Adaptive Localized Resource Allocation with Access Point Coordination in Cellular Networks

Bijan Golkar and Elvino Sousa
Deparment of Electrical and Computer Engineering, University of Toronto
10 King's College Road, Toronto, Ontario, Canada, M5S 3G4
Emails: {bijan,sousa}@comm.utoronto.ca

***Abstract*—This paper proposes an adaptive fractional frequency reuse (FFR) resource allocation scheme for downlink transmission of OFDMA cellular networks. Resource allocation is localized in the sense that in each region system resources are assigned based on local traffic demand. Furthermore, the allocated resources in each region adapt to changes in the environment (i.e. channel gains and number/mobility of active terminals). To this end, a multi-stage proportional fair scheduler is introduced. The performance of the proposed scheme is compared with a variation of the well-known FFR technique. Numerical results studying the average and cell edge spectral efficiencies show promising improvements.**

***Index Terms*—Cellular network, Downlink, Inter-cell interference coordination, Resource allocation**

I. Introduction

An ever increasing traffic demand translates into the need for exceedingly high data rate transmission and hence a high spectral efficiency in cellular networks. The low frequency re-use of traditional voice-centric designs is no longer adequate. While aggressive spectrum re-use seems to be the inevitable solution, simply reducing the frequency re-use factor - in non-CDMA systems - would have detrimental consequences as intolerable interference levels would disrupt the performance.

A smart interference management strategy through coordination of Access Points (APs), can increase frequency re-use and at the same time keep interference levels at low levels, which in turn results in higher system capacity. Over the past few years, inter-cell interference coordination (ICIC) has rightfully attracted a lot of attention. FFR is one method which achieves a compromise between the two conflicting goals. Soft frequency re-use (SFR) and partial frequency re-use (PFR) are the two well-known variations of this method whose performances have been studied in [1]. In [2], state-of-the-art ICIC techniques are discussed, wherein a semi-static (adaptive) FFR method is proposed which provides limited frequency allocation adaptation based on traffic demand.

In this paper, an adaptive localized scheduling infrastructure for cellular networks is proposed. The hierarchical scheme assigns resources based on local traffic demand. To this end, a multi-stage proportional fair scheduler is introduced. The first stage locally assesses the traffic demand of each AP and accordingly assigns resources to each AP. The second stage performs link scheduling based on the resource allocation decisions of the first stage. System resources assigned to each AP are dynamically adjusted to the variations in the environment - i.e. channel gains and mobility/number of active terminals - once every few frames. Link scheduling is performed every subframe. Throughout the paper, the structure of Long Term Evolution (LTE) air interface technology is considered [3].

The paper is organized as follows. Section II presents the concept of ICIC, discusses the shortcomings of the conventional methods and introduces the proposed scheduling technique. In section III the scheduling algorithms are presented. Section IV presents the system model and elaborates on the numerical results. In the end, section V concludes the paper with the main results and future work.

II. Inter-cell interference coordination

SFR and PFR are the two ICIC methods widely studied in the literature. In these methods, the terminals assigned to each cell are partitioned into cell center and cell edge terminals. Cell center terminals are qualitatively defined as the terminals which receive insignificant interference from co-channel transmitters, and cell edge terminals are defined as the terminals whose links are more sensitive to interference. While a lower re-use factor for the former increases the cell capacity, a higher re-use factor for the latter reduces interference on the more vulnerable terminals.

Consider a cellular network with trisector cells, where APs are positioned at the cell centers, in Fig. 1. Each cell is partitioned into 6 allocation regions. In region R_i, frequency resources $\mathbf{f}_i$ are utilized with no re-use allowed within one region. The regions R_1, R_2 and R_3 denote the regions where cell center terminals reside. Similarly, R_4, R_5 and R_6 denote the cell edge terminal regions. In order to reduce the interference level for cell edge terminals, no re-use is allowed across R_4, R_5 and R_6. Henceforth, the region covered by R_4, R_5 and R_6 will be referred to as the *orthogonal zone*.

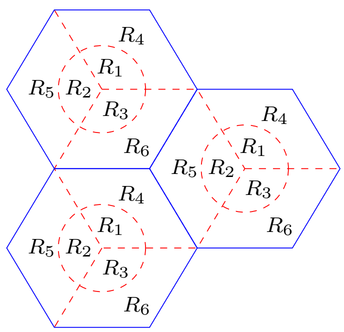

Fig. 1. Frequency allocation regions

Let $\mathbf{W}$ denote the available frequency spectrum. In SFR, the pairs $(\mathbf{f}_i, \mathbf{f}_{i+3})$ for $i = 1, 2, 3$ form a partition of $\mathbf{W}$ and hence a frequency re-use factor of $\frac{1}{3}$ is achieved (i.e. the available spectrum is re-used three times in one cell). Furthermore, the frequency resources utilized in cell edge regions R_4, R_5 and R_6 are chosen to be equal in size (i.e. $|\mathbf{f}_4| = |\mathbf{f}_5| = |\mathbf{f}_6| = |\mathbf{W}|/3$). In PFR, the frequency resources are allocated to the regions in a slightly different manner: A portion of the spectrum ($(1-\alpha)|\mathbf{W}|$), exclusively allocated to the cell edge terminals, is evenly distributed across the regions R_4, R_5 and R_6. The rest of the spectrum is reused in all cell center regions. It is easy to see that this method achieves a frequency re-use factor of higher than $\frac{1}{3}$ (i.e. less re-use compared to SFR) depending on $0 \leq \alpha \leq 1$. The two frequency allocation methods are illustrated in Fig. 2.

Although these techniques improve the performance, they share one major shortcoming: Consider a cellular network where SFR (or PFR) is implemented. The frequency allocation which was originally designed for a cluster of 3 cells is now applied to the entire network. The problem arises from the fact that in order to preserve the orthogonality property of the *orthogonal zones*, the frequency allocation across all cells should be perfectly symmetric. In other words, the same frequency blocks should be assigned to the corresponding region of every single cell in the network! and yet the traffic demand in each cell is unique, which clearly calls for a localized approach.

Traditionally, we think of a cell as the coverage area associated to an AP positioned in the middle. In this paper, we propose the concept of scheduling cell (SC)

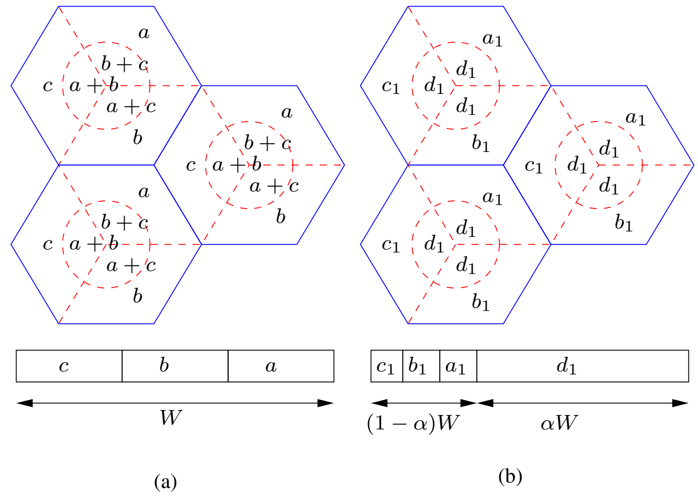

Fig. 2. Well-known ICIC frequency allocation methods (a) Soft frequency re-use ($|\mathbf{a}| = |\mathbf{b}| = |\mathbf{c}| = \frac{|\mathbf{d}|}{3}$), (b) Partial frequency reuse ($|\mathbf{a}_1| = |\mathbf{b}_1| = |\mathbf{c}_1| = \frac{(1-\alpha)|\mathbf{d}_1|}{3}$)

defined as the coverage area associated to not one but a subset of APs whose lack of coordination would result in intolerable interference levels. A SC is depicted in Fig. 3 - with APs located at three cell corners. Each terminal is assigned to one AP with the strongest channel gain. In the SC, the center terminals experience weak channel gains to their APs and thus should be allocated orthogonal channels. A portion of the spectrum (i.e. $(1-\alpha)|\mathbf{W}|$) is allocated to the orthogonal zone which based on the traffic of the engaged APs will be partitioned as:

$$\begin{cases} |\mathbf{y}_i| = \beta_i(1-\alpha)|\mathbf{W}| \\ \sum_i \beta_i = 1, \beta_i \geq 0 \end{cases} \quad \text{for} \quad i = 1, 2, 3 \qquad (1)$$

The corner terminals in the SC operate on frequency resources $\mathbf{x}_1$=$\mathbf{x}_2$=$\mathbf{x}_3$ equal to the spectrum not assigned to the orthogonal zone.

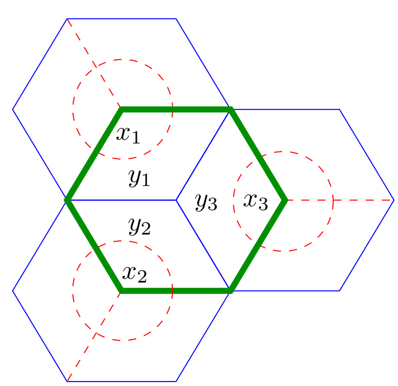

Fig. 3. Scheduling cell

In a sense, SCs define autonomous resource allocation entities in the cellular network. Fig. 4 illustrates how SCs can tessellate the coverage area of a network.

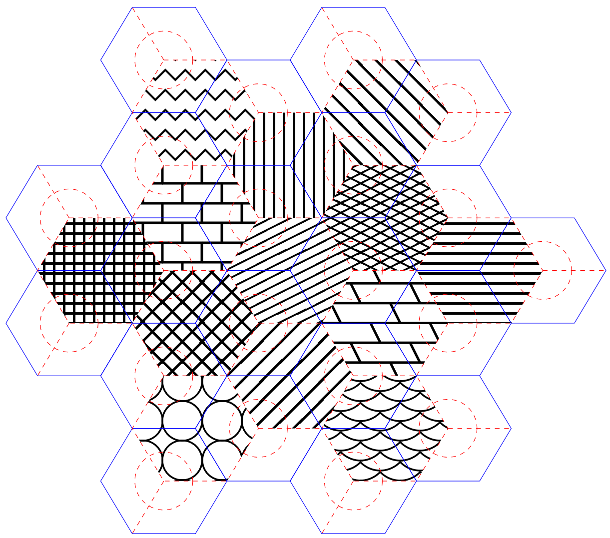

Fig. 4. Each shaded area represents one scheduling cell.

III. Scheduling Cell Corners and Orthogonal Zone Frequency Allocation

In this section we propose a multi-stage proportional fair scheduler which adaptively assigns resources to the active terminals in each SC. Before presenting the algorithm the following definitions are required:

Consider a SC v with three cell sectors and K_v active terminals:

Definition 1 (Cell edge/center terminal) Terminal k assigned to cell sector i_k in a SC v is defined to be a cell edge terminal if,

$$\sum_{j\neq i_k, j\in\mathcal{C}_v} \frac{h_{kj}^{(v)}}{h_{ki_k}^{(v)}} > g \qquad , \quad k\in\mathcal{K}_v \tag{2}$$

where, $h_{kj}^{(v)}$ is the large-scale fading channel gain of terminal k from cell sector j in SC v, $\mathcal{C}_v$ and $\mathcal{K}_v$ are the set of cell sectors and set of users in SC v respectively. System parameter g is the cell edge threshold. Terminal k is defined to be a cell center terminal if it is not a cell edge terminal.

Definition 2 (Virtual cell edge/center user - k_v^e, k_v^c) Virtual cell edge user k_v^e and virtual cell center user k_v^c represent the cell edge and cell center terminals in SC v respectively, whose instantaneous and average rates are defined in Definitions 3 and 4.

Definition 3 (Virtual instantaneous rates - $r_n(k_v^e), r_n(k_v^c)$) Virtual instantaneous rates when users k_v^e and k_v^c are assigned resource block[1] (RB) n are defined as:

$$r_n(k_v^e) = \frac{1}{K_v^e}\sum_{k\in\mathcal{K}_v^e}\frac{12\cdot 14}{1\,\text{ms}}\log_2\left(1+\frac{\overline{\text{SNR}}_n(k)}{2}\right) \tag{3}$$

$$r_n(k_v^c) = \frac{1}{K_v^c}\sum_{k\in\mathcal{K}_v^c}\frac{12\cdot 14}{1\,\text{ms}}\log_2\left(1+\frac{\overline{\text{SINR}}_n(k)}{2}\right) \tag{4}$$

where K_v^e and K_v^c are the number of cell edge and cell center terminals respectively, $\overline{\text{SNR}}_n(k)$ is the average signal-to-noise ratio at terminal k on RB n and $\overline{\text{SINR}}_n(k)$ is the average signal-to-interference-plus-noise ratio at terminal k on RB n, considering only the interference from within the SC:

$$\overline{\text{SINR}}_n(k) = \frac{1}{12\cdot 14}\sum_r \frac{p_k h_{ki_k}^{(v)}(n,r)}{\sum_{j\neq i_k, j\in\mathcal{C}_v} p_j h_{kj}^{(v)}(n,r)+p_{\text{noise}}}, k\in\mathcal{K}_v^c \tag{5}$$

where, $h_{kj}^{(v)}(n,r)$ is the slow-fading channel gain between terminal k and cell sector j in SC v for resource element r of RB n and p_{noise} is the Gaussian background noise power.

Definition 4 (Virtual average rates - $\bar{r}(k_v^e), \bar{r}(k_v^c)$) Virtual average rate of user k after assigning RB n to either of the virtual users, $\bar{r}_n(k)$, is defined as:

$$\bar{r}_n(k) = \left(1-\frac{1}{n}\right)\bar{r}_{n-1}(k) + \frac{1}{n}r_n(k) \tag{6}$$

with $k\in\{k_v^e, k_v^c\}$ and $n = 1, 2, \cdots, N$. Obviously if RB n is not assigned to user k, then $r_n(k) = 0$.

A. Cell edge and cell center resource requirement assessment

Let $\mathcal{N} = \{1, 2, \cdots, N\}$ be the available RB set. The following algorithm partitions the system spectrum $\mathcal{N}$ into two RB subsets $\mathcal{N}_v^c$ and $\mathcal{N}_v^e$ representing the assigned RBs to the cell center and cell edge terminals respectively, such that $\mathcal{N}_v^e \cup \mathcal{N}_v^c = \mathcal{N}$ and $\mathcal{N}_v^e \cap \mathcal{N}_v^c = \emptyset$.

Algorithm 1 Cell Proportional Fair Scheduler (CPFS)

```
Initialize N_O = N_R = ∅ and 0 < r̄_0(k_O) = r̄_0(k_R) ≪ 1.
for n = 1 to N do
    k*_n = argmax_k ( r_n(k_O) / r̄_{n-1}(k_O) , r_n(k_R) / r̄_{n-1}(k_R) ).
    r̄_n(k) = (1 − 1/n) r̄_{n-1}(k) + (1/n) r(k)  for k ∈ {k_O, k_R}.
    N_{k*_n} = N_{k*_n} ∪ {n}.
end for
```

[1] In LTE, a resource block is defined as a chunk of system resources in time and frequency.

Henceforth, $\mathcal{N}_v^c = \{n_v^c(1), n_v^c(2), \cdots, n_v^c(N_v^c)\}$ and $\mathcal{N}_v^e = \{n_v^e(1), n_v^e(2), \cdots, n_v^e(N_v^e)\}$ denote the system resources assigned to cell center and cell edge terminals respectively.

B. Cell center terminal scheduling

The available spectrum, $\mathcal{N}_v^c$, is reused at the three corners of SC v. Let $\mathcal{K}_v^c(s)$ be the number of cell center terminals in corner s. A proportional fair scheduler with partial updating (PFS-PU) assigns the RBs in subframe p as follows:

Algorithm 2 Cell Center PFS-PU (CCPFS-PU)

1: Initialize $\bar{r}(k,t) = \left(1 - \frac{1}{t}\right)\bar{r}(k,t)$.
2: **for** $n = 1$ to P' **do**
3: **for** $i = 1$ to N_R **do**
4: Set $n = n_R(i)$ and find $k_n^* = \text{argmax}_{k \in \mathcal{K}'_R(p)} \frac{r_n(k)}{\bar{r}(k,t)}$.
5: Set $n = n_R(i)$ and calculate $\bar{r}(k_n^*, t) = \bar{r}(k_n^*, t) + \frac{1}{t} r_n(k_n^*)$.
6: **end for**
7: **end for**

C. Cell edge terminal scheduling

A coordinated proportional fair scheduler among the cell sectors within the orthogonal zone in SC v is proposed. The scheduler is similar to CCPFS-PU, with the difference that no re-use is allowed in the orthogonal zone.

Algorithm 3 Cell Edge PFS-PU (CEPFS-PU)

1: Initialize $\bar{r}(k,t) = \left(1 - \frac{1}{t}\right)\bar{r}(k,t)$.
2: **for** $i = 1$ to N_O **do**
3: Set $n = n_O(i)$ and find $k_n^* = \text{argmax}_{k \in \mathcal{K}'_O} \frac{r_n(k)}{\bar{r}(k,t)}$.
4: Set $n = n_O(i)$ and calculate $\bar{r}(k_n^*, t) = \bar{r}(k_n^*, t) + \frac{1}{t} r_n(k_n^*)$.
5: **end for**

It should be noted that when calculating the data rates (in above scheduling algorithms), out-of-scheduling-cell interference is intentionally left out which reduces the required amount of control messages between APs. Furthermore, unlike CPFS, fast channel variations are taken into account in CCPFS/CEPFS-PU link scheduling algorithms. In addition, although link scheduling is performed every subframe, the center/edge terminal resource redistribution according to CPFS is invoked once every few frames.

IV. System model and numerical results

A. System model

Simulation parameters are provided in Table I. BS power budget is evenly distributed across all subcarriers, which amounts to power budget of 18.22dBm per subcarrier. In FFR methods, while the cell edge transmissions occur at 18.22dBm per subcarrier, the center terminals are served with half of the allocated power budget i.e. 15.21dBm. Each directional antenna has a beampattern $A(\theta)$, where θ is calculated from the boresight direction of the corresponding sector:

$$A(\theta) = -\min\left[12\left(\frac{\theta}{\theta_{3\text{dB}}}\right)^2, A_{\max}\right] \tag{7}$$

where $A_{\max} = 20$dB is the maximum attenuation and $\theta_{3\text{dB}} = 70°$ is the 3dB beamwidth.

TABLE I
System parameters

System parameter	Value
Carrier frequency	2GHz
Bandwidth	10MHz
Terminal velocity	30 Kmph
BS power budget	46dBm
BS antenna gain	17dB
Noise figure at terminal	7dB
Background noise	−174dBm/Hz
Traffic model	Full buffer

B. Numerical results

System performance is evaluated in presence of two rings of interfering cells with regular hexagonal AP deployment pattern. The performance of the proposed adaptive FFR (a-FFR) scheme is compared against that of fixed-FFR (f-FFR) and a network with frequency reuse factor of 1 (FR1). For f-FFR we assume the structure in Fig. 2(b), where it is assumed 25 RBs are assigned to cell center terminals and cell edge terminals in the three sectors are assigned 8, 8 and 9 RBs respectively[2]. PF schedulers similar to CCPFS-PU and CEPFS-PU are implemented for f-FFR and a simple PF scheduler is assumed for FR1.

Fig. 5 depicts the average spectral efficiency of the three methods. Due to multiuser diversity gain, the performance of all three systems improve as the number of users increases. The average spectral efficiency of the proposed technique is already 40% better than that of f-FFR for $K = 5$ users and the gap widens as

[2]This choice of spectrum partitioning for f-FFR is arbitrary.

the number of users increases, which can be explained as follows: In the FFR system, regardless of how the terminals are distributed in a cell, the system resources are allocated according to a predetermined pattern. In the simulations, 50% of the resources are allocated to the center cell and 16% to each edge cell sector region. The terminal distribution, on the other hand, clearly does not always follow that of the system resources. For example, it is observed that f-FFR performs slightly worse than even FR1 for small number of users ($K = 5$). This behavior is expected as static off-line resource allocation can severely degrade the performance. On the other hand, the proposed approach distributes the system resources across the zones in each SC based on the actual distribution of terminals.

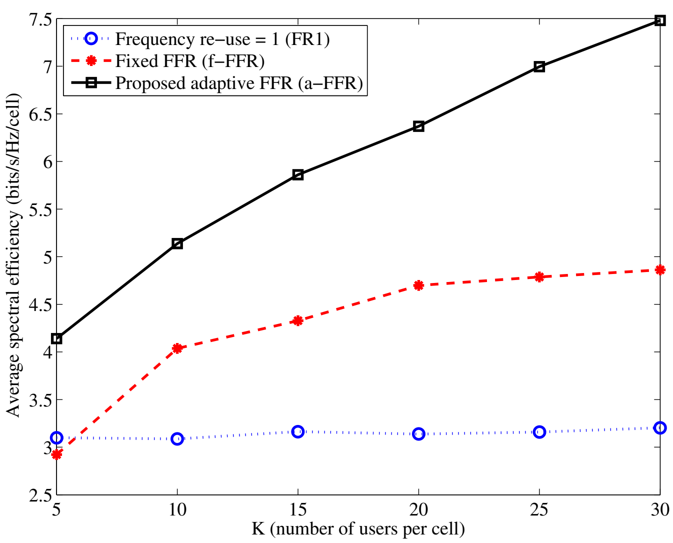

Fig. 5. Average spectral efficiency comparison

The cell edge spectral efficiency[3] of the three systems are compared in Fig. 6: For less than 20 users per cell, the improvements of the average spectral efficiency do not compromise the cell edge performance. After the number of users exceed 20, the cell edge spectral efficiency starts to drop below that of f-FFR — by 9% for $K = 30$. This drop was expected as the performance of cell edge terminals residing on the boundary of a scheduling cell are compromised due to lack of coordination between adjacent scheduling cells. This does not occur for smaller number of terminals as the majority of cell edge terminals reside at the center of each SC away from the adjacent interfering SCs. It should also be noted that the majority of the terminals at the boundary of each SC experience a strong desired channel gain due to proximity to the desired AP.

[3]The cell edge spectral efficiency is defined as the 5%-point of the spectral efficiency CDF of the active terminals in the network.

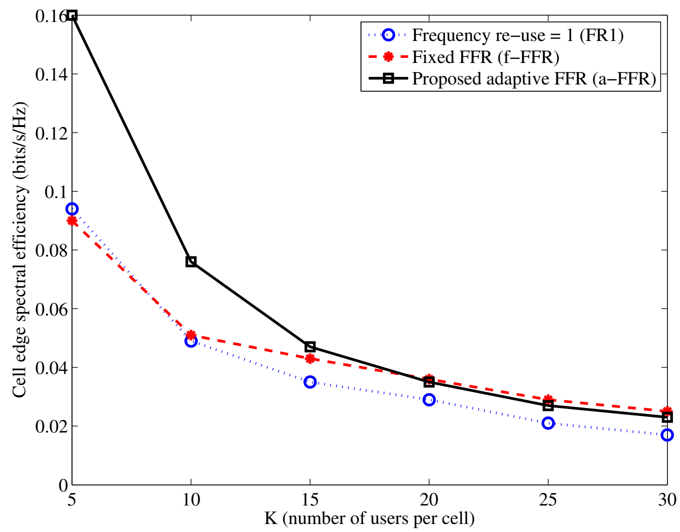

Fig. 6. Cell edge spectral efficiency comparison

V. Summary and Future Work

In this paper a practical resource allocation scheme for cellular networks is proposed. A scheduling cell is defined as a set of APs with coordinated resource allocation, wherein a multi-stage proportional fair scheduler allocates the system resources to the active terminals. The proposed strategy provides future cellular networks with the capability for localized adaptive resource allocation. The resources are assigned according to the current local traffic demand in each region. The performance of the proposed method is compared against one of the well-known FFR techniques and the superiority of the proposed technique is verified.

We are currently working on a more generic and rigorous definition for the novel concept of scheduling cell introduced in this paper with application in scenarios with nonuniform AP deployment and traffic patterns.

References

[1] Y. Xiang, J. Luo, E. Schulz, and C. Görg, “Performance impact of flexible power arrangement in OFDMA based cellular communication networks,” *Annals of Telecommunications*, vol. 63, pp. 271–280, June 2008.

[2] G. Boudreau, J. Panicker, N. Guo, R. Chang, N. Wang, and S. S. Vrzic, “Interference coordination and cancellation for 4G networks,” *IEEE Communications Magazine*, vol. 47, pp. 74–81, Apr. 2009.

[3] “3GPP TS 36.211 - Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation,”