AN HIERARCHICAL APPROACH FOR INTER-CELL SCHEDULING IN INTERFERENCE-LIMITED CELLULAR NETWORKS

Rafael B. Moreira, Francisco R. P. Cavalcanti

GTEL - Wireless Telecom Research Group
Federal University of Ceara, Fortaleza, Ceara, Brasil
{rafaelbm,rodrigo}@gtel.ufc.br

ABSTRACT

Interference management is one of effective means of improving system throughput, which is particularly important for the emerging 4G wireless networks that demand increasing data rates. In order to mitigate the inter-cell interference we evaluate the performance of an hierarchical centralized inter-cell scheduling method which aims at improving the system throughput. The proposed algorithm, which is based on an existing one, besides selecting the BSs allowed to transmit, performs an exhaustive power control in order to find the optimal power levels of transmitting BSs. Simulation results show that the proposed method outperforms classical approaches in terms of spectral efficiency improvements.

1. INTRODUCTION

Future wireless networks have posed huge challenges to the designers, since they are increasingly converging the classical mobile services, such as voice and SMS, and broadband Internet-based services. This convergence demands high data rates and bandwidths, which are usually achieved through aggressive channel reuse. However it is well known that aggressive channel reuse generates intolerable co-channel interference (CCI) levels in the system, which in turn affect the overall network capacity. Thus, researchers have focused on the development of methods that handle this tradeoff between capacity and co-channel interference. Special attention has been given to a relatively recent concept: coordination of transmissions among base stations (BSs), also known as *inter-cell scheduling* [1]. This method is intended to manage the radio resources among the cells in the network, in order to improve the overall capacity.

In [2], Vemula *et. al.* propose a technique based on scheduling of users inside each cell and opportunistic beamforming based on channel state information of each user which are reported to a central coordination unit. In [3] it is proposed an inter-cell scheduling scheme comprised by interference avoidance and load balancing which allocates users to BSs based on the cell load. In [4], an inter-cell coordination technique is proposed for 3GPP's LTE technology. The method allocates cell-edge users by adjusting their traffic load, while cell-center users can reuse frequency resources more aggressively among neighbor cells, with reduced power.

In this paper we address the problem of interference coordination by means of inter-cell scheduling inspired by ideas exposed in the works by Gesbert *et. al.* [1] and Rahman *et. al.* [5]. The proposed inter-cell scheduling is based on cell clusterization and results in two levels of interference coordination: an intra-cluster coordination level and an inter-cluster coordination level. Performance results in terms of network throughput for various configuration scenarios are shown. Comparisons are provided with other scheduling approaches including the case where intra-cell cluster scheduling only is performed in a distributed fashion. We also explore how multiple discrete power levels and multi-user diversity impacts performance. The main objective of the presented technique is to maximize the network throughput. For this, the key idea is to explore the channel conditions of previously scheduled users in each cell and allow for transmission those BSs that maximize the overall network capacity, while the others remain in silence.

This paper is organized as follows. Section 2 presents the system model used in our simulations, including the centralized model adopted. The proposed technique, the motivation for its development and the evaluation metric are presented in section 3. Section 4 shows the parameters used in our simulations campaign and our simulation results, obtained by comparing the proposed technique with three other implemented for comparison, considering important aspects such as number of power levels and the number of mobile stations (MSs). Section 5 concludes the paper.

2. SYSTEM MODEL

Consider the downlink of a multi-cell system composed by N_c cells, with BSs placed at the center of the cell. We assume a unitary frequency reuse, which means that all radio resources are used in all cells of the network and consequently each MS receives co-channel interference from all neighboring cells. Our focus will be on the scheduling of one single channel per BS, but the approach here proposed can be extended to more channels per BS. MSs in a cell are served by the associated BS according to an intra-cell scheduling policy. Only one MS is served per transmission opportunity, i.e., intra-cell orthogonality is achieved by means of opportunistic time division multiple access. Fig. 1 shows a network setup consisting of 9 cells clustered into 3 clusters of 3 cells each. Clusterization in the context of this paper is needed only from a control and resource allocation perspective, since full frequency reuse is assumed and no frequency reuse pattern is needed.

We also assume a peak power constraint per BS equal to P_{max}. Within each cell, there are N_M MSs uniformly distributed over each cell.

The channel model adopted here includes the effects of log-normal shadowing, distance-dependent path-loss and Rayleigh fading. Further model specifications are given in section 4. The signal

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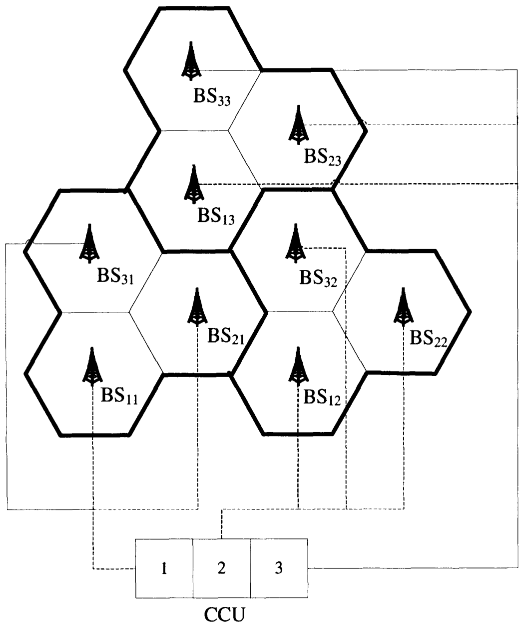

Fig. 1. Example of network configuration: three clusters with three cells each, and the CCU than controls all nine cells.

to noise plus interference ratio ($SINR$) of MS i is

$$\gamma_i = \frac{p_i g_{i,i}}{\sigma^2 + \sum_{n \neq i}^{N} p_n g_{n,i}} , \tag{1}$$

where p_k is the transmission power of BS k, $g_{k,i}$ is the channel gain between BS k and MS i, which includes the effects mentioned above, and σ^2 denotes the noise power.

The power transmission p_k may assume discrete levels, as suggested in [1,6]. Our interest here will be mainly in binary (on-off) power allocation, based on the suggestive results in [1] indicating close-to-optimal performance. Nonetheless, we also consider power allocation with more power levels in order to investigate potential gains.

It is assumed the existence of a central control unit (CCU), to which are converged all channel state information necessary to perform the proposed inter-cell scheduling scheme. On this matter, we assume that the channel coherence time is long enough to allow for each MS estimate the gain of its channel in each time interval, send this information back to the BS which, in turn, reports it to the CCU. The CCU can then, based on the collection of all channel estimates, take scheduling decisions that will last for the next transmission interval. How this is performed is explained in the next section.

3. HIERARCHICAL INTER-CELL SCHEDULING

Interference Coordination stands for the class of techniques which aim at dealing with the existing interference and extract higher performance, without any pre- or post-processing. In this sense, we propose an approach, namely Hierarchical Non-orthogonal Opportunistic Scheduling, or simply HINOIS, which performs scheduling in two levels. Referring again to Fig. 1, in the first level, for each cluster of cells, it opportunistically schedules for transmission the BS (or BSs) which yields the highest aggregate spectral efficiency. Based on the same criterion, in the second level, the technique schedules for transmission the cluster (or clusters) which yields the highest overall spectral efficiency.

3.1. Algorithm Description

The procedure explained below is performed in each transmission time interval. First, each active MS sends its channel estimation (SINR) via a separate control channel (or in a preamble of the traffic channel) to its serving BS. Then, each BS schedules one of the active MS following the intra-cell scheduling policy. In our case, as we aim at maximizing the network throughput, the Rate Maximization scheduler is adopted. Next, each BS sends to the CCU the estimated SINR of the selected MS.

With these measurements, the CCU performs the first level (intra-cluster) of the hierarchical scheduling. For this, for each possible combination of one or more BS within a specific cluster, it first computes the individual spectral efficiency of each cell i belonging to the combination, which is denoted by η_i and is expressed according to Shannon as

$$\eta_i = \log_2 (1 + \gamma_i) \tag{2}$$

and then estimates the time each packet transmission will last, which is given by

$$t_i = \frac{L_p}{\eta_i B} , \tag{3}$$

where L_p and B are the length of the transmitted packet and the channel bandwidth, respectively. Then, the CCU performs an exhaustive search, within each cluster, in order to find the optimal BSs combination which yields the higher aggregate spectral efficiency, which is expressed as [5]:

$$\overline{\eta} = \sum_{i \in \Phi} \eta_i \frac{t_i}{\max_i t_i} , \tag{4}$$

where Φ denotes the set of BS in each possible combination, which may consider multiple discrete power levels, as exposed before. Each term of the summation in (4) is weighted by a ratio which represents the portion of time the corresponding BS effectively uses the wireless medium, according to its spectral efficiency.

When the first level of inter-cell scheduling is finished, the CCU starts the second (inter-cluster) level, in order to find the best combination of *clusters* allowed to transmit in that time interval. One cluster which is not scheduled is entirely shutted off, even if any of its BSs was previously scheduled in the first level of scheduling. The input variables for the second level of scheduling are the average transmission time and the aggregate spectral efficiency of scheduled BSs in each cluster. The procedure is quite similar to that performed in the first level (4).

3.2. Scalability and Complexity Issues

The number of BSs managed by the CCU plays an important role on the algorithm complexity. For instance, for a brute-force exhaustive search algorithm, a total of $N_p^{N_c} - 1$ combinations must be tested, where N_p and N_c denote the number of discrete power levels and the number of cell in the network, respectively. This exponential growth precludes the use of this technique even for few cells. On the other hand, in the proposed hierarchical approach, for N_k clusters each with N_{kc} cells per cluster, the number of combinations to search for is given by

$$NC = N_k(N_p^{N_{kc}} - 1) . \quad (5)$$

For instance, for a network with 9 cells and 3x3 clusters, considering binary power control, the total combinations for exhaustive search is 511 and in the proposed Hierarchical approach is 21.

For very large networks, with many clusters, HINOIS can be employed independently to every group of N_k clusters. In this case, complexity in Eq. (5) scales linearly with the number of cluster groups.

4. SIMULATION PARAMETERS AND RESULTS

4.1. Adopted System Configuration

In this section, we present the parameters used in our simulation campaign and its most important results. We consider BSs with backlogged traffic. They reuse the same bandwidth with power transmission defined as solution of the considered inter-cell scheduling algorithm. The MSs are uniformly distributed over the cell area, and served by the BS which has the strongest long term channel gain.

Basically, the metric used to evaluate the methods is the aggregate network spectral efficiency based on (4). The results to be presented were obtained through Monte Carlo simulations and the statistics are taken over 10000 runs of each scenario. Table 1 summarizes the system parameters used in our simulation.

Table 1. Simulation Parameters

PARAMETERS	VALUE
Number of snapshots	10,000
Number of clusters	3
Number of cells per cluster	3
Hexagonal Cell Radius (km)	1
Number of users$^{(1)}$ (per cell)	{1 2 3 5 10}
BS antenna gain (dB)	12.2 (omni)
Transmission direction	Downlink
Reuse Factor	1/1
Maximum Power$^{(2)}$, P_{max} (dBm)	35
Number of Power Control Levels	{2 3 5}
Noise Power, P_N (dBm)	-103
Shadowing model	lognormal
Shadowing standard deviation (dB)	6
Fast-fading model	Rayleigh
Path-loss model (dB)	128.1 + $10\kappa\log_{10}(d)$
Path-loss exponent (κ)	3.76
Packet length, L_p (bits)	256

(1) before performing MS scheduling (2) per BS

As Table 1 informs, we consider three power levels for comparison. They are:

1. Two power levels: $\{0\ 1\}P_{max}$
2. Three power levels: $\{0\ 0.5\ 1\}P_{max}$
3. Five power levels: $\{0\ 0.25\ 0.5\ 0.75\ 1\}P_{max}$

The considered network configuration is as shown in Fig. 1 with $N_k = 3$ clusters and $N_{kc} = 3$ cells per cluster totalizing 9 cells.

4.2. Algorithms for Comparison

In order to compare the performance of the proposed method (HINOIS), some other strategies were selected and implemented. The first one is ST (Simultaneous Transmission). It allows every BS and every cluster transmitting in every time interval. There is no coordination neither between BSs nor between clusters. Thus, we are able to evaluate the performance gain obtained through centralized coordination of BSs. The next algorithms are similar to those used in [5] also for comparison. OIS (Orthogonal Inter-cell Scheduling) selects only one BS per cluster for transmission in each time interval. Thus, there is coordination between BSs, but not between clusters. NOIS (Non-Orthogonal Inter-cell Scheduling), in turn, may select more than one BS per cluster for transmission. Like OIS, it assumes coordination between BSs, but no coordination between cluster. Thus, the greater improvement that we found in HINOIS is due to its coordinated scheduling among clusters.

In addition to the approaches mentioned above, the proposed technique is also compared to an interference-free limit. This limit is obtained by ignoring the inter-cell interference and having all BSs transmitting in full power, as suggested in [1], and computed according to (4).

4.3. Binary Power Control

First, let us consider the most simple configuration. We assume only one user per cell, and the binary power control scheme.

Fig. 2 shows the CDF of each technique's system spectral efficiency, in addition to the CDF of the interference-free limit. As we can observe, it is worth to perform the inter-cluster scheduling, even if it means to shut off an entire cluster, since the overall system throughput is improved.

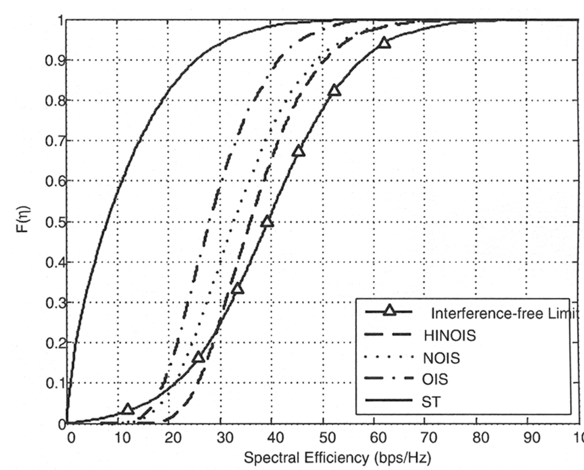

Fig. 2. CDF of each technique's spectral efficiency at the system level, for binary power control and one MS per cell.

Table 2 shows the 10*th*, 50*th* and 90*th* percentiles of each spectral efficiency CDF of each algorithm and interference-free limit, in bps/Hz, considering the entire network.

Considering the 10*th* percentile, we found that the introduction of the inter-cluster scheduling proposed by HINOIS provides a capacity improvement of about 20% with respect to the second best of the algorithms (NOIS), which do not perform inter-cluster scheduling. From Fig. 2 and Table 2 a curious results is observed. The performance of HINOIS is better than the interference-free limit. This is due to the fact that links with worst SINR conditions dominates

Table 2. Aggregate Network Spectral Efficiencies (bps/Hz) for Binary Power Control

Algorithm	10*th* percent.	50*th* percent.	90*th* percent.
IF limit	21.34	39.42	58.01
HINOIS	25.62	36.00	50.64
NOIS	21.21	32.70	49.14
OIS	18.95	28.02	41.60
ST	0.82	8.10	25.57

the transmission and the weighted average in Eq. (4). While HINOIS can avoid these links by turning off the corresponding BSs, interestingly, even in the absence of interference as supposed in the interference-free limit definition, the resulting spectral efficiency can become very low when continuous transmissions from all BSs is assumed.

4.4. The effects of the number of power levels

In the previous analysis, the on-off power control was used. Of course, it represents the simplest approach in terms of complexity due to its reduced design space. However, according to [6], we should expect that by increasing the the number of power levels, there will be a capacity improvement. Thus, it is useful to investigate how the each technique's performance behaves when we increase the number of power levels to be searched over. The simulation setup is the same of the previous analysis, with only one MS per cell, and we consider three different number of power levels: two, three and five.

Fig. 3 shows the 10*th* percentile of the spectral efficiency CDF of each technique, as function of the number of power levels.

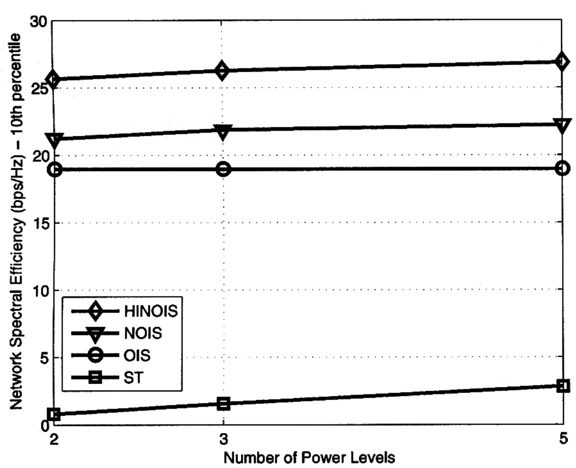

Fig. 3. 10*th* percentile of spectral efficiency CDF, at the network level, for one user per cell and different number of power levels.

The important remark here is that all scheduling policies improve only marginally when the number of power levels is increased. This results is in accordance with recent results in [1], attesting close-to-optimal performance of binary power control.

4.5. The effects of the number MSs per cell

The results presented in previous section considered that there was only one MS per cell to perform the intra-cell scheduling. With respect to multi-user diversity (MUD), this setup represents the worst case. In a realistic scenario, the intra-cell scheduler usually handles several MSs. In this section we are interested in evaluating how the MUD impacts the performance of the inter-cell schedulers considered in this work. For this purpose, we consider different amount of MSs in each cell (cell load): 1 (no MUD), 2, 3, 5 and 10.

We should expect that the MUD gain provides a performance gain, independent on the inter-cell technique adopted, since as the number of MSs increases, there is a higher probability that one of them is experiencing good channel conditions, and this is the MS that shall be scheduled with the Rate Maximization intra-cell scheduling policy.

Fig. 4 shows the 10*th* percentile of the spectral efficiency CDF of each technique, as function of the number of active MSs. The relative advantage of HINOIS over NOIS is kept around 20% for lower loads, diminishing to around 10% for higher loads.

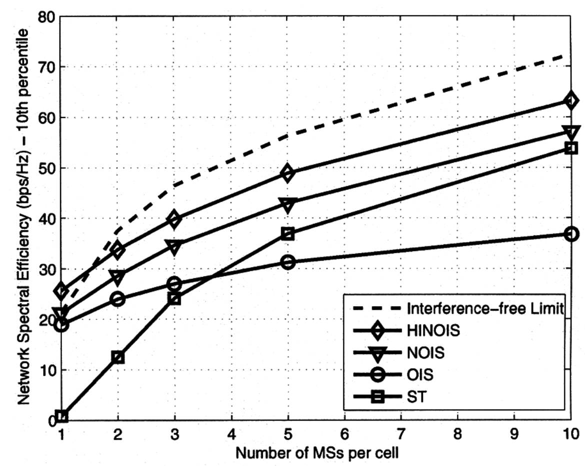

Fig. 4. 10*th* percentile of spectral efficiency CDF, at the network level, for two power levels and different number of MSs per cell.

As expected, we observe that all algorithms take advantage from the MUD and improve their performance. The capacity increase with MUD is roughly proportional to $\log(N_M)$, as suggested in [1].

Once again HINOIS presents the best results, in the considered scenario, among all evaluated inter-cell scheduling techniques. As we can observe, it is capable of extracting significant gain from the provided MUD and translating it directly in improvement of spectral efficiency.

One interesting remark is that all non-orthogonal algorithms (the exception is OIS) have a remarkable capacity increase with larger number of MSs, approaching the interference-free limit. This is also in accordance with recent results from [1] attesting the reduced impact of inter-cell interference in systems with large number of users, as multi-user diversity dominates performance.

5. CONCLUSIONS

This paper analyzed several aspects about interference coordination in a multi-cell multi-user cellular system. We propose a centralized inter-cell scheduling technique, namely Hierarchical Non-orthogonal Inter-cell Scheduling (HINOIS), that handles the co-channel interference in two different levels: an intra-cluster level and an inter-cluster level. Its objective is to maximize the network spectral efficiency.

We observed that, in all considered cases, the HINOIS algorithm presented the best performance among other simpler alternatives. This occurs because HINOIS performs coordination in two levels and thus, extract performance gain in these two levels. Because of this reason, HINOIS outperforms the NOIS technique in the overall system performance.

The network capacity gain of inter-cluster coordination (HINOIS) over intra-cluster only (NOIS) has been measured to be around 20% for low cell loads (low multi-user diversity gain) diminishing to around 10% for higher loads. ST algorithm has very poor performance for low loads but approaches the performance of NOIS and HINOIS for higher ones. In higher loads, the performance of all algorithms (except OIS) approaches the interference-free limit.

Binary (on-off) power control has shown performance very close to ones in scenarios with 3 and 5 discrete power levels, in accordance with recent theoretical results from the literature.

These results suggest that network designers and operators are faced with a number of trade-offs to analyze when considering or not the implementation of inter-cell scheduling with diverse degrees of signaling and computational load requirements.

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