Subchannel Allocation and Power Control in Femtocells to Provide Quality of Service

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Abstract—**Femtocells are a new concept which improves the coverage and capacity of a cellular system. We consider the problem of channel allocation and power control to different users within a Femtocell. Knowing the channels available, the channel states and the rate requirements of different users the Femtocell base station (FBS), allocates the channels to different users to satisfy their requirements. Also, the Femtocell should use minimal power so as to cause least interference to its neighboring Femtocells and outside users. We develop efficient, low complexity algorithms which can be used online by the Femtocell. The users may want to transmit data or voice. We compare our algorithms with the optimal solutions.**

Keywords- Femtocell, channel allocation, power control, QoS, voice and data users, cellular communication.

I. INTRODUCTION

Recent studies have found that most of the data traffic and also the voice traffic in a cellular system originates indoors. It is also found that due to attenuation caused by the walls of the buildings, the voice quality and the data rates indoors are often low. Improving the service indoors requires substantially more transmit power from the Base station (BS) and the mobile stations (MSs), which can be costly and can cause health hazards. This also increases the interference to the neighboring cells. Thus recently Femtocells (FCs) are being considered as an attractive option [14].

Femtocell access points (FAPs) are low power, low cost, small base stations deployed indoors [3], [4]. These are generally being used to provide service to MSs inside a building and are connected to the cellular network via DSL lines or cable TV. This improves coverage and capacity for indoor environment. Also this enables a substantial part of the cellular traffic to be offloaded from the cellular network reducing cell density and electromagnetic radiation in dense urban areas.

Although, deployment of FAPs in a macrocell (MC) environment improves the performance of the users inside the FC, it causes interference to the MSs outside the building using the macro BS (MBS). Thus FAPs should use appropriate transmit power [5], [6], [9]. If the transmit power is too high, they may cause interference to neighboring Macro and Femto cells. On the other hand if the transmit power is low, this may limit the coverage and quality of service (QoS) within the FC. Also an upper limit must be imposed on the transmit power of the MSs within the FC.

In addition to using appropriate transmit power, the FAP also needs to allocate subchannels available to its different users so as to make an efficient use of resources while providing the users their QoS. We address these problems in this paper.

In the following we provide the related literature survey. Interference analysis based on a realistic OFDMA macro/femtocell scenario is provided in [10]. FC carrier selection, transmit power control and interference management are studied in [13]. In [8] open loop and closed loop interference mitigation strategies are proposed to suppress the cross-tier interference at a MBS. Suboptimal methods for interference mitigation that rely on transmit beamforming are proposed in [7]. In [2] fractional frequency reuse (FFR) is used to reduce the effect of co-channel interference.

In this paper we propose subchannel allocation and power control algorithms for uplink and downlink users within a FC in a multi FC sparse scenario (e.g., suburban/rural environment) where interference between the FCs are neglected. Our model includes subchannel power constraints, considers QoS to voice and data traffic and provides fair, efficient, low complexity algorithms. The previous studies do not include these features explicitely in their solutions. The proposed algorithms not only improve the QoS of MSs within the FC and the Macro cell (MC) but also cause less interference to the outside MSs by minimizing the transmit power of FC users. Looking forward, if several neighboring FCs have to interact to jointly solve power control and subchannel allocation problems, efficient algorithms developed here will be very useful. FCs will play an important role in providing green communication in future [1] and our energy efficient solution will be very useful in that context.

This paper is organized as follows. Section II describes the system model and formulates the problem. Section III provides optimal, efficient and computationally inexpensive algorithms. Section IV shows the efficacy of the algorithms via simulations. Section V concludes the paper.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider a two tier cellular system in which within a MC there may be many FCs. The cellular system may be using OFDMA (e.g., LTE or WiMAX) and the subchannels are shared by the FCs and the outdoor users in the MC. The MSs outside are directly served by a MBS, while the MSs inside a building may be supported by an FAP if there is an FAP in that building. Within a FC one expects less than

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ten users transmitting at the same time. The transmissions between the FAP and the MSs are in the uplink, downlink or both directions. Here for simplicity we consider the downlink scenario only. The FAP can use the same algorithms to allocate power and channel for the uplink also (it will require appropriate signalling which is available in, say, WiMAX). The users can be transmitting voice, data or video and hence would expect certain QoS. We consider voice and data users which are the dominant users in the current scenario but video can also be easily included in our setup.

Since the MSs within a FC are also the MSs which could as well be using the MBS, they have the information from the MBS about the subchannels being used at a given time by the MBS as well as by the MSs transmitting in the Macrocell. These channels may not be used by the FC at that time. The indoor MSs can also sense the SINR in each subchannel and can further be directed by the MBS on the maximum power they can use in transmitting in different available subchannels. This information can be sent to the FBS by the MSs within its domain or by the MBS directly (see, e.g., [15]). An FBS uses this information to decide on subchannel allocation and power control within its FC to provide QoS to its users while using minimum power within the limits prescribed by the MBSs.

Motivated by the above setup, in the following we provide our notation and formulate the problem we address. Let there be M FC users and N subchannels available for use. We assume that the FAP knows the subchannel gains $G_{i,j}$ of channel i to the user j within the FC. This may be directly available to the FBS in case of Time Division Duplex (TDD) channels at the FCs or fed back by the MSs to the FBS.

Let user j requires $\bar{R}_j$ bps for satisfactory QoS. Also let $\bar{P}_i$ be the maximum transmit power that can be used in subchannel i. This could be decided by the MBS based on the interference it and/or neighboring FCs can tolerate in that subchannel. Let σ^2 be the receiver noise power (for simplicity taken same for all users) and let $I_{i,j}$ be the interference (caused by outdoor users, MBS) experienced by user j in subchannel i. Based on this information the FAP has to decide the subchannel allocation to different users and the power P_i to be used in subchannel i such that the rate $\bar{R}_j$ is received by each user j.

Let

$$A_{i,j} = \begin{cases} 1, & \text{if subchannel } i \text{ is assigned to user } j, \\ 0, & \text{otherwise.} \end{cases}$$

Also let $C_{i,j} = \log_2\left(1 + \frac{P_i G_{i,j}}{\sigma^2 + I_{i,j}}\right)$. We assume that if power $\bar{P}_i$ is used by user j on channel i then rate $\bar{C}_{i,j}$ is achieved. We address the following problem.

OP:

Find $P_i, i = 1,2,..,N \quad and \quad A_{i,j}, i = 1,2,...,N, j = 1,2,...,M$ to

$$min \quad \sum_{i=1}^{N} P_i \tag{1}$$

such that

$$\sum_{i=1}^{N} C_{i,j} A_{i,j} \geq \bar{R}_j, \quad \forall j = 1,2,...,M, \tag{2}$$

$$P_i \leq \bar{P}_i, \quad \forall i = 1,2,...,N, \tag{3}$$

$$\sum_{j=1}^{M} A_{i,j} \leq 1, \quad \forall i = 1,2,...,N. \tag{4}$$

The equations (2) and (3) specify QoS requirements and power constraints. The constraint (4) ensures that any subchannel is allocated to only one user within the FC.

We provide efficient algorithms for this problem. Often in an FC the number of users $M < N$. This scenario will be handled in the rest of the paper. Even if $M > N$, the scheduling and power control is done by the FC for one or more frames at a time. Thus there will be multiple slots to be assigned for each channel. Our algorithms will allocate each slot of each channel separately, thus effectively considering NL channels where L is the number of slots considered. Thus we ignore the rare case of $M > N$ in this paper although we can easily modify our algorithms to obtain a good solution for this case also.

III. EFFICIENT ALGORITHMS

The problem (1)-(4) is a nonlinear constrained optimization problem with binary and real decision variables. Thus its complexity is very high even in a FC environment for online operation. Furthermore, if the requirements $\bar{R}_j$ for each user cannot be satisfied due to insufficient resources, we will not get any solution. Thus we look for efficient suboptimal solutions.

We solve the optimization problem (1)-(4) in the following steps:

Step 1: Take $P_i = \bar{P}_i, i = 1,2...N$. Now we need to find only the binary solution $A_{i,j}$ to the optimization problem.

This will be called "subchannel allocation problem". If *step 1* provides a (feasible) solution then go to *step 2* (to minimize power). If it does not, then go to *step 3* (to provide a 'fair' solution). This problem still has a high complexity (it is NP complete). Below we will find a suboptimal low complexity algorithm for this problem.

Step 2: If there is a feasible solution to the problem in *Step 1*, i.e., there exists an $R = (R_j, \forall j = 1,2,...,M)$, satisfying (2)-(4) such that $R \geq \bar{R}$, where $\bar{R} = (\bar{R}_j, \forall j = 1,2,...,M)$, then lower the transmit powers to get $R = \bar{R}$.

Step 3: If there is no feasible solution with $P_i = \bar{P}_i, i = 1,2,...,N$, then it is not possible to satisfy rate requirements of all the users simultaneously. Thus we obtain a *fair* solution by using the optimization problem:

OFP:

Fix $P_i = \bar{P}_i, i = 1,2,...,N$. Find $A_{i,j}$ that

$$max \quad \alpha \tag{5}$$

such that

$$\sum_{i=1}^{N} \bar{C}_{i,j} A_{i,j} \geq \alpha \bar{R}_j, \forall j, \quad \sum_{j=1}^{M} A_{i,j} \leq 1, \forall i. \tag{6}$$

If sufficient resources are not available to satisfy every user's requirement $\bar{R}_j$, in *Step 3* we obtain an optimal 'fair' solution which satisfies the maximum possible fraction α of demand of each user. This concept of fairness is intuitive, leads to efficient algorithms and has been used before [11]. Below, we will provide an efficient suboptimal algorithm to compute its solution.

This fair solution can be a satisfactory solution for data users, but may not be satisfactory for voice users (as the quality of voice received can be very bad if α is less than 0.9). In the following we address this problem.

Step.4: If both voice and data users co-exist and there is a feasible solution in *Step 1*, then we are done after *Step2* of minimizing the power consumption. If not, then we allocate subchannels to voice users to satisfy their requirements in such a way that as much capacity is left for data users as possible and then that is used to provide a fair solution for the data users. This is done by the optimal solution via the following optimization problem.

OFVD:

Let V be the set of voice users and D be the set of data users. Fix $P_i = \bar{P}_i$.

$$max \quad \alpha \tag{7}$$

such that

$$\sum_{i=1}^{N} \bar{C}_{i,j} A_{i,j} \geq \bar{R}_j, \forall j \in V, \quad \sum_{i=1}^{N} \bar{C}_{i,j} A_{i,j} \geq \alpha \bar{R}_j, \forall j \in D, \tag{8}$$

$$\sum_{j} A_{i,j} \leq 1, \quad i = 1, 2, ..., N. \tag{9}$$

We will provide an efficient algorithm to solve this problem. An assumption in this problem formulation is that since the voice users have low rate requirements, there are enough resources to satisfy at least voice users. This should be ensured by an admission controller over the voice users. It can be done in such a way that a certain fraction of bandwidth is reserved for data traffic.

A. Subchannel allocation algorithm

Solving the optimization problem (1)-(4), in four steps given above reduces the complexity of the problem. However the subchannel allocation problems in *Step 1, OFP ((5)-(6))* and *OFVD ((7)-(9))* may still be computationally complex. This is because even if the number of users in the FC may be small, the number of channels to choose from can be large (in an OFDMA system). Thus in the following we propose heuristic, less complex algorithms. We will compare their performance via simulations. Our first algorithm is HSA. This algorithm simply gives a subchannel to the user with the best channel gain and which still needs throughput (rate). Complexity of this algorithm is much lower than binary integer programming. Therefore, to check the feasible solution in *step 1*, we could use HSA instead of binary integer programming. If HSA provides a feasible solution then go to *step 2*. If not, theoretically there is still a chance that the optimal algorithm can provide a feasible solution. Thus we can run the binary integer programming to check for the feasible solution. An altenative is that since the chances of the optimal algorithm finding a feasible solution are small once HSA did not provide one, we can directly go to *step3*. If there is a feasible solution, *step 3* will provide a feasible solution with $\alpha \geq 1$. Of course the complexity of algorithm (5)-(6) is higher than the one in *step 1*.

Algorithm 1 Heuristic Subchannel Allocation Algorithm (HSA)

```
Input = $N, M, \bar{C}_{i,j}, \bar{R}_j, i = 1, 2, ...N, j = 1, 2, ...M$.
Take $A_{i,j} = 0, i = 1, 2, ...N, j = 1, 2, ...M$ and $R_{alloted}(j) = 0, j = 1, 2, ...M$
for $i = 1$ to $i = N$ do
    $j^* = \arg\max_j \bar{C}_{i,j}$
    if $(\bar{C}_{i,j^*} \neq 0)$ then
        $A_{i,j^*} = 1, R_{alloted}(j^*) = R_{alloted}(j^*) + \bar{C}_{i,j^*}$
    end if
    if $((\bar{R}_{j^*} - R_{alloted}(j^*) < 0)$ then
        $\bar{C}_{i,j^*} = 0, i = 1, 2, ...N$
    end if
    if $((\bar{C}_{i,j} \forall i = 1, 2, ...N, j = 1, 2, ...M) = 0)$ then
        Exit from the for loop
    end if
end for
```

B. Optimal power allocation

After channels are allocated and we are able to satisfy every user's rate requirements, we minimize the power used in the FC to satisfy the rate requirements (*Step 2*). This optimization problem is a *decoupled constrained optimization problem*, where we find power allocation for each user separately. Power allocation for the j^{th} user is given by :

$$min \quad \sum_{i=1}^{N} P_i A_{i,j} \tag{10}$$

such that

$$\sum_{i=1}^{N} \left[\log_2\left(1 + d_{i,j} P_i\right)\right] A_{i,j} \geq \bar{R}_j, \quad 0 \leq P_i \leq \bar{P}_i, \forall i, \tag{11}$$

where $d_{i,j} = \frac{G_{i,j}}{\sigma^2 + I_{i,j}}$. Using KKT conditions [12], we can show that

$$P_i = \left(\frac{\lambda A_{i,j}}{A_{i,j} + \mu_i} - \frac{1}{d_{i,j}}\right)^+, i = 1, 2, ..., N \tag{12}$$

where $(x)^+ = max(x, 0)$ and λ, $\mu_i, i = 1, 2, ..., N$ are Lagrange multipliers such that first inequality in (11) is satisfied with equality.

C. Fair allocation algorithm

If there is no feasible solution with $P_i = \bar{P}_i, i = 1, 2, ...N$, then we obtain a fair solution (*Step 3*) by solving problem (5)-(6).

Let $h_{i,j} = \frac{\bar{C}_{i,j}}{\bar{R}_j}$. In the *OFP* we can rewrite first inequality in (6) as

$$\sum_{i=1}^{N} h_{i,j}A_{i,j} \geq \alpha, \quad A_{i,j} \in \{0,1\}. \tag{13}$$

The optimal solution to this problem can be obtained via integer programming by first fixing α (starting small) and then finding a feasible solution of *OFP*. If still some subchannels are left, increase α.

A low complexity suboptimal solution is given below (algorithm 2, HFSA). Let H be the matrix with the (i,j)th element $h_{i,j}$.

Algorithm 2 Heuristic Subchannel Fair Allocation Algorithm (HFSA)

```
Input = $N, M, H$
Take $A_{i,j} = 0, \forall i = 1,2,...,N, \forall j = 1,2,...,M$
Initialization : $\alpha_j = 0, \forall j = 1,2,...,M$
for $j = 1$ to $M$ do
    $i^* = \arg\max_i h_{i,j}$
    $\alpha_j = h_{i^*,j};\ A_{i^*,j} = 1$
    $h_{i^*,j} = 0, \forall j = 1,2,...,M$
end for
Repeat: $j^* = \arg\min_j \alpha_j$
$i^* = \arg\max_i h_{i,j^*}$
if $(\alpha_{j^*} < 1)$ then
    $\alpha_{j^*} = \alpha_{j^*} + h_{i^*,j^*}$
    $A_{i^*,j^*} = 1;\ h_{i^*,j} = 0, \forall j = 1,2,...,M$
else
    $h_{i,j^*} = 0, \forall i = 1,2,...,N$
end if
if $(h_{i,j} \neq 0, \forall i,j)$ then
    go to Repeat:
end if
```

In this algorithm, in the first step, we give the best channel to each user. From then onward, we pick the user j with the lowest α_j and allocate him the best available channel.

D. Subchannel allocation algorithm for coexistent voice and data users:

If the fair heuristic algorithm *HFSA* in Subsection C, provides a solution such that each voice user is satisfied (this may happen because the voice users require low rate) then use (12) over the voice users to get the minimum power to satisfy their rate requirements. If some voice user is not fully satisfied by the solution in Subsection C, then we run the following algorithm on the solution obtained from *HFSA* to ensure that all the voice users are fully satisfied.

Algorithm 3 Voice-Data Allocation

```
1.Find the user in $D$ whose $\alpha_j$ is maximum.
2.For that particular data user find the allocated subcarrier whose $h_{i,j}$ is minimum and allocate this subcarrier to the unsatisfied voice user and recalculate the $\alpha_j$ value and repeat this procedure till all voice users requirements are satisfied.
```

We call the *HFSA* along with the above algorithm as *HFSVD*.

IV. EXAMPLES

In this section, we compare the heuristic schemes with the optimal solutions for a few examples. We consider FCs each with 4 users and 10 subchannels deployed sparsely in a MC for the case of Time division duplexing (TDD) scenario where all parameters such as rate requirement, interference matrix and subchannel gain matrix do not change significantly within a given TDD duration. We use the following parameters.

Subchannel bandwidth B = $180kHz$,
Noise Power Spectral Density $N_0 = 10^{-9}$W/Hz,
Noise variance $\sigma^2 = N_0 B = 1.8 \times 10^{-4}$watt-sec,
Total transmission power of FAP $P_{total}(mw) = 100$.

A. Subchannel allocation and Power control algorithm - feasible solution case : (OP, HSA)

Number of users $M = 4$, Number of subchannels $N = 10$.

Interference matrix (mw):

$$I^T = \begin{pmatrix} 4 & 3 & 7 & 7 & 1 & 4 & 4 & 6 & 7 & 7 \\ 11 & 4 & 9 & 3 & 5 & 2 & 7 & 2 & 5 & 6 \\ 8 & 9 & 5 & 1 & 1 & 12 & 8 & 2 & 8 & 12 \\ 9 & 13 & 1 & 2 & 6 & 4 & 3 & 8 & 5 & 15 \end{pmatrix}$$

Subchannel gain matrix:

$$G = \begin{pmatrix} 0.9172 & 0.9340 & 0.1656 & 0.1524 \\ 0.2858 & 0.1299 & 0.6020 & 0.8258 \\ 0.7572 & 0.5688 & 0.2630 & 0.5383 \\ 0.7537 & 0.4694 & 0.6541 & 0.9961 \\ 0.3804 & 0.0119 & 0.6892 & 0.0782 \\ 0.5678 & 0.3371 & 0.7482 & 0.4427 \\ 0.0759 & 0.1622 & 0.4505 & 0.1067 \\ 0.0540 & 0.7943 & 0.0838 & 0.9619 \\ 0.5308 & 0.3112 & 0.2290 & 0.0046 \\ 0.7792 & 0.5285 & 0.9133 & 0.7749 \end{pmatrix}$$

Maximum Power constraint on each subchannel (mw):

$\bar{P} = \left[\begin{array}{cccccccccc} 10, & 10, & 10, & 10, & 10, & 10, & 10, & 10, & 10, & 10 \end{array}\right]$

Rate requirement of the users (kbps):

$\bar{R} = \left[\begin{array}{cccc} 100, & 60, & 20, & 400 \end{array}\right]$

Subchannel Allocations: $A_{heuristic}$ and A_{opt} by the heuristic and the optimal algorithms are $(CA(i) \triangleq j$ if $A_{i,j} = 1)$

$CA_{HSA} = \left[\begin{array}{cccccccccc} 1 & 3 & 4 & 2 & 0 & 0 & 0 & 0 & 0 & 0 \end{array}\right]$

$CA_{OPT} = \left[\begin{array}{cccccccccc} 1 & 1 & 4 & 3 & 3 & 2 & 3 & 2 & 1 & 1 \end{array}\right]$

The corresponding rates obtained by different users are provided in Table 1.

Table1: Rates obtained by users via *OP* and *HSA*

User	$\bar{R}$	R_{HSA}	R_{OPT}
1	100	301.6	802.7
2	60	235.5	641.5
3	20	131.0	1101.1
4	400	445.6	445.6

We observe that each user gets more rate than needed in both the HSA and the optimal solution. With the given allocation of channels we minimize the power to satisfy the requirements of the users (*Step 2*). The minimal powers needed for each solution are (in mw) :

$P_{HSA} = \left[\begin{array}{cccccccccc} 2.1, & 1.2, & 8.0, & 1.0, & 0, & 0, & 0, & 0, & 0, & 0 \end{array}\right],$
$P_{OPT} = \left[\begin{array}{cccccccccc} 2.1, & 0, & 8.0, & 0, & 0.1, & 0, & 0 & 0.7, & 0, & 0 \end{array}\right],$
hence $P_{HSA-TOTAL} = 13.1$ and $P_{OPT-TOTAL} = 11$.

We see that the total optimal power needed by the heuristic algorithm and the optimal algorithm are quite close. However the time taken for running the two subchannel allocation algorithms (on our computer) are :optimal = $0.390s$, heuristic $< 0.001s$.

B. Subchannel allocation algorithm-non feasible solution case (HSA,HFSA,OFP):

We take M, N, I and G matrices as above.
Maximum Power constraint on each subchannel (in mw) : $\bar{P} = \begin{bmatrix} 2.1, & 1.2, & 8.0, & 1.8, & 2.0, & 1.5, & 7.0, & 3.3, & 4.5, & 7.7 \end{bmatrix}$
Rate requirement of the users (in kbps):
$\bar{R} = \begin{bmatrix} 650, & 600, & 60, & 75 \end{bmatrix}$

Now it is not possible to satisfy the requirements of all the users. The optimal algorithm OP does not provide any solution. The heuristic algorithm HSA provides the rates given in Table2. We see that some users get the rates more than they need but the others less than their requirements. Thus, next we employ the fair algorithm *HFSA* and *OFP*. These provide the rates given in Table 2. The channel allocations by *HSA*, *HFSA* and *OFP* are

$$CA_{HSA} = \begin{bmatrix} 1 & 1 & 4 & 3 & 1 & 2 & 2 & 2 & 1 & 1 \end{bmatrix}$$
$$CA_{HFSA} = \begin{bmatrix} 1 & 2 & 1 & 4 & 3 & 2 & 2 & 2 & 2 & 1 \end{bmatrix}$$
$$CA_{OFP} = \begin{bmatrix} 1 & 1 & 4 & 2 & 1 & 2 & 3 & 2 & 2 & 1 \end{bmatrix}$$

Table2: Rates obtained via *HSA, HFSA, OFP*

User	$\bar{R}$	R_{HSA}	R_{HFSA}	R_{OFP}
1	650	486.54	415.01	411.96
2	600	297.33	368.97	382.53
3	60	179.71	200.96	84.68
4	75	399.07	155.86	399.07

The α_{max} obtained by *HFSA* is 0.6150 and α_{max} obtained by *OFP* is 0.6650.

C. Subchannel allocation algorithm by giving priority to voice users-non feasible solution case (HSA,HFSA,HFSVD):

We take M, N, I, G matrices as above.
Maximum Power constraint on each subchannel (in mw): $\overline{P} = \begin{bmatrix} 1, & 1, & 0.1, & 0.1, & 1.0, & 1.0, & 0.1, & 1, & 1, & 1 \end{bmatrix}$
Rate requirement of the users (in kbps) :
$\bar{R} = \begin{bmatrix} 350, & 200, & 25, & 30 \end{bmatrix}$

Users 3 and 4 are voice users while users 1 and 2 are data users. Now, it is not possible to satisfy the rate requirements of all the users. The optimal algorithm does not provide any solution. The heuristic algorithm *HSA* and Optimal fair algorithm *OFP* provide the rates given in Table 3. After giving priority to voice users, the Heuristic *HFSVD* and Optimal algorithms *OFSVD* provide the rates given in Table 4.
subchannel allocation:

$$CA_{HSA} = \begin{bmatrix} 1 & 1 & 4 & 3 & 3 & 2 & 4 & 2 & 1 & 1 \end{bmatrix}$$
$$CA_{HFSA} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 4 & 1 & 2 & 2 & 2 \end{bmatrix}$$
$$CA_{OFP} = \begin{bmatrix} 1 & 4 & 4 & 3 & 1 & 2 & 3 & 2 & 1 & 1 \end{bmatrix}$$

Channel assignments via *HFSVD, OFVD* are:

$$CA_{HFSVD} = \begin{bmatrix} 1 & 1 & 1 & 4 & 1 & 4 & 4 & 2 & 3 & 3 \end{bmatrix}$$
$$CA_{OFVD} = \begin{bmatrix} 1 & 4 & 4 & 3 & 1 & 2 & 3 & 2 & 1 & 1 \end{bmatrix}$$

Table3: Rates obtained by users via *HSA, HFSA, OFP*

User	$\bar{R}$	R_{HSA}	R_{HFSA}	R_{OFP}
1	350	119.14	152.34	169.36
2	200	118.02	95.83	118.02
3	25	133.46	18.78	15.44
4	30	12.45	26.14	27.37

Table4: Rates obtained by users via *HFSVD* and *OFVD*

User	$\bar{R}$	R_{HFSVD}	R_{OFSVD}
1	350	149.15	151.31
2	200	80.68	95.83
3	25	25.95	30.50
4	30	38.61	37.73

The α obtained by *HFSVD* is 0.4034 and α_{max} obtained by *OFSVD* is 0.4323. Thus we observe that both *HFSVD* and *OFSVD* satisfy the voice users and provide fair allocation to the data users. The performance of *HFSVD* is close to that of the optimal.

We have also ran the above algorithms for other examples, in particular for 10 users and 50 subchannels and obtained similar results.

V. CONCLUSIONS

We have considered the problem of providing QoS for the MSs within a FC when the channel states and interference are known. The users may be transmitting data or voice. We have developed efficient, fair, low complexity algorithms for channel allocation and power control that can be used online. Their performance is close to optimal solutions.

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