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Flow-level performance of proportional fairness with hierarchical modulation in OFDMA-based networks

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ABSTRACT

Proportional Fairness (PF) is known to achieve a good trade-off between efficiency and fairness by an opportunistic allocation of resources to users with good radio conditions, without sacrificing fairness towards the other users of the system who have worse radio conditions. On the other hand, Hierarchical Modulation (HM) is a means to increase the spectral efficiency of a given system by superposing an additional information stream over a basic one, by means of embedded constellations. This, in turn, results in a high resource utilization and hence overall system throughput. In this work, we model the system performance, obtained by jointly using PF with HM, for a realistic dynamic setting where users come to the system at random time epochs and leave it after a finite duration, upon the completion of their data transfers. We show that, in the presence of HM, a simple cyclic service, such as round robin, yields a better performance than PF, along with less complex implementation.

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1. Introduction

Orthogonal Frequency Division Multiple Access (OFDMA) is, as its name indicates, a multiple access technique used in wireless networks which inherits OFDM's immunity to Inter Symbol Interference (ISI) and frequency selective fading, and which yields, in turn, high system throughput [1,2].

Using OFDMA, the total bandwidth is divided into a set of orthogonal subcarriers which can be shared by several users in the same time slot. In order to exploit multi-user diversity, Adaptive Modulation and Coding (AMC) [2] assigns different modulation-coding pairs to users experiencing different radio conditions so as to increase each user's throughput, and hence the overall system capacity. For instance, with AMC, a user with good radio conditions will be assigned a large constellation, such as 16-QAM, as compared to a user with worse radio conditions which will be assigned a small constellation, such as 4-QAM.

Hierarchical Modulation (HM) [3], also termed superposition coding or yet embedded constellations, is an old technique that has been introduced in digital broadcast systems so as to increase their throughput [4]. The idea is to send two data streams to two different users using a single subcarrier: one basic data stream and one extra, additional stream. To do so, users should be using different constellations and hence of different radio conditions so that each user would be able to decode its own signal. This results in an increase in the resource utilization and hence the overall system throughput.

Now, as far as radio resource allocation is concerned, many algorithms have been proposed in the context of wireless networks in general and OFDMA in particular so as to meet some objective, such as users' quality of service requirement, fairness or else high overall system throughput.

One of the simplest algorithms is Round Robin (RR) which serves users in a cyclic manner, on a time basis [5]. RR achieves fairness in terms of time but does not take into consideration the users diversity, in terms of radio conditions, which may lead to a poor utilization of the resources

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and hence a poor overall system throughput. On the other hand, Proportional Fairness (PF) [6] is an opportunistic algorithm that makes it possible to exploit the user diversity: it allocates resources primarily to users with good radio conditions because they would be able to take full advantage of these resources and finish their data transfers quickly. Resources can then be given to the other users, with worse radio conditions. Of course, some fairness should be guaranteed in order for the users with good radio conditions not to cause the starvation of the others. PF is known to achieve the highest overall system throughput among all so-called α-fair allocation strategies that are all collectively known to maximize the stability region[1] of these systems [7]. The parameter α summarizes the trade-off between fairness and efficiency. It is, for instance, equal to 1 in the case of PF, and tends to infinity in the case of Max–min, which ensures fairness, in terms of throughput, between the different users in the system [8].

Our aim in this work is to study PF in the presence of HM and see whether it still is the optimal strategy in the sense of α-fair allocation strategies. We will specifically model the system performance under a realistic system setting where users of different radio conditions come to the system at random times and leave it after a finite duration, upon the completion of their respective file transfers. We will next quantify the achieved performance, notably in terms of mean transfer times and blocking probabilities. We will last compare the performance of PF with that of simpler, cyclic RR scheduling, as well as Max–min, both in the absence and presence of HM.

The remainder of this paper is organized as follows. In Section 2, we report on related works on PF and on PF with HM. In Section 3, we describe our system. In Section 4, we show our model for PF. In Section 5, we describe the system model, at the flow level, and derive some performance measures. In Section 6, we present HM, explicit its algorithm and show how it impacts our previous model. In Section 7, we first validate the PF analytical model against simulations, and next show a comparison with RR and Max–min. Section 8 eventually concludes the paper.

2. Related work

In the literature, different expressions for the throughput obtained under PF result from the use of different metrics in choosing the user to which the resources are allocated.

In [5], the authors use the Signal-to-Noise-Ratio (SNR) and allocate the resources to the user whose SNR is maximal. This approximation corresponds in fact to the ideal case where all users experience symmetric fading conditions [9].

In [10], the authors make, again, use of the SNR in selecting the user. The calculation of the throughput follows two models: a first one where the feasible rate is considered to be a linear function of the SNR and a second one in which the relationship is logarithmic, as is the case of the Shannon formula.

[1] The maximum set of input traffic intensities for which the system is stable.

In [11], the authors make use of the ratio of the instantaneous SNR to the average SNR to select the user to be served. The calculations make again use of a linear and logarithmic expressions, but this time using the previously mentioned ratio of the SNRs.

With the linear model, the gain achieved by PF as compared to a fair time allocation, such as RR for instance, is given by the following expression:

$$\sum_{i}^{K} \frac{1}{i}$$

where K is the number of users simultaneously active in the system.

These models are simple and thus mathematically attractive. The linear model, however, is known to overestimate the feasible rate and hence the gain achieved by PF [12].

The use, instead, of a Gaussian approximation has been shown in [13,14] to model very accurately the feasible rate in the cases of Raleigh and Rician fadings.

In [15], the authors make use of this Gaussian approximation and show that the gain is much lower than in the linear case. However, only symmetric channels have been considered. In [12], the same approach is used, but this time, for asymmetric channels. Using simulations, the expression of the gain has been modified to match different fadings: Raleigh and Rician.

As of PF in the context of HM, the work contained in [16] proposes that the first user, in HM, is chosen as the one with the best radio condition, whereas the second is chosen based on PF, i.e., as the user who has the largest ratio of instantaneous to average SNR.

Contrary to the previous work, the scheduling scheme we study in this paper is one where resources are, first, allocated to users based on PF. If the selected user has a low (absolute) SNR, we, then, use HM to superpose, if possible, a user with high SNR on the same subcarrier. And we do this, at the flow level, for a dynamic user configuration.

3. System

Let us consider a downlink OFDMA system where the total bandwidth is divided into N orthogonal subcarriers and where the time resource is divided into time slots; a frame is constructed by a number of slots.

Subcarrier allocation is done in the time–frequency domain: a flow may share a subcarrier with other users. This is illustrated in Fig. 1 where users 2, 3, 4 and 5 occupy each one subcarrier half of the time while user 1 occupies one subcarrier all the time.

With OFDMA, the user device could choose subcarriers based on geographical location with the potential of eliminating the impact of deep fades. Indeed, and as indicated in Section 1, depending on the SNR, each user will be assigned a coding and modulation scheme, as dictated by the AMC feature, in use in IEEE802.16 WiMAX or LTE; with a more robust modulation and coding for users with lower SNR. If we consider the path loss only, this results in the division of the cell into J co-centric regions, as shown in Fig. 2, each of radius r^j, $j = 1, \ldots, J$; each region containing

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