International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:1, No:12, 2007

Downlink Scheduling and Radio Resource Allocation in Adaptive OFDMA Wireless Communication Systems for User-Individual QoS

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***Abstract*—**In this paper, we address the problem of adaptive radio resource allocation (RRA) and packet scheduling in the downlink of a cellular OFDMA system, and propose a downlink multi-carrier proportional fair (MPF) scheduler and its joint with adaptive RRA algorithm to distribute radio resources among multiple users according to their individual QoS requirements. The allocation and scheduling objective is to maximize the total throughput, while at the same time maintaining the fairness among users. The simulation results demonstrate that the methods presented provide for user more explicit fairness relative to RRA algorithm, but the joint scheme achieves the higher sum-rate capacity with flexible parameters setting compared with MPF scheduler.

***Keywords*—**OFDMA, adaptive radio resource allocation, scheduling, QoS.

I. INTRODUCTION

FUTURE wireless and mobile communication systems are expected to offer higher data rates, to support a large number of subscribers and to ensure the fulfillment of quality of service (QoS) requirements, given the limited availability of frequency spectrum and time varying channels. Orthogonal Frequency Division Multiple Access (OFDMA) is a promising candidate because it not only inherits OFDM's immunity to inter-symbol interference and frequency selective fading, but also increases multi-user diversity by acting the channel fading as a channel randomizer [1].

The significant performance gain of OFDMA system, including frequency diversity and multi-user diversity gain can be achieved by using adaptive radio resource allocation (RRA) and scheduling algorithms [2-6]. The objective of RRA is to maximize the sum-rate capacity (i.e. total throughput) of OFDMA downlink by allocating each sub-carrier to the user with the best channel in each fading state, which has been investigated in [2]-[4] under the constraints of the user's bit error rate (BER) and minimum data rate requirements. The scheduling algorithm is intended to provide equal chance to transmit data for all active users. Unfortunately, the RRA algorithm maximizing the total throughput, which is called as K&H algorithm in single carrier system [5], always yields unfairness. Instead, fair scheduling algorithm gives rise to the loss of the total throughput [5].

In multi-user system sharing a time varying channel, a compromise between fairness and high system throughput is the proportional fair (PF) scheduling [7], which is extended to multi-carrier transmission systems by H.Kim and Y.Han [6]. However, the performance of multi-carrier proportional fair (MPF) scheduling algorithm is not evaluated in [6]. In this paper, we modify the MPF scheduler in [6] to assure the user-individual QoS requirements and propose a joint K&H/MPF algorithm which is superior to both K&H and MPF taking into account throughput and fairness simultaneously. It provides for user fairness with explicit QoS guarantees, as well as approaches to the maximum sum-rate capacity achieved by K&H.

The remainder of this paper is organized as follows. We first describe the system model and the assumptions used by us in section II. In section III, the K&H and multi-carrier proportional fair scheduling strategies for OFDMA system are addressed. Then, we propose the joint radio resource allocation and scheduling algorithm, K&H/MPF scheduler, with different QoS provisioning. Section IV shows the simulation results which illustrate the performance improvement of K&H/MPF over K&H and MPF. In section V, a conclusion is remarked.

II. SYSTEM MODEL

Fig. 1 shows the architecture of downlink OFDMA system for transporting multi-user traffic over time varying fading channels. A cellular wireless network is assumed, but a single cell is considered, where the interference from other cells is modeled as background noise.

In order to overcome frequency selective fading causing inter-symbol interference, the bandwidth of each sub-carrier is

Manuscript received December 9, 2005. This work was supported by the Innovation Fund for Outstanding Scholar of He'nan Province (No. 04210000100), the National Science Foundation of China (No.60472070) and the Key Project of Chinese Ministry of Education (No.105035)

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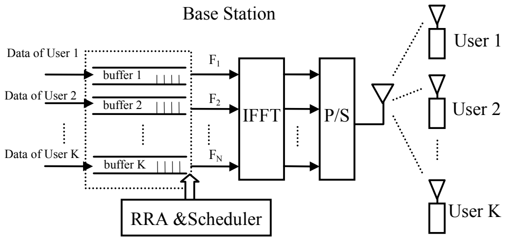

Fig. 1 Multi-user OFDMA downlink architecture

chosen to be sufficiently smaller than the coherence bandwidth of the channel, so it is reasonable to assume that base station transmits data over N parallel, independent channels to K mobile user terminals, each of which requires certain QoS guarantees.

Further, we assume that each OFDM sub-carrier n, as perceived by user k, is subject to flat Rayleigh fading, path loss and shadowing with channel gains $\alpha_{k,n}$. The signals suffer from AWGN noise, whose single-sided noise power spectral density level N_0 is considered equal to unity (i.e. N_0=1), for all sub-carriers and is the same for all users. The Base Station (BS) has a perfect knowledge of the Channel State Information (CSI) i.e. $\alpha_{k,n}$, and the channel is slowly variable so that the proposed allocation algorithm convergence within the channel coherence time. In addition, we assume that a fluid model for packet transmission, and the packets destined to different mobile users are put into separate queues as shown in Fig. 1.

Using known CSI, the radio resource allocation module and scheduler in BS assign different sub-carrier to different user, and determine the number of bits/OFDM symbol to be transmitted on every sub-carrier.

Let $c_{k,n}$ denote the numbers of bits assigned to the kth user on the nth sub-carrier in one OFDM symbol, so $c_{k,n}$ must be integer in the set D={0,1,2,…,M}. As no more than one user is allowed in a sub-carrier of an OFDM symbol, it follows that for each n, if $c_{k',n} \neq 0$, $c_{k,n}$=0 for all $k \neq k'$. We define $\rho_{k,n}$ as the indicator of allocating the nth sub-carrier to the kth user. That is, $\rho_{k,n}$=1 when the nth sub-carrier is assigned to the kth user, otherwise $\rho_{k,n}$=0. The required QoS of the kth user is described by its minimum data rate requirement equal to R_k bits per OFDM symbol, target bit error rate BER_k and time delay constraints τ_k in OFDM symbol.

The transmission power allocated to the nth sub-carrier of the kth user is expressed as:

$$P_{k,n} = \frac{g_k\left(c_{k,n}, BER_k\right)}{\alpha_{k,n}^2} \tag{1}$$

Where $g_k(c_{k,n}, BER_k)$ is the required received power with unity channel gain for reliable reception of $c_{k,n}$ bits per symbol, and it depends on the target BER of the kth user. Obviously, $c_{k,n}$ is the function of the target BER_k, the transmit power $P_{k,n}$ and channel gains $\alpha_{k,n}$. That is

$$c_{k,n} = f\left(BER_k, P_{k,n}, \alpha_{k,n}\right) \tag{2}$$

III. Joint K&H/MPF Algorithm

This section is composed of three contents. Section III-A describes the radio resource allocation scheme achieving maximum throughput, which is also referred as K&H algorithm in OFDMA system as in single carrier system. In section III-B, the MPF scheduler is presented to guarantee the QoS requirements of different users. In section III-C, we develop the joint K&H/MPF algorithm which utilizes both multi-user diversity and frequency diversity to achieve maximum capacity gain and fairness among users, by coordinating K&H and MPF.

A. Radio Resource Allocation - K&H

The goal of the K&H allocation algorithm is to find the best assignment of $c_{k,n}$ so that the total system throughput is maximized for given transmitted power constrains.

Mathematically, we can formulate the K&H problem as:

$$\max_{c_{k,n},\rho_{k,n}} \sum_{k=1}^{K}\sum_{n=1}^{N}\rho_{k,n}c_{k,n} \tag{3}$$

Subject to

$$\sum_{k=1}^{K}\sum_{n=1}^{N}P_{k,n} \leq P_{\max} \tag{4}$$

Where P_{max} is the total power constraint, and $\rho_{k,n}$=1 when the nth sub-carrier is assigned to the kth user, otherwise $\rho_{k,n}$=0.

This is a non-linear optimization problems and computationally complex. To reduce the complexity, we convert it into a linear one by equally distributing the transmit power over the sub-carriers, since the benefit of having adaptive power control is marginal if an adaptive rate scheme is already implemented [8,9].

Since the transmit power $P_{k,n}$ is fixed and $\alpha_{k,n}$ is known, if corresponding modulation scheme is used in each sub-carrier depending on the number of bits assigned to it, the $c_{k,n}$ can be pre-calculated with definite target BER_k[10].

Based on the aforementioned analysis, the K&H algorithm can be simplified as selecting the user k^* to transmit data in n^{th} sub-carrier if the user's channel gain $\alpha_{k,n}$ is the best or whose $c_{k,n}$ is the largest. That is

$$k^* = \arg\max_{k\in\{1,\dots,K\}} c_{k,n} \tag{5}$$

From formula (2)-(5), it is shown that the K&H strategy maximizes the total system throughput in the absence of delay or QoS constraints. In reality, there are latency requirements, in which case the average throughputs over the delay time scale is the performance metric of interest. Inevitably, the K&H algorithm produces unfairness when some users' channel is much stronger than the others on the average, which may be starved.

B. MPF Scheduling with QoS Provisioning

In this section, a proportional fair scheduler for OFDMA system, MPF, is proposed, which is an extension of single-carrier PF algorithm. Its key features are that it can accommodate multiple QoS classes and has a tunable fairness level.

We assume that each user k belongs to a QoS class with parameters R_k, BER_k and τ_k, which is the target rate in bits/OFDM symbol, target bit error rate and averaging window time in OFDM symbols respectively. The averaging window time reflects the target delay of the QoS-class.

The basic definition of MPF is that in each OFDM symbol the n^{th} sub-carrier picks the user k^* to transmit data.

$$k^* = \arg \max_{k\in\{1,\dots,K\}} \frac{c_{k,n}}{\overline{R}_k / R_k} \tag{6}$$

where $c_{k,n}$ is the numbers of bits of the user k can support on the nth sub-carrier under current OFDM symbol, and $\overline{R}_k$ is the average achieved rate defined as the average data rate effectively received by user k, whose unit is bits/OFDM symbol. It is necessary that $\overline{R}_k$ are normalized by their respective target data rate R_k due to different QoS requirements of each user. All $\overline{R}_k$ are updated at each OFDM symbol, according to the following rule:

$$\overline{R}_k = \left(1 - \frac{1}{\tau_k}\right)\overline{R}_k + \frac{1}{\tau_k} r_k \qquad \forall k \in \{1,\dots,K\} \tag{7}$$

where r_k is the total numbers of bits transmitted by user k in current OFDM symbol.

$$r_k = \sum_{n=1}^{N} \rho_{k,n} c_{k,n} \qquad \forall k \in \{1,\dots,K\} \tag{8}$$

where $\rho_{k,n}$=1 when the nth sub-carrier is assigned to the kth user, otherwise $\rho_{k,n}$=0.

From formula (6)-(8), we observe that MPF scheduler can implement satisfactory fairness among users and takes into account individual QoS requirements of each user, but the total throughput is discounted compared with K&H algorithm when users' average SNR are quite different. To squeeze out more capacity in this case, a possible solution is to design a joint K&H/MPF scheduler, which attempts to provide more frequency diversity gain and multi-user diversity gain.

C. K&H/MPF Strategy

The key idea designing K&H/MPF algorithm is that a capacity gain approaching to maximum throughput can be achieved and fairness among users can be ensured simultaneously, if radio resource allocation cooperates with packet scheduling.

The algorithm is developed as follows: First, the sub-carriers are allocated to maximize the throughput (3) without considering the target rates and time delay constraints. This yields an optimum solution corresponding to K&H allocation. Afterwards, the sub-carrier allocation is adjusted by MPF scheduler to satisfy the target rates and delay constraints. By doing so, fairness among users is fulfilled. In the following, the algorithm is described in detail.

1) Work out the $c_{k,n}$ according to the current channel information and target BER requirements in given OFDM symbol assuming the assigned power to each sub-carrier is equal.

$$c_{k,n} = f\left(BER_k, P_{k,n}, \alpha_{k,n}\right)$$

2) Allocate the sub-carriers for each user according to formula (5). That is selecting the user k^* to transmit data in each sub-carrier.

$$k^* = \arg \max_{k\in\{1,\dots,K\}} c_{k,n}$$

When the nth sub-carrier is assigned to the kth user, $\rho_{k,n}$=1, otherwise $\rho_{k,n}$=0. This is K&H allocation which achieves the maximum throughput defined by formula (3).

3) Determine all r_k using formula (8), which is the total numbers of bits transmitted by each user in current OFDM symbol.

$$r_k = \sum_{n=1}^{N} \rho_{k,n} c_{k,n} \qquad \forall k \in \{1,\dots,K\}$$

4) Update the average data rate of user k one by one.

$$\overline{R}_k = \left(1 - \frac{1}{\tau_k}\right)\overline{R}_k + \frac{1}{\tau_k} r_k \qquad \forall k \in \{1,\dots,K\}$$

5) Examine whether R_k, the target data rate of each user, has been approached by average rate $\overline{R}_k$. For user k, if $\left|\overline{R}_k - R_k\right| / R_k \le \delta$, we consider the user's rate requirement has been guaranteed; if $\left(\overline{R}_k - R_k\right) / R_k > \delta$, it indicates the user's average data rate is so high that the sub-carriers belonging to them need to be reallocated to the users whose $\left(R_k - \overline{R}_k\right) / R_k > \delta$, i.e. whose target rate constraints have not been satisfied yet. δ is an adjustable parameter, which affects the number of reallocation operations. For convenience, we denoted the users whose $\left|\overline{R}_k - R_k\right| / R_k > \delta$ as k', and the sub-carrier owned by the users whose $\left(\overline{R}_k - R_k\right) / R_k > \delta$ as n'.

6) Reallocate the sub-carriers marked as n' among the users marked as k' employing MPF scheduler. That is selecting the user k^* to transmit data for each sub-carrier n'.

$$k^* = \arg \max_{k\in\{1,\dots,K\}} \frac{c_{k,n}}{\overline{R}_k / R_k}$$

In this step, $\overline{R}_k$ is initial value at the beginning of the current OFDM symbol, not the ones figured out by step 4).

7) Modify r_k and $\overline{R}_k$ according to step 3) and step 4) for all users denoted as k', respectively.

The K&H/MPF algorithm is carried out on an OFDM symbol by symbol, until all QoS constrains are satisfied.

IV. SIMULATION RESULTS

To evaluate the performance of K&H, MPF and K&H/MPF algorithms, we have conducted simulations using system and channel model described in section II. We consider a cell which radius is 500m, and the users are distributed within the cell independently and uniformly. The path loss is considered as a zero-mean Gaussian variable in the logarithmic scale responsible for shadowing with a standard deviation 8dB, and the path loss exponent is 4. Furthermore, we assume that the QoS requirements of all users are identical, and the target rate and target bit error rate are equal to 64bits/OFDM symbol and 1.0e-4, respectively. The averaging window time τ_k is marked as τ for all users, which is a variable parameter.

In the simulation, an OFDMA downlink system with 128 sub-carriers is considered. The velocity of users is very slowly so the impact of the Doppler frequency shift is negligible.

Fig. 2 and Fig. 3 respectively show the total throughput achieved by different algorithms versus the number of users and average received SNR in dB, with $\tau=2$ and $\delta=0.1$. In Fig. 2, the average transmitted SNR in base station (BS) is set to 12 dB. From Fig. 2 and Fig. 3, it is demonstrated that the total capacity gain implemented by K&H/MPF algorithm is obvious compared with MPF, but it is always under the K&H allocation.

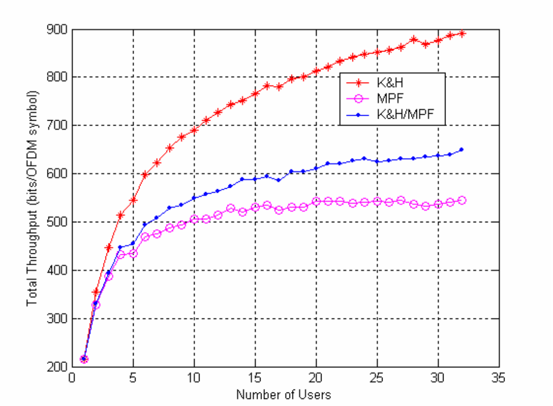

Fig. 2 Total throughput achieved by different algorithms versus the number of users with $\tau=2$ and $\delta=0.1$

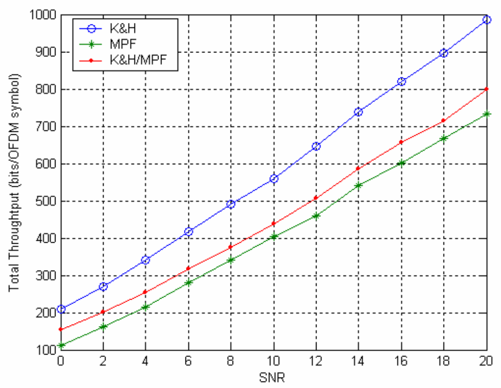

Fig. 3 Total throughput achieved by different algorithms versus the average transmitted SNR in a ten-user system, with $\tau=2$ and $\delta=0.1$

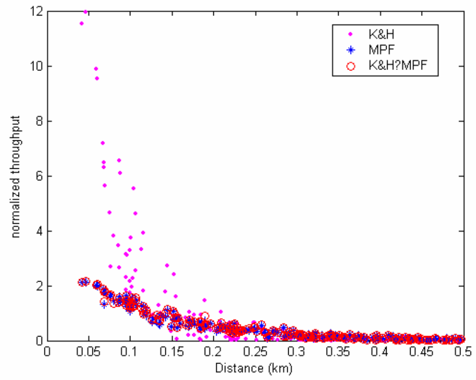

Fig. 4 Fairness achieved by different algorithms with average transmitted SNR equal to 16dB

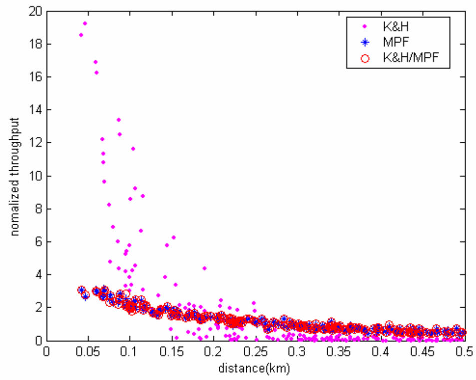

Fig. 5 Fairness achieved by different algorithms with average transmitted SNR equal to 30dB

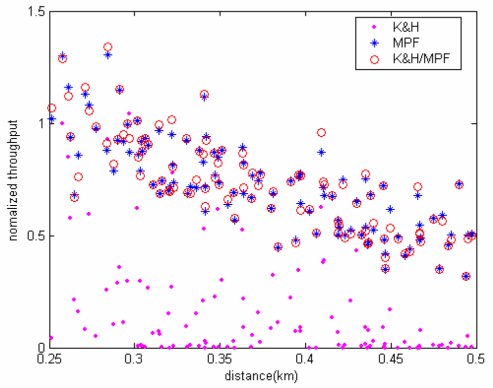

Fig. 6 A part of Fig.5 with X label from 0.25 to 0.5, and Y label from 0 to 1.5

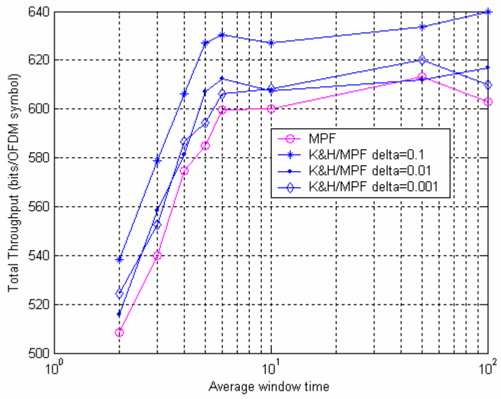

Fig. 7 Total throughput achieved by different algorithms versus various τ in a ten-user system

To evaluate the fairness achieved by different algorithms, we plot the pattern of 200 users in a ten-user system with $\tau=2$ and $\delta=0.1$ in Fig. 4 and 5, where each dot is corresponded to the normalized throughput of one user and its distance from BS. All users are distributed within the cell independently and uniformly, and their velocity is equal to zero. The normalized throughput of the k^{th} user is defined by $\overline{T}(k)$, $\overline{T}(k)=\overline{R}_k/R_k$, where, $\overline{R}_k$ and R_k are the average throughput and target rate of user k, respectively. Obviously, the fairness of algorithm is best, when the normalized throughput of all users is equal to 1.

From Fig. 4 and Fig. 5, we observe that the normalized throughputs of users achieved by K&H allocation are very difference on the basis of their distance from BS, but those of MPF and K&H/MPF are approached to 1, especially when the transmitted power of BS is high (see Fig. 5). To make out the result more clearly, a part of Fig. 5 with X label from 0.25 to 0.5, and Y label from 0 to 1.5 is shown in Fig. 6. From Fig. 4 to Fig.6, it indicates that MPF and K&H/MPF provide transmitting rate approximating to their target rate for all users impartially, and their fairness is explicitly superior to K&H allocation.

Fig. 7 shows the impact of average window time τ and δ on total throughput achieved by different algorithms in a ten-user OFDMA system, where the values of τ are 2, 3, 4, 5, 6, 10, 50 and 100 OFDM symbol, and the average transmitted SNR in base station (BS) is 12 dB.

From Fig. 7, it can be observed that the total throughput increases with τ for both MPF and K&H/MPF scheduler when δ is fixed. In fact, the larger time delay requirement user can tolerant, the more window time is, so τ should be set very small for no time delay constrain traffic. Moreover, we find that the visible capacity gain can be obtained by K&H/MPF compared with MPF when the value of δ is more than 0.1. This is mainly because the fewer the sub-carriers are reallocated by MPF in the K&H/MPF scheduler with the larger δ, where MPF scheduler decreases the total throughput. Note that δ is denoted as delta in Fig. 7.

The fairness of K&H/MPF algorithm is no difference with MPF scheduler, so the curves of fairness verse τ and δ are not shown in the paper.

V. CONCLUSION

In this paper, we modify the MPF scheduler in [6] to assure the user individual QoS requirements and propose a joint K&H/MPF algorithm with several adjustable parameters, such as τ and δ, whose influence on the performance of algorithm are examined carefully. The results show that K&H/MPF is flexible algorithm, which provides more fairness for users compared with K&H, as well as improves the capacity achieved by MPF scheduler without impact on its fairness.

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