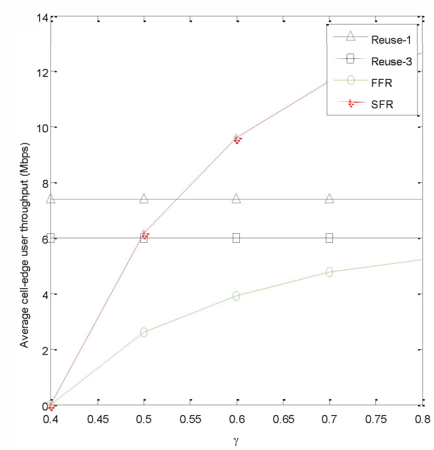

Fig. 7. Average cell-edge user throughput for Reuse-1, Reuse-3, FFR, and SFR, with $\alpha = 0.4$, and SFR power ratio $\beta = 0.1$ as a function of γ

Another important parameter is β, the power ratio, used in SFR. To evaluate the performance of SFR under different β values, a simulation was performed for values $0.1 \leq \beta \leq 0.8$, while fixing α at 0.4 and γ at 0.8. The result is presented in Fig. 8 and Fig. 9.

The average throughput decreases for smaller β values as is seen in Fig. 8. This is due to the increase in interference, or decrease in SINR for cell-edge users as is shown in Fig.9. SINR for cell-edge decreases because of the increase in

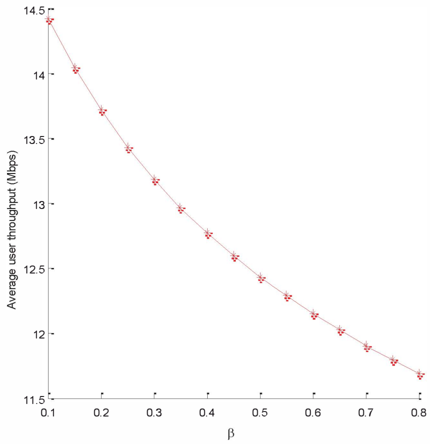

Fig. 8. Average user throughput for SFR with $\alpha = 0.4$, and $\gamma = 0.8$, as a function of power ratio β.

transmit power on inner RBs as β increases. When the transmit power on inner RBs for a cell increases, SINR for inner-cell users increases by reducing the interference from adjacent cells. However, adjacent cell-edge users are highly affected by interference from the cell's inner RBs. The resulting decrease in SINR is slightly higher than the gain achieved by inner-cell users, from having their inner RBs transmit at higher power, that it decreases the average user throughput.

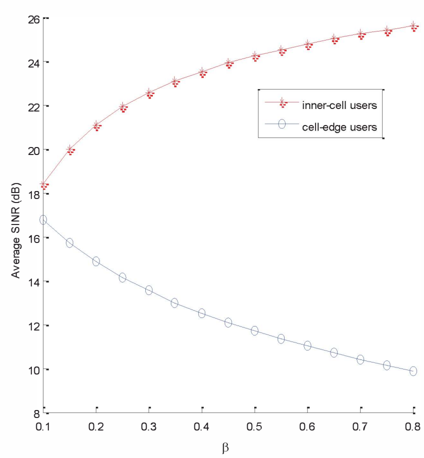

Fig. 9. Average cell-edge, and inner-cell user SINR for SFR with $\alpha = 0.4$, and $\gamma = 0.8$, as a function of power ratio β.

V. Conclusion

In this paper, we presented a comprehensive performance evaluation of Reuse-1, Reuse-3, fractional frequency reuse (FFR), and soft frequency reuse (SFR), that are used as inter-cell interference avoidance techniques in the OFDMA cellular downlink with varying input parameters, such as inner radius and power ratios. By considering these parameters, the performance in terms of average user throughput and SINR, average cell-edge user throughput and SINR, and average inner-cell user throughput and SINR, has been evaluated in this work.

The results obtained show that Reuse-1 suffers the most interference while Reuse-3 achieves the lowest interference. Although all resources are used, because of its low average SINR for both cell-edge and cell-center users, Reuse-1 provides low throughput. Reuse-3, on the other hand, avoids interference by reusing its RBs far apart and has the highest SINR. However, the smaller number of available RBs means lower average throughput. In SFR, smaller inner to outer cell ratio provides the highest average user throughput of all the techniques. However, cell-edge users suffer the most interference in SFR. It was also observed that for higher power ratios, average SINR for inner users is increased, but the average cell-edge user SINR decreases, resulting in the decrease of the overall system average user throughput.

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