Distributed and Collaborative Radio Resource Allocation in the Downlink of OFDMA Systems

Bahareh Jalili, Mehrdad Dianati, Barry G. Evans
Center for Communication Systems Research (CCSR)
Department of Electronic Engineering
University of Surrey
Guildford, GU2 7XH, United Kingdom

Abstract

This paper investigates collaboration among neighboring Base Stations (BSs) for the downlink of OFDMA based cellular networks, in the absence of a centralized control unit, which is a defining characteristic of 4G wireless networks. We propose a novel scheme for collaboration among a cluster of neighbouring base stations. Simulation based performance analysis demonstrates effectiveness of the proposed collaborative resource allocation scheme among the neighboring base stations for OFDMA systems, particularly for the users located near the cell edges.

I. Introduction

The demand for reduced latency and higher data rate support by wireless access networks, along with the need for less complex network monitoring methods, has led to the introduction of a flat architecture for Radio Access Network (RAN) in 4G standards such as Long Term Evolution (LTE). In these networks, the Base Station Controller (BSC) in 2G or Radio Network Controller (RNC) in 3G systems, which functioned as a coordinating and controlling node among the base stations is removed from the architecture. Instead, high speed backhaul links are introduced to connect the base stations so that they can exchange information and collaborate/coordinate their different functionalities, which were traditionally performed by BSC/RNC. Consequently, the existing coordinated/collaborative radio resource allocation schemes, that can significantly improve spectral efficiency [1]-[3], may not be directly deployed in 4G networks. In other words, the concept of collaborative/coordinated resource allocation needs to be implemented in a distributed manner. Such techniques have to be implemented in a network with an OFDMA multiple access technology that has been adopted by the majority of 4G networks. In addition, opportunistic resource allocation concept is desirable to be employed in order to further improve spectral efficiency by harvesting multi-user diversity gain. These specifications define a non-trivial, distributed resource allocation problem in four dimension which is the scope of this paper.

Some aspects of the problem have been investigated by some of the existing studies in the past few years. Resource allocation for single-cell, multi-carrier systems has been fairly studied in recent years [1]-[3]. The challenge is usually represented as an optimization problem, where the objective is to maximize the overall cell throughput, subject to some constraints such as fairness and transmission power [4]-[7]. Alternatively, the problem can be transformed into a utility maximisation problem. Utility function $U(.)$ is used in order to quantify the level of user satisfaction rather than system-centric metrics like throughput and outage probability. Utility functions map the network resources used by users, into a number that shows the user satisfaction, which is usually a function of achieved data rate [8]-[10]. The concept of multi-cell resource allocation has been mostly investigated for the conventional 3G networks and for WCMDA in the recent years. [11]-[14] propose power control methods in order to maximize the capacity or minimize the transmitted power, while [14] uses a collaborative scheme where a specific user is served by the base station which has the best channel gain to that user. Most of the papers that extend the resource allocation problem to OFDMA multi-cell scenarios, mainly deal with the intercell interference issues. [15] proposes a multi-cell semi-distributed scheme, where Radio Resource Management (RRM) for a group of base stations controlled by one RNC is split between the RNC and the base station. The scheme in [15] proves to be efficient; however, the drawback is the semi-distributed approach in the sense that RNCs are used in the architecture.

There are also some studies that aim at performing the radio resource allocation in a totally distributed manner. [16] proposes a distributed power allocation and scheduling scheme. In this scheme, each cell uses the local information in order to calculate the capacity increase, if a specific cell is on and transmits information to the users. In the next step, if when a cell is on, it does not contribute enough capacity to the system compared to the interference degradation it causes to the rest of the network, that cell will be deactivated during that interval. In [17] the authors propose a method for large "interference ideal" networks to simplify the the problem and propose a ranking system for scheduling the users. A self-organizing multi-cell cooperation scheme is proposed in [18], where transmit powers allocated to different users, in each sub-band are systematically adjusted in order to maximize the overall network utility. A graphic framework is proposed in [19], where resource allocation is performed in two phases of coarse scale intercell interference management and a fine scale channel aware resource allocation. Although most of the works in literature, use cooperation / collaboration among the base stations for intercell interference coordination, it can not be only limited to frequency coordination and interference avoidance schemes. The presence of multiple base stations in itself offers the advantages associated with spatial diversity [14], which we refer to as BS diversity in this paper. Taking advantage of BS diversity has been studied in [14] for CDMA networks, and it provides a good frame work to be expanded for OFDMA. In this paper, we consider the scheduling problem for the downlink of an OFDMA system, and propose a collaboration scheme, where the entire coverage area is divided to a number of 3-sector cells, and each cell is covered by a group of sectors from the neighboring base stations. The network has a flat architecture, i.e., there are no controlling entities; instead, the base stations are connected to each other via high speed backhaul links. RRM functionalities are performed locally in each BS. We introduce a framework for the adjacent sectors to communicate effectively and perform scheduling in a distributed and collaborative manner. In the proposed system, in order to take advantage of spatial diversity, each user is dynamically served by the BS that has the best downlink channel towards it, instead of being served a single serving BS. Simulation results demonstrate that the proposed scheme can improve system performance in terms of spectral efficiency, while maintaining a good level of fairness among the users.

The rest of this paper is organized as follows. The system model and basic assumptions are discussed in section II. Section III explains the proposed distributed collaborative scheduling scheme. Simulation results are presented in section IV, followed by the conclusions in section V.

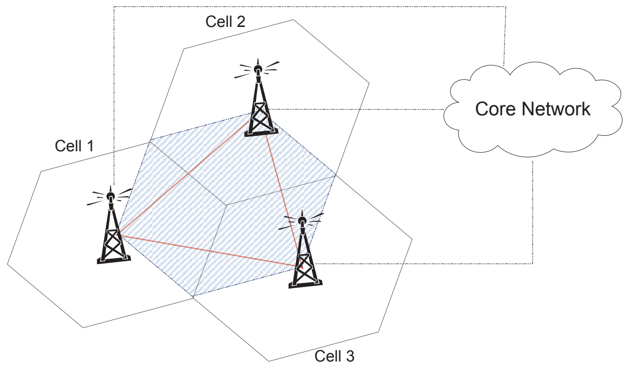

Fig. 1. Network model

II. System Model

We consider the downlink of an OFDMA system with M base stations. The base stations are connected to each other via high speed, high capacity backhaul links as shown in Fig.1. Each base station uses 3-sector antennas located at the centre of it, and each cluster of collaborating base stations is built by the three most interfering sector antennas. These sector antennas belonging to three adjacent base stations are indexed with $m \in \{1, 2, 3\}$. The corresponding base stations collaborate in resource allocation and scheduling in the reference area that is overlooked by three sector antennas, as shown in the shaded area in Fig.1.

There are a total of K users, and in order to reduce the required signaling, clusters of adjacent subcarriers are grouped together to form N resource blocks (RBs) in each cell. We index the users with $k \in \mathcal{K} = \{1, 2, \ldots, K\}$ and RBs with $n \in \mathcal{N} = \{1, 2, \ldots, N\}$. A saturated case is considered, where users always have backlogged traffic. The partial Channel State Information (CSI) of users is available at the corresponding base stations. Frequency Division Duplex (FDD) CSI can be obtained using the reference symbols which are transmitted on the downlink with a certain pattern in time and frequency domain. For Time Division Duplex systems (TDD), the CSI is obtained using uplink measurements if we consider reciprocity of down and up links. In a conventional scenario without collaboration, where users are served by their corresponding base stations, each BS receives the incoming traffic destined to its users through the core network, and independently performs resource allocation. However, in the proposed scheme, the core network uses the backhaul links to direct the traffic to the collaborating BS that will temporarily serve a specific user. We are mainly interested in resource allocation for the users located on the cell edges, as this is where BS diversity gain will be maximum.

III. Distributed Collaborative Scheduling Scheme

In this section, first the multi-cell resource allocation is formulated as an optimization problem in III-A. Subsequently as this is an NP-hard problem that can not easily be solved within reasonable time scale for real time resource allocations; two heuristic methods are proposed in order to provide a feasible solution to the problem in a reasonable time scale and with a low level of complexity. Then, in III-B a framework for collaborative, distributed resource allocation among a cluster of three neighboring base stations is proposed, where the first subsection introduces a scheme for sharing the information among the collaborating base stations, followed by full explanation of the heuristic methods used in resource allocation. The practical aspects of communication with core network and information exchange is discussed in III-C, and finally in III-D, we discuss the multiuser diversity gain, which is used in our proposed scheme in order to improve the system throughput.

A. Problem formulation

The objective in the long term is to maximize throughput, while satisfying the fairness constraints among the neighbouring base stations. Let $\phi_{k,n}^{(m)} \in \{0,1\}$ be the allocation variable for user k on resource block n in base station m , i.e., $\phi_{k,n}^{(m)} = 1$ if resource block n is assigned to user k, otherwise $\phi_{k,n}^{(m)} = 0$. Signal to noise ratio (SNR) for user k on RB n in cell m is defined as:

$$SNR_{k,n}^{(m)} = \frac{p_{k,n}^{(m)}\, g_{k,n}^{(m)}}{N_0 B} = p_{k,n}^{(m)} \beta_{k,n}^{(m)}, \tag{1}$$

where $g_{k,n}^{(m)}$ is the channel gain from base station m to user k on RB n, which includes path loss, shadowing, and frequency selective fast fading. $p_{k,n}^{(m)}$ is the transmit power allocated to user k on RB n by the base station m. N_0 is the noise spectral density and B is the bandwidth allocated to the resource block. For the purpose of analyzing the performance of resource allocation scheme only, we can assume that the physical layer modulation and coding can achieve Shannon's normalized capacity given by:

$$r_{k,n}^{(m)} = log_2(1 + p_{k,n}^{(m)} \beta_{k,n}^{(m)}) \quad b/s/Hz. \tag{2}$$

This is a useful and safe simplification of the physical layer, as we aim to compare the performance of radio resource allocation schemes, not the physical layer schemes. The total transmission rate to user k at each scheduling epoch equals to

$$R_k^{(m)} = \sum_{n=1}^{N} \phi_{k,n}^{(m)}\, log_2(1 + p_{k,n}^{(m)} \beta_{k,n}^{(m)}). \tag{3}$$

Note that we do not consider simultaneous transmission from multiple sector antennas to a single user in this paper. Thus, the total instantaneous throughput for sector antenna m is given by

$$R_m = \sum_{k=1}^{K} \sum_{n=1}^{N} \phi_{k,n}^{(m)}\, log_2(1 + p_{k,n}^{(m)} \beta_{k,n}^{(m)}). \tag{4}$$

It has been shown that opportunistic scheduling, where scheduling decisions are made based on the quality of channels for different users, is a throughput optimal resource allocation scheme [20]. However, opportunistic scheduling tends to be an unfair resource allocation scheme whenever there are significant discrepancies among the average quality of channels for different users. To overcome the problem of unfairness; opportunistic fair scheduling schemes have been proposed [5]. Inspired by this, we adopt an opportunistic scheduling scheme with a balancing mechanism to improve fairness among the users. We perform scheduling by dividing the users' achievable rate in the current transmission to users' average throughput in past transmission intervals. If the normalized average throughput of users are not equal, the scheduling scheme will give higher priority to users with relatively lower average rates. Using a moving average calculator from [22], the instantaneous average rate for user k in all three sectors, $\tilde{R}_k(t)$, is updated in each scheduling epoch t as follows

$$\tilde{R}_k(t) = (1 - \frac{1}{T_c})\tilde{R}_k(t-1) + \frac{1}{T_c} R_k(t). \tag{5}$$

where T_c is a time constant for the moving average calculator, and $R_k(t)$ is the kth user's achievable rate on all RBs in time t.

We can define the objective function of the scheduling scheme problem as follows:

$$\max_{\phi_{k,n}\ p_{k,n}} \sum_{m=1}^{M} \sum_{k=1}^{K} \sum_{n=1}^{N} \phi_{k,n}^{(m)}\, log_2(1 + p_{k,n}^{(m)} \beta_{k,n}^{(m)}) / \tilde{R}_k \tag{6}$$

Subject to

$$\sum_{m=1}^{M} \sum_{k=1}^{K} \sum_{n=1}^{N} \phi_{k,n}^{(m)}\, p_{k,n}^{(m)} \leq P_{BS} \tag{7}$$

$$\sum_{k=1}^{K} \phi_{k,n}^{(m)} = 1 \qquad \forall n \tag{8}$$

$$p_{k,n}^{(m)} \geq 0 \qquad \forall n, k \tag{9}$$

where P_{BS} in (7) is the total power available to all three sector antennas. (8) assumes the exclusive allocation of each RB to one user only. The problem in (6) is an NP-hard optimization problem that can not be solved using conventional techniques; some reasonable simplifications are required in order to reduce the complexity of the problem. On the other hand, as the scheduling needs to be performed almost in real time, we can not afford using highly resource demanding computational schemes. Thus, the simplifications and heuristic approaches are required for practical reasons, and are presented in the following.

1) Equal Power Allocation: The complex solution to the problem (6) is to find the optimal RB and power allocation. We separate these two components and consider equal power allocation first, i.e., the available power budget is equally divided among RBs as follows:

$$p_{k,n}^{(m)} = \frac{P_{BS}}{N} \tag{10}$$

In order to satisfy the constraint in (8), the scheduler only transmits to the user with the best channel gain on each RB. Equal power allocation, and exclusive RB allocation, can reasonably simplify the problem. So the problem in (6) can be reduced to:

$$\max_{\phi_{k,n}} \sum_{m=1}^{M} \sum_{k=1}^{K} \sum_{n=1}^{N} \phi_{k,n}^{(m)} \, log_2(1 + p_{k,n}^{(m)} \beta_{k,n}^{(m)}) / \tilde{r}_{k,n}^{(m)}. \tag{11}$$

Here, the optimisation parameter is $\phi_{k,n}^{(m)}$, and $\tilde{r}_{k,n}^{(m)}$ is computed in each scheduling epoch as follows

$$\tilde{r}_{k,n}^{(m)}(t) = (1 - \frac{1}{T_c})\tilde{R}_k(t-1) + \frac{1}{T_c} r_{k,n}^{(m)}(t). \tag{12}$$

2) Serial RB selection and Water-Filling: This approach aims to simplify the resource allocation problem by separating user selection and power allocation problems. First, the user to be served on each RB in each base station is selected, and then the power allocation is performed, according to water-filling algorithm.

In order to select the best user-base station-RB combination, a *"selection coefficient"* $\alpha_{k,n}^{(m)}(t)$ is defined as follows:

$$\alpha_{k,n}^{(m)}(t) = \beta_{k,n}^{(m)}(t) / \tilde{g}_{k,n}^{(m)}(t) \tag{13}$$

where:

$$\beta_{k,n}^{(m)}(t) = g_{k,n}^{(m)}/N_0 B \tag{14}$$

and

$$\tilde{g}_{k,n}^{(m)}(t) = (1 - \frac{1}{T_c})\tilde{R}_k(t-1) + \frac{1}{T_c} g_{k,n}^{(m)}(t). \tag{15}$$

In this approach, the best user k^* to be served by cell m^* on each RB, can be:

$$k^*, m^* = \arg\max_{k,m} \alpha_{k,n}^{(m)} \qquad \forall n. \tag{16}$$

Having identified the set of user-base station-RB combinations, the water-filling power allocation can be performed in the system, in order to identify the power p^* to be allocated to each user on each RB from the serving base station.

B. Distributed collaborative Scheduling Schemes

Considering the fact that there is no central node to gather all the information and perform the best RB allocation and scheduling, the proposed schemes rely on limited coordination and collaboration among the adjacent sector antennas. In this schemes, each base station has the user information as well as the average past transmitted rates, and the partial CSI. Each sector antenna independently performs the scheduling by calculating a *"Scheduling Coefficient"* $Sc_{k,n}^{(m)}$, which is, the coefficient associated with user k on RB n in cell m, and can be flexibly defined according to the scheduling policy. For instance, if we use a pure opportunistic scheduling scheme with equal power allocation, $Sc_{k,n}^{(m)}$ will indicate the channel gain for user k on RB n from cell m. Alternatively, if we use a proportional fair scheme discussed in III-A1, $Sc_{k,n}^{(m)}$ will be user k's achievable rate on RB n divided by user's average throughput; that is $r_{k,n}^{(m)}/\tilde{r}_{k,n}^{(m)}$. For the scenarios discussed in section III-A2, it can be defined as $\alpha_{k,n}^{(m)}$. For other scheduling scheme, $Sc_{k,n}^{(m)}$ can be flexibly defined according to the parameters used in that particular scheduling scheme.

1) Information Exchange among Base Stations: In the first step, sector antenna m independently calculates a "Scheduling Coefficient Matrix" (SCM), which contains all the scheduling coefficients for all the users on all RBs, denoted by

$$SCM^{(m)} = [Sc_{k,n}^{(m)}]_{K\times N}. \tag{17}$$

Then, each SA m, locally chooses the highest scheduling coefficient on each RB and records the coefficient along with the ID of the corresponding user, by making two separate matrices, called ”Best Matrix” and ”Best$_{ID}$ matrix” respectively. Best Matrix is built by scanning each column ($n = 1, \ldots, N$) of the scheduling matrix for all the users ($k = 1, \ldots, K$) and choosing the highest Sc on each RB, which results in creating a $1 \times N$ matrix, denoted by $SC^{(m)}_{best}$ for each cell.

$$SC^{(m)}_{best} = \{Sc^{(m)}_{k^*,n} : k^* = \arg\max_{k} \ Sc^{(m)}_{k,n} \ ; \ n = 1, \ldots, N\} \tag{18}$$

Next, the Best$_{ID}$ matrix, of the size $1 \times N$, is built by recording the ID of the user with highest Sc on each RB, denoted by:

$$ID^{(m)}_{best} = \{k^* : k^* = \arg\max_{k} \ Sc^{(m)}_{k,n} \ ; \ n = 1, \ldots, N\}. \tag{19}$$

In the next step, the information exchange takes place, and each sector uses the backhaul links to send these two matrices containing the best scheduling coefficients along with the user ID associated with the best user on each RB to both neighbouring sectors.

Then, each sector appends all the three $SC^{(m)}_{best}$ matrices, and builds the ”Scheduling Matrix” of the size $3 \times N$. This ”Scheduling Matrix”, which is denoted by Ω is mapped to a user ID (UID) matrix of the same size, denoted by Ω_{ID}. Ω_{ID} stores the user index for each component of the Scheduling Matrix.

$$\Omega = \begin{bmatrix} Sc^{(1)}_{k,n} \\ Sc^{(2)}_{k,n} \\ Sc^{(3)}_{k,n} \end{bmatrix} \tag{20}$$

$$\Omega_{ID} = \begin{bmatrix} ID^{(1)}_{best} \\ ID^{(2)}_{best} \\ ID^{(3)}_{best} \end{bmatrix} \tag{21}$$

This is the common information available in all 3 sectors, and is used for the actual scheduling.

2) Collaborative Scheduling with Equal Power Allocation: In the case of equal power allocation to all the RBs, the amount of power to be used for each RB is calculated using (10). As shown in Fig. 2 in order to select the user-SA-RB combination, each sector antenna scans the scheduling matrix for each RB, and finds the highest scheduling coefficient associated to that RB.

If the highest scheduling coefficient is associated with an RB on the same sector, the sector will use the UID matrix that stores the user ID associated with that particular RB, and transmit

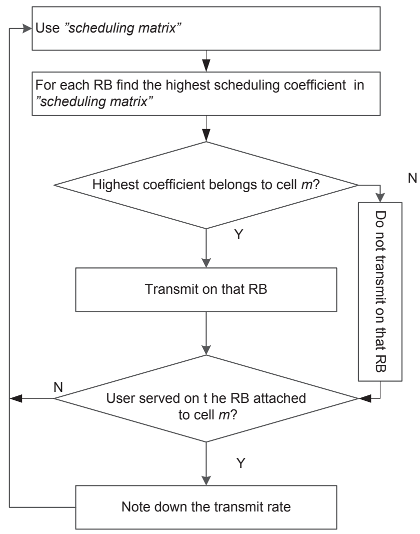

Fig. 2. Equal power allocation

to that user on that RB, in other words,

$$m^* = \arg\max_m (\Omega) \; ; \; n = 1, \ldots, N \tag{22}$$

$$k^* = \Omega_{ID}(m^*, n) \; ; \; n = 1, \ldots, N \tag{23}$$

To this end, in the optimization problem in (11), for the sector that transmits to user k^* on RB n in cell m^*, $\phi_{k^*,n}^{(m^*)} = 1$; otherwise, $\phi_{k^*,n}^{(m^*)} = 0$. The original serving SA then uses the data in the scheduling matrix to compute the rate associated to that particular user for that interval such that it can later be used for scheduling in next scheduling intervals.

3) Collaborative Scheduling with Serial RB selection and Water-Filling: When it comes to serial RB selection and power allocation, the information are exchanged among the base stations as mentioned before. In the first step, scanning each row, each base station decides if the user with the highest scheduling coefficient on each RB belongs to that base station (user-RB selection). Performing user-RB selection, each SA determines a list of users to be served by that sector antenna. The remaining problem is power allocation for each RB. Depending on the degree of distribution in the algorithm, different approaches can be taken for power allocation problem. The proposed approaches are presented in the following:

- *Distributed RB selection with Centralized Water-Filling:*

  We use this scenario only as a bench mark and for the comparison of the performance of distributed algorithms that will be discussed later. In this method, having selected the users to be served by each SA, one BS acts as the master BS, and using scheduling matrix Ω; for each RB, it selects the user to be served and the SA to serve the user on each RB. Then the master BS prepares a new matrix, which contains a list of all RBs, the base station to serve that RB, and the scheduling coefficient. In the next step, the lead cell performs the water-filling power allocation algorithm, using the scheduling coefficient of each RB and allocates power for each RB. Finally using the backhaul links, the assigned value of the power is transmitted to the other two base stations.

- *Distributed RB selection with Distributed Water-Filling:*

  For the fully distributed water-filling algorithm, each SA uses scheduling matrix Ω to find out the RBs and the users it has to serve, and each SA m comes up with the total number of RBs to be served by the SA and also the total number of available RBs. Using this information, each SA calculates its own share of power from the total available power, which is allocated as a ratio of the serving RBs to the total number of available RBs. The power share for SA m is calculated as:

  $$P_{SA}^{(m)} = P_{BS} \times n_t^{(m)}/N. \tag{24}$$

  Where $P_{SA}^{(m)}$ shows the amount of power allocated to SA m, and $n_t^{(m)}$ shows the total number of RBs served by SA m, and N is number of RBs available in total. Knowing the total available power for each SA, and also each user's channel gain on the specific RB, each SA performs water-filling and allocates power for different RBs.

C. Core Network Communications

In providing a feasible solution to collaborative radio resource allocation problem, issues like communications required to the core network and handling and the flow of the data also need to be addressed, in order to make the proposed solution practically feasible.

In conventional cellular networks, each user is statically assigned to a serving base station, and

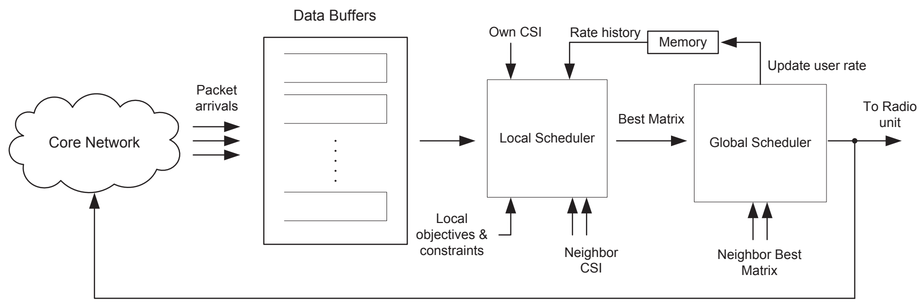

Fig. 3. Communication with the core network

the core network knows the associated BSC/RNC for the BS serving the user; so the data intended for user k under BS m is directed by the core network to its serving BSC/RNC and from there to the serving BS m. However, with the removal of the BSC/RNC from the architecture, and dynamically serving the users with the BS that has the best scheduling coefficient for the user, the data also needs to be sent to the serving BS. One simplistic approach to solving this issue, would be sending the data destined to a particular user, to all the three sectors that could possibly serve that user. However, this is not an optimal approach, as it overloads the backhaul links with non revenue generating traffic, and in fact triples the amount of communication required to serve a user.

In order to avoid overutilizatin of backhaul links and sending triple messages for each user to be served, the inherent modularity in our proposed scheme can be used. That is, as shown in Fig. 3, the base stations communicate to the core network as a peer node, meaning that the core network, also receives a copy of the scheduling matrix, and the information that is exchanged among the base stations. Having access to the information that the actual resource allocation is bases on, provides the core network with the ability to work out the results, and hence send the data that need to be transmitted to user k to its serving SA m at any time instance. Although this method implies that core network also needs to perform some computations, however, as the calculations are fairly simple, it does not impose a high computational load on the core network. In fact, the amount of computation in core network is a trade off between the back haul overutilization and a more rationale usage of backhaul links.

D. *Multi-user Diversity Gain associated with Collaborative Resource Allocation Schemes*

Revisiting the setup, and the way resource allocation in collaborative scenarios is approached, we can see that the gain associated to the proposed scheme is from the same nature, as the multi-user diversity gain. For a multi-user OFDMA system, as we saw previously, we denote the channel gain from BS m to user k on RB n with $g_{k,n}^{(m)}$. When a transmitter is serving a total number of $K1$ users, the achievable rate on each RB can be approximated by

$$[r_{k,n}^{(m)}]_{K1} = log_2[1 + \frac{p_{k,n}^{(m)}}{N_0 B} \max_k (g_{1,n}^{(m)} \dots g_{K1,n}^{(m)})]. \tag{25}$$

Now if the number of users is increased from $K1$ to $K2$ the achievable rate for RB n in cell m will be

$$[r_{k,n}^{(m)}]_{K2} = log_2[1 + \frac{p_{k,n}^{(m)}}{N_0 B} \max_k (g_{1,n}^{(m)} \dots g_{K2,n}^{(m)})]. \tag{26}$$

considering the fact that $K2 \geq K1$, and since $log(.)$ is a monotonically increasing function, then for any $K2 \geq K1$, $[r_{k,n}^{(m)}]_{K2} \geq [r_{k,n}^{(m)}]_{K1}$. So with higher number of users in a system, the system is bound to having higher capacity.

In the proposed collaborative resource allocation algorithms, the fact that the users are not dedicated to a specific cell, and each user can be served by any best station that has a good channel gain to that user, can practically be seen as tripling the number of users in each cell, which will cause to higher levels of multiuser diversity gain. So in the proposed scheme, assuming a total of K users being served by the three sectors, if $K/3$ of the users are dynamically served with each cell the achievable rate will be $[r_{k,n}^{(1)}]_{K/3} + [r_{k,n}^{(2)}]_{K/3} + [r_{k,n}^{(3)}]_{K/3}$. However if the users are dynamically served by the three sectors the achievable rate will be $[r_{k,n}^{(1)}]_K + [r_{k,n}^{(2)}]_K + [r_{k,n}^{(3)}]_K$. This in fact implies that by virtually increasing the number of users to be served in each cell, the collaborative scheduling scheme increases the multi-user diversity gain. Fig. 4 shows a simple scenario with three users. Instead of each cell serving one user, and one channel gain to choose, with the collaborative scheme, each cell can decide and use one of the three channels provided.

IV. Simulation Results

The simulation model in this paper comprises 3 neighboring SAs in reference area shown in Fig. 1. This is the common area that is covered by 3 most interfering sector antennas from the

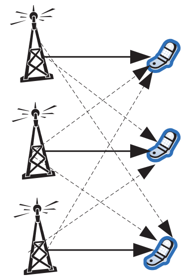

Fig. 4. Multi-user diversity gain

3 base stations. According to the proposed schemes, no RB will be used by 2 cells at the same time.Thus, the interference is mitigated by using the proposed scheduling schemes, as explained in previous sections. Each sector has a total power of 20W (43 dBm). Time slot duration is 1 ms; the total bandwidth is 5 MHz, which is divided into 24 RBs, each consisting of 12 subcarriers with the bandwidth of 15KHz. The channels from the BSs to the users are modelled considering path loss, shadowing, and fast Rayleigh fading. We define Non-Collaborative (NCP) scheme, where each user is served by a fixed BS, and Collaborative (CP) scheme, where each user is dynamically served by the best BS using the distributed collaborative scheduling scheme. Both schemes are implemented using a proportional fair resource allocation scheme as described in III-A. For NCP scheme, we implement three independent schedulers, each using a third of available RBs, for three different sectors at the common coverage area. For CP scheme, the distributed collaborative scheduler schemes explained in section III-B are implemented.

In order to investigate the fairness of the schedulers, Gini fairness index is used to ensure accuracy of results as follows:

$$I = \frac{1}{2K^2\bar{u}} \sum_{x=1}^{K} \sum_{y=1}^{K} |u_x - u_y|. \tag{27}$$

Where $u = \{u_i | u_i = \tilde{R}_i\}$ and $\bar{u} = (\sum_{i=1}^{K} u_i)/K$.

Below, we present and discuss the simulation results for the performance of the proposed schemes in different scenarios.

A. Equal Power Allocation

In this scheme, the total transmission power, allocated to each cell, is equally divided among the available resource blocks. In the next step, each base station calculates the scheduling coefficients of the users on different RBs. This information is then shared among the neighbouring base stations. Finally, each base station, independently makes the resource allocation decisions using the scheme described in section III-B2. Different simulated scenarios are as follows:

1) Symmetric Users Around the Center of Coverage Area: In this scenario, the users are distributed around the center of the three cells, where the interference levels are high. A benchmark case for worst case scenario is when the users are very close to the centre of the coverage area. This is not a realistic scenario; however, we can use it as a bench mark for comparison of the performance of different scheduling schemes. To implement this scenario, a central area with a fairly small radius of d at the center is defined, and equal number of users are located in the coverage area associated with each sector, then both NCP and CP scheduling schemes are performed. The system throughput versus the number of users for cell radius of 500m is shown in Fig. 5 (NCP/CP-Eq. P curves). In terms of throughput, it can be seen that CP scheduling significantly outperforms the NCP scheme. As the number of users in the system increases, the throughput curves also increase due to multi-user diversity gain.

Gini fairness index versus the number of users for the same scenario is shown in Fig. 6. In terms of fairness, as both schemes employ proportional fair scheduling algorithms, they both show good levels of fairness, however collaborative scheme performs better than non-collaborative scheme, where fairness remains almost constant with the growth of number of users.

2) Asymmetric Users Around the Cell Edge Area: In this scenario, each user has different average channel gains to different sector antennas. Thus, the interference will be lower in this scenario compared to symmetric user distribution. here, the equal number of users in each cell, are randomly distributed close to the cell edge area. Total system throughput for the CP and NCP is shown in Fig. 7 (NCP/CP-Eq. P curves) for cells with a radius of 500m. As the results show, collaborative scheme provides a higher total cell throughput. In addition, compared to the symmetric scenario, as the users are less prone to interference, the overall throughput in this scenario is higher than the symmetric scenario.

Fig. 8, shows the fairness index for CP and NCP. As it can be seen, CP scheme performs better than NCP in terms of fairness. Besides, in this scenario that the users are distributed on the cell

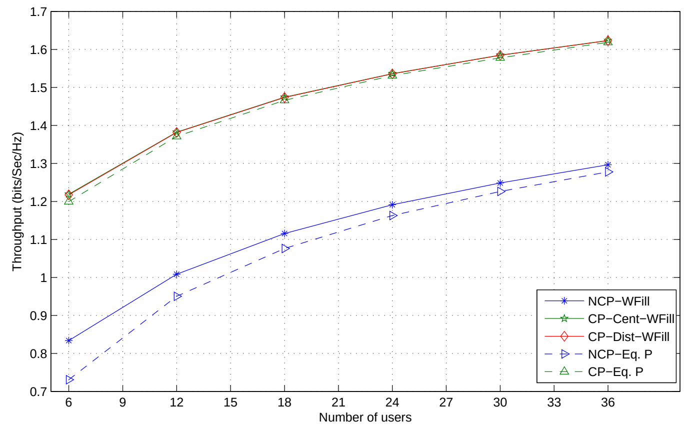

Fig. 5. System throughput for symmetric user distribution, with different power allocation schemes

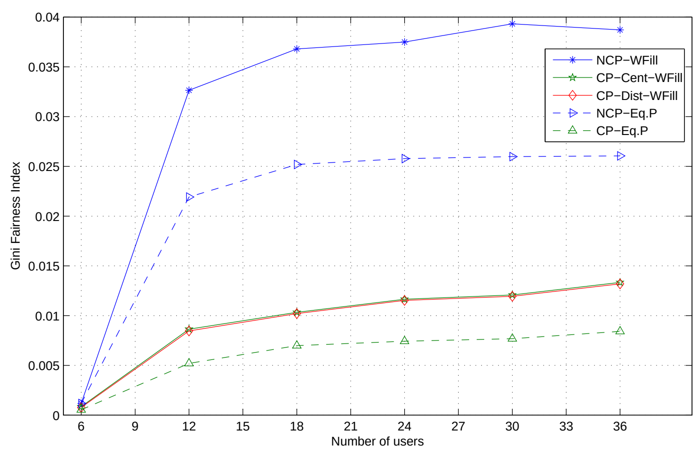

Fig. 6. Fairness Index for symmetric users distribution, with different power allocation schemes

edge, higher throughputs are achieved compared to the scenario where users are symmetrically distributed around the centre.

3) Asymmetric cluster of users : Here, the users are distributed according to a normalized parameter defined as symmetry coefficient. When the symmetry coefficient is equal to zero, we have the least symmetry in the system. On the other hand, the user distribution is fully symmetric when the symmetry coefficient is equal to one. This is in fact similar to user distribution in section IV-A. The results for cell throughput and fairness index with different symmetry coefficients are

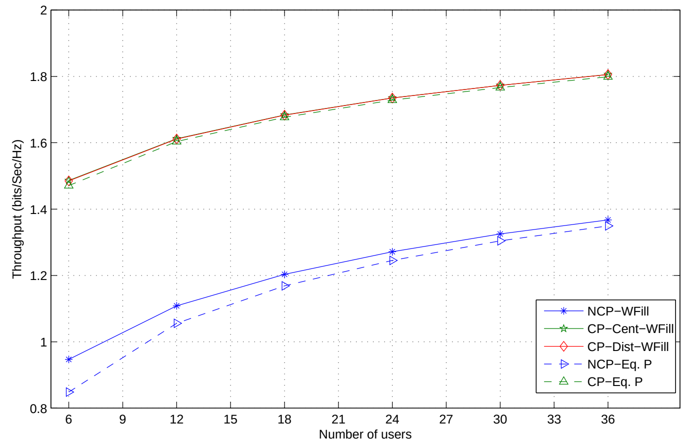

Fig. 7. System throughput for asymmetric user distribution, with different power allocation schemes

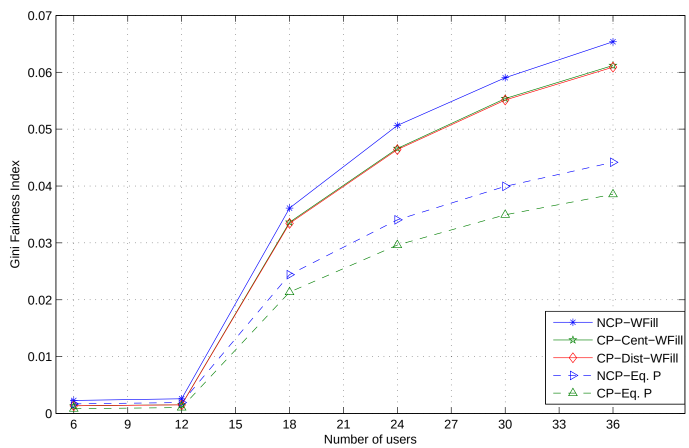

Fig. 8. Fairness Index for asymmetric users distribution, with different power allocation schemes

displayed in Fig. 9, and Fig. 10 respectively.

The results are provided for a total number of 36 users, moving in clusters according to the symmetry coefficient from the BS towards the centre of the 3 cells. As it can be seen, the CP scheme always outperforms the NCP scheme. However, as the users are located in different locations inside the cell, instead of moving on the cell edges, and the reception from neighbouring base station is very weak, this improvement is marginal. In order to further investigate the results, we use the same concept, but move the cluster of the users along the cell edge. As there is a

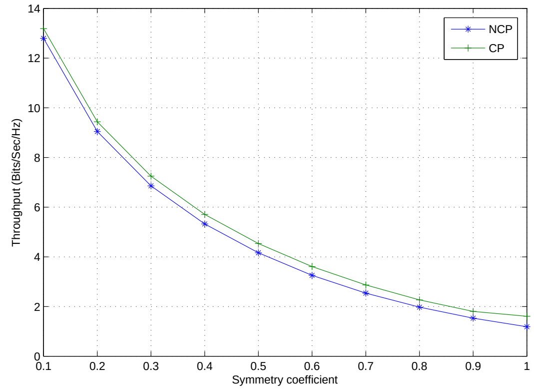

Fig. 9. System throughput for cluster of users with different symmetry coefficients, moving on the line connecting to BS

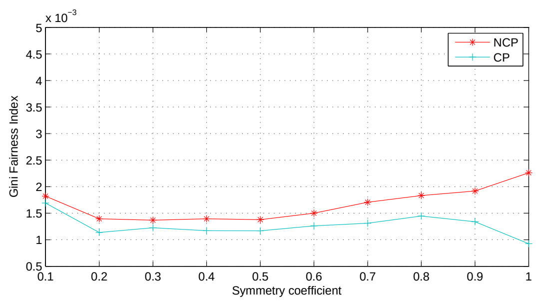

Fig. 10. Fairness Index for cluster of users with different symmetry coefficients, moving on the line connecting to BS

better chance of having a good channel to the neighbouring cells, when the users are located around the cell edge area. The results are provided in Fig. 11, and Fig. 12. As we can see, the throughput using CP scheme is much higher compared to NCP scheme, which is due to higher levels of spatial diversity obtained at the edge of the cell. As it is shown in Fig. 11, as the symmetry coefficient is increased from 0 to 0.5 the system throughput constantly increases, and, when symmetry coefficient equals 0.5, the system throughput is maximized. This is due the fact that at this point, the distance between the users on the cell edge to both base stations is minimum, which causes less path loss, and better channels, and hence higher system throughput. As the symmetry coefficient increases further from 0.5 to 1, this distance increases and the system throughput decreases.

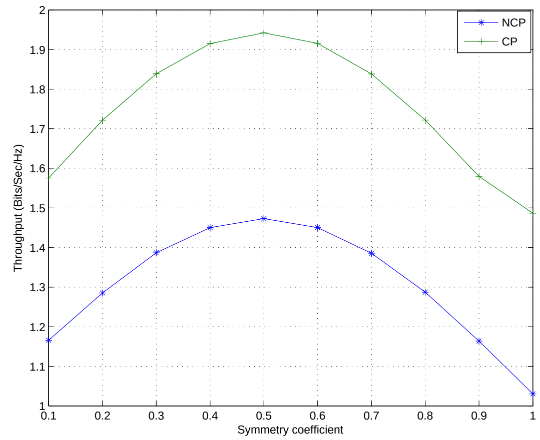

Fig. 11. System throughput for cluster of users with different symmetry coefficients - moving on cell edge

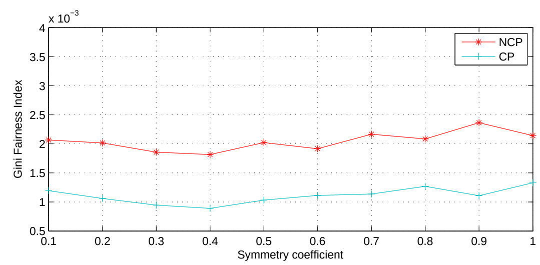

Fig. 12. Fairness Index for cluster of users with different symmetry coefficients - moving on cell edge

B. Serial RB selection and Water-Filling

This subsection presents the results for the resource allocation scheme discussed in Section III-B3. For the ease of notation, in referring to different schemes mentioned in III-B3, we refer to ”Distributed RB selection with Centralized Water-Filling” , and ”Distributed RB selection with Distributed Water-Filling” with notations of ”Cent-WFill” and ”Dist-WFill in result graphs. The simulation results for different scenarios follow in the next subsections.

1) Symmetric Users Around the Center of Coverage Area: This scenario is similar to the scenario discussed in section IV-A1, where users are located symmetrically around the centre. The main difference with the algorithm in IV-A1 is that, instead of using equal power allocation, here, we use the algorithms explained in III-B3. The system throughput for different number of users and cell radius of 500m is shown in Fig. 5 (NCP-WFill and CP-Cent/Dist-WFill curves). As it can be seen, the proposed collaborative (CP) schemes, outperform the non-collaborative (NCP) scheme. The centralized and distributed algorithms achieve same system throughputs, however, compared to equal power allocation scheme, the water-filling scheme performs marginally better. The Gini fairness index for this scenario is shown in Fig. 6. Although a similar proportional fair scheme is used in all the schemes, the collaborative schemes have a better level of fairness. It can also be seen that, all the two scenarios which use collaborative distributed water-filling technique provide almost the same level of fairness, which is slightly worse than the equal power allocation scheme. This is due to the greedy nature of water-filling algorithms, as it allocates higher powers to the users with better channel conditions .

2) Asymmetric Users Around the Cell Edge Area: This scenario is similar to that of section IV-A2, where the users are located around the cell edges. Thus we expect to see the high spatial diversity gains. In terms of power allocation, we use the three algorithms explained in III-B3. Fig. 7. (NCP-Wfill and CP-Cent/Dist-WFill curves), shows the results for different schemes. As we can see, the collaborative scheme again outperforms the non-collaborative scheme. The collaborative distributed water-filling power allocation scheme, has the same performance as the centralized version, and they are both marginally better that equal power allocation scheme in terms of system throughput. Gini fairness index is shown in Fig. 8, as we can see CP schemes using water-filling out perform NCP schemes using water-filling. However due to the nature of water-filling, all these schemes perform worse in terms of fairness, when compared with equal power allocation schemes.

C. Efficiency and trade offs for the Proposed Schemes

So far, we have presented the simulations for two distinct categories in terms of power allocation strategy. In this subsection, the results for these two approaches are compared. In the symmetric scenario, users are located on a circle with a radius of 500m around the centre of the three adjacent cells, and for the asymmetric scenario, the users are located at the edge of the cell. Fig. 5 and 7 show the comparison of the results in terms of system throughput for symmetric and asymmetric scenarios. As it can be seen, in both figures, equal power allocation performs marginally worse than water-filling power allocation schemes both for collaborative and non-collaborative schemes. This marginal gain is achieved in the expense of more computational complexity. In terms of fairness, as it can be seen in Fig. 6 and 8, equal power allocation in non-collaborative and collaborative scenarios outperforms water-filling power allocation in terms of fairness index. This is due to the fact that, any channel aware power allocation scheme, like water-filling, allocates the power to the resources in proportion to the channel gain. Specifically water-filling aims at maximizing the overall system throughput by allocating more power to users with better channel gains. Although we have applied a fairly simple scheme to provide fairness, the effect of water-filling takes over, and the fairness is degraded when water-filling power allocation is implemented.

V. Conclusion

In this paper, a distributed and collaborative radio resource allocation scheme for the downlink of an OFDMA cellular network was proposed. The scheme enables each sector to independently perform the resource allocation task, and through exchange of limited information, the base stations make the scheduling decisions. The proposed scheme maintains orthogonality in terms of frequency allocation, and provides a dynamic framework for frequency allocation and hence mitigates interference among most interfering cells. Simulation results demonstrate effectiveness of the proposed scheme in terms of spectral efficiency and fairness. The proposed scheme particularly improves efficiency of radio resource allocation for the users located at the cell edges.

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