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Performance Analysis of Frequency Reuse Techniques under varying Cellular Network scenarios

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***Abstract*—Fractional Frequency Reuse (FFR) schemes are frequency allocation techniques used in cellular systems for interference mitigation and enhancing resource utilization. In this paper, analysis is presented comparing FFR and other FR algorithms under realistic network situations. Most implementations in literature considered uniform mobile placements and perfect grid models where well-defined hexagonal layouts are used for the Base station (BS) deployment. More practical scenarios are considered here including random mobile placements and irregular BS deployments. Results are presented using the relevant performance metrics; signal-to-interference-noise ratio (SINR) and capacity. The relationship between SINR and capacity, as well as comparison between FFR schemes over different parameter configurations are presented. The investigations provide valuable insights into the practical performance of FFR; crucial for optimizing cellular design.**

I. Introduction

A. Background

Mobile communication systems have evolved significantly over the last three decades due to improvements in the technology, system efficiency, user devices and available services. Currently, fourth generation (4G) - Long Term Evolution (LTE) networks are being deployed globally offering fast-speed data services; a sharp contrast to the analogue telecommunication systems deployed in the 1980"s. The proliferation of intelligent devices like smart phones and tablets, as well as the data intensive applications that run on them have created a massive data demand. Consequently, there is need to constantly improve the system capacity and efficiently utilize the wireless spectrum. Frequency Reuse (FR) is a method used to manage the limited frequency spectrum. In FR, Base stations (BS) at different locations are made to utilize similar frequency bands for their communication with mobile devices, also called user equipment (UE) [1], [2].

The basic FR schemes can be divided into two; integer frequency reuse (IFR) and fractional frequency reuse (FFR). In IFR, the BS sectors are fully classified according to frequency bands as shown in Figs. 1(a) and 1(b). However in FFR, each sector is partitioned into center and edge regions before classification as shown in Figs. 1(c) and 1(d). IFR can be divided into frequency reuse one (FR1) and frequency reuse three (FR3) techniques. FR1 involves complete reuse of the entire frequency spectrum in all sectors, while in FR3, each sector uses a third of the spectrum. FR1 increases the number of UEs that can be connected but the LTE network capacity is severely limited by inter-cell interference (ICI). On the other hand, FR3 results in resource underutilization though it is less affected by interference. To tackle these challenges, FFR schemes like the Strict FR (StrictFR) and Soft FR (SFR) have been developed. In StrictFR, as described in Fig. 1(c), each BS sector is partitioned into two regions and each region is given a different frequency band. The center regions (which are closer to the BS) utilize the same frequency bands, different from the edge regions (which are farther away and are where UEs experience the highest interference). This ensures reduced ICI impact on the vulnerable UEs located in the edge regions. SFR differs from StrictFR in the sector frequency allocations as can be seen in Fig. 1(d). In SFR, the frequency bands available for center regions are increased to improve the data rate (capacity). Center regions of the sectors utilize similar frequency bands to edge regions in other sectors, unlike the strict demarcation in StrictFR [3].

Although several implementations of FFR have been presented in literature, more efficient algorithms are still being required. In this article, extensive analysis is presented of static FR applications in different cellular deployment scenarios. The aim is to extend the understanding of the cellular system so as to aid the development of more optimized FFR schemes.

B. Organization of Paper

The remaining part of this paper is organized thus: Performance analysis and evaluations presented in literature, as well as the contributions of this paper are presented in Section II, the system model in III, Results are presented and discussed in IV and V is the Section for conclusion and future research.

II. Related Work and Contributions of paper

The parameters that determine the performance at any given time of a cellular system employing FFR include the center radius, power ratio (between edge and center transmission regions) and traffic load. These affect the degree of interference and user bandwidth and determine the resulting signal-to-interference-ratio (SINR) and capacity. Several research works exist in literature that present performance analysis of FFR techniques. In [4], the authors showed how the system performance of the FR schemes varies over different center radius and power

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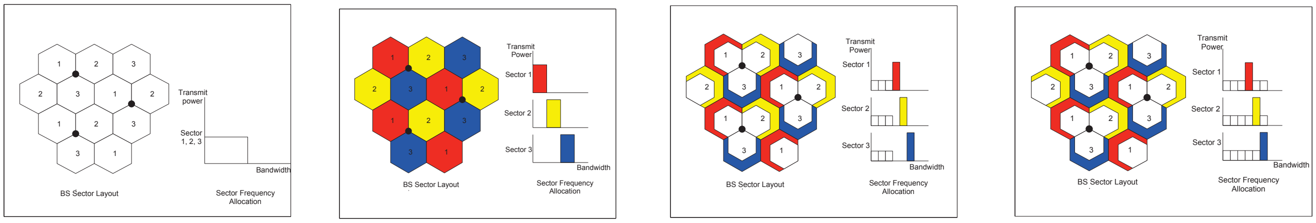

(a) FR1 (b) FR3 (c) StrictFR (d) SFR

Fig. 1: Frequency and power assignments for different FR schemes

ratios. Specific performance of center and edge users were also considered. The authors in [5] presented an evaluation of the capacity of SFR under different traffic loads and power ratio configurations. Analytical derivations and simulations were used in [6] to compare the FR techniques and provide design guidelines. The metrics used were outage probability, network capacity, SINR and spectral efficiency under different center radius and power ratios. In [7], the system capacity was studied under different scheduling techniques.

In this paper, existing analyses of FR performance is extended by consideration of more network parameters and scenarios. Specifically, realistic assumptions for BS deployments and UE placements are considered. Practical cellular networks usually consist of macro BS that are not arranged perfectly to form hexagonal radiation patterns as those shown in Fig. 2. UEs are also not always located uniformly across the system space. However, most of the previous research works have assumed hexagonal BS deployments over uniform UE placements. The analysis presented here show how the FR schemes perform over random and clustered UE placements, as well as over irregular BS deployments (e.g in Fig. 3). It extends the system evaluation over varying center radius, power ratios and traffic loads. To aid the analysis, equations and metrics are proposed to compute UE random placements and irregularity of BS locations. The performance of SINR and capacity over different center radii is also critically investigated. This is crucial for the development of efficient FFR algorithms using dynamic implementation.

III. System Model

A. Base station and User Layout Model

The downlink transmission of an orthogonal frequency division multiple access (OFDMA) cellular network is considered. It comprises of macro BSs and several UEs positioned within the BS regions. Each BS has three sectors, covered by three antennas and each UE connects to the BS sector from which it receives the highest signal power. Two cases of UE positioning are considered; uniform placement and random placement. To model variations of UE positioning in the random placement, the UEs in a sector are assumed to be clustered to varying degrees in three positions. These positions define: locations close to the sector antenna, l_1, locations at the sector center, l_2 and locations at the edge of the sector l_3. For each UE in the set U, connected to a BS sector in the set A, the 2D coordinate location is given by:

$$\begin{bmatrix} x_{u,i}, \\ y_{u,i} \end{bmatrix}_{i \epsilon U} = \begin{bmatrix} x_{s,j} + rand((x_{s,j} - \alpha r), (x_{s,j} + \alpha r)), \\ y_{s,j} + rand((y_{s,j} - \alpha r), (y_{s,j} + \alpha r)) \end{bmatrix}_{j \epsilon A}, \tag{1}$$

where $x_{s,j}, y_{s,j}$ is the 2D location of either l_1, l_2 or l_3, $rand(a, b)$ is a random number generated between a and b, α is a factor to specify the degree of clustering, and r is the radius of a BS sector.

Two cases of BS deployments are also considered; hexagonal grid (cloverleaf) model where the sector power radiation patterns form regular hexagons and the more realistic irregular BS model. These are shown in Figs. 2 and 3 respectively. For effective comparison and analysis between the two models, the same number of BS is assumed in both cases. For the irregular BS model, each BS location in the hexagonal model is shifted randomly within certain constraints which will determine the degree of irregularity of the new BS. For each BS m in the set C of irregular BS, the 2D coordinate location is given by:

$$\begin{bmatrix} x_i, \\ y_i \end{bmatrix}_{i \epsilon C} = \begin{bmatrix} rand((x_j - \beta r), (x_j + \beta r)), \\ rand((y_j - \beta r), (y_j + \beta r)) \end{bmatrix}_{j \epsilon B}, \tag{2}$$

where x_j, y_j is the 2D location of the corresponding hexagonal BS, n, $rand(a, b)$ is a random number generated between a and b, β is a factor to specify the degree of deviation m from n and r is the radius of a BS sector. With these equations listed, different UE and BS patterns can be generated and the resulting system parameters studied.

B. Bandwidth Allocation

Fig. 1 shows the frequency allocation techniques for the different FR schemes. The technique used in each scheme determines the amount of interference that UEs experience. For the FFR schemes, this can be further analysed based on the

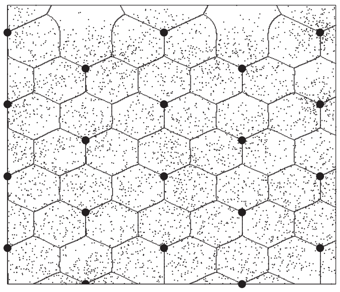

Fig. 2: Uniform BS placement

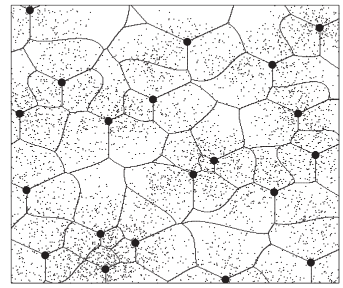

Fig. 3: Irregular BS placement

interference received at center UEs and edge UEs. In addition, the frequency allocations also determine how much bandwidth each UE will receive. This is an important parameter because it determines the data rate (capacity) UEs experience. If the total Bandwidth per sector is $\mathcal{B}_T$, the required bandwidth per UE is $\mathcal{B}_r$ and the total number of connected UEs in a sector is N_i, the bandwidth allocated per UE, $\mathcal{B}_i$, for each scheme are given by:

FR1:

$$\mathcal{B}_i = \begin{cases} \mathcal{B}_r, & if(\mathcal{B}_T/N_i > \mathcal{B}_r) \\ \mathcal{B}_T/N_i, & otherwise. \end{cases} \tag{3}$$

FR3:

$$\mathcal{B}_i = \begin{cases} \mathcal{B}_r, & if(\mathcal{B}_T/(3 \times N_i) > \mathcal{B}_r) \\ \mathcal{B}_T/(3 \times N_i), & otherwise. \end{cases} \tag{4}$$

StrictFR: The bandwidth allocated for center UEs is:

$$\mathcal{B}_{i,c} = \begin{cases} \mathcal{B}_r, & if(\mathcal{B}_T/(2 \times N_{i,c}) > \mathcal{B}_r) \\ \mathcal{B}_T/(2 \times N_{i,c}), & otherwise. \end{cases} \tag{5}$$

The bandwidth allocated for edge UEs is:

$$\mathcal{B}_{i,e} = \begin{cases} \mathcal{B}_r, & if(\mathcal{B}_T/(6 \times N_{i,e}) > \mathcal{B}_r) \\ \mathcal{B}_T/(6 \times N_{i,e}), & otherwise, \end{cases} \tag{6}$$

SFR: The bandwidth allocated for center UEs is:

$$\mathcal{B}_{i,c} = \begin{cases} \mathcal{B}_r, & if((5 \times \mathcal{B}_T)/(6 \times N_{i,c}) > \mathcal{B}_r) \\ (5 \times \mathcal{B}_T)/(6 \times N_{i,c}), & otherwise. \end{cases} \tag{7}$$

The bandwidth allocated for edge UEs is:

$$\mathcal{B}_{i,e} = \begin{cases} \mathcal{B}_r, & if(\mathcal{B}_T/(6 \times N_{i,e}) > \mathcal{B}_r) \\ \mathcal{B}_T/(6 \times N_{i,e}), & otherwise. \end{cases} \tag{8}$$

where $N_{i,c}$ and $N_{i,e}$ are the number of connected center and edge UEs respectively in StrictFR and SFR. $N_i = N_{i,c} + N_{i,e}$.

C. Performance metrics

For analysis, the metrics utilized are SINR and capacity. Assuming P_b is the transmit power of the serving BS sector antenna, h_b is the fading component, G_b is the channel path-loss between the UE and BS and σ^2 is the noise power, the SINR equations differ for the different FR schemes and are presented below:

FR1: As seen in Fig. 1(a), all BS sectors utilize the entire available spectrum. For a given UE, i in the set U, the equation for the SINR in FR1 is [6]:

$$SINR_i = \frac{P_b h_b G_b}{\sigma^2 + \sum\limits_{j \epsilon I} P_j h_j G_j}, \tag{9}$$

where I is the set of interfering sectors which comprise all other sectors excluding sectors of the serving BS and P_j, h_j, G_j represent the sector transmit power, fading component and BS to UE path-loss of the interfering BS sectors respectively.

FR3: In this scheme, only BS sectors with the same number utilize the same frequencies, as shown in Fig. 1(b), the SINR of a UE is given by:

$$SINR_i = \frac{P_{b,a} h_{b,a} G_{b,a}}{\sigma^2 + \sum\limits_{j \epsilon I, c=a} P_{j,c} h_{j,c} G_{j,c}}, \tag{10}$$

where a and c are the sector numbers of the serving BS and interfering BSs respectively. I is a new set of interfering sectors with the same sector number as the serving BS.

StrictFR: This is an FFR scheme where the sector regions are partitioned into two regions as shown in Fig. 1(c). The UEs are classified as center and edge users based on their location. For the center and edge users respectively, the SINR is given by:

$$SINR_{i,c} = \frac{P_{b,c} h_b G_b}{\sigma^2 + \sum\limits_{j \epsilon C} P_{j,c} h_j G_j}, SINR_{i,e} = \frac{P_{b,e} h_b G_b}{\sigma^2 + \sum\limits_{k \epsilon E} P_{k,e} h_k G_k}, \tag{11}$$

where c and e are the center and edge parameters of the serving BS sector respectively, while C and E are the set of interfering center and edge BS sector transmissions respectively. C includes

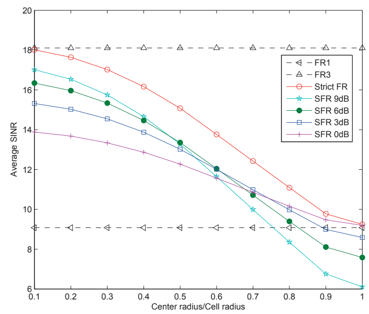

Fig. 4: Average SINR(dB) for different FR schemes

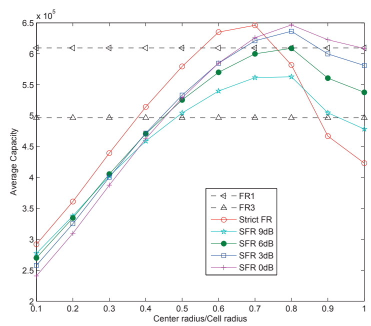

Fig. 5: Average capacity(Bits/Sec/Hz) for different FR schemes

all sector center transmissions other than those of the serving BS and E includes all edge transmissions from sectors with the same number as the serving BS sector.

SFR: Fig. 1(d) shows that in this scheme, both the sector center and the sector edge transmissions contribute interference in varying degrees to any given UE. The SINR for center users is:

$$SINR_{i,c} = \frac{P_{b,c}h_bG_b}{\sigma^2 + \sum\limits_{j\epsilon C} P_{j,c}h_jG_j + \sum\limits_{k\epsilon E} P_{k,e}h_kG_k}. \quad (12)$$

Similarly the edge users SINR is given by:

$$SINR_{i,e} = \frac{P_{b,e}h_bG_b}{\sigma^2 + \sum\limits_{j\epsilon C} P_{j,c}h_jG_j + \sum\limits_{k\epsilon E} P_{k,e}h_kG_k}. \quad (13)$$

where c and e are the center and edge parameters of the serving BS sector respectively, while C and E represent the sets (as presented in Fig. 1(d)), of interfering center and edge BS sector transmissions respectively.

The capacity (throughput or data rate) of any UE i is [3]:

$$Cap_i = \mathcal{B}_i \times \log_2(1 + SINR_i), \quad (14)$$

where $\mathcal{B}_i$ is the UE bandwidth and $SINR_i$ is the SINR of user i.

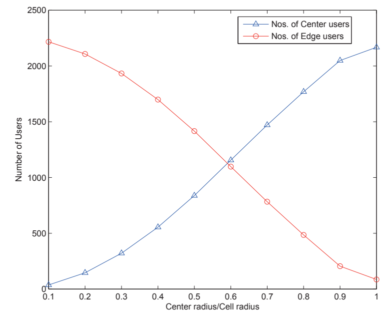

Fig. 6: Number of Center and Edge Users

IV. Results and Analysis

In this section, analysis of the network performance is presented for different UE scenarios under both Hexagonal (uniform) and Irregular (random) BS placements. Figs. 2 and 3 show the BS layout structure and power radiation patterns for the three-sectored hexagonal and irregular BS placements respectively; the big black dots representing the BS locations. The UE scenarios considered are uniform, random and over-loaded UE deployments.

A. Simulation Parameters

Every network implementation is realized with 20 macro BS each having three sectors, giving a total of 60 sectors. For the cases involving hexagonal BS deployments, the cloverleaf model is adopted. The number of Physical resource blocks (PRB) per sector chosen is 48 and the bandwidth of each PRB is 180kHz. Since the PRB corresponds to the total number of connected users, the overall number of users for fully (normally) loaded UE deployment is 2880. The total sector radius is 500m, system bandwidth considered is 10MHz and the total transmit power is 43dBm. The path loss considered is $128.1 + 37.6 \log D$ and the antenna radiation model is defined by the pattern equation model as presented in [8] i.e. $A(\theta) = -min\left[12(\frac{\theta}{\theta_{3dB}})^2, A_m\right], -180 \leq \theta \leq 180$ where θ_{3dB} is the half power beamwidth (65^o) and A_m is the maximum attenuation. The antenna gain is therefore expressed as $G(\theta) = A(\theta) + G_m$ where $G_m$is the maximum antenna gain given as $15dBi$ for a 3 sector antenna.

B. Hexagonal BS with uniform and fully loaded UE deployment

Firstly, a cellular network where BSs are deployed to form a hexagonal radiation pattern and UEs are uniformly placed is considered. The UEs are assumed to be fully deployed and active in each BS sector. Figs. 4 and 5 show the average SINR and capacity respectively, for the different FR schemes. Although FR1 and FR3 schemes do not involve the partitioning of UEs into center and edge like the FFR schemes, they are included in the graph (and repeated across the x-axis) for the basis of comparison. As expected, FR3 gives the best SINR performance respectively, consistent with algorithm descriptions in Fig. 1, while FR1 has a better capacity than FR3.

For the FFR algorithms, the curves show a difference in the performance of SINR and capacity. While the SINR is generally inversely proportional to the center radius, the Capacity initially rises with increasing radius to a maximum value before falling. The SINR reduces as the center radius increases because of increased interference from neighbouring sectors. Figs. 1(c) and 1(d) show that FFR algorithms reduce the interference experienced by edge UEs while center UEs employ more frequency reuse. Consequently, when the center radius increases, the amount of interference from center sector transmissions increase and the SINR drops.

On the other hand, the capacity is affected not only by the SINR, but also by the UE bandwidth as seen in (14). Therefore, even though the SINR falls with increased center radius (and increased center UEs), the Capacity initially increases because the UE bandwidth increases. This is explained by (5-8), as well as Figs. 1(c) and 1(d), which show that FFR schemes allocate more of the system bandwidth to center UEs. Fig. 6 shows that when the center radius is least, majority of the UEs are classified as edge and this is when the SINR is maximum (from results in Fig. 4). This implies that the network has the best SINR performance when most of the UEs are allocated just $1/6$ of the available bandwidth; as (6) and (8) reveal. Consequently resource utilization is low and this reflects on the performance of capacity in Fig. 5. The capacity performance therefore provides a more realistic system assessment than the SINR for FFR schemes. Therefore, in the remaining parts of the paper, results will be presented for only the average capacity of the network. The results also show that for optimal network performance, it is necessary to choose appropriate radii that balance efficient bandwidth allocation and interference mitigation.

The effect of the center transmit powers can also be studied from the graphs. Figs. 4 and 5 show that when the center radius is low, lower power transmission from the center regions give better performance (SFR 9dB). The reverse is the case at larger center radii where SFR 0dB performs better. This depends on the degree of interference that BS pose to each other and is reliant on the path loss and BS radius as shown in (11-13).

C. Irregular BS deployment

In this section, varying BS and UE scenarios are considered and highlighted. Figs. 9 and 10 show the average Capacity performance for random BS deployments in both uniform UE and random UE placements, respectively. Similar to the preceding section, FR1 performs excellently when compared to static FFR schemes. To improve the resource utilization of the FFR schemes for better performance, dynamic allocation of center radii for sectors has to be adopted as opposed to the similar radii assumed here. In Fig. 10, it is further observed that SFR performs better than StrictFR in irregular network conditions.

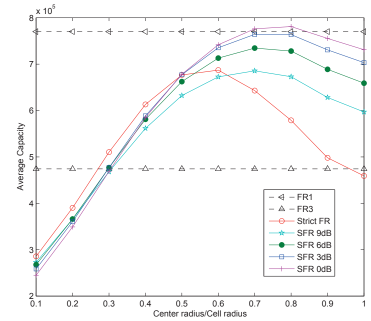

Fig. 7: Average capacity(Bits/Sec/Hz) for random UE in uniform BS

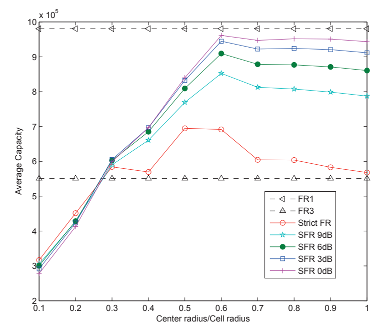

Fig. 8: Ave. Capacity(Bits/Sec/Hz) for high clustered rand. UE in uniform BS

D. SFR Comparison

The SFR network performance is analysed for different network conditions in this section. Fig. 11 is a summary of maximum SFR performance for different scenarios considered so far of full UE loading. All cases are for the same number of UEs but different UE or BS positioning. As seen from the plots, the highest capacities are obtained when UEs are clustered around the BSs and the least is obtained when the BSs are irregular. This seems to suggest that the BS deployment has more effect on the system performance than UE placements. Algorithms have to be developed to enhance SFR schemes to account for irregular BS deployments. Fig. 12 is a comparison for cases where the network is overloaded by twice the number of UEs in the case of full loading. The values for average capacity are lower than in the cases of full loading due to the fact that the average bandwidth per UE is reduced in dense UE deployments. However, the poorest performance is seen in the case of Irregular BS, as also observed in the case of full loading.

V. Conclusion and Future Research

In this paper, an analysis of Frequency reuse schemes in mobile communication networks was presented for realistic system scenarios. Practical assumptions for UE placements and

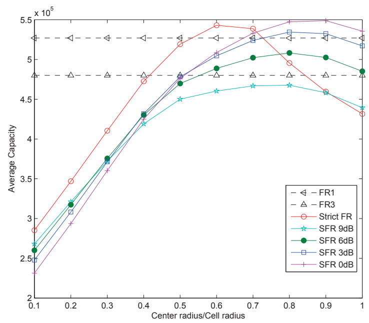

Fig. 9: Average Capacity(Bits/Sec/Hz) for uniform UE in random BS

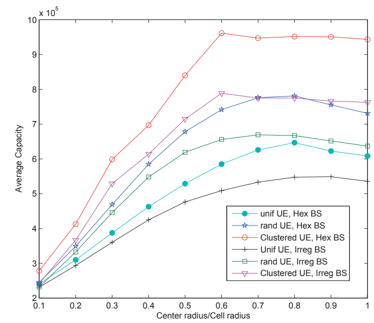

Fig. 11: SFR Ave. Capacity(Bits/Sec/Hz) Comparison for full loaded Network

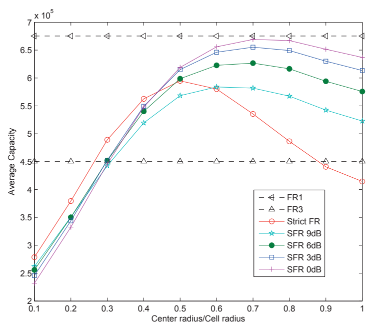

Fig. 10: Average Capacity(Bits/Sec/Hz) for random UE in random BS

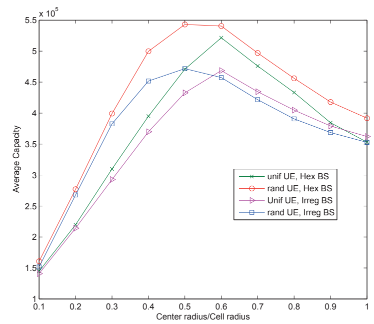

Fig. 12: SFR Ave. Capacity(Bits/Sec/Hz) Comparison for Overloaded Network

BS deployments were considered and the system performance was made using average SINR and capacity. Investigation on the performance of FFR schemes was emphasized and results showed how they behave under different center radii values. The insights obtained from the analysis would be useful to develop self-organized algorithms for the SFR which enhances the system capacity by exploiting the flexible frequency allocation of the basic SFR. The study confirms that dynamic implementations of FFR schemes as opposed to static techniques are required for optimal network performance. In other ongoing research, the authors are investigating techniques for optimizing different BS deployments and UE placements in homogeneous and heterogeneous cellular networks where more than one BS tier exists. New variants of SFR e.g. in [9] are also being considered and the option of using tractable mathematical tools like stochastic geometry for better insights and analysis [6].

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REFERENCES

[1] Christopher Cox, ”An introduction to LTE : LTE, LTE-advanced, SAE and 4G mobile communications”, *John Wiley and Sons, Ltd*, 2012. ISBN 978-1-119-97038-5

[2] M. Qian, W. Hardjawana, Y. Li, B. Vucetic, X. Yang and J. Shi, ”Adaptive soft frequency reuse scheme for wireless cellular networks”, *IEEE Transactions on Vehicular Technology*, vol. 64, no. 1, pp. 118-131, 2015

[3] O.G. Aliu, M. Mehta, M. A. Imran, A. Karandikar and B. Evans, ”A New Cellular Automata based Fractional Frequency Reuse Scheme,” *IEEE Transactions on Vehicular Technology*, vol. 64, no. 4, pp. 1535 - 1547, 2015.

[4] B. M. Hambebo, M. M. Carvalho, and F. M. Ham, ”Performance evaluation of static frequency reuse techniques for OFDMA cellular networks,” in *IEEE 11th International Conference on Networking, Sensing and Control (ICNSC)*, April 2014 , pp. 355-360.

[5] Y. Yu, E. Dutkiewicz, X. Huang, M.Mueck and G. Fang, ”Performance analysis of soft frequency reuse for inter-cell interference coordination in LTE networks”, in *IEEE International Symposium on Communications and Information Technologies (ISCIT)*, October 2010, pp. 504-509.

[6] T. Novlan, J. G. Andrews, I. Sohn, R. K. Ganti, and A. Ghosh, ”Comparison of fractional frequency reuse approaches in the OFDMA cellular downlink,” in *IEEE Global Telecommunications Conference (GLOBECOM 2010)*, December 2010, pp. 1-5.

[7] A. Gok, and M. Koca, ”Performance evaluation of frequency planning and scheduling schemes in OFDMA Networks” in *IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom)*, May 2014, pp. 149-153.

[8] 3GPP Technical Report TR 36.942 v10.2.0, Radio Frequency (RF) system scenarios,December 2010.

[9] Y. Xuezhi. ”A multi-level soft frequency reuse technique for wireless communication systems,” *IEEE Communications Letters*, vol. 19, no. 11, November 2014.