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Short-Term Multi-Cell Dynamic Resource Allocation in Future Cellular Networks

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ABSTRACT

In future cellular system, it is becoming more challenging to optimize the radio resource management and maximize the system capacity whilst meeting the required quality of service from user's point of view. Traditional schemes have approached this problem mainly focusing on resources within a cell and to large extent ignoring effects of multi-cell architecture. For multi-cell systems employing intra-cell orthogonal communication channels, inter-cell interference mitigation techniques are expected to be one of the key radio resource management functions. In this paper, we propose a multi-cell coordinated and un-coordinated dynamic resource sharing algorithms and reuse techniques among base station/ relay station cells. The sub carrier allocation and power allocation are performed on the basic of sum-rate maximization, by considering the load over the cell (3-sector cell). The simulation results show the performance comparison between both coordinated and un-coordinated resource allocation schemes with different sum-rate maximization algorithms.

KEYWORDS

Sum-rate maximization, Coordinated radio resource allocation, Un-coordinated radio resource allocation, Multi- cell interference and Inter-cell interference.

1. INTRODUCTION

Today's framework for radio spectrum regulation and spectrum usage is undergoing fundamental changes. Due to the scarce radio resources available, the research community are initiating promising approaches towards a more flexible spectrum usage [1]. The goal is to enhance system spectral efficiency by recognizing the non-stationary traffic (either in space and time) in the short term (frame-wise) [2].

Since for higher spectral efficiency the system will likely operate under low frequency reuse factor and it is important to consider dynamic radio resource reuse. Several solutions are aiming at avoiding catastrophic inter-cell interference (e.g. fractional frequency reuse) at an expense of degradation in spectrum efficiency [3]. To avoid this, joint decision on dynamic time-frequency allocation and scheduling across cells is considered to mitigate the potential interference between cells, when high reuse is foreseen [4]. Unlike the frequency planning in conventional cellular networks, depending on the traffic demands and parameters effecting the network performance, dynamic resource sharing and allocation to different base station (BS)/relay station (RS) cells based should be performed. Introducing RS's in the system is another way to provide high data rates to cell edge users [5]. Transmission from RS might cause a significant amount of interference among neighboring cells. Therefore, dynamic reuse schemes need to be re-visited to take into account the existence of relays and the cooperation capabilities. Inter-BS's coordination will thus be required.

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The implementation of fixed frequency reuse patterns enable the adaption of the network operation to average expected traffic load through careful design of the cell radius and the reuse factor [6]. The impact on the system throughput of the specific reuse factor selected depends highly on the mobile station (MS) distribution and the channels conditions of the users to be served [7]. For users closer to other sectors, an exclusive allocation of spectrum is better because of the interference and for users close to the corresponding BS, reuse of the resources is more efficient without the consideration of interference. The scheduling policy impacts on the suitability of the reuse factor, as it determines which users are to be served [15]. Therefore, it makes sense to consider the reuse factor as a result of the scheduling decision.

This paper addresses the coordination among neighboring sectors, where alternative links connecting base stations enable the use of the instantaneous sector bandwidth allocation [8]. A general framework for sequential coordinated resource sharing and allocation between interfering sectors of adjacent base stations is proposed and evaluated. In the uplink scenario, the available spectrum is orthogonally shared in a sequential manner: first base station in the sequence has the chance to select from a wider range of available resources [7]. In the downlink scenario, different base stations take turns to sequentially allocate the resources leaving specified margins for the base stations to follow in the sequence. The order of the base stations in the sequence is changed over time to ensure fairness between them.

The remainder of the paper is organized as follows: Section II, represents a detailed system model of cellular system with interfering sectors of the adjacent base stations. Resource allocation and multi cell coordination are discussed in detail for both uplink and downlink. The channel state information, different types of sub-optimal coordination resource sharing are considered for resource allocations like subcarrier allocation and power allocation in Section III. In Section IV, the coordinated and uncoordinated resource sharing schemes are presented for both uplink and down link. Simulation results of sum rate coordination and uncoordination resource allocation scheme are compared for both uplink and downlink are provided in Section V. In Section IV, we conclude.

2. SYSTEM MODEL

The feasibility of coordination between interfering sectors of the adjacent cells in a cellular system is studied. We present a generalized system model for the uplink and downlink of a coordinated cellular system. From the multi cell scenarios we focus on the specific case of three interfering sectors of adjacent base stations (outer coordination). Interference from other sectors in the cellular system is modeled as a rise in the Gaussian noise floor at the receiving end.

Assuming $N = 3$ base stations (BS), M orthogonal equal-width sub-bands in the given spectrum, and K user terminals (UT). We also denote the set of BS's, sub-bands, and UT's with $\boldsymbol{N}$, $\boldsymbol{M}$, and $\boldsymbol{K}$, respectively. The overall input and output relation of the system can be written as [9]:

$$y = Hx + n \tag{1}$$

Where for uplink, $H \in C^{NB \times KB}$ is the overall channel matrix, $x \in C^{KB \times 1}$ is the overall vector of the transmitted signals by all UT's over all sub-bands, $n \in C^{NB \times 1}$ is the AWGN vector, and finally $y \in C^{NB \times 1}$ is the vector of overall received signals by all N base stations over all sub-bands. Let $h_b^{(k,n)}$ denote the channel gain of k^{th} UT to n^{th} BS on sub-band b. It is assumed that each user is served by a single base station only. We call this base station as the server base station.

Similar to uplink, in downlink the relation between transmitted and received signals can be computed through a MIMO channel matrix **H**. For this case $x \in C^{NB\times1}$ will be the signal transmitted by all the N BS's, $H \in C^{KB\times NB}$ the overall channel matrix, $Y \in C^{KB\times1}$ the received signal by all K MS's, and $n \in C^{KB\times1}$ the AWGN at front end of UT receivers.

2.1 Multi-Cell Coordination

In the conventional schemes, the resources are kept orthogonal between the interfering cells. This approach is good for interference limited cases, since avoidance of interference provide a significant gain in the SNR [10]. However in the case of spatially well separated point-to-point transmissions, reuse of the resources is more justified.

To show this in a simple analytical model, consider a simplified scenario of three base stations and three "symmetric" users: i.e. the users which are equidistant from their serving base stations as shown in Figure 1. The distance from the base station to the common vertex of three hexagonal coverage areas is given as r and the position of the user as a function of there distance is given as αr. Now considering any one of the users as the desired user (other two have the same results), we can find the desired channel's mean strength as

$$\rho_s = \frac{L_0}{(d_s)^n}, d_s = \alpha r \tag{2}$$

Using simple geometrical relation, we can also express the mean channel strength of the interference channels as

$$\rho_i = \frac{L_0}{(d_i)^n}, d_i = \sqrt{(\alpha r)^2 + D^2 - 2\alpha r D \cos\frac{\pi}{6}} \tag{3}$$

where α is the location indicator and D represents the inter-site distance The result show that, when the users are at the cell edges the resources need to be re-used to have higher sum-rate. The region where the re-use approach is better for the denser cellular systems as expected. System sum rate for the orthogonal use of three partitions of the spectrum will be given as

$$R_A = \frac{1}{3}\log_2\left(1 + \frac{\rho_s 3P}{\sigma^2}\right) \tag{4}$$

While, the sum rate for the reuse case will be given as

$$R_B = \log_2\left(1 + \frac{\rho_s P}{2\rho_i P + \sigma^2}\right)$$

If resources are re-used within the adjacent cells, the need for coordination in the radio resources becomes even more justified. The coordinating base stations (more specifically the coordinating sectors of three adjacent base stations) exchange the channel state (amplitude only) on all sub-bands for all the users, which is available over the channels of adjacent (non-serving) cell. This exchange of (limited) information is termed as coordination.

The overall exchange of information and the sequence of resource allocation are depicted in Figure 2. The "filter information" block selects the relevant information to share with the other base stations in order to keep the amount of the coordinated information within a reasonable limit [11]. One example is to just share the sub-band's channel magnitudes.

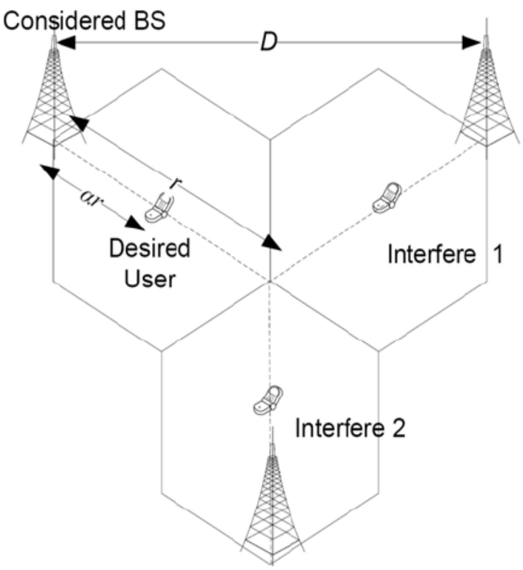

Figure 1: Illustrating reuse of resources if the three users are closer to their serving base station.

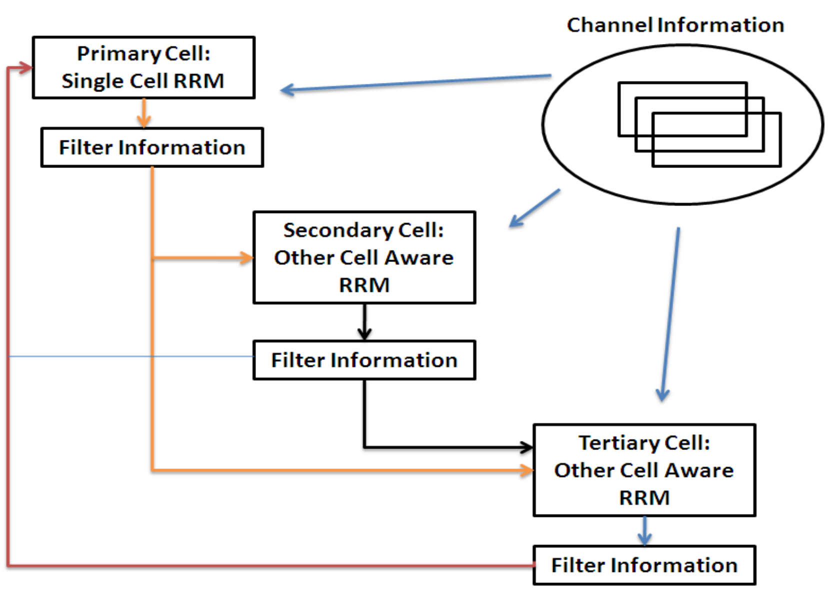

Figure 2: The sequence of resource allocation and information flow for the coordination scheme.

The base stations allocate the available resources to a fixed number of served users and pass over the allocation control to the next base station in the scheduling. In this manner, the first base station has the advantage to use the best of all available resources and is called the primary user. However, this base station is constrained to keep only a limited number of resources and free up the resources for the subsequent base stations for their use. The second base station is called secondary base station and the third is called tertiary base station. The secondary and the tertiary base stations allocate the leftover resources. Since the first base station gets an advantage in this allocation scheme, we change the schedule in round robin fashion to ensure fairness by giving equal chance for all base stations as shown in the Figure 3.

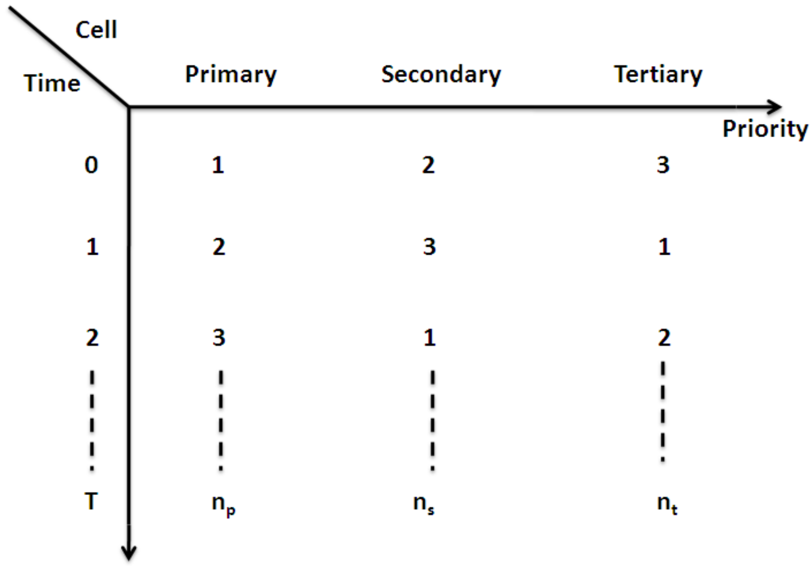

Figure 3: The allocation schedule

Multi-Cell coordination relies only on single cell signal processing and detection to avoid complex detection, but it incorporates efficient procedures to minimize the negative impact of the cell's operations over each other. This approach requires sharing of a part of global CSI and their backhaul load compared to joint multi-cell processing methods. We make following assumptions in using these mechanisms.

Assumptions:

- Each UT's signal is processed by only one BS. We call this as the server BS.
- Selection of server BS generally depends on UT's channel gain with all BS's over all bands. We use following criterion for the selection of server BS:

$$\eta(k) = \arg \max_{n \in \mathrm{N}} \sum_{b \in \beta} \left| h_b^{(k,n)} \right|^2 \tag{5}$$

We define $\mathbf{K_n} = \{k \mid \eta(k) = n\}$ as the set of users served by BS n.

- Each BS performs a band and power allocation algorithm for its associated UT's. This allocation can be based on an adopted policy maximizing a proprietary measure such as sum-rate, weighted sum-rate, or a given utility function. We denote band and power allocation with matrix **P**:

  $$P = [p_1, p_2, ..., p_k] \tag{6}$$

  Where, $p_k = [p_{1,k}, p_{2,k}, ..., p_{B,k}]^t \ \forall k \in \mathbf{K}$ *with* $p_{b,k}$ denoting power allocated to k^{th} UT over band b. For the uplink/downlink cases the overall transmitted power by each UT/BS will be limited to a maximum value: $\sum_{b \in \beta} p_{b,k} \le \overline{P}_k$ for uplink and $\sum_{k \in \mathbf{K}_n} \sum_{b \in \beta} p_{b,k} \le \overline{P}_n$ for downlink.

- The whole or a part of the channel state information of **H** can be available to the set of cells. Usually phase information for the (best) server and amplitude information of a sub-set of users for the other cells. Let $\mathbf{H}_{n,m}$ denotes part of the channel $\mathbf{H}$ related to UT's in K_m UT and n^{th} BS (size of this matrix will be $B\times|K_m|B$ for uplink and $|K_m|B\times B$ for downlink. FH(.) represents an arbitrary filtering function. One example of filtering will be elimination of the phase information (channel gain squared norm).

Intra-cell orthogonality implies: $p_{b,k} > 0 \Rightarrow p_{b,j} = 0, \forall j \neq k, j \in \mathbf{K}_n$, with $n = \eta_k$

Notation: UT served by n^{th} BS with allocated band b is denoted by $k(n,b)$.

Let's consider k^{th} UT with server $\eta(k) = n$ and allocated band b, then:

Uplink:

$$E[|\, y_b^{(n)} \,|] = \rho_b^{(k,n)} p_{b,k} + \sum_{j \in K \setminus \{k\}} \rho_b^{(j,n)} p_{b,j} + \sigma_{\mathbf{N}}^2 \tag{7}$$

$$= \rho_b^{(k,n)} p_{b,k} + \sum_{m \in \mathbf{N} \setminus \{n\}} \rho_b^{(\mathbf{K}(m,b),n)} p_{b,\mathbf{K}(m,b)} + \sigma_{\mathbf{N}}^2 \tag{8}$$

Downlink:

$$E[|\, y_b^{(k)} \,|] = \rho_b^{(k,n)} p_{b,k} + \sum_{j \in \mathbf{K} \setminus \{k\}} \rho_b^{(k,\eta(j))} p_{b,j} + \sigma_{\mathbf{N}}^2 \tag{9}$$

$$= \rho_b^{(k,n)} p_{b,k} + \sum_{m \in \mathbf{N} \setminus \{n\}} \rho_b^{(k,m)} p_{b,\mathbf{K}(m,b)} + \sigma_{\mathbf{N}}^2 \tag{10}$$

The interference caused by the other cells on band b of cell n depends on the band-power allocation outcome of the other cells and the associated channel gain of the interfering other-cell UT's.

Let's define:

Uplink:
$$\xi_b^{(n)} = \sum_{m \in \mathbf{N} \setminus \{n\}} \rho_b^{(\mathbf{K}(m,b),n)} p_{b,\mathbf{K}(m,b)} + \sigma_{\mathbf{N}}^2 \tag{11}$$

Downlink:
$$\xi_b^{(k)} = \sum_{m \in \mathbf{N} \setminus \{n\}} \rho_b^{(k,m)} p_{b,\mathbf{K}(m,b)} + \sigma_{\mathbf{N}}^2 \tag{12}$$

as the noise plus interference (NI) level of n^{th} BS/k^{th} UT at band b. Let $\beta_k = \{b \,|\, \mathbf{K}(\eta(k),b) = k\}$ as the set of bands allocated to user k. Assuming interference term of $\xi_b^{(n)} / \xi_b^{(k)}$ as an extra additive noise, i.e. single cell signal processing, and also assuming a capacity achieving code, the achieved rate of user k served by BS $\eta(k) = n$ can be expressed as follows:

Uplink:
$$R_k = N_{SB} \sum_{b \in \beta_k} \log(1 + \rho_b^{(k,n)} p_{b,k} / \xi_b^{(n)}) \tag{13}$$

Downlink:
$$R_k = N_{SB} \sum_{b \in \beta_k} \log(1 + \rho_b^{(k,n)} p_{b,k} / \xi_b^{(k)}) \tag{14}$$

Where, N_{SB} denotes the number of subcarriers per each band. For simplicity, we will drop this multiplicative factor as it is same for all the users and will not affect the scheduling policy. As it is clearly noticeable the allocated rate of a user not only depends on the resource (power and band) allocation of its serving cell, but also depends on the scheduling outcome of the other cells due to their inflicted interference. Therefore RRM of the cells are coupled and a joint approach can maximize the overall efficiency of the multi-cell system.

3. RADIO RESOURCE MANAGEMENT

Joint Multi-cell Weighted-Sum-Rate maximization (*JM-WSR*), perform band and power allocation for all the UT's of the multi-cell system collectively to maximize users weighted sum rate:

$$\max_{\{p_k \mid k \in \mathbf{K},\, p_k \in \mathbf{P}_{SC}\}} \sum_{k \in \mathbf{K}} w_k R_k \tag{15}$$

$\mathbf{P}_{SC}$, denotes single cell band and power allocation policy. Therefore intra-cell orthogonality and UT/BS maximum power transmission are implicit within the policy $\mathbf{P}_{SC}$.

3.1. Short term versus long term CSI

When channel gains vary noticeably within one data frame, provision for up to date short term (instantaneous) CSI at schedulers will not be possible [12]. In this case, each band will be defined to contain a distributed set of subcarriers. CSI will be on a long term basis with $\rho^{(k,n)} = E_b\left[\rho_b^{(k,n)}\right]$ with same average gain over all bands (E_b means expectation over available bands). Even though the average channel gains are no more varying over the bands, the noise and interference profile is defined as:

Uplink:

$$\xi_b^{(n)} = \sum_{m \in \mathbf{N} \setminus \{n\}} \rho_b^{(\mathbf{K}(m,b),n)} p_{b,\mathbf{K}(m,b)} + \sigma_{\mathbf{N}}^2 \tag{16}$$

Downlink:

$$\xi_b^{(k)} = \sum_{m \in \mathbf{N} \setminus \{n\}} \rho_b^{(k,m)} p_{b,\mathbf{K}(m,b)} + \sigma_{\mathbf{N}}^2 \tag{17}$$

3.2. Interference averaging (randomization)

The above is based on the common definition of bands over all the cells. However, conventional approach that does not require any form of dynamic/static coordination is randomization of the interference. In this approach, bands definition (mapping of logical bands to physical subcarriers) varies from one cell to the other and is based on a distributed subcarrier mapping. For total number of bands B, each band can potentially interfere with any band of any other cell with the suppression factor of $1/B$ due to the randomization. This will result an interference averaging over the bands. The noise and interference profile for this case will be

Uplink:

$$\xi^{(n)} = \frac{1}{B} \sum_{m \in \mathbf{N} \setminus \{n\}} \sum_{b \in \beta} \rho^{(\mathbf{K}(m,b),n)} p_{b,\mathbf{K}(m,b)} + \sigma_{\mathbf{N}}^2 \tag{18}$$

Downlink:

$$\xi^{(k)} = \frac{1}{B} \sum_{m \in \mathbf{N} \setminus \{n\}} \sum_{b \in \beta} \rho^{(k,m)} p_{b,\mathbf{K}(m,b)} + \sigma_{\mathbf{N}}^2 \tag{19}$$

as it is noted interference randomization renders a constant noise and interference profile.

3.2.1 Sub-optimal sequentially coordinated resource sharing

For the uplink scenario, the sequential coordination between the base stations in order to share a given pool of sub-band resources is required. In one scheme each server base station allocates the resources to its served users from a pre-allocated pool of exclusively available sub-bands. The served users are selected by measuring and reporting the overall strength of all sub-band channels to the BS's. We call this scheme as uncoordinated allocation.

In the other scheme, the users report the channel strength on each sub-band separately and the serving base station on each sub-band can be selected separately. In both uncoordinated and coordinated allocation scenarios, the available resources are allocated to the served users using the algorithm adopted from [13]. The main adaptation is to meet the requirement of freeing up the predefined share of resources for the subsequent allocation by the other base stations. The modified algorithm is briefly explained below.

3.2.1.1 Sub-carrier allocation for weighted sum-rate Maximization

We consider the weighted sum-rate allocation over the subcarriers available to each user in the uplink. The weights (corresponding to each user) can be selected to bias the allocation to offer better service to the users at worst position. The allocation for all served users of a single base station is assumed to be done centrally at each of the serving base station assuming that the CSI at each user terminal (for the reverse channel to the base station) is fed back. In case of coordination between the base stations, it is further assumed that the information about the magnitudes of the channels is also shared between the base stations (Filtering information block in Figure 3). Using this magnitude information, a given base station can make allocation decisions. As a starting point, we assume orthogonal sub-band allocation between all the cells. We further assume that each base station adopts the policy of maximizing the weighted sum-rate of the users. Rayleigh fading narrow band channel is assumed for each sub-band and a multi-tap wideband fading model is assumed for the aggregate spectrum available.

Assume $p_{b,k}$ as allocated power at sub-band b k^{th} UT, where $p_k^{(b)} = 0$ implies that sub-band b is not allocated. The objective of resource allocation is to maximize the weighted sum-rate and is given as

$$R_n = \sum_{k \in \mathbf{K}_n} \sum_{b=1}^{B} w_k \log_2\left(1 + \frac{p_{b,k} \,|\, h_b^{(k,n)} \,|^2}{\sigma_n^2}\right) \tag{20}$$

Where, w_n (k) is the assigned weight for user k with respect to the base station n and σ^2 is the noise power at each sub-band and also includes the interference originating from the sources out of the considered three sectors. The allocation is subject to the following conditions:

The allocated powers are non-negative with each user observing a maximum transmit power constraint is given as

$$\sum_{b=1}^{B} p_{b,k} < p_{\max} \tag{21}$$

The weights are positive with the sum of weights over all served users for a base station equal to unity:

$$\sum_{k \in \mathbf{K}_n} w_k = 1 \tag{22}$$

The subcarrier is offered to each user, to offers maximum incremental gain in sum rate if the sub-band is allocated to it. To allocate the power available for each user over the subcarriers, we use the iterative waterfilling over all the offered subcarriers. The details of the iterative waterfilling algorithm are given in [13].

3.2.1.2. Uncoordinated Allocation

In this multi-cell allocation approach, the subsets of the available sub-bands are pre-allocated to each base station for their exclusive use. Hence, each base station has a limited pool of available subcarriers and needs to orthogonally allocate to the served user using the weighted sum-rate maximization scheme mentioned above. We use this approach for comparing the performance of the coordinated allocation scheme as mentioned next.

3.2.1.3. Coordinated Allocation

In this scheme, each base station measures the channel gains of each user (within a range where the channel state can be measured and reported back to the base station) on all subcarriers and this information is shared (coordination). Following a predefined schedule (an example is shown in Figure 3), the BS acting as a primary base station allocates the best subcarriers to its served users. The primary allocator ensures that it only uses a limited number of best subcarriers while freeing up a certain number of subcarriers for the subsequent allocators. The remaining set of subcarriers is passed over to the second base station. The secondary allocator makes best allocation of a subset of these subcarriers to its served users ensuring that a pre-determined number is left over for the last cell.

In order to improve the fairness without severely penalizing the users in good channel conditions, we propose to use the user weights in such a manner that the primary allocator allocates the resources with higher weights to the users, usually the users at the cell edge. The other two cells can either keep the equal rate policy or alternatively adopt a more unfair approach (giving advantage to the users closer to the cell centre) to balance the sum-rate.

3.2.2. Sub-optimal sequentially coordinated scheduling

For the downlink scenario, we consider a more sophisticated coordinated sub-band and power scheduling. Centralized coordinated scheduling requires gathering all the CSI information in one central node and performing a joint scheduling as outlined in [14]. This may heavily load the backhaul and also may cause delay. Here, we describe a class of sequential approaches that introduces an efficient coordination mechanism without any centralization. Let $\pi(n)$ for $n \in \mathbf{N}$ denote an ordering of BS's for a given scheduling epoch. In a sequential approach first BS $\pi(1)$ performs its scheduling without consideration of the other cells and then sends its scheduling outcome as well as some filtered other-cell CSI to next BS $\pi(2)$, and so on. The other-cell aware single cell scheduler at BS $\pi(t)$ will do the following band-power allocation.

3.2.2.1. Other-cell Aware Weighted-Sum-Rate maximization (OCA-WSR)

It performs band and power allocation for cell n to maximize the weighted sum-rate of its served (home cell) users

$$\max_{\{p_k \mid k \in \mathbf{K}_n\}} \sum_{k \in \mathbf{K}_n} w_k \widehat{R}_k \tag{23}$$

by exploiting

A) *Home cell CSI knowledge*, CSI related to the home-cell users

$$\{h_b^{(k,n)}\} \forall k \in \mathbf{K}_n, b \in \beta \tag{24}$$

B) *Other cell interference knowledge,* an estimate on the interference caused by other cell signals to home cell receivers.

Uplink:
$$\hat{\xi}_b^{(m \to n)} = \begin{cases} \rho^{(\mathbf{K}(m,b),n)} p_{b,\mathbf{K}(m,b)} & m \in \overline{\mathbf{N}}_n \\ \varsigma & m \in \underline{\mathbf{N}}_n \end{cases} \quad (25)$$

Downlink:
$$\hat{\xi}_b^{(m \to k)} = \begin{cases} \rho^{(k,m)} p_{b,\mathbf{K}(m,b)} & m \in \overline{\mathbf{N}}_n \\ \rho^{(k,m)} \varsigma & m \in \underline{\mathbf{N}}_n \end{cases} \quad (26)$$

and satisfying the following constraints:

Home cell constraints*:* maximum power transmission related to home cell transmitters, and home cell exclusivity on band allocation.

Uplink:
$$\sum_{b \in \beta_k} p_{b,k} \le \overline{p}_k \forall k \in \mathbf{K}_n \text{ and } \beta_k \cap \beta_j = \phi \ \forall\ j,k \in \mathbf{K}_n \quad (27)$$

Downlink:
$$\sum_{k \in \mathbf{K}_n} \sum_{b \in \beta_k} p_{b,k} \le \overline{p}_n \text{ and } \beta_k \cap \beta_j = \phi \ \forall\ j,k \in \mathbf{K}_n \quad (28)$$

Other cell interference constraints: Power transmission mask over bands to limit the interference of home cell signals on the other cell receivers.

$$p_{b,k} \le \overline{p}_b^{(n)} \ \forall k \in \mathbf{K}_n \quad (29)$$

Where $\overline{\mathbf{N}}_n / \underline{\mathbf{N}}_n$ denote the set of cells scheduled before/after cell *n*. $\hat{R}_k$ is an estimate on achievable rate for user *k* based on the approximate knowledge of noise and interference profile

Uplink:
$$\hat{R}_k = \sum_{b \in \beta_k} \log_2 \left(1 + \rho_b^{(k,n)} p_{b,k} / \hat{\xi}_b^{(n)} \right) \text{ with } \hat{\xi}_b^{(n)} = \sum_{m \in \mathbf{N} \setminus \{n\}} \hat{\xi}_b^{(m \to n)} + \sigma_n^2 \quad (30)$$

Downlink:
$$\hat{R}_k = \sum_{b \in \beta_k} \log_2 \left(1 + \rho_b^{(k,n)} p_{b,k} / \hat{\xi}_b^{(k)} \right) \text{ with } \hat{\xi}_b^{(k)} = \sum_{m \in \mathbf{N} \setminus \{n\}} \hat{\xi}_b^{(m \to k)} + \sigma_k^2 \quad (31)$$

Where, ζ is a parameter used to control the interference allowance margin for the cells that yet to be scheduled. This parameter is also used to get a conservative estimate on the interference of those cells on the considered cell *n*. *Other cell* interference *constraint* related to cell *m*:

Uplink:

$$\rho_b^{(k,m)} P_{b,k} + \sum_{l \in \overline{\mathbf{N}}_n \setminus \{m\}} \rho_b^{(\mathbf{K}(l,b),m)} P_{b,\mathbf{K}(l,b)} + |\underline{\mathbf{N}}_n \setminus \{m\}| \zeta \le (\overline{NR} - 1)\sigma_N^2, \forall k \in \mathbf{K}_n \quad (32)$$

this means $P_{b,k} \le \overline{P}_b^{(n \to m)} \forall k \in \mathbf{K}_n$ *with*

$$\overline{P}_b^{(n \to m)} = \left((\overline{NR}-1)\sigma_N^2 - \sum_{l \in \overline{\mathbf{N}}_n \setminus \{m\}} \rho_b^{(\mathbf{K}(l,b),m)} P_{b,\mathbf{K}(l,b)} - |\underline{\mathbf{N}}_n \setminus \{m\}| \zeta \right) / \rho_b^{(k,m)} \tag{33}$$

Downlink, $m \in \overline{N}_n$:

$$\rho_b^{(\mathbf{K}(m,b),n)} p_{b,k} + \sum_{l \in \overline{\mathbf{N}}_n \setminus \{m\}} \rho_b^{(\mathbf{K}(m,b),l)} p_{b,\mathbf{K}(l,b)} + \zeta \sum_{l \in \underline{\mathbf{N}}_n \setminus \{m\}} \rho_b^{(\mathbf{K}(m,b),l)} \le (\overline{NR}-1)\sigma_N^2, \forall k \in \mathbf{K}_n \tag{34}$$

this means $p_{b,k} \le \overline{P}_b^{(n \to m)} \forall k \in \mathbf{K}_n$ *with*

$$\overline{p}_b^{(n \to m)} = \left((\overline{NR}-1)\sigma_N^2 - \sum_{l \in \overline{\mathbf{N}}_n \setminus \{m\}} \rho_b^{(\mathbf{K}(m,b),l)} p_{b,\mathbf{K}(l,b)} - \zeta \sum_{l \in \underline{\mathbf{N}}_n \setminus \{m\}} \rho_b^{(\mathbf{K}(m,b),l)} \right) / \rho_b^{(\mathbf{K}(m,b),n)} \tag{35}$$

Downlink, $m \in \underline{N}_n$:

$$\overline{p}_b^{(n \to m)} p_{b,k} + \sum_{l \in \overline{\mathbf{N}}_n \setminus \{m\}} \overline{\rho}^{(l \to m)} p_{b,\mathbf{K}(l,b)} + \zeta \sum_{l \in \underline{\mathbf{N}}_n \setminus \{m\}} \overline{\rho}^{(l \to m)} \le (\overline{NR}-1)\sigma_N^2, \forall k \in \mathbf{K}_n \tag{36}$$

this means $p_{b,k} \le \overline{p}_b^{(n \to m)} \forall k \in K_n$ *with*

$$\overline{p}_b^{(n \to m)} = \left((\overline{NR}-1)\sigma_N^2 - \sum_{l \in \overline{\mathbf{N}}_n} \overline{\rho}^{(l \to m)} p_{b,\mathbf{K}(l,b)} - \zeta \sum_{l \in \underline{\mathbf{N}}_n \setminus \{m\}} \overline{\rho}^{(l \to m)} \right) / \overline{\rho}^{(n-m)} \tag{37}$$

where $\overline{NR}$ is the maximum allowable noise rise and $\overline{\rho}^{(l \to m)}$ is average channel power gain between BS l and users of cell m. The overall power mask for cell n will be

$$\overline{p}_b^{(n)} = \max_{m \in \mathbf{N} \setminus \{n\}} \overline{p}_b^{(n \to m)} \tag{38}$$

3.2.2.2. Other Cell Aware Subcarrier and Power Allocation for Downlink OFDMA

We assume, a BS serves its UT (**K**) which is constrained to a maximum power profile mask in order to satisfy interference limit to a predetermined set of primary UT's. This will create awareness towards the needs of other cells. We define following weighted sum rate maximization problem.

Other-cell aware weighted sum rate maximization:

$$\max_{\{P_k | k \in \mathbf{K}\}} \sum_{k \in \mathbf{K}} w_k \sum_{b \in \beta_k} \log(1 + \rho_{b,k} p_{b,k} / \xi_b^{(k)}) \tag{39}$$

Subject to $\sum_{k \in \mathbf{K}} \sum_{b \in \beta_k} p_{b,k} \le \overline{P}$ (total transmit power constraint) and

$p_{b,k} \le \overline{p}_b \forall k \in \mathbf{K} \,\&\, b \in \beta$ (power mask constraint)

The optimal power allocation for *Other-cell aware weighted sum rate maximization* problem with a fixed band (subcarrier) allocation $\{K(b)\}_{b \in \beta}$ is given by the following constrained multi-level water filling:

$$p_b = \min\left(\left[\mu w^{(b)} - \frac{1}{\gamma_b}\right]^+, \overline{p}_b\right) \tag{40}$$

where p_b is a short hand for $p_{b,\mathbf{K}(b)}$ the power to be used on subcarrier *b* that is allocated to user $\mathbf{K}(b).\gamma_b = \rho_{b,\mathbf{K}(b)} / \xi_b^{(\mathbf{K}(b))}$ with a unit power SNR (SNR when transmission power is 1). The notation $[a]^+$ is used for max(*a*,0) and μ is water filling level to be adjusted to ensure $\sum_{b \in \beta} p_b \le \overline{P}$. Under the condition of $\sum_{b \in \beta} \overline{p}_b \le \overline{P}$, the total power $\overline{P}$ will not be utilized. For the considered system, *Other-cell aware weighted sum rate maximization* satisfies the following property:

For $k = \mathbf{K}(b) and\, j \ne k$:

$$w_k \log(1 + \rho_b^{(k)} p_b / \xi_b^{(k)}) \ge w_j \log(1 + \rho_b^{(j)} p_b / \xi_b^{(j)}) \tag{41}$$

4. SIMULATION RESULTS

4.1. Uplink Scenario

The coordinated and uncoordinated resource sharing schemes presented in section 3.2.1 are simulated. The following parameters are used to plot the results presented in this section.

Parameter	Symbol	Value
Number of sub-bands	M	18
Number of user	K	18
Uplink MS power constraints	P_{max}	100mW
Receiver Noise	σ^2	-169dBmW
Background interference		100μW
Path loss exponent	η	3.8
(power) loss at reference	L_0	38dB
Multi-tap wide band channel		Four taps of equal strength at relative delays [0 -4 -7 -9.5]dB

Other variable parameters are mentioned with the corresponding results. In the first result shown in Figure 4, the coordinated and uncoordinated schemes are compared when the inter-site distance is varied in the cellular system. As the inter-site distance is increased, the sum-rate decreases as expected in this scenario. However the advantage of coordinated resource allocation is visible in all inter-site distance range considered here and it appears more significant in the dense cellular environment. However a closer inspection of the percentage gain for the sum-rate of the proposed coordination scheme over the uncoordinated scheme, we observe that the gain in sparse cellular system case is quite significant as well (the gain ranges from 12-15%).

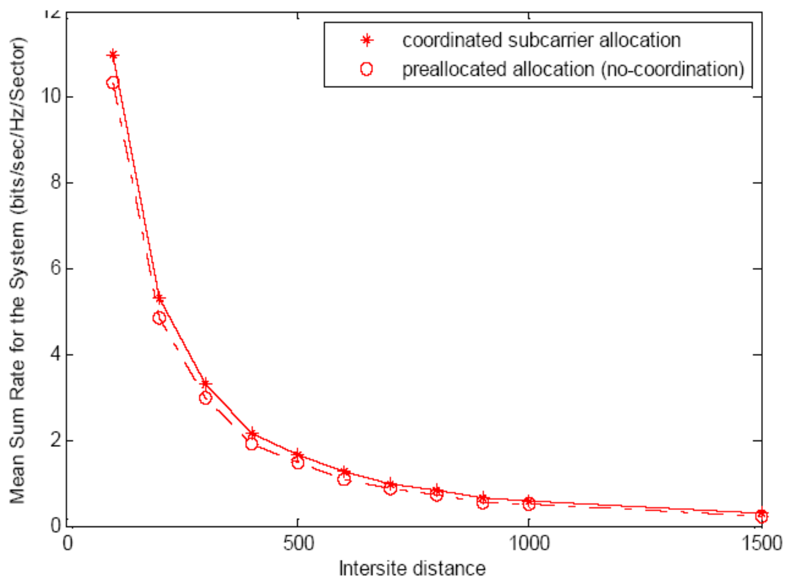

Figure. 4: Comparison of coordinated and uncoordinated orthogonal resource scheduling. Variation of the per-sector sum-rate as a function of the inter-site distance.

In Figure 5, the comparison of the rate share of the three cells is shown for the two schemes. The solid lines are for the coordinated scheme and the dashed lines are for the uncoordinated scheme. It can be observed that for the uncoordinated scheme all three cells get nearly the same rate share. This is intuitively plausible since all cells get equal treatment in this case. However in coordinated scheme the primary cell obtains the highest share, followed by the secondary and tertiary cell. This is due to a larger pool of resources available to the primary cell when it performs the resource allocation.

Figure 6, provides the comparison of the two schemes for various path loss environments. The inter site distance is fixed to 500m. It can be observed that in case of low path loss exponent the gain is more significant. A possible reason is that the cells become more “coupled” when the path loss exponent is low. A rigid server cell selection for all the sub-bands becomes less efficient. On the other hand the coordination scheme provides the flexibility of re-selecting the best users on each sub-band as the channels change over time.

Figure 7, shows that increasing the transmit power constraint for a fixed noise power, the gain becomes more significant (while the percentage gain is roughly the same). This also shows the potential of the coordination scheme to save transmit energy and effectively elongating the battery life for ensuring a fixed sum-rate performance of the system.

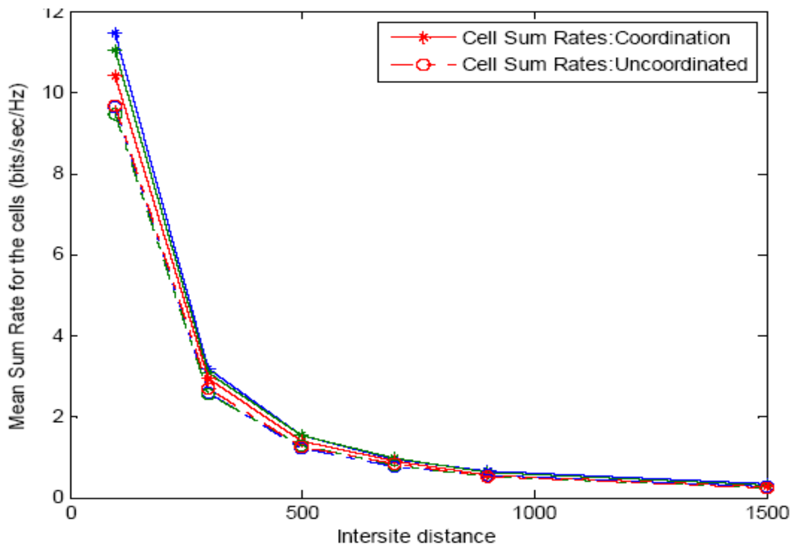

Figure 5: The share of each sector in the sum-rate. Coordinated and uncoordinated schemes compared.

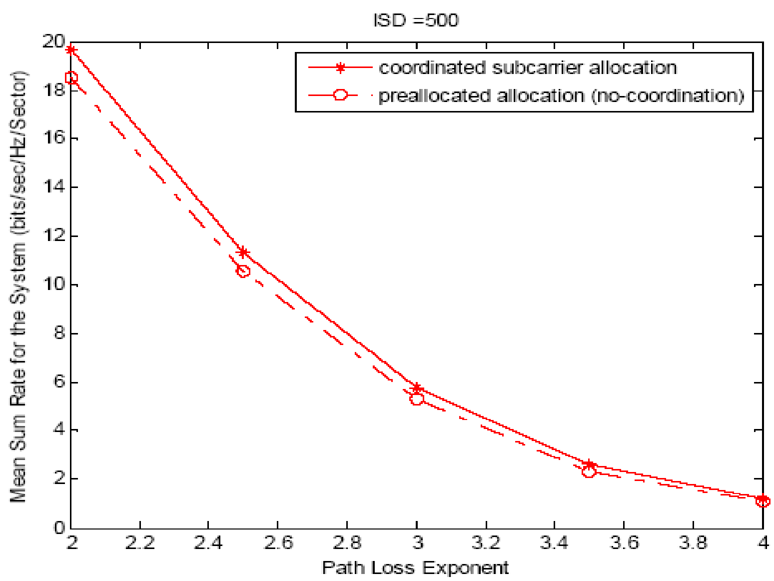

Figure 6. Comparison of the two schemes for various path loss environments.

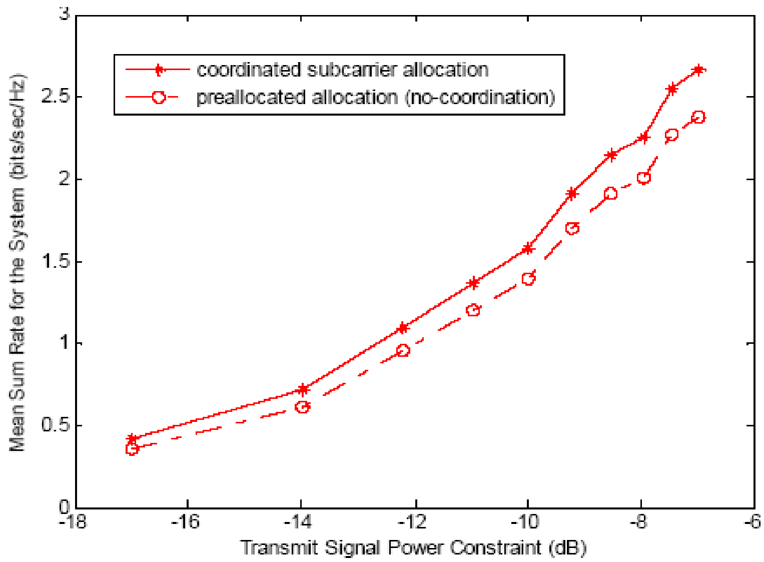

Figure 7: Comparison of two schemes for varying transmit power constraint (20mW to 200mW), ISD=500.

4.2. Downlink Scenario

For the downlink scenario, we simulate the suboptimal sequentially coordinated scheduling technique discussed in more detail in section 3.2.2. Same values for path loss factor, power loss at the reference distance and multi-tap fading channel are used as in the uplink scenario. Since total power of all served users is constrained in the downlink scenario, we use sum power constraint of P_{max} = 50W instead of per user power constraint. For comparison two benchmark schemes are considered. In one scheme (Orthogonal Allocation) the available spectrum is divided in three equal non-overlapping parts (sub-bands are selected such that maximum benefit can be reaped from the frequency diversity for each base station). In another scheme, full reuse is employed in a certain region of the cellular coverage (non-critical region) which is closer to the serving base station. For the simulations the cut off boundary is defined as the distance that is half the cell radius, users within this boundary with respect to the serving base station are allowed to reuse the subcarriers while leaving a reasonable interference margin for neighboring cells. Orthogonal allocation is used in the region out of the noncritical region i.e. the region close to the cell edges (called the critical region).

The three coordinating cells are assigned a priority order (which changes over time for long term fairness). Depending on the priority order and the available knowledge of home cell CSI and other cell interference, the sub-band and power is allocated in such a manner that the home cell power constraints and other cell interference constraints are satisfied.

In Figure 8, (Power constraint of 50 W, 144 sub-bands and 16 users per cell, noise and interference profile factor, 0.1) we plot the mean sector sum rate of the proposed Other Cell Aware allocation (OCA Scheme) working sequentially at all coordinating sectors. The first sector makes the allocations leaving some margin for the re-use of each allocated subcarrier. However as the primary allocator, it can define the mask for the allocation of other sectors which make decisions later in the sequence. Noise and Interference Profile factor (NIP) defines what factor of maximum power is allowed to be used by secondary and tertiary sectors in their allocations. NIP factor of zero implies that the subcarrier is exclusively occupied by the primary and NIP factor 1 means that the primary has most generous allocation for the other sector (primary sector leaves a margin for full power allocation by the other sector).

Focusing on the allocations of sequential Other Cell Aware Sub-band and Power Allocation (OASPA), we plot the rate share of the primary, secondary and tertiary sector in the sequence of allocation in Figure 8. It can be observed that the depending on the NIP factor (how conservative/generous the primary is in leaving a margin for the others) the subsequent sectors may do even better in terms of performance, in a case when the primary is too generous. However since tertiary has to accommodate the tighter of the two constraints placed by the prior allocations it performs worse as compared to the primary and secondary in general.

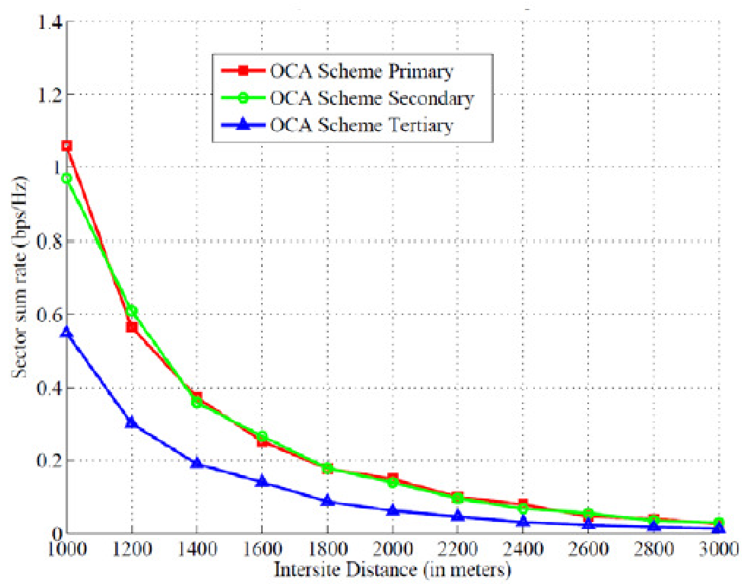

Figure 8: Comparison of the rate share for primary, secondary and tertiary sector in sequential Other Cell Aware Sub-band and Power Allocation

5. CONCLUSION

Sequential coordinated resource management has a potential to improve the performance of the system at a cost of increased overhead of information exchange between the coordinating sector antennas of adjacent base stations. Two coordination strategies, one for the uplink and another one for the downlink were simulated and the results suggested that the system performance can be improved by using the coordination strategies. For the uplink scenario the sequential resource sharing scheme was studied. The coordinating sectors sequentially select a pre-determined portion of available resources in contrast to fixed pre-allocation. The scheme requires larger number of channel measurements and the information need to be exchanged between the coordinating sectors. Sequential sub-band and power allocation with additional constraints for other cell allocations is more challenging and a general framework for this scheme is presented.

In sequential other cell aware sub-band and power allocation scheme the three coordinating cells are assigned a priority order (which changes over time for long term fairness). Depending on the priority order and the available knowledge of home cell CSI and other cell interference, the sub-band and power is allocated in such a manner that the home cell power constraints and other cell interference constraints are satisfied.

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