Maintaining Utility Fairness Using Weighting Factors in Wireless Networks

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***Abstract*—Maintaining fairness using weighting factors is a common approach in resource allocation. However, computing weighting factors for multiservice wireless networks is not trivial because users' rate requirements are heterogeneous and their channel gains are variable. In this paper, we propose weighting factor computation and scheduling schemes for orthogonal frequency division multiple access (OFDMA) networks. The weighting factor computation scheme determines each user's share of rate for maintaining a utility notion of fairness. We then present a scheduling scheme which takes the users' weighting factors into consideration to allocate sub-carriers and power in OFDMA networks. The simulation results demonstrate that the proposed scheduling scheme outperforms an opportunistic scheme in terms of fairness performance in different scenarios, where the users are fixed or mobile.**

I. INTRODUCTION

Opportunistic scheduling, which allocates resources to users with the best channel quality in each scheduling interval, can achieve optimal throughput for wireless networks with fading channels [1]. Despite throughput and channel utilization enhancement, severe unfairness occurs by opportunistic scheduling schemes when users' average channel gains differ dramatically. A variant of opportunistic scheduling that maintains a level of fairness, namely, opportunistic fair scheduling, is needed in practical networks.

As wireless channel is highly dynamic, short-term fairness provisioning is not efficient in terms of spectrum utilization. Thus, long term fairness, i.e., balancing resource utilization among users over a period of time, is usually preferred [2]–[4]. A well known example is the proportional fair scheduling scheme, proposed for the high data rate packet scheduling in $CDMA2000\ 1x$ evolution [5], that maintains fairness among long-term averages of users' rates. Proportional fair scheduling is effective for fairness provisioning in networks with a single type of service, such as, data service. In multiservice networks, in which users' requirements are different, using weighting factors, which represent the fair share of available resources associated to each user over a long time, is usually adopted.

Some of the existing works, e.g., [6]–[8], have addressed the issue of fairness provisioning assuming that the weighting factors are determined by service providers. Temporal fairness and "utilitarian" fairness approaches are proposed in [6]. The temporal fairness approach allocates a certain portion of service time to each user in long term, and the "utilitarian" fairness approach allocates a portion of the overall average throughput to each user. The portion of time or overall average throughput that should be allocated to a user is assumed to be predefined in this work. Enforcing fairness through weighting factors for OFDMA networks is proposed in [8]. However, computation of the weighting factors has not been specified. Majority of the existing works mainly focus on proposing low complexity schemes for resource allocation rather than providing an approach for computing weighting factors.

In this paper, we propose a solution to compute weighting factors according to users' traffic types. The proposed solution associates the values of weighting factors with utility functions of users and their average channel quality. The perceptual utilities which represent users satisfaction of received rate is used. Therefore, the weighting factors indicate the application level rate requirement of users and their long term fair share of transmission rate, which is a function of spectrum and power resources. The weighting factors are then used for fair scheduling in the downlink of an OFDMA wireless network. The proposed scheduling scheme intends to maintain fair allocation of sub-carriers and transmission power in long term according to the weighting factors. We use appropriate algorithms to solve the associated optimization problems representing each part and perform simulations to demonstrate effectiveness of the weighting factors in maintaining fairness and the ability of the proposed scheduling scheme in achieving multi-user diversity gain.

The remainder of the paper is organized as follows. In subsection II, the problem of utility-fair weight computation is formulated and solved. The proposed scheduler for OFDMA and the corresponding optimization problem and solution are presented in section III. Numerical results are presented in section IV, and concluding remarks are given in section V.

II. WEIGHTING FACTOR COMPUTATION SCHEME

The simplest form of fairness can be considered as equal rate allocation. However, when users have diverse service requirements and channels characteristics, equal rate allocation causes poor resource utilization for network operators. For example, a user with voice service requirement needs less rate than a user with video service requirement to be satisfied. An equal rate allocation to these users may cause excessive rate allocation to the first user and starvation of the second user.

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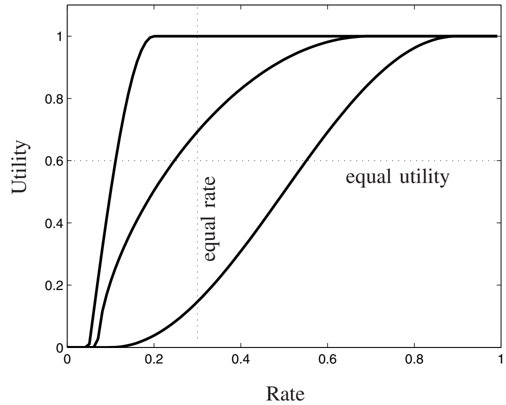

Fig. 1. Comparison between equal rate and equal utility allocation

Table I
LIST OF SYMBOLS

Symbol	Description
M	number of users in the network
K	number of OFDMA sub-carriers
N	number of OFDMA symbols in the down-link interval
i	user index belongs to $\mathcal{M} := \{1, 2, ..., M\}$
j	sub-carrier index belongs to $\mathcal{K} := \{1, 2, ..., K\}$
n	symbol index belongs to $\mathcal{N} := \{1, 2, ..., N\}$
R_i	average transmitted rate to user i
W_i	fair weight of user i
P_{BS}	BS total power budget
α_{ijn}	channel gain of user i on sub-carrier j of OFDMA symbol n
p_{ijn}	required power by user i on sub-carrier j of OFDMA symbol n to transmit r_{ijn}
r_{ijn}	achievable rate by user i on sub-carrier j of OFDMA symbol n

This fact can be further explained by Fig. 1, which depicts the utilities of three different applications. The vertical dashed line labeled "equal rate" illustrates that equal rate allocation does not provide equal user satisfaction. On the other hand, equal allocation of utilities, which is shown by the horizontal dashed line, labled by "equal utility", utilizes the network resource more efficiently. Therefore, utility fairness instead of rate fairness has been proposed for multiservice networks [3], [9].

The notion of utility fairness used in this paper is utility proportional fairness where the allocated resources are proportional to users' demands and channel gain averages. Utility proportional fairness is defined as follows:

Definition 2.1: A set of utilities $U = \{U_1, U_2, \ldots, U_M\}$ is *utility proportional fair* if for any feasible utility set $\hat{U} = \left\{\hat{U}_1, \hat{U}_2, \ldots, \hat{U}_M\right\}$, the sum of proportional changes in their utilities is non-positive:

$$\sum_{i=1}^{M} \frac{\hat{U}_i - U_i}{U_i} \leq 0. \tag{1}$$

Consider $\mathcal{U} = \{u_k | u_k = \{u_{k1}, u_{k2}, \ldots, u_{kM}\}\}$, a bounded set of M users' feasible utility subset u_k, where u_{ki} is the utility of user i. A straightforward way to obtain a proportional fair allocation $u_k \in \mathcal{U}$ is to find a set of u_{ki}'s that maximizes $\sum_i \log(u_{ki})$ over the convex set of feasible allocations $\mathcal{U}$ [10], [11]. u_{ki} is a function of r_i, consequently, corresponding to a proportional fair allocation u_k, there is a set of allocated rates to users denoted as $\overline{r_i}$. We suggest a set of weighting factors W_i based on the utility proportional fair rates $\overline{r_i}$:

$$W_i = \frac{\overline{r_i}}{\sum_{i=1}^{M} \overline{r_i}}. \tag{2}$$

Now, if the resources are allocated to users such that in a long duration of time the set of aggregate transmitted rates to users, $\widehat{R_i}$, is proportional to the set of weigthing factors, W_i, i.e.,

$$\frac{\widehat{R_1}}{W_1} = \frac{\widehat{R_2}}{W_2} = \cdots = \frac{\widehat{R_M}}{W_M}, \tag{3}$$

the allocation will be utility proportional fair.

A. Formulation of Weighting Factor Computation Problem

For ease of reading, Table I tabulates symbols representing various network parameters used in the rest of the paper. The set of utility proportional rates $\overline{r_i}$ is the solution of the optimization problem that maximizes the aggregate logarithms of utility functions of users, $\sum_i \log(U_i)$, subject to the network resource limits. Consider an OFDMA multi-carrier network where a base station (BS) allocates its power, P_{BS}, to users. We obtain a utility proportional fair rate allocation $\overline{r_{ij}}$ by solving the optimization problem P_1:

$$P_1: \quad \max_{\overline{r_{ij}}} \sum_i \log(U_i(\overline{r_{ij}})) \tag{4}$$

$$\text{s.t} \quad \sum_{i=1}^{M}\sum_{j=1}^{K} \frac{2^{\overline{r_{ij}}} - 1}{\overline{a_{ij}}} \leq P_{BS}, \tag{5}$$

$$\overline{r_{ij}} \geq 0 \quad \forall i \in \mathcal{M}, \quad \forall j \in \mathcal{K}, \tag{6}$$

where $\overline{r_{ij}}$ is allocated rate to user i on sub-carrier j for the average channel gain $\overline{a_{ij}}$. Constraint (5) poses the BS power limit. As we attempt to find a long term fair allocation of resources, average CSI (over multiple frames) is used in the problem, and we assume perfect CSI is available in the BS. In practical networks, CSI is inaccurately received at the BS, and our scheme proposed in [12] accounts for estimation of CSI and delay errors which provides better estimation of CSI for resource allocation.

Problem P_1 is a non-linear programming (NLP) optimization problem. When users' utilities are convex functions, P_1 can be solved by traditional solver packages for NLP problems, such as the NLP problem solver of MATLAB, *fmincon* function. However, when utilities are non-convex, solving P_1 is challenging. We have investigated the non-convex case and proposed an approach for the problem in [13].

Problem P_1 is required to be solved only when the network characteristics, e.g., users' average channel gain or the number of admitted users to the network, change. The scheduling

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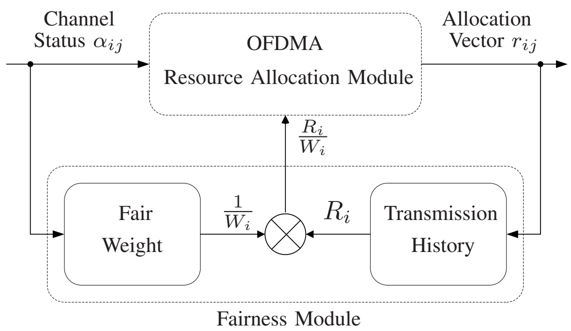

Fig. 2. Architecture of proposed scheduler

scheme starts with a set of default weighting factors, e.g., all equal to one, and updates the weighting factors with the ones obtained by solving P_1 during the first iterations of the scheduling scheme.

III. Fair Scheduling Scheme

We propose a fair scheduling scheme for a network consisting of a BS and multiple users located in one hop neighborhood from the BS. Users' backlogged traffic, buffered in separate queues at the BS, is scheduled at the beginning of each down-link interval consisting of N OFDMA symbols.

The proposed scheduler contains a fairness module and an OFDMA resource allocation module. The fairness module computes the weighting factors, as described in section II, and measures the average transmission rate to each user for the operation of the OFDMA resource allocation module as shown in Fig. 2. The OFDMA resource allocation module assigns sub-carriers to users and allocates the BS power to sub-carriers at each scheduling instance.

To satisfy the set of equations (3) in a long time, the scheduler attempts to allocate resources to users that have lower $\frac{R_i}{W_i}$, where R_i is the average transmitted rate to user i. R_i is updated at the beginning of each scheduling interval n by an exponentially weighted moving average (EWMA) technique:

$$R_i(n) = (1 - \frac{1}{T_c})R_i(n-1) + (\frac{1}{T_c})r_i(n-1), \tag{7}$$

where r_i is the transmitted rate to user i in the last scheduling interval, and T_c is a constant that determines smoothness of exponential decrease. EWMA puts more emphasis on recent data and less emphasis on older data, so the fairness scheme compensates for unfairness of recent allocations as soon as possible.

A. OFDMA Resource Allocation Problem

The OFDMA resource allocation is an optimization problem whose objective function represents the scheduler objectives, and its constraints are determined based on OFDMA network specifications.

Without loss of generality, we assume that noise spectral density and sub-carriers bandwidth equal one. Then, allocated rate to user i on sub-carrier j of OFDMA symbol n, r_{ijn}, is

$$r_{ijn} = \log_2(1 + \alpha_{ijn} p_{ijn}). \tag{8}$$

Total allocated power to the sub-carriers of each OFDMA symbol is limited by P_{BS}, i.e.,

$$\sum_{i=1}^{M}\sum_{j=1}^{K} p_{ijn} \le P_{BS} \quad \forall n \in \mathcal{N}. \tag{9}$$

Implementation of OFDMA requires exclusive allocation of a sub-carrier to a single user. This constraint is mathematically represented by

$$r_{\hat{i}jn} \cdot r_{ijn} = 0 \quad \forall \hat{i} \in \mathcal{M}, i \ne \hat{i}, \ \forall j \in \mathcal{K}, \ \forall n \in \mathcal{N}. \tag{10}$$

Constraint (10) implies that if sub-carrier j is assigned to user $\hat{i}$, i.e., $r_{\hat{i}jn} \ne 0$, allocated rate to every other user on sub-carrier j of OFDMA symbol n must be zero.

To balance the achievable transmission rate and fairness, the opportunistic fair scheduler allocates sub-carrier j of OFDMA symbol n to user i that has the maximum $r_{ijn}/(R_i/W_i)$. The probability of assigning sub-carrier j to user i is higher when the achievable transmission rate of user i on sub-carrier j is high or average transmitted rate to user i is smaller than its fair weight. The objective can mathematically be written as

$$\max \sum_{n=1}^{N}\sum_{j=1}^{K}\sum_{i=1}^{M}\left(\frac{r_{ijn}}{\frac{R_i}{W_i}}\right). \tag{11}$$

The objective function (11) along with constraints (8), (9), (10) form the mathematical optimization problem P_2:

$$P_2: \quad \max_{r_{ijn}} \quad \sum_{n=1}^{N}\sum_{j=1}^{K}\sum_{i=1}^{M}\left(\frac{r_{ijn}}{\frac{R_i}{W_i}}\right) \tag{12}$$

$$\text{s.t} \quad \sum_{i=1}^{M}\sum_{j=1}^{K}\frac{2^{r_{ijn}}-1}{\alpha_{ijn}} \le P_{BS} \qquad \forall n, \tag{13}$$

$$r_{\hat{i}jn} \cdot r_{ijn} = 0 \quad \forall \hat{i}, \ i, \ j, \ n \ \& \ i \ne \hat{i}, \tag{14}$$

$$r_{ijn} \ge 0 \qquad \forall i, \ j, \ n. \tag{15}$$

The optimal solution of P_2 offers allocated rate to users on all sub-carriers for each OFDMA symbol in a scheduling interval that achieves maximum throughput subject to the fairness criterion defined by (3). In practice, providing CSI of each sub-carrier over all symbols of each scheduling interval results in large overhead on the reverse feedback channel. Besides, because of the correlation among CSI of a sub-carrier over consecutive symbols, it is assumed that CSI of each sub-carrier remains constant for all symbols over a scheduling interval. Accordingly, index n representing symbols of each scheduling interval can be dropped, and P_2 can be simplified to problem

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P_3:

$$P_3: \max_{r_{ij}} \sum_{j=1}^{K}\sum_{i=1}^{M}\left(\frac{r_{ij}}{\frac{R_i}{W_i}}\right) \quad (16)$$

$$\text{s.t} \quad \sum_{i=1}^{M}\sum_{j=1}^{K}\frac{2^{r_{ij}}-1}{\alpha_{ij}} \leq P_{BS}, \quad (17)$$

$$r_{\hat{i}j}\cdot r_{ij} = 0 \qquad \forall \hat{i},\, i,\, j \;\&\; i \neq \hat{i}, \quad (18)$$

$$r_{ij} \geq 0 \qquad \forall i,\, j. \quad (19)$$

B. OFDMA Resource Allocation Problem Solution

Problem P_3 is a non-convex optimization problem and finding its optimal solution is complex [14]. We use a Lagrange dual decomposition method to solve P_3. The method does not guarantee an optimal solution, but it is shown that it can efficiently obtain near optimal solution(s) with a practical number of sub-carriers [15]. The rationale is the duality gap[1] of using Lagrange dual method vanishes when the number of sub-carriers increases. The method is explained in the following.

If $\mu_i = W_i/R_i$, the objective function of P_3 is to maximize $\sum_{i=1}^{M}\left(\mu_i \sum_{j=1}^{K} r_{ij}\right)$. Constraints (18) and (19) form domain $\mathcal{D}$ that Lagrangian of P_3 can be defined over it as

$$\mathcal{L}\left(\{r_{ij}\},\lambda\right) = \sum_{i=1}^{M}\sum_{j=1}^{K}\mu_i r_{ij} - \lambda\left(\frac{2^{r_{ij}}-1}{\alpha_{ij}} - P_{BS}\right), \quad (20)$$

where λ is the Lagrange multiplier. The dual problem of P_3, is expressed as

$$\min_{\lambda}\max_{\{r_{ij}\}\in\mathcal{D}} \mathcal{L}\left(\{r_{ij}\},\lambda\right). \quad (21)$$

The solution of the dual problem gives λ that minimizes the maximum value of $\mathcal{L}$ over domain $\mathcal{D}$ and determines the set of rate allocation to sub-carriers, r_{ij}, that maximizes $\mathcal{L}$. The optimization problem (21) is a minimization problem with one scalar variable λ that can be solved by an iterative algorithm. We use Algorithm 1 to solve the problem. In each iteration of Algorithm 1, the set of r_{ij} that maximizes $\mathcal{L}$ is determined by solving K decomposed problems of rate allocation to sub-carriers. As allocation of sub-carriers to users are independent, the optimization problems (22) are solved in parallel to obtain allocated rate to sub-carriers.

$$\max_{\{r_{ij}\}\in\mathcal{D}} \sum_{i=1}^{M}\mu_i r_{ij} - \lambda\left(\frac{2^{r_{ij}}-1}{\alpha_{ij}}\right) \;\; \forall j = 1\cdots K. \quad (22)$$

The decomposition of (21) into K equations (22) reduces the problem's exponential complexity to a linear one in terms of K [15]. The solution of (22) is obtained by a heuristic search method due to the non-convexity of domain $\mathcal{D}$. The size of $\mathcal{D}$ is confined by the number of modulation levels, users, and sub-carriers, denoted by Q, M, and K, respectively. In each iteration of the $while$ loop in Algorithm 1, a set with QM size is searched for rate allocation to each sub-carrier. If the $while$ loop requires N_{while} iterations to converge, then the set of equations (22) will be solved in $KQMN_{while}$ iterations. Whereas solving the equation (21) with an exhaustive search requires searching over a set of size $(QM)^K$.

[1]the difference between the primal optimal and dual optimal solution

Algorithm 1 Solution algorithm for the dual problem

```
Input: M, K, P_BS, α_ij, μ_i, bit loading set
Result: r_ij
begin
    Setting up and initialization:
    Set h = 1, ε = 1, Exit_flag = 1, λ_{h-1} = λ_h = 0.
    Solve (22) for r_ij.
    Compute Δp = P_BS − p_ij.
    if Δp > 0 then
        return r_ij.
    else
        while Exit_flag > 1e − 5 do
            if Δp > 0 then
                ε = 0.99 ∗ ε.
                λ_h = λ_{h-1}.
                Δp_h = Δp_{h-1}.
            else
                λ_{h-1} = λ_h.
                Δp_{h-1} = Δp_h.
            end
            λ_h = λ_h + |ε ∗ Δp|.
            Solve (22) for r_ij.
            Update Δp.
            Exit_flag = λ_h − λ_{h-1}.
            h = h + 1.
        end
    end
    return r_ij.
end
```

IV. Numerical Results

Performance of the proposed fair scheduling scheme along with the weighting factors are evaluated in this section. Performance metrics are the overall network throughput and fairness index of the proposed scheme which are compared with the ones of a pure opportunistic scheduling scheme. We implement a multi-carrier pure opportunistic scheme where $\frac{R_i}{W_i} = 1$ for $i = 1\cdots M$. The weighting factors of the fair scheduling scheme are obtained by solving problem P_3 with $fmincon$ function of $MATLAB$, assuming $logarithm$ utility function for each user. Users are heterogeneous in terms of their distance from the BS.

The simulation scenario consists of a BS with total power equal to 20 Watts located at the center of the cell with 800m radius. The BS transmits backlogged data in its queues to the users via 64 sub-carriers. We investigate the network performance in two scenarios. In the first scenario, as shown in Fig. 3-a, half of the users are located on a circle with 50 meters radius, and half of them are located on the cell edge at equal angular distance. Users in the first scenario have diverse channel gains, so we investigate the effect of multi-user diversity on throughput and fairness performance of the scheduling schemes using this scenario. In the second

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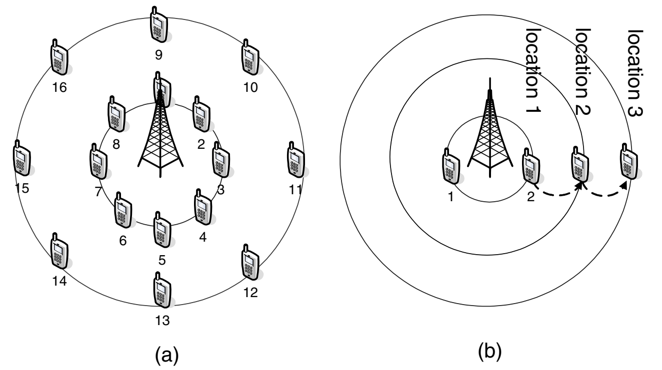

Fig. 3. Simulated scenarios: (a) fixed users (b) mobile users

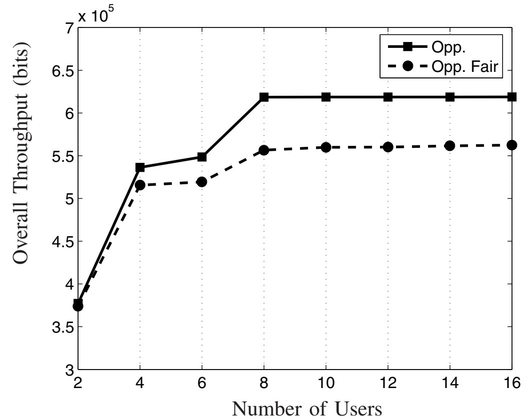

Fig. 4. Overall network throughput of the first scenario

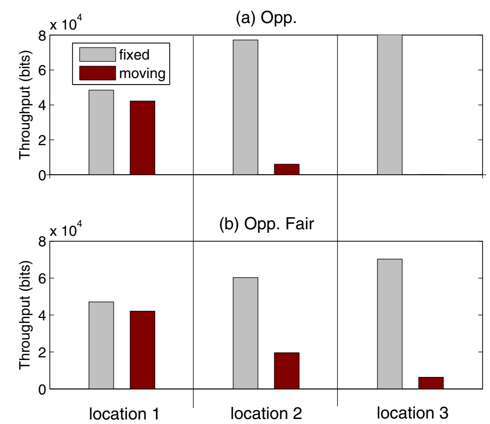

Fig. 5. Fixed and mobile users' total throughput at different locations: (a) opportunistic scheduling, (b) opportunistic fair scheduling

scenario, shown in Fig. 3-b, a fixed user and a mobile user that moves away from the base station are considered. We use the second scenario to show the adaptivity of the opportunistic fair scheduling to the variation of wireless channel.

The wireless channel is simulated to experience both frequency selective and large-scale fading. The users receive six Rayleigh distributed multipath signals. The real and imaginary components of the received signals to different users are generated from an uncorrelated multidimensional Gaussian distribution with zero mean and an identity covariance matrix. Uncorrelated multi-path components lead to uncorrelated user frequency responses in the frequency domain. Thus, full multiuser diversity can be exploited. The large-scale fading is distance dependent and follows the inverse-power law:

$$|\gamma_{ij}|^2 = D_i^{-\kappa}|\alpha_{ij}|, \tag{23}$$

where D_i is the distance between the BS and user i in meters, κ is path loss exponent, and γ_{ij} is path loss of user i on sub-carrier j. The numerical values of the wireless channel used in the simulation are: Doppler frequency= 30 Hz, and $\kappa = 2$.

A. *Overall Throughput*

Fig. 4 shows overall throughput versus the number of users for the opportunistic and opportunistic fair scheduling schemes in the first scenario. As the opportunistic scheme assigns a sub-carrier to a user that has the highest channel gain on that sub-carrier, its throughput is the upper bound. The opportunistic fair scheduling achieves lower throughput than the opportunistic one because in some scheduling intervals it assigns a sub-carrier to a user that lacked service for a long time. Both scheduling schemes gain from multi-user diversity as more users join the inner circle, i.e., when the number of users increases from 2 to 8 in Fig. 4. Users 9 to 16 are far from the BS and their channel gains are always much lower than the users located on inner circle, so they do not increase multi-user diversity gain.

Using the second scenario, we investigate the adaptivity of the opportunistic fair scheduling in capturing the network status variations. At the beginning, users 1 and 2 are located close to the BS with the same distance. Then, user 2 moves away from the BS toward the edge of the cell. Fig. 5 shows the users' total throughput at three positions when the scheduling schemes are opportunistic, Fig. 5-a, and opportunistic fair, Fig. 5-b. As user 2 moves away from the BS and its channel gain drops, the opportunistic scheduling allocates less rate to it and finally ignores it when it is very far. On the other hand, the opportunistic fair scheduling scheme, while trying to allocate proportional rates to the weigthing factors, allocates more rate to user 2 than the one with opportunistic allocation.

B. *Fairness*

To compare the performance in terms of fairness, we quantify the fairness first. We use Gini fairness index which is an inequality measure of resource sharing that measures deviation from equations (3) for each scheduler. Consider total allocated rate to user i over the simulated intervals is $\tilde{R}_i$. We examine the inequality among the set of proportions $z = \{z_i \mid z_i = \tilde{R}_i/W_i\}$ by Gini fairness index, I, defined as

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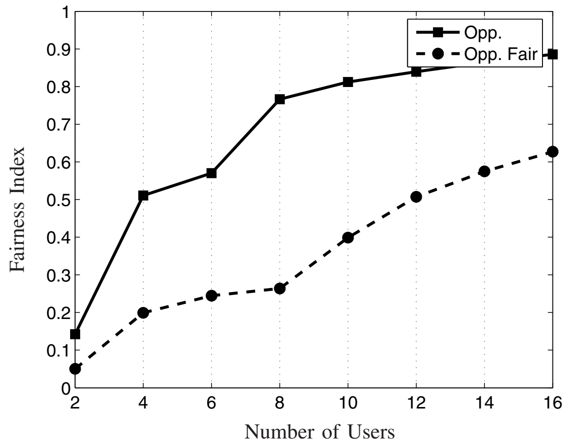

Fig. 6. Fairness index of the first scenario

Table II
FAIRNESS INDEX OF THE SCHEDULING SCHEMES

Scheduling Scheme	Location 1	Location 2	Location 3
Opportunistic	0.029	0.390	0.495
Opportunistic Fair	0.023	0.162	0.294

follows:

$$I = \frac{1}{2M^2\bar{z}} \sum_{x=1}^{M}\sum_{y=1}^{M} |z_x - z_y|, \tag{24}$$

where $\bar{z} = \frac{\sum_{i=1}^{M} z_i}{M}$. The Gini fairness index varies between 0 and 1. A rate allocation is perfectly fair if $I = 0$. The higher value of I indicates higher unfairness among the proportions.

Fig. 6 shows the Gini fairness index of the first scenario. The fairness index of opportunistic and opportunistic fair increases as the number of users increases. Increasing user diversity has an adverse effect on fairness. However, this effect is moderated in the opportunistic fair scheduling especially when the user diversity is low, when users 1 to 8 are considered.

Table II gives the Gini fairness index of the opportunistic and opportunistic fair scheduling in the second scenario. When both users are close to the BS and their channels are almost similar, unfairness of opportunistic scheduling is not observed. However, as user 2 moves and its channel condition degrades, the opportunistic fair scheme treats it more fairly than the opportunistic scheme, so the fairness index of the opportunistic scheme increases more when user 2 is at locations 2 and 3.

V. CONCLUSIONS

We have proposed a weighting factor computation scheme, to maintain resource fairness, in multichannel and multiservice wireless networks. The proposed scheme considers users' heterogeneous quality of service requirements (in terms of rate) and average channel gains. The fair weights can be modified or adapted dynamically when the network parameters change due to mobility of users, admitting a new user, or changing the fairness policy of the service provider, e.g., adopting max-min instead of proportional fairness. We have also proposed a fair scheduling scheme, based on the weighting factors, that takes sub-carriers channel gain and fairness requirements into consideration to assign sub-carriers to users and allocate rate to each sub-carrier. Separating the tasks of the fairness and the OFDMA resource allocation schemes in the proposed scheduler reduces the complexity of scheduling process.

In our future work, we intend to analytically determine the appropriate time intervals for updating the weighting factors based on channel information.

REFERENCES

[1] R. Knopp and P. A. Humblet, "Information Capacity and Power Control in Single Cell Multiuser Communications," in *Proc. IEEE International Conference on Communications (ICC)*, 1995, pp. 331–335.

[2] M. Mehrjoo, M. Dianati, X. Shen, and K. Naik, "Opportunistic Fair Scheduling for the Downlink of IEEE 802.16 Wireless Metropolitan Area Networks," in *QShine '06: Proceedings of the 3rd international conference on Quality of service in heterogeneous wired/wireless networks*, 2006, pp. 52–60.

[3] M. Dianati, X. Shen, and K. Naik, "Coperative Fair Scheduling for the Downlink of CDMA Cellular Networks," *IEEE Trans. Veh. Technol.*, vol. 56, no. 4, pp. 1749–1760, 2007.

[4] M. Dianati, X. Shen, and S. Naik, "A New Fairness Index for Radio Resource Allocation in Wireless Networks," in *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, vol. 2, 2005, pp. 712–717.

[5] A. Jalali and R. Padovani, "Data Throughput of CDMA-HDR a High Efficiency-High Data Rate Personal Communication Wireless System," in *Proc. IEEE Vehicular Technology Conference (VTC)*, 2000.

[6] Z. Zhang, Y. He, and E. K. P. Chong, "Opportunistic Scheduling for OFDM Systems with Fairness Constraints," *EURASIP Journal on Wireless Communications and Networking*, pp. 275–277, 2008.

[7] A. Wang, L. Xiao, S. Zhou, X. Xu, and Y. Yao, "Dynamic resource management in the fourth generation wireless systems," in *Proc. International Conference on Communication Technology (ICCT)*.

[8] I. C. Wong and B. L. Evans, "Optimal Downlink OFDMA Resource Allocation With Linear Complexity to Maximize Ergodic Rates," *IEEE Trans. Wireless Commun.*, vol. 7, no. 3, pp. 962–971, 2008.

[9] T. Harks, "Utility Proportional Fair Bandwidth Allocation: An Optimization Oriented Approach," in *In Proc. of 3 rd International Workshop on QoS in Multiservice IP Networks (QoS-IP)*. Springer.

[10] F. Kelly, "Charging and rate control for elastic traffic," *European Transactions on Telecommunications*, vol. 8, pp. 33–37, 1997.

[11] J.-Y. Boudec, "Rate adaptation, Congestion Control and Fairness: A Tutorial."

[12] M. Awad, V. Mahinthan, M. Mehrjoo, X. Shen, and J. Mark, "Downlink Resource Allocation for OFDMA-based Multiservice Networks with Imperfect CSI," in *Proc. IEEE International Conference on Communications (ICC)*, 2009.

[13] M. Mehrjoo, S. Moazeni, and X. Shen, "An Interior Point Penalty Method for Utility Maximization Problems in OFDMA Networks," in *Proc. IEEE International Conference on Communications (ICC)*, 2009.

[14] M. Mehrjoo, S. Moazeni, and X. Shen, "A New Modeling Approach for Utility-Based Resource Allocation in OFDM Networks," in *Proc. IEEE International Conference on Communications (ICC)*, 2008, pp. 337–342.

[15] W. Yu and R. Lui, "Dual Methods for Nonconvex Spectrum Optimization of Multicarrier Systems," *IEEE Trans. Commun.*, vol. 54, no. 7, pp. 1310–1322, 2006.

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