Network-Load Dependent Partial Frequency Reuse for LTE

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***Abstract*—Inter-cell Interference (ICI) is a key issue in Orthogonal Frequency-Division Multiple Access (OFDMA) systems. Since OFDMA was proposed to be used in next generation networks several schemes have been investigated for mitigating the ICI. One of the techniques that promises improvement in reducing ICI is Partial Frequency Reuse (PFR). In this paper we investigate a Flexible Bandwidth Allocation (FBA) scheme for PFR depending on the network-load, which allocates bandwidth dynamically in the network. The scheme is based on the assumption that a cell is not loaded homogeneously. We develop a suitable network description to obtain the optimum PFR zone partitioning as a function of the dynamic bandwidth allocation. Thus, our paper presents a general framework for intelligent frequency planning in wireless networks. Compared to simpler PFR schemes, our simulation results show that the cell capacity for reuse-1 can be increased by 2 b/s/Hz when our scheme is used by exploiting the inhomogeneities in the load.**

I. INTRODUCTION

Next generation cellular networks are based on Orthogonal Frequency Division Multiple Access (OFDMA). OFDMA is used by WiMax, DVB-T, WLAN and 3GPP Long Term Evolution (LTE). An important feature of OFDMA is its flexibility in bandwidth scaling [1]. Generally in cellular networks, the users at the cell edge suffer from more Inter-Cell Interference (ICI) than users closer to their serving base station. If all base stations re-use the same frequency band (like e.g. in LTE), then ICI mitigation becomes a major concern and several ICI mitigation techniques for that have been discussed in the literature [2]. One of these techniques which is different from traditional frequency reuse (reuse-1 and reuse-3) is Soft Frequency Reuse (SFR) which has been explained in [3], [4], [5], [6]. Another scheme which is a different form SFR is Partial Frequency Reuse (PFR). This scheme was used in [2], [4], [6], [7], [8] and seems to be the most promising technique for 3GPP LTE. This technique consists of splitting the bandwidth into two parts: Full Reuse (FR) part and Partial Reuse (PR) part. The FR-part is like reuse-1 which is the same for all cells in the network. The PR-part is allocated to the cell edge users such that the signals are orthogonal to the neighbor users. A combination of PFR with Soft Handover (SH) is given in [4] which indicates that there is an improvement on the throughput in PR-zone but we loose in the throughput in FR-zone. This happen because of the resources in FR-zone are shared with the users which are in PR-zone. In [7] is used a modified PFR scheme which is named Two Level Power Control (TLPC). This scheme consists in allocation of different power in different zones. Xiang, Luo and Hartman [6] have mentioned that the PR-band can be re-used for the FR-band whenever the cell edge users are idle. This is remembered also by Chiu and Huang [4]. To our knowledge there is not any paper which explains the way of using the PR-band for FR-band. In this paper we have implemented Flexible Bandwidth Allocation (FBA) scheme which consist of using the PR-band for FR-band by assuming that the user load is higher in the center cell region. The system model is formulated in section II which is similar to [8]. In section III the bandwidth allocation of the partial re-use scheme is explained. Section IV formulates the optimization problem for maximizing the cell capacity. Simulation results are discussed in Section V and we formulate the conclusions in Section VI.

II. SYSTEM MODEL

The system model which is considered [8] contains a base station in the center BS_0 and a ring of six hexagonal neighbor base stations $BS_1 ... BS_6$. This model is shown in Fig. 1.

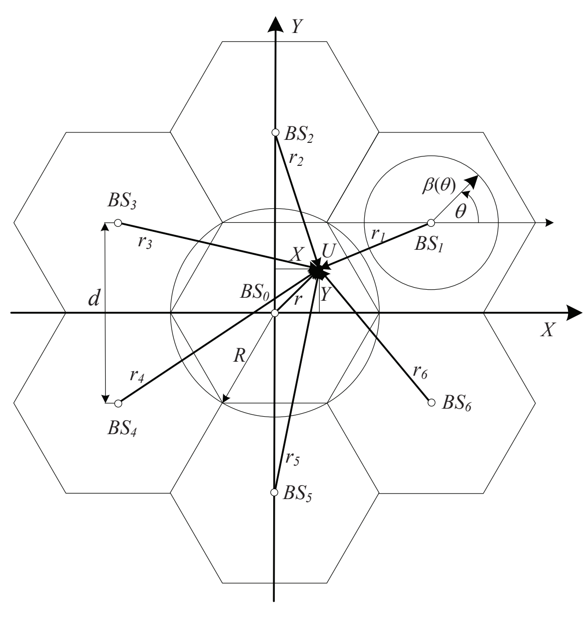

Fig. 1. Cell cluster

Base stations are equipped with sectorized antennas. Each base station contains tree sectors where the angle beetwen sectors is 120^0. As it is shown in the figure, the user $U(X,Y)$ is located at the distance $r=\sqrt{X^2+Y^2}$ from the center of BS_0. Generally speaking, the Signal-to-Noise and Interference Ratio (SINR) is given by

$$\mathrm{SINR}=\frac{P_r}{P_{intra-cell}+P_{inter-cell}+N_0}, \quad (1)$$

where P_r is the received power density from user, $P_{intra-cell}$ is the interference that comes from users inside the cell, $P_{inter-cell}$ is the interference from neighbor cells and N_0 is the noise power. LTE as modulation technique uses OFDMA in the downlink [1] hence there is no intra-cell interference present. We are interested to mitigate the inter-cell interference. The received power density from the user can be described as [8]

$$P_r=p\,G(r), \quad (2)$$

where p is the power spectral density which is given as ratio of total power and total bandwidth $p=P_{tot}/B_{tot}$ and $G(r)$ is the pathloss. We use the pathloss exponent model $G(r)=L/r^{\alpha}$, where L denotes loss and α denotes the pathloss exponent. Accordingly [8], the average SINR can be evaluated by

$$\Gamma(X,Y)=\frac{pL/r^{\alpha}}{N_0+\sum_{i=1}^{n}pL/r_i^{\alpha}}, \quad (3)$$

where $r_i, i=1...6$ are the distances of user U from the neighbor cells. In the following, let us normalize the coordinates (X,Y) to the radius of the cell R, denoted by (x,y). The expression for the SINR in normalized coordinates according to [8] is

$$\gamma(x,y)=\frac{\Gamma_e}{(x^2+y^2)^{\alpha/2}\left[1+\Gamma_e S(x,y)\right]}, \quad (4)$$

where Γ_e is the edge SNR defined by

$$\Gamma_e=\frac{pL}{N_0R^{\alpha}}. \quad (5)$$

The sum of all pathloss distances r_i defined by $S(x,y)$ is given by expression

$$S(x,y)=\sum_{i=1}^{n}\left[(x-x_i)^2+(y-y_i)^2\right]^{-\alpha/2}. \quad (6)$$

The ICI is usually critical for cell edge users because the neighbor cells may use the same carriers in a simple frequency network. Also the users in the center of the cell use the same carriers but they are more isolated from ICI because of the macro-scale pathloss. In order to minimize the ICI, a common approach is to split the cells into two regions: in a so-called FR-region and a PR-region. The FR-region is located around the base station, and the PR-region is located at the cell edge. All three sectors in FR-region use the same frequency like reuse-1. In PR-region the three sectors uses different frequencies. Implying this frequency planning of the PR frequency bands, the PR-region can be considered ICI-free because the frequencies which are allocated for users in this region are different from the frequencies which are allocated to the users in neighboring cells. The position of the user in cell is determined based on its received SINR. There is a threshold for the received SINR and if the received SINR is less than the threshold, the user is considered to be cell edge user otherwise as cell center user. After this the scheduler decides which Physical Resource Blocks (PRB) to allocate to the user. A PRB contains 12 subcarriers where each subcarrier is 15 kHz in frequency domain [9]. Let us denote the boundary between these two regions in polar coordinates as $\beta(\theta)$, with θ specifying the azimuth angle. Furthermore let us approximate that the azimuth angle is $\theta=0$. Now the boundary between these two regions is defined by $\beta(0)=\rho$. The SINR for these two regions in polar coordinates can then be given by

$$\gamma_\rho(r)=\begin{cases}\frac{\Gamma_e}{r^{\alpha}[1+\Gamma_e S(r)]}, 0<r\le\rho,\\ \frac{\Gamma_e}{r^{\alpha}}, \rho<r\le 1,\end{cases} \quad (7)$$

and the capacity density in bps/m^2 that can be achieved by a user is [8]

$$c_\rho(r)=b(r)\log_2[1+\gamma_\rho(r)], \quad (8)$$

where $b(r)$ is the bandwidth allocation density which is allocated to the user.

III. Bandwidth Allocation

An exemplary frequency reuse pattern model which is similar to the models presented in [4], [10] is shown in Fig. 2

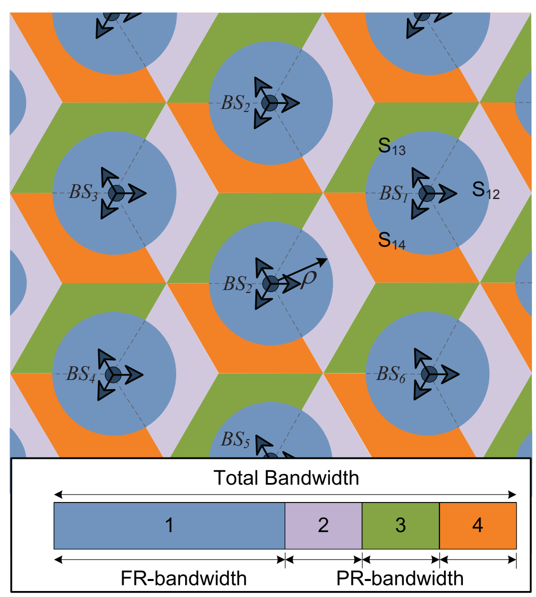

Fig. 2. Frequency reuse pattern and bandwidth partitioning

In Fig. 2 the sectors are denoted by S_{12}, S_{13} and S_{14} where the indexes denote the FR-band and PR-bands. The equation for the total bandwidth based on the model which is shown in Fig. 2 is given by

$$B_{tot} = B_{FR} + 3B_{PR}, \tag{9}$$

where B_{FR} denotes the bandwidth used in FR-region and B_{PR} the bandwidth used in PR-region. Here is assumed the ratio between bandwidths as $B_{FR}/B_{PR} = 3$. Let us now assume all cells to be populated homogeneously with users over their area. This means that in average all cells utilize the same transmit power. PFR consists that all subcarriers in all regions of the cell have the same transmit power in downlink [11]. The bandwidth allocation per subcarrier where all sucarriers have the same transmit power in the downlink is shown in Fig. 3

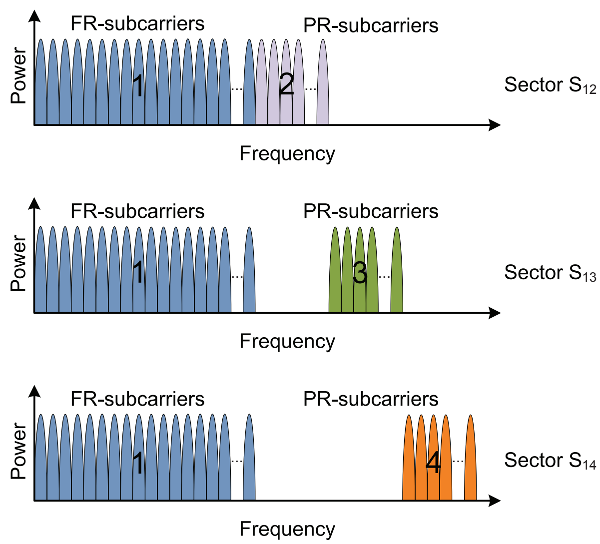

Fig. 3. Downlink subcarrier allocation

The cell capacity is defined as sum of capacities in these two regions for considered cell

$$C = C_{FR} + C_{PR}, \tag{10}$$

where C_{FR} denotes the capacity in FR-region and C_{PR} the capacity in PR-region in considered cell. The expressions for these capacities can be calculated by integrating the capacity density given in Eq. (8) over the corresponding region area. We assume the bandwidth density allocated in each region is constant for given ρ, thus $b(r)$ becomes B_{FR} in FR-region and B_{PR} in PR-region. Now the expressions for C_{FR} and C_{PR} become

$$C_{FR} = 2\pi \int_0^{\rho} B_{FR} \log_2 \left(1 + \frac{\Gamma_e}{r^{\alpha}\left[1 + \Gamma_e S(r)\right]}\right) r\mathrm{d}r, \tag{11}$$

$$C_{PR} = 2\pi \int_{\rho}^{1} B_{PR} \log_2 \left(1 + \frac{\Gamma_e}{r^{\alpha}}\right) r\mathrm{d}r. \tag{12}$$

We are interested to maximize the cell capacity for given ρ so the optimization problem becomes

$$\begin{array}{ll} maximize & C \\ subject\ to & 0 \leq \rho \leq 1. \end{array} \tag{13}$$

IV. Flexible Bandwidth Allocation

In practical systems over the area of cells users are not distributed uniformly which means that more users can be concentrated in the area of FR-region than in the area of PR-region. In this case we can say that the cell is not loaded homogeneously over its area. Now we are interested how to allocate the bandwidth in FR-region by taking some bandwidth from PR-region. In order to do this we introduce the parameter t in Eq. (12) and split the PR-bandwidth in two parts, so

$$\begin{aligned} C_{PR} &= 2\pi \int_{\rho}^{1} t B_{PR} \log_2 \left(1 + \frac{\Gamma_e}{r^{\alpha}}\right) r\mathrm{d}r \\ &+ 2\pi \int_{\rho}^{1} (1-t) B_{PR} \log_2 \left(1 + \frac{\Gamma_e}{r^{\alpha}}\right) r\mathrm{d}r. \end{aligned} \tag{14}$$

Also we write ρ for the upper bound and zero for the lower bound of the first integral in Eq. (14). Now the expression for capacity in PR-region becomes

$$\begin{aligned} C_{PR}(t) &= 2\pi \int_{0}^{\rho} t B_{PR} \log_2 \left(1 + \frac{\Gamma_e}{r^{\alpha}}\right) r\mathrm{d}r \\ &+ 2\pi \int_{\rho}^{1} (1-t) B_{PR} \log_2 \left(1 + \frac{\Gamma_e}{r^{\alpha}}\right) r\mathrm{d}r. \end{aligned} \tag{15}$$

The way of allocating the bandwidth from PR-region in FR-region is shown in the model presented in Fig. 4.

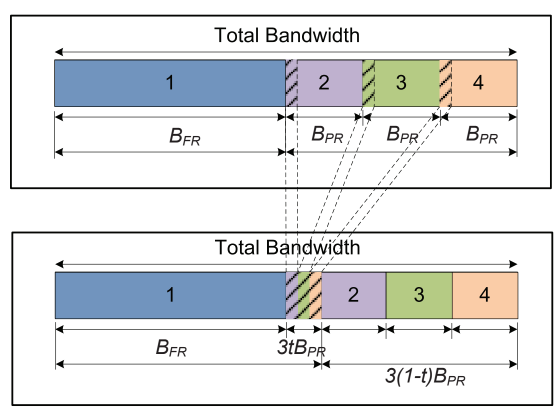

Fig. 4. Proposed model for frequency reuse pattern and bandwidth partitioning

The bandwidth which is used from PR-bandwidth for FR-bandwidth is considered to be ICI-free. Now the equation for the capacity of considered cell is

$$
\begin{aligned}
C(t,\rho) &= 2\pi \int_0^{\rho} B_{FR} \log_2\left(1+\frac{\Gamma_e}{r^{\alpha}\left[1+\Gamma_e S(r)\right]}\right) r\mathrm{d}r \\
&+ 2\pi \int_0^{\rho} t B_{PR} \log_2\left(1+\frac{\Gamma_e}{r^{\alpha}}\right) r\mathrm{d}r \\
&+ 2\pi \int_{\rho}^{1} (1-t) B_{PR} \log_2\left(1+\frac{\Gamma_e}{r^{\alpha}}\right) r\mathrm{d}r. \qquad (16)
\end{aligned}
$$

By increasing the parameter t we allocate more bandwidth from PR-region in FR-region. By considering the parameter t as constraint the optimization problem becomes

$$
\begin{array}{ll}
\mathit{maximize} & C(t,\rho) \\
\mathit{subject\ to} & 0 \le \rho \le 1 \\
 & 0 \le t < t^{*}.
\end{array} \qquad (17)
$$

Based on Eq. (16) one may think that by increasing the parameter t up to 1 we can use all the bandwidth resources from PR-region for FR-region. To evaluate how much bandwidth resources we can use from the PR-region for the FR-region we set the first derivative of Eq. (16) w.r.t. ρ and equal it to zero. The resulting optimum frequency partitioning radius is denoted by $\hat{\rho}$. The equation for $\hat{\rho}$ depending on parameter t is

$$
3\log_2\left(1+\frac{\Gamma_e}{\hat{\rho}^{\alpha}\left[1+\Gamma_e S(\hat{\rho})\right]}\right) = (1-2t)\log_2\left(1+\frac{\Gamma_e}{\hat{\rho}^{\alpha}}\right). \qquad (18)
$$

Eq. (18) tells us that the cell capacity can be maximized for a given t when spectral efficiency in FR-region times the reuse factor is equal with the spectral efficiency in PR-region times the factor $(1-2t)$. From Eq. (18) we define the theoretical results for the upper bound t^{*} of parameter t and we find that $t < 0.5$. However we are interested to see if the simulation results approaches with theoretical results.

V. Simulation Results

TABLE I
Simulation parameters

parameters	value
Total bandwidth B_{tot}	20 MHz
Maximum total power p	1 W
Noise spectral density N_0	-174 dBm/Hz
Center frequency f	2 GHz
Pathloss exponent α	3.6
Cell radius R	100 m

By using the data given in Table I and Eq. (18) we have simulated the optimal frequency partitioning radius versus parameter t for constant power $p = 1\,\mathrm{W}$ which is shown in Fig. 5.

From simulation results shown in Fig. 5 we see that values of $\hat{\rho}$ are in $[0, 1]$ when values of parameter $0 \le t \le 0.42$. We conclude that simulation results for $\hat{\rho}$ approach with theoretical results when the values of parameter t are in $[0, 0.42]$. Based on the upper bound for the parameter t we see that we can not re-allocate more than 42% of the bandwidth from PR-region in FR-region. This is a boundary which is important for simulating the cell capacity C. To get the simulation results for cell capacity we use the data given in Table I and the Eq. (16). The simulation results are shown in Fig. 6.

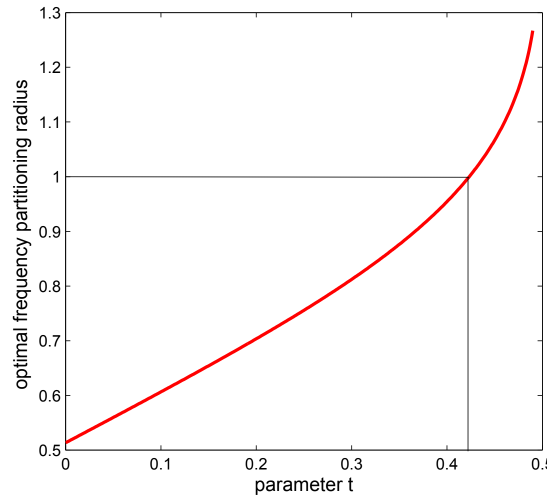

Fig. 5. Optimal frequency partitioning radius versus parameter t and total power

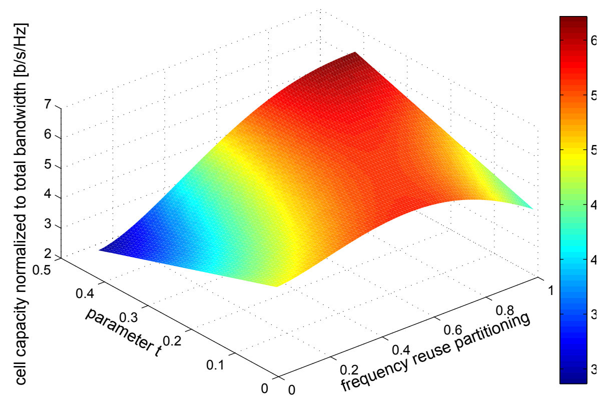

Fig. 6. Cell capacity versus frequency-reuse partitioning radius for different values of parameter t

When $\rho = 0$ and $t = 0$ all the bandwidth is used for PR-reuse in three sectors and the cell capacity has a value. When we increase the ρ we start to share some band with reuse-1 and the cell cpacity increases. Cell capacity increases until the frequency reuse partitioning achieves its optimal value which on this case is $\rho = 0.65$. After this value by incrasing the frequency reuse partitioning we increse the FR-band so we increase the ICI. As a result of this the cell capacity decreases. However the simulation results that are shown in Fig. 6 tells us that by increasing the parameter t also the cell capacity increases when we are going for reuse-1. This happen because we are using the PR-band for FR-band by assuming that the cell edge users are idle. Also based on Fig. 6 we conclude that optimization problem given by Eq. (17) is quasiconcave [12], because if we look at the graphical representation we see that $C(t, \rho) > \delta$, where δ is the sub level set of $C(t, \rho)$. In Fig. Fig. 7 is shown how the maximum cell capacity changes when parameter t increases and frequency partitioning achieves its optimal value.

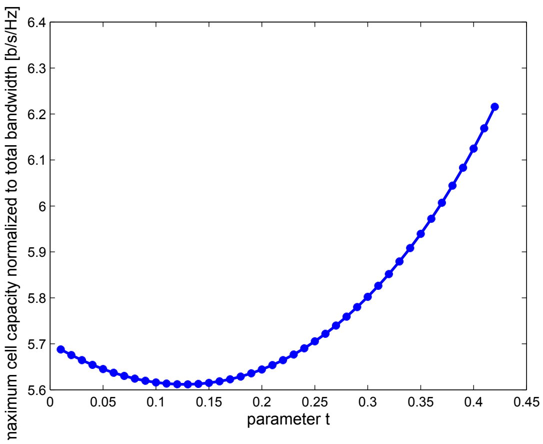

Fig. 7. Maximum cell capacity versus parameter t for optimal frequency partitioning radius

In Fig. 8 are shown the simulation results for cell capacity in FR and PR-regions versus parameter t. From the simulation results shown in Fig. 8 we see that by increasing the parameter t, the capacity in FR-region increases and at the same time the capacity in PR-region decreases because we are using PR-band for FR-band.

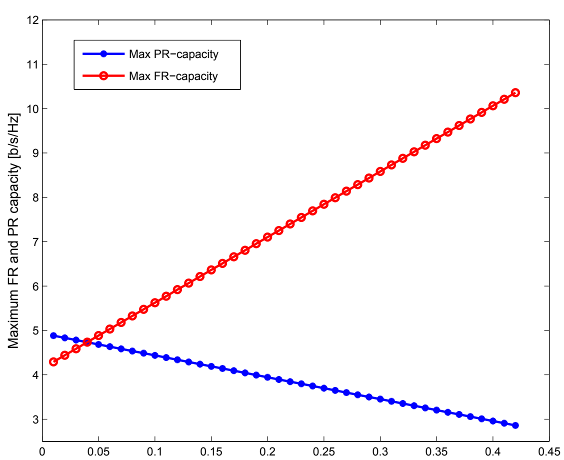

Fig. 8. Cell capacity versus parameter t in FR-region and PR-region for considered cell

VI. Conclusion

In this paper we have proposed and analysed a novel FBA scheme for PFR depending on the network-load, which allocates the bandwidth in the cell in response to the traffic load. We have formulated a semi-analytical model for this scheme and the numerical evaluation is carried out based on this semi-analytical model. We have shown that our scheme provides improved performance for the cell capacity compared to the simpler PFR scheme for the values of the parameter t between 0 and 0.4.

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