Proactive Proportional Fair: A Novel Scheduling Algorithm Based on Future Channel Information in OFDMA Systems

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Abstract—**Radio resource scheduling is one of the most important issues in OFDMA systems, in which real-time and historical channel information are utilized to schedule the current radio resource allocation, such that system throughput can be maximized while user fairness is guaranteed. Recently, some studies have shown that wireless channel parameters can be predicted by exploiting the time dependence of fading channels. In this paper, we exploit this new degree of freedom and propose a novel scheduling algorithm, proactive proportional fair (PPF), in which future channel information is jointly considered with the past and current channel parameters. Simulation results show that the proposed PPF algorithm outperforms the generalized proportional fair algorithm in terms of system throughput by more than 40% when high user fairness is guaranteed.**

Index Terms—**Channel prediction, OFDMA, radio resource scheduling.**

I. INTRODUCTION

Radio resource scheduling is one of the most important issues in OFDMA systems [1–3], which determines how the time-frequency resource blocks are allocated to each user in each transmission time interval (TTI) [4]. Among all the metrics that are utilized to evaluate the performance of radio resource scheduling, system throughput and user fairness are mostly considered. Network operators always need to increase the system throughput, such that the service capacity is maximized, while at the same time, guarantee the user fairness since all mobile users are charged at the same price. Therefore, the trade-off between system throughput and user fairness is crucial for the performance of a scheduling algorithm.

A variety of scheduling algorithms have been proposed to achieve the best trade-off between system throughput and user fairness in OFDMA systems as can be found in the literature. Max-rate (MR) only focuses on the aggregate throughput of the entire system, which allocates radio resources to the user with the highest channel parameter in the current TTI [5]. Max-min fairness (MMF) has a strict fairness criterion that gives the highest priority to the user with the lowest average data rate in the past [6]. Proportional fair (PF) achieves a trade-off between system throughput and user fairness by jointly considering the instantaneous data rate in the current TTI and the average throughput in the past [7]. Generalized proportional fair (GPF) extends the PF algorithm by introducing two hyperparameters, such that the trade-off between system throughput and user fairness can be adjusted in a flexible way [8].

The existing scheduling algorithms utilize the past and the current channel information to decide the current radio resource allocation. Recently, some studies have shown that small-scale channel parameters can be predicted by exploiting the time dependency of fading channels [9, 10], which provides a new degree of freedom for radio resource scheduling. In fact, some studies have utilized the predicted channel parameters to schedule radio resources. In [11] the authors proposed a scheduling algorithm that estimates users' average throughput in the future by iteration, and in [12] the authors introduced a joint algorithm that is effective when channel quality information is predicted imperfectly.

In this paper, we assume the channel parameters can be predicted, and propose a novel scheduling algorithm, proactive proportional fair (PPF), in which future channel information is jointly utilized with the past and current channel information to decide the current radio resource allocation. Simulation results show that the proposed PPF algorithm outperforms the GPF algorithm in terms of system throughput by more than 40% when high user fairness is guaranteed.

The rest of the paper is organized as follows. In section II the system model of packet scheduling for an OFDMA system is provided, and key issues regarding to the design of packet scheduler are presented. In section III the existing scheduling algorithms are elaborated and analyzed, which shows that future channel information can be utilized to improve the performance of the system. In section IV simulation results are shown to compare the proposed algorithm with the existing algorithms in terms of both system throughput and user fairness. Finally, in section V we draw our conclusion, and discuss some directions of the future work.

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II. SYSTEM MODEL

In OFDMA systems, radio resources are abstracted into time-frequency resource blocks (RBs), as shown in Fig. 1. Each RB represents a subchannel with bandwidth w within a TTI τ. We consider a network with N users and K subchannels. In order to avoid co-channel interference, each RB can be allocated to at most one user. A scheduling algorithm is to decide how to allocate the K RBs to the N users at TTI t [13]. We denote by $h_{i,k}(t)$ as the channel parameter of user $i \in \mathcal{N}$ under subchannel $k \in \mathcal{K}$ at TTI t, and the signal to interference plus noise of user i under subchannel k at TTI t can be given by

$$SINR_{i,k}(t) = \frac{P_{i,k}(t)|h_{i,k}(t)|^2}{\sum_{k' \neq K} P_{i,k'}(t)|h_{i,k'}(t)|^2 + wn_0}, \quad (1)$$

where $P_{i,k}(t)$ is the transmission power of user i on subchannel k at TTI t, w denotes the bandwidth of each subchannel and n_0 denotes the thermal noise density of white Gaussian noise.

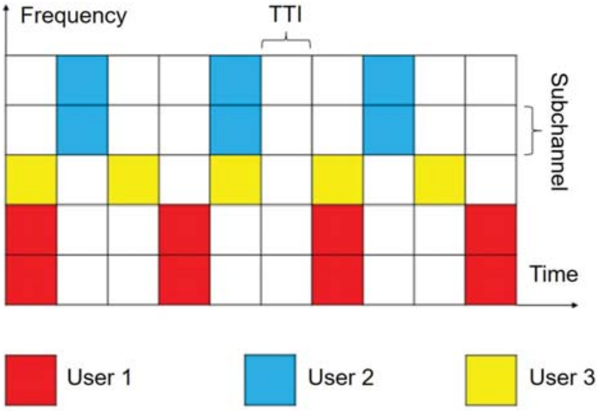


Fig. 1. Radio resource scheduling in OFDMA systems.

For any TTI t, we denote by $x_{i,k}(t)$ the indicator for subchannel $k \in \mathcal{K}$ and user $i \in \mathcal{N}$, in which $x_{i,k}(t) = 1$ represents that subchannel k is allocated to user i in TTI t and $x_{i,k}(t) = 0$ represents the opposite. Most scheduling algorithms can be presented in a general framework, in which a weight factor $m_{i,k}(t)$ is assigned to each user i for each subchannel k, and the subchannels are allocated to the user with the largest weight factor, i.e.,

$$x_{i,k}(t) = \begin{cases} 1, & m_{i,k}(t) = max_{j \in \mathcal{N}} m_{j,k}(t), \\ 0 & \text{, otherwise.} \end{cases} \quad (2)$$

Here, $m_{i,k}(t)$ can be seen as the preference of subchannel k for user i at TTI t, and the subchannel is allocated to the user that is most preferred. Therefore, the difference between scheduling algorithms is how the preferences $m_{i,k}(t)$ are determined.

To decide the optimal weight factors, a variety of performance metrics have been considered in the literature. Some of the most popular metrics are presented as follows:

- **Real-time Throughput**: Let $d_{i,k}(t)$ denote the real-time throughput of user i in subchannel k at TTI t. This metric can be directly calculated by using the current channel parameters, given by

  $$d_{i,k}(t) = w \log[1 + SINR_{i,k}(t)], \quad (3)$$

  where $SINR_{i,k}(t)$ denotes the signal to interference plus noise ratio of user i in subchannel k at TTI t.
- **Average Throughput**: Let $\overline{r_i}(t)$ denote the average throughput of user i for TTI t [14], which can be given by

  $$\overline{r_i}(t) = (1 - \frac{1}{N_T})\overline{r_i}(t-1) + \frac{1}{N_T} r_i(t), \quad (4)$$

  where $r_i(t)$ denotes the data throughput that user i achieves at TTI t and N_T denotes the time window over which the average throughput is calculated. $r_i(t)$ can be calculated as follows:

  $$r_i(t) = \sum_{k=1}^{K} x_{i,k}(t) d_{i,k}(t). \quad (5)$$
- **Fairness Index**: User fairness is one of the most important issues in wireless communication networks, for which various fairness indexes have been proposed. The most famous fairness index is the Jain's fairness index [15], which is defined as:

  $$F(T) = \frac{\left(\sum_{i=1}^{N} R_i(T)\right)^2}{N \sum_{i=1}^{N} R_i(T)^2}, \quad (6)$$

  where $R_i(T)$ denotes the total throughput received by user i within the considered time period T, given by

  $$R_i(T) = \sum_{t=1}^{T} r_i(t). \quad (7)$$

  The value of Jain's fairness index is between 0 and 1. The user fairness increases as the value of Jain index approaches 1. When the total throughput of each user is equal to each other, we have $F(t) = 1$.

III. PROACTIVE SCHEDULING USING FUTURE CHANNEL INFORMATION

We first show how the current scheduling algorithms decide weight factors. Then we propose a novel PPF algorithm, which introduces a new degree of freedom by using future channel information.

A. *Existing Scheduling Algorithms*

The MR algorithm aims at maximizing the overall throughput by allocating each RB to the user that achieves the largest throughput in the current TTI. Formally, the weight factors of the MR algorithm are given by

$$m_{i,k}^{MR}(t) = d_{i,k}(t). \quad (8)$$

The MMF algorithm seeks for absolute fairness by allocating each RB to the user that has achieved the lowest throughput in previous TTIs. Formally, the weight factors of the MMF algorithm are given by

$$m_{i,k}^{MMF}(t) = \frac{1}{\overline{r_i}(t-1)}. \tag{9}$$

To achieve a balance between system throughput and user fairness, PF is proposed, in which the real-time throughput and average throughput are jointly considered. Formally, the weight factors of the PF algorithm are given by

$$m_{i,k}^{PF}(t) = \frac{d_{i,k}(t)}{\overline{r_i}(t-1)}. \tag{10}$$

To control the trade-off between system throughput and user fairness, PF has been extended to GPF, in which two hyperparameters, α and β, are introduced to adjust the weights of real-time throughput and average throughput. Formally, the weight factors of the PPF algorithm are given by

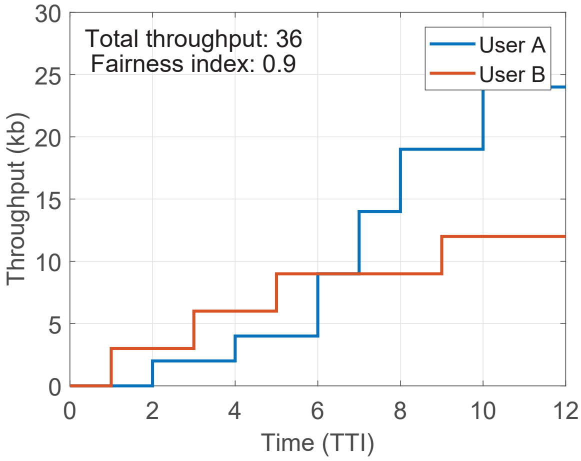
$$m_{i,k}^{GPF}(t) = \frac{[d_{i,k}(t)]^{\alpha}}{[\overline{r_i}(t-1)]^{\beta}}. \tag{11}$$

If α is increased, the real-time throughput is preferred and the system throughput is increased. If β is increased, the average throughput is preferred and the user fairness is increased.

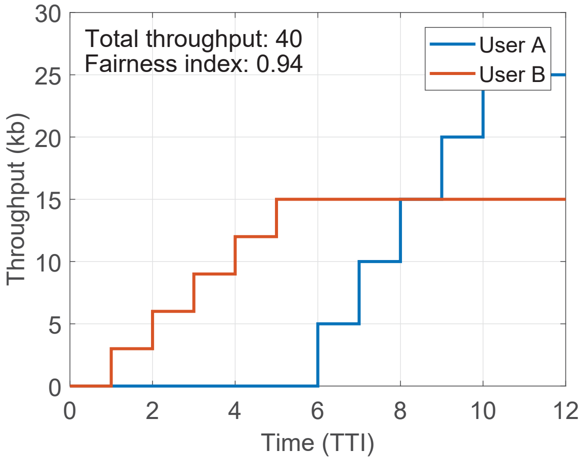
B. Potential of Future Channel Information

Traditionally, small-scale channel information is considered as random parameters that cannot be predicted. However, recent studies have shown that fading channels are time dependent and it may be reasonable to speculate the fading process as a deterministic mathematical model in a short interval, which implies that channel parameters can be predicted in such a short interval. It has been shown in [9] that channel parameters within 25 milliseconds can be predicted with 99% accuracy. The predictability of channel parameters provides a new dimension for radio resource scheduling, which may highly increase the scheduling performance if such information is well exploited.

We provide a simple example to show how future channel information can be exploited to increase the scheduling performance. Here we consider a system with two users A and B, and one subchannel. All the channel parameters are assumed to be predicted with 100% accuracy in the next 10 TTIs, in which the real-time data rate of user A is 2 kb/TTI in the first 5 TTIs and 5 kb/TTI in the last 5 TTIs, while the real-time throughput of user B is constantly 3 kb/TTI in all 10 TTIs. If PF is utilized, as shown in Fig. 2(a), the total throughput of user A is 24 kb, and the total throughput of user B is 12 kb. Thus, the system throughput is given by 36 kb and the Jain fairness index is given by 0.9. If the scheduler utilizes the future channel information and realize that the real-time data rate of user A becomes larger in the last 5 TTIs, it can allocate all resources to user B in the first 5 TTIs and then allocate all resources to user A in the last 5 TTIs such that subchannels can be efficiently utilized, as shown in Fig. 2(b). By using this scheduling policy, the total throughput of user A is 25 kb and the total throughput of user B is 15 kb, which yields a better system throughput 40 kb and a better fairness index 0.94 compared with the PF.



(a) The PF algorithm



(b) The algorithm using future channel information

Fig. 2. An example with two users and one subchannel.

C. Proactive Proportional Fair

We propose a novel scheduling algorithm, PPF, in which the future channel information is jointly considered with the current and past channel parameters. Formally, the weight factors of the proposed PPF algorithm are given by

$$m_{i,k}^{PPF}(t) = \frac{[d_{i,k}(t)]^{\alpha}}{[\overline{r_i}(t-1)]^{\beta} + [\overline{r_i}^{*}(t+1)]^{\gamma}}, \tag{12}$$

where $\alpha, \beta, \gamma > 0$ are hyperparameters which are utilized to keep a balance among the current, past and future channel conditions, and $\overline{r_i}^{*}(t+1)$ denotes the estimated channel quality of user i in future M_T TTIs, and given by

$$\overline{r_i}^{*}(t+1) = \frac{1}{M_T N}\sum_{m=1}^{M_T}\sum_{k=1}^{K} d_{i,k}(t+m). \tag{13}$$

In Eq. (13), we simply assume that the RBs in the next M_T TTIs are randomly allocated to all users such that the average data rate in the future can be estimated by using a factor $\frac{1}{N}$, and each user is expected to get $\frac{K}{N}$ subchannels at any TTI in the futue.

As we can see in Eq. (12), the weight factor $m_{i,k}^{PPF}(t)$ increases if the real-time throughput is increased, and it decreases if the average throughput in the past or in the future is increased. Therefore, the proposed PPF algorithm prefers to allocate RBs to the users that can efficiently utilize the current radio resources, while at the same time, have low average throughput in the past TTIs and may not achieve high throughput in the future TTIs.

Compared with GPF, the future channel information is involved by introducing a new hyperparameter γ in our proposed PPF. The basic idea behind Eq. (12) is that users with a good future channel condition can leave the current RBs to other users and wait for a better TTI to access the channel with higher spectrum efficiency. Similar with GPF, the hyperparameters should be carefully adjusted to achieve a trade-off between system throughput and user fairness.

IV. SIMULATION RESULTS

Consider the downlink scheduling problem of an OFDMA system with $K = 10$ subchannels. The number of users N varies from 6 to 20. The bandwidth of each subchannel is 180 kHz, and the TTI is 1 ms. The transmission power of each subchannel is 10 mW. We adopt the path loss model as in [16], $132.9 + 37.6lg(d)$ dB, in which d denotes the distance from the user to the base station, and Rayleigh fading model for small-scale channel parameters. The thermal noise is given by -174 dBm and the simulation duration is 6000 ms. The users are randomly dropped within the cell range with radius 1 km. The time window of past channel conditions is 100, and the time window of future channel condition is 25. The users are assumed to be fixed, which implies that the large-scale fading is time-invariant during our simulation. The simulation parameters are listed in Table I.

TABLE I. SIMULATION PARAMETERS

Parameter	value/situation
Number of cells	1
Number of users (N)	6-20
Number of subchannels (K)	10
Subchannel bandwidth (w)	180 kHz
TTI (τ)	1 ms
Simulation duration (T)	6000 ms
Thermal noise density	-174 dBm/Hz
Cell radius	1km
Transmission power	10mW
Path loss model	132.9+37.6lg(d) dB
Previous time window (N_T)	100
Future time window (M_T)	25
User Motion Mode	fixed

We compare our proposed algorithm with the conventional GPF algorithm. The weight of current throughput α, the weight of past average throughput β and the weight of estimated channel quality in the future should be carefully chosen to make the system efficient and fair. In GPF, the hyperparameters are set as $\alpha = 1$ and $1 \leq \beta \leq 3$, as given in [16]. In the proposed PPF, the hyperparameters are set as $\alpha = 1, \beta = 1$ and $0.8 \leq \gamma \leq 1$. Since channel prediction has been solved by other studies, we assume that the channel parameters in the next M_T TTIs can be perfectly predicted.

In Fig.3 we show the total throughput of all users in OFDMA system as a function of the fairness index for both the proposed PPF algorithm and the conventional GPF algorithm, where the number of users is 10. For both algorithms, the system throughput decreases as the user fairness is improved. When the fairness index is above 0.6, the proposed PPF achieves a better trade-off between system throughput and user fairness. When the fairness index is above 0.8, our proposed PPF outperforms the conventional GPF by 49% in terms of system throughput.

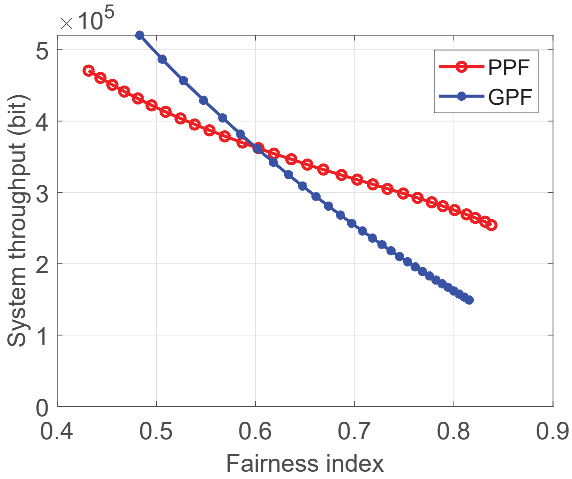


Fig. 3. System throughput as a function of fairness index for the proposed PPF algorithm and the GPF algorithm.

In Fig.4 we show the distribution of user throughput in the system for the proposed PPF algorithm and the GPF algorithm, where the fairness index is 0.8 and the number of users is 10. It can be seen from the picture that when the demand of fairness index is same, users in the proposed PPF algorithm are more likely to achieve high throughput than those in the GPF algorithm, which makes the system achieve more total throughput.

In Fig.5 we show the total throughput as a function of the number of users in the system, where the fairness index is 0.75. It can be seen that as the number of users increases, the system throughput decreases. The reason is that RBs needs to be allocated to more users with low SINRs, such that the fairness requirement is satisfied. We can see that the proposed PPF algorithm outperforms the conventional GPF by more than 40% even if the number of users tends to 20.

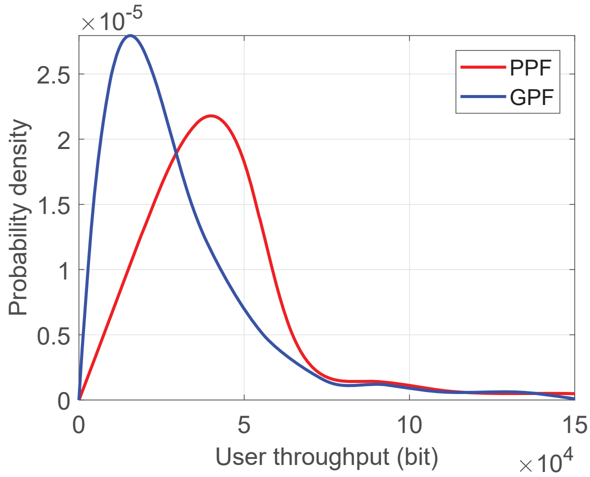


Fig. 4. The distribution of user throughput for the proposed PPF algorithm and the GPF algorithm.

In Fig.6 we show the throughput of each user as a function of the simulation time for the proposed PPF algorithm and the conventional GPF algorithm, where the total throughput is equal in both two algorithms. The throughput curves of users are marked with different colors. It can be seen that the curves of users' total throughput in the proposed PPF algorithm tend to be closer to each other than that in the conventional GPF algorithm. In fact, the proposed PPF outperforms the conventional GPF algorithm in terms of fairness index by more than 10%.

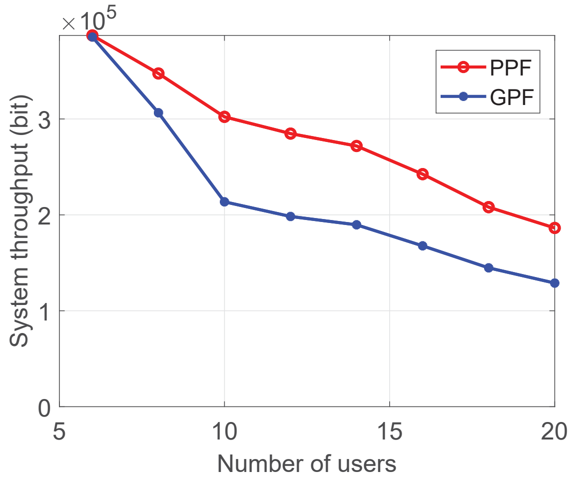
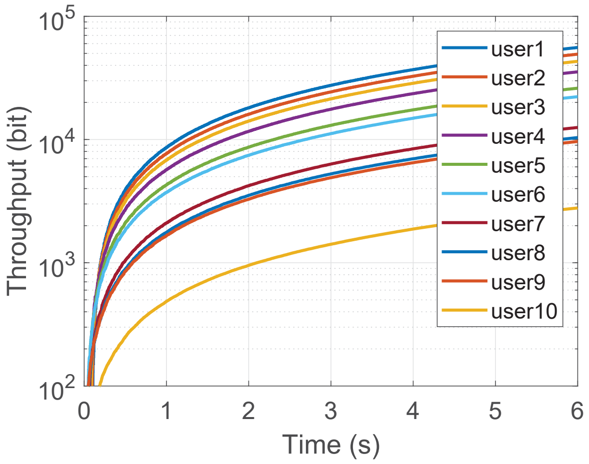


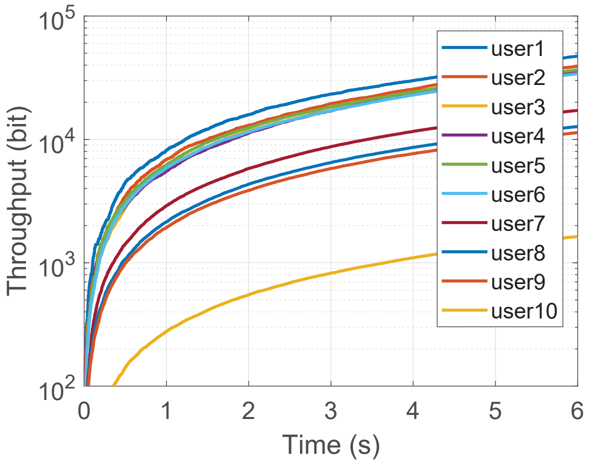
Fig. 5. System throughput as a function of the number of users for the proposed PPF algorithm and the GPF algorithm.

V. CONCLUSION

In this paper, we have analyzed that the predictability of small-scale channel parameters can provide another degree of freedom for radio resource scheduling, and proposed a PPF scheduling algorithm for the OFDMA systems, where future channel information is utilized to decide the current radio resource allocation. Simulation results show that our proposed PPF algorithm outperforms the generalized GPF by more than 40% in terms of system throughput while high user fairness is guaranteed. We believe that the potential of future channel information can be further, which could be investigated in future work.



(a) The conventional GPF algorithm



(b) The proposed PPF algorithm

Fig. 6. The throughput of each user as a function of the simulation time for the proposed PPF algorithm and the conventional GPF algorithm.

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