New framework for interference and energy analysis of soft frequency reuse in 5G networks

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ABSTRACT

Cellular networks are expanding massively due to high data requirements from mobile devices. This has motivated base station densification as an essential requirement for the 5G network. The implication is obvious benefits in enhanced system capacity, but also increased challenges in terms of interference. One important interference management technique which has been widely adopted in cellular networks is frequency reuse. In this article, an analysis is presented based on network interference and energy expended by base stations in downlink communication when Soft frequency reuse (SFR) is deployed. A framework is presented that captures the bandwidth overlaps in SFR across base station assignments, computes the interference probabilities arising and derives new performance equations which are verified using simulations. Results show an improvement of 43% over previous SFR implementations that do not consider the interference probabilities. Thus, a more in-depth and accurate modelling of SFR in 5G networks is achieved. Furthermore, the downlink power allocation is investigated as against other parameters like the center ratio and edge bandwidth. The result shows that signal-to-interference-noise ratio (SINR) and spectral efficiency give different performance under energy consideration. A framework is developed on how to tune a base station to achieve desired network performance in user SINR or cell spectral efficiency depending on the operator's preference.

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1. INTRODUCTION

In recent times, a lot of effort has been geared towards development and implementation of 5G cellular networks both in research circles and the industry. Higher data rates and improved coverage for better user experience are two requirements for 5G realization. To achieve these target goals, one strategy is to increase the density of base stations (BS) in the network. With more BS, cells reduce in size and reuse of the spectrum can be implemented across several locations in the network [1, 2]. However, the amount of interference from neighbouring BS towards user equipment (UE) depends on the nature and extent of frequency reuse (FR) deployed. As interference severely affects UE performance and Quality of service (QoS), interference management is an important consideration, and intelligent FR is used for inter-cell interference cancellation (ICIC) and efficient resource allocation in cellular networks [2-5]. Soft frequency reuse (SFR) is a spectrum allocation technique where the coverage area in a cell is divided into two regions;

UE are classified, and their bandwidth also allocated based on the region of their location. The coverage regions are called center (closer to the serving BS) and edge (closer to the cell boundary of the serving BS). Amongst FR techniques, the SFR protects edge UE from interference caused by neighbouring BS and in a way better than the Fractional frequency reuse (FFR) technique it guarantees high resource utilization. SFR scheme is designed to permit greater flexibility in the adjustment of BS parameters to varying network conditions [6]. SFR, FFR and their variants have been utilized to address the major challenge of interference in cellular networks which greatly affects edge UE. Due to their exposure to high interference from neighbouring BS, edge UE are vulnerable and susceptible to low signal-to-interference-noise ratio (SINR). There is the added challenge for high capacity in order to drive sophisticated and data intensive applications now running on mobile devices. Therefore, a typical network with several BS and high number of UE is a complex system that is difficult to analyse, design or optimize and in the context of 5G these challenges are still issues. Improvements in cellular systems are hence required in the areas of providing more accurate modelling of the network, adequate classification of network scenarios, and development of algorithms where BS parameters are enhanced to achieve desired performance. In this paper, analysis is provided for cellular networks where the interference model and BS power allocation in SFR are considered.

Previous research has focused on tackling the problem of interference through 1) performance analysis studies of the complex scenarios around BS parameters when FR is employed, 2) modification of the structure of baseline FR schemes and 3) optimization studies where parameters are enhanced to give optimal FR based on selected metric(s) of interest. In [6-10], performance evaluations are presented of FR techniques by considering how BS parameters like the center ratio, power ratio and frequency allocations alter UE QoS. This is carried out separately for the different UE classes (center and edge) and for other network considerations like BS placements and UE density. Due to the variety of configurations BS can attain, the network with FR is a complex one that necessitates extensive performance analyses using simulations. The second type of studies involves modification of the fixed rules and allocations of BS parameters in standard FR algorithms to improve UE performance even without system optimizations. By modifying the spectrum allocation rules, modified FR schemes have been proposed in [11-20]. These works have shown how FR can be deployed as an underlying technique under other cellular network paradigms and technologies like Heterogeneous cellular networks (HetNets), Device-2-Device (D2D) communication and millimeter wave (mmWave) networks. In [11], a modified SFR algorithm is presented to support a network where millimeter wave spectrum is used alongside the traditional microwave spectrum. [12, 13] show how FR can be implemented by adding space as a parameter in the technique and using several SFR implementations in a multilevel manner, respectively. [14-16] provide FR implementations for HetNets while [17-20] are D2D networks enabled with FR technology. Thirdly, some works employing optimization algorithms have also been presented including cellular automata [12], Game theory [21, 22], Iterative algorithms for optimization [23] and multi-objective optimization [24, 25].

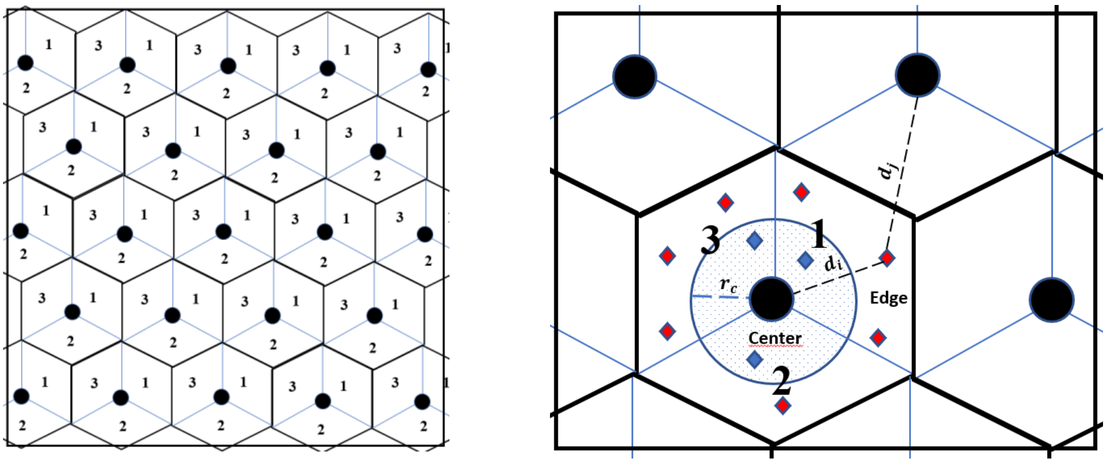
It is pertinent to note that significant performance gains can be achieved with simple modification of the basic SFR technique, even without use of optimization techniques. After modified SFR schemes are developed, better results can then be obtained from deployment of optimization procedures. Accurate modelling and analysis of the network is also a crucial requirement for this modification. In this paper, the contribution is covering analysis of SFR technique for cellular networks. First, deeper insight is provided, and a new framework is presented for interference analysis in SFR. As an extension to previous work in [26], new equations are derived for SINR of UE in cellular networks employing SFR with consideration for the probability that interference occurs based on overlapping allocation of bandwidth. This framework is verified by simulations to provide a more accurate computation of the SINR compared to previous works. Furthermore, analysis is presented on the impact of downlink power allocation on UE performance when other factors like the center ratio and edge bandwidth are considered as secondary parameters. This contributes clearer analysis of energy management under SFR and will be of immense benefit to research on development of enhanced SFR techniques and for operators who need to set BS parameters to achieve their performance goals.

2. SYSTEM MODEL AND METHOD OF ANALYSIS

In this section, the system model and parameters for a cellular network where SFR is deployed are provided. SFR algorithm is described and the framework for analysis is presented which contains derived equations for SINR and spectral efficiency.

2.1. Soft frequency reuse specification

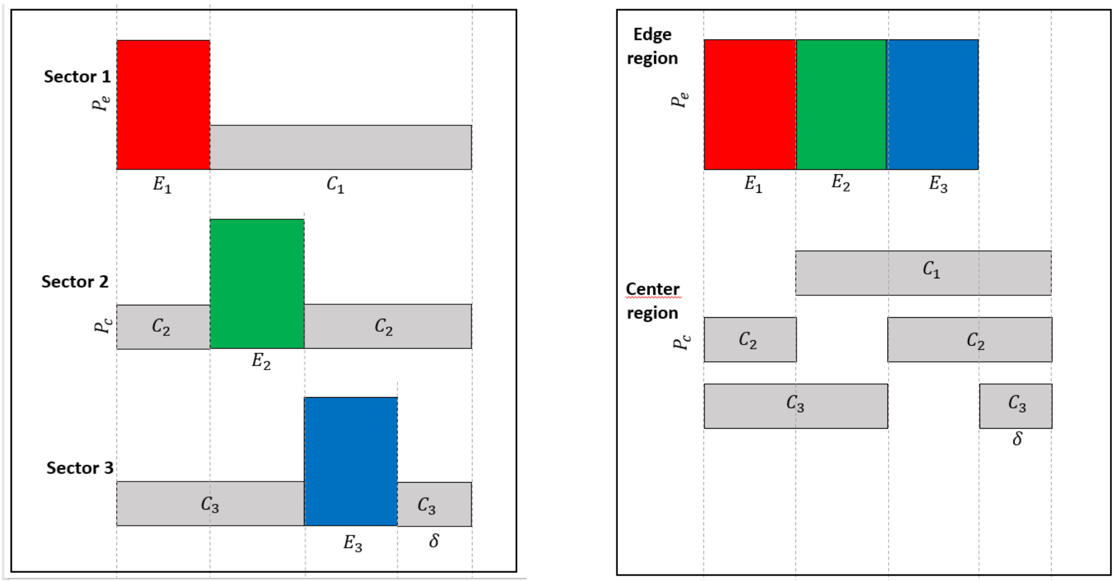
A cellular network comprising BS with three sectors (via sectored antennas) is assumed as shown in Figure 1 (a), with the labels 1,2,3 representing the first, second and third sectors respectively. The coverage pattern generated is from the regular hexagonal arrangement of cellular BS. SFR is a technique where the coverage area of each sector is divided into two regions. This is depicted in Figure 1 (b) for a reference BS, where r_c (center ratio) is the radius that separates the center region from the edge region, d_i is the distance between a UE and its serving BS and d_j is the distance between the UE and an interfering BS.



(a) (b)

Figure 1. Coverage patterns for cellular network, (a) Base stations in network, (b) Reference base station with SFR (red diamonds-edge UE, blue diamonds-center UE)

For each region, separate bandwidth and energy parameters are specified based on sector number and according to the description in Figure 2. In Figure 2 (a), the Power versus Bandwidth graphs are shown separately for each of the three sectors, containing both center and edge regions. Figure 2 (b) presents the same information as Figure 2 (a), but with a different representation where the graphs are shown separately for each of the two coverage regions, with the sectors placed side by side. Both Figures 2 (a) and 2 (b) show how the spectrum is separated and reveal the areas of overlapping bandwidth allocation between regions which give rise to interference between and within sectors and regions.



(a) (b)

Figure 2. Soft frequency reuse power vs. bandwidth allocation, (a) Allocation per sector, (b) Allocation per base station region

Let the total system bandwidth which is available in each sector be $\mathcal{B}$. Therefore, from Figure 2

$\mathcal{B} = E_1 + E_2 + E_3 + \delta = E_1 + C_1 = E_2 + C_2 = E_3 + C_3$.

Deriving from Figure 2, let $P_{e,i}$, $P_{c,i}$ be the BS transmission power to the edge and center regions respectively from sector i of a BS, then if $N_{e,i}$ is the number of UE in the edge of sector i, $N_{c,i}$ is the number of UE in the center of sector i and N_i is the total number of UE in sector i, $N_{e,i} + N_{c,i} = N_i$ and $P_{e,i}N_{e,i} + P_{c,i}N_{c,i} = P_t$ and the following holds: [26]

$$P_{e,i} = \frac{\mu_i P_t}{N_{e,i}(\mu_i - 1) + N_i}, \; P_{c,i} = \frac{P_t}{N_{e,i}(\mu_i - 1) + N_i} \tag{1}$$

where $\mu_i = {P_{e,i}}/{P_{c,i}}$ is called the power ratio and P_t is the power budget in each sector.

2.2. Parameters for performance assessment

UE QoS can be measured using performance parameters like the SINR, coverage probability, data rate and spectral efficiency. The SINR and spectral efficiency are used in this study.

2.2.1. SINR

Considering the *reference sector* 1 of the *reference* BS shown in Figure 1 (b), the SINR of any connected UE is given by:

$$SINR_u = \frac{p_i h_i G_i}{\sigma^2 + \sum I} \tag{2}$$

Where p_i is either $P_{e,i}$ (if the UE is in the edge region) or $P_{c,i}$ (if the UE is in the center region), h_i is the fading component, G_i is the pathloss relating the UE and sector i of the transmitting BS, σ^2 is the noise component and $\sum I$ is the total interference from nearby BS sectors. $\sum I$ follows from the SFR rules as highlighted in Figure 2. For edge UE in sector 1, interference is received *fully* from the center region transmissions of different sectors (sectors 2 and 3) of neighbouring BS and from the edge region transmissions of the same sector number (sector 1) of neighbouring BS. On the other hand, center UE in sector 1 receive interference partially (with some probability) from the center and edge region transmissions of sectors 2 and 3 of neighbouring BS, and full interference from the center region transmissions of sector 1 of neighbouring BS. The quantity of interference received in a region depends on the probability that the bandwidth assigned in the serving BS region overlaps (is the same as) that of the interfering BS. The probabilities that regions will receive interference from other regions are computed from careful consideration of the overlapping bandwidth portions shown in Figure 2 and presented in Table 1 (Note the following assumption: $E_1 = E_2 = E_3 = E$).

Table 1. Probability of Interference between base station regions

			Receiving region					
			Edge			Center		
			Sector1	Sector2	Sector3	Sector1	Sector2	Sector3
Originating region	Edge	Sector1	1	0	0	0	$\frac{E}{2E+\delta}$	$\frac{E}{2E+\delta}$
		Sector2	0	1	0	$\frac{E}{2E+\delta}$	0	$\frac{E}{2E+\delta}$
		Sector3	0	0	1	$\frac{E}{2E+\delta}$	$\frac{E}{2E+\delta}$	0
	Center	Sector1	0	1	1	1	$\frac{E+\delta}{2E+\delta}$	$\frac{E+\delta}{2E+\delta}$
		Sector2	1	0	1	$\frac{E+\delta}{2E+\delta}$	1	$\frac{E+\delta}{2E+\delta}$
		Sector3	1	1	0	$\frac{E+\delta}{2E+\delta}$	$\frac{E+\delta}{2E+\delta}$	1

SINR for Edge UE: Therefore, the SINR for an edge UE of sector i can be computed using Table 1 by considering the appropriate column and from (1) and (2) is given by:

$$SINR_{edge} = \frac{\mu_i P_t d_i^{-\alpha} / N_{e,i}(\mu_i - 1) + N_i]}{\sigma^2 + \sum_{j \neq i, j \in Z}\left(\frac{0 \times \mu_j P_t}{N_{e,j}(\mu_j - 1) + N_j} + \frac{P_t}{N_{e,j}(\mu_j - 1) + N_j}\right) d_j^{-\alpha} + \sum_{k = i, k \in Z}\left(\frac{\mu_k P_t}{N_{e,k}(\mu_k - 1) + N_k} + \frac{0 \times P_t}{N_{e,k}(\mu_k - 1) + N_k}\right) d_k^{-\alpha}} \tag{3}$$

$$= \frac{\mu_i P_t d_i^{-\alpha} / [N_{e,i}(\mu_i - 1) + N_i]}{\sigma^2 + \sum_{j \neq i, j \in Z} \frac{P_t d_j^{-\alpha}}{N_{e,j}(\mu_j - 1) + N_j} + \sum_{k = i, k \in Z} \frac{\mu_k P_t d_k^{-\alpha}}{N_{e,k}(\mu_k - 1) + N_k}} \tag{4}$$

Where i, j, k are the sector numbers, d_i is the distance between the UE and serving BS as shown in Figure 1 (b), d_j and d_k are distances between the UE and interfering BS, from (2) h_i=1, the pathloss from (2) is $G_i = d_i^{-\alpha}$, α is the path loss exponent and Z is the set of interfering BS to the reference UE.

SINR for Center UE: Similarly, the SINR for a center UE of sector i can be computed and by considering the probabilities in Table 1 and the expansion of (2) to give:

$$SINR_{\text{center}} = \frac{P_t d_i^{-\alpha} / [N_{e,i}(\mu_i - 1) + N_i]}{\sigma^2 + \sum_{j \neq i, j \in Z}\left(\frac{E}{2E+\delta} \times \frac{\mu_j P_t}{N_{e,j}(\mu_j - 1) + N_j} + \frac{E+\delta}{2E+\delta} \times \frac{P_t}{N_{e,j}(\mu_j - 1) + N_j}\right) d_j^{-\alpha} + \sum_{k = i, k \in Z}\left(\frac{P_t}{N_{e,k}(\mu_k - 1) + N_k}\right) d_k^{-\alpha}} \tag{5}$$

The equations derived (3)-(5) are new equations for the SINR of UE in cellular networks where SFR is employed for resource allocation. This is an extension to the earlier work presented in [26] for a HetNet scenario where the equations were not verified. This framework is for analysis of SFR with improved accuracy and its validation through simulations is described in Section 3.

2.2.2 Spectral efficiency

The spectral efficiency at a BS cell gives a measure of spectrum resource utilization and is given by: [12] where $\mathcal{B}$ is the total available bandwidth, U is the set of users in the cell, B_i is the bandwidth assigned to user identified by i and $SINR_i$ is the SINR of user identified by i.

$$\eta = \frac{1}{\mathcal{B}} \sum_{i \epsilon U} B_i \log_2(1 + SINR_i)\,, \tag{6}$$

3. RESULTS AND DISCUSSION

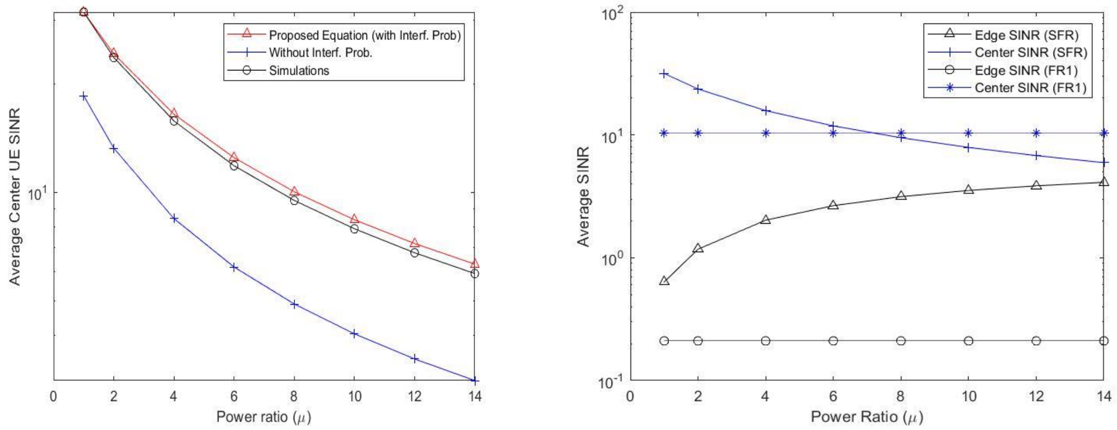
3.1. Simulation parameters

Simulation of the network and UE performance is carried out using MATLAB. The BS parameters selected are $P_t = 43dBm,$ coverage radius, $r = 0.5Km,$ total physical resource blocks (PRBs) $= 48$ and the assumption of fully connected and active BS regions is made. In addition, 1 PRB is assigned per UE $(N_i = N_j = N_k = 48)$. Other parameter assignments include $h = 1, \alpha = 3, \sigma^2 = 0.$ The total system bandwidth considered is $\mathcal{B} = 10MHz$ and bandwidth per PRB $B_i = 180KHz$. The network consists of hexagonal coverage layout for macro base stations with 1 central *reference* BS where all analysis and results are considered for its first sector and 19 surrounding interfering BS in two rings around it. The UE are uniformly deployed in the network. From Figure 2, the edge bandwidth allocations for each sector are assumed equal for simplicity, i.e $E_1 = E_2 = E_3 = E$ and E takes the following range $B_i \leq E \leq 15B_i$. The parameter δ in Figure 2 and Table 1 is obtained as $(N_i B_i - 3E)$ and so takes the following range $45B_i \geq \delta \geq 3B_i$ since $N_i = 48$. In all BS it is assumed, r_c, E are the same and $\mu_i = \mu_j = \mu_k = \mu$

3.2. Validation of SINR equation

Table 1 contains the values for the probabilities that interference arrives at a region of a BS sector. It shows the expected amount of interference UE will experience based on their region of location. The edge regions are shown to receive interference with probabilities of either 0 or 1. However, the center regions receive interference with four different probabilities $(0, \frac{E}{2E+\delta}, \frac{E+\delta}{2E+\delta}$ and 1). Based on these values, the SINR for center UE in (5) is dependent on E and δ, unlike that of edge UE in (4). The new SINR equation presented in (5) is used to compute SINR for center UE and the results are validated with simulations as shown in Figure 3 (a). The following BS parameters are assumed in each cell; r_c is set at $0.75r$, $E = 15B_i$ and results are obtained for $2 \leq \mu \leq 14, (\mu_i = \mu_j = \mu_k = \mu)$. The figure shows that the proposed equation is more accurate than standard equations from previous works where the interference probabilities are not captured.

From the result obtained, there is an improvement in the accuracy of computation of the SINNR by up to 43% over the case where the interference probabilities are not considered and full interference in the center region is assumed to be received from neighbouring center regions. (a) Validation of equation (b) Comparing edge, center SINR (for SFR) and average SINR (for FR1) The same BS parameters are set to obtain the results in Figure 3 (b) which show the SINR for edge and center UE under SFR and UE under FR1. Even though UE are not grouped in the FR1 scheme, the average SINR for the same center and edge UE classified under SFR are also computed using FR1 for the purposes of comparison. Figure 3(b) shows the best SINR performance occurs with the center UE under SFR at low μ. This is expected since $\mu_i = {P_{e,i}}/{P_{c,i}}$ and (3)-(5) show that a high value of μ gives higher transmit power to (and hence higher SINR for) edge UE and lower transmit power to (lower SINR for) center UE. For the entire range of μ considered, the average center UE SINR always exceeds that of edge UE. The worst performance is obtained for the edge UE under FR1 scheme which adopt full reuse across the spectrum and provides no grouping nor special protection for edge UE.



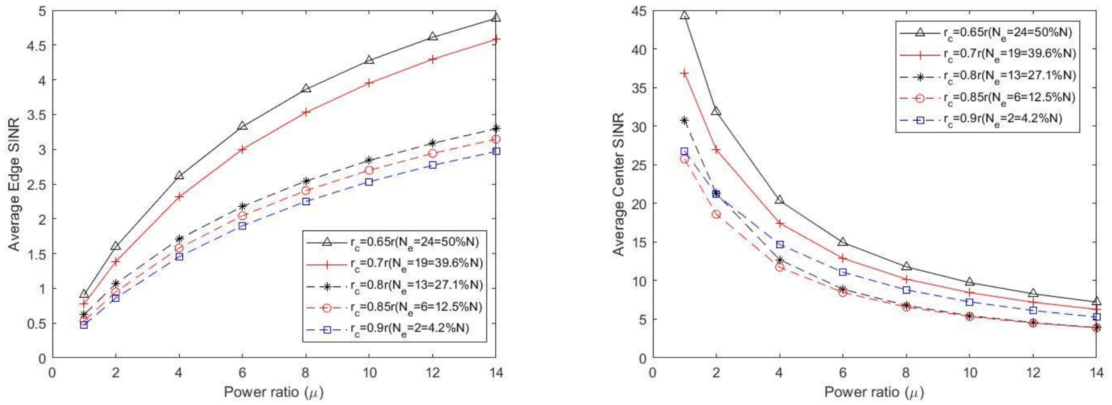
(a) (b)

Figure 3. SINR results

3.3. Analyzing power ratio and center ratio

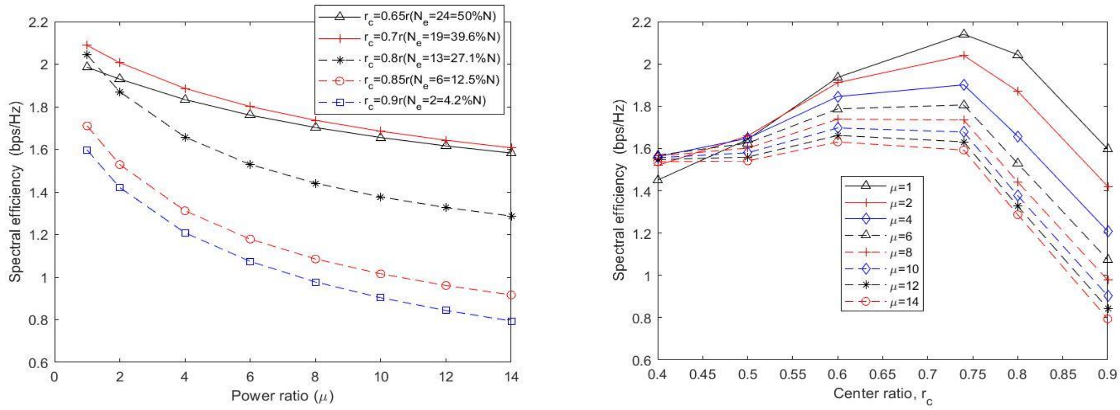
In (3)-(5) show the different parameters that contribute to the SINR of UE and include the power ratios (μ_i, μ_j, μ_k), the number of UE classified as edge UE in each BS sector ($N_{e,i}, N_{e,j}, N_{e,k}$), the UE positions (which determine the distance between UE and both their serving and interfering BS) and the interference probabilities. While $N_{e,i}, N_{e,j}, N_{e,k}$ depend on the center ratio, r_c which is used to classify UE, the interference probabilities depend on the edge bandwidth, E and δ. P_t and N_i are constants. This article considers the energy allocation at the reference BS so the major parameter considered is the power ratio. Figures 4(a) and 4(b) show the edge and center UE SINR plots when μ is varied across the range $2 \leq \mu \leq 14$ and this is repeated for several values of r_c corresponding to $N_{e,i} = 24{,}19{,}13{,}6{,}2$. It can be observed that in all cases edge UE SINR reduces as r_c increases (and $N_{e,i}$ reduces). The center UE SINR does not however perfectly obey this rule and the least value occurs when $r_c = 0.85r$. It exceeds the edge UE SINR in all cases, showing the effect interference has on edge UE performance despite the protection offered by SFR.

The results of spectral efficiency for similar BS parameter settings are shown in Figures 5 (a) and 5 (b). Generally, an increase in r_c results in a decrease in spectral efficiency except between $r_c = 0.65r$ and $r_c = 0.7r$. In Figure 5 (b), more ranges of r_c are added for $r_c < 0.65$ and it can be observed that the maximum spectral efficiency is obtained when $r_c = 0.75r$ for all cases of μ, similar to the value of best result in [9]. When r_c is very low, the coverage space for the edge region is higher than the center (consistent with Figure 1 (b)) so more UE are classified as edge UE. This setting is not so desirable with SFR since the technique is designed to allocate more resources to the center region and not the edge as shown in Figure 2; hence r_c should typically be in the range $r_c \geq 0.6r$ (for more UE to be classified as center UE). So, although Figure 4 shows the highest SINR is obtained for the lowest r_c, Figure 5 reveals this is not the best center ratio for efficient allocation of bandwidth. Hence in the network, it is essential to compare the performance of SINR and spectral efficiency and choose an appropriate balance for the BS parameters to meet desired performance. If the goal is to maximize SINR, then a low r_c is preferred but if resource utilization is required, r_c should be carefully selected to obtain maximum spectral efficiency. Similarly, μ needs to be set to achieve the desired improvement (to the detriment of center UE) in edge UE performance.



(a) (b)

Figure 4. SINR variation with respect to Power and Center ratios

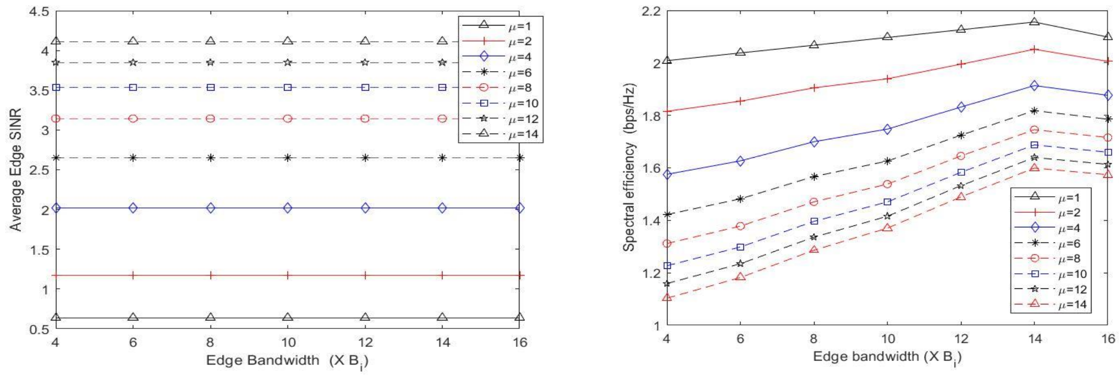


(a) (b)

Figure 5. Spectral efficiency variation with respect to power and center ratios

3.4. Analyzing power ratio and edge bandwidth

In the final analysis, performance is compared over varying power ratio and edge bandwidth, for $r_c = 0.75r$ ($N_{e,i} = 13$) and results presented in Figure 6. The average SINR for edge UE remains constant over varying edge bandwidths for each setting of the power ratio. The same applies for center UE, consistent with the (3)-(5) but the different behaviour of edge and center UE with respect μ to still holds consistent with results in Figures 4, 5 and 6 (a). Figure 6 (b) shows the variation of spectral efficiency over edge bandwidth for various settings of the power ratio. It is observed that the maximum spectral efficiency occurs when $E = 14B_i$ in all cases because $N_{e,i} = 13, N_i = 48$ and when $E = 14B_i$ the fairest and most efficient allocation of bandwidth is achieved as 13 is closest to 14 among the options.



(a) (b)

Figure 6. Performance evaluation with respect to power ratio and edge bandwidth, (a) Edge SINR, (b) Spectral efficiency

3.5. Summary of results

The results show that the proposed new SINR equation provides better accuracy especially for center UE whose interference is usually not full under SFR but based on probability. Investigations for BS energy usage (based on power ratio) show that edge UE and center UE exhibit opposite reaction to an increase in power ratio. Edge UE SINR increases with μ while center UE SINR decreases. Interestingly, spectral efficiency also reduces with μ. Based on the studies on UE classification, both center and edge UE SINR were observed to decrease with increase in r_c, but the maximum spectral efficiency occurred when $r_c = 0.75r$, i.e when the number of UE classified as edge and center is properly balanced with the SFR bandwidth allocation rules in Figure 2. Finally, the analysis carried out on bandwidth allocation showed that center and edge UE SINR are not altered by change in edge bandwidth. However, the edge bandwidth must be carefully selected if the maximum spectral efficiency is desired. The findings of this research provide a useful framework and guide for tuning BS parameters in cellular networks. Based on the goal of the operator or designer, the center ratio, power ratio and edge bandwidth can be adjusted depending on whether maximum SINR (minimum interference) or maximum spectral efficiency (optimal resource utilization), or a middle ground is preferred.

4. CONCLUSION

In this article, frameworks for accurately modelling interference and energy in cellular networks employing Soft frequency reuse (SFR) have been presented and verified. The nature of SFR reveals that there are overlapping regions (which have been typically overlooked previously) of the bandwidth allocation to different regions of a cell. These overlapping regions are considered and the interference probabilities they create are defined and used to derive new signal-to-interference-noise ratio (SINR) equations. The equations are verified using simulations for center users which are mostly affected by the interference probabilities with an improvement of 43% achieved. Furthermore, the power ratio which is the main energy parameter from BS transmission is analyzed in the context of other parameters like the center ratio and edge bandwidth. The results obtained give more insight into the operation of SFR in cellular networks. Specifically, the SINR and spectral efficiency result shows varying patterns, corroborating the widely held notion that BS parameters would have to be tuned differently at various times to favor a performance goal to the detriment of others. An operator would need to specify if edge UE SINR or spectral efficiency is preferred to be maximized and the guidelines proposed here can direct on how BS parameters can be set to achieve the goal. In future work, investigation would be made for the case of irregular and random UE placements and irregular BS deployments.

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