Round Opportunistic Fair Wireless Downlink Scheduling with Performance Guarantees

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Abstract—Round opportunistic fair (ROF) scheduling is a heuristic algorithm that has been proposed in [1] for improving fairness in wireless downlink scheduling. ROF represents a trade-off between achievable throughput and fairness. However, the fairness advantage of ROF (e.g., compared to proportional fairness (PF) scheduling) comes at the expense of some loss in achieved throughput.

In this paper, we impose a minimum performance guarantee (MPG) on ROF to allow increasing the throughput. In the proposed ROF with MPG algorithm (ROF-MPG), the scheduled user must have an achievable throughput that is not lower than a certain minimum. As confirmed by extensive computer simulations. this new version of ROF increases the achieved throughput while achieving excellent air time and throughput fairness.

Index Terms—Downlink transmission; opportunistic scheduling; air time fairness, throughput fairness.

I. INTRODUCTION

Wireless spectrum efficiency is steadily gaining significance nowadays with the increasing demand on wideband wireless services [2]. With the growing popularity of wireless technologies, more flexible and efficient use of the scarce spectral resources is increasingly in demand [3]. Scheduling can be a very effective means to increase throughput, and hence spectral efficiency, of wireless systems [4].

A scheduling policy is a rule, or set of rules, used to specify which user is scheduled to transmit/receive data during a time slot [5]. Scheduling allow dynamic resource allocation and resource sharing among multiple users [6]. Opportunistic scheduling algorithms dynamically allocate radio resources based on the channel state information (CSI) of the users [7]. Opportunistic scheduling prioritizes users with better channel conditions, and can lead to substantial resource utilization gains [8]. This is because when a user with good channel conditions is scheduled for transmission, a very high symbol rate is achievable [9]. In fact, it is optimal to schedule at any one time instant the only user with the best channel [10]. On the negative side, opportunistic scheduling algorithms lead to unfair allocation of systems resources to users. [11]. Users with best channel conditions take most advantage of opportunistic scheduling, while other users can be given only few and far-between transmission opportunities. Intutively, this results in low levels of fairness in assigning resources to users [11].

As in [1], the term fairness is generally used in this paper to imply balanced (not necessarily equal) user access to radio resources. However, the adopted fairness definition does imply equal access to resources when all users have equal access priorities (or belong to same traffic class). Good scheduling is required to improve the overall throughput by exploiting the channel state information, under certain quality of service (QoS) and/or fairness constraints. Uses can be initially assigned equal target shares (single-class traffic) or unequal target shares (multi-class traffic) of air time. Balanced user access to radio resources means that the scheduling algorithm should try to avail to each user the same share of air time as its pre-assigned share.

For the sake of providing fair access to system resources, the round opportunistic fair (ROF) scheduling algorithm [1] takes rounds over the users to be scheduled for downlink transmissions. However. ROF does not schedule users in a round robin manner; because it prioritizes users with better channel conditions. Meanwhile, ROF does not always schedule the user with the absolute best channel conditions; in order to allow fairness in scheduling user transmissions. The main idea of ROF is to limit scheduling to a subset of so-called candidate users. These are the users that have waited the longest times since they have last been scheduled.

In this paper, and in order to avoid scheduling users with poor channel conditions, we impose a minimum performance guarantee (MPG) on ROF. The scheduled candidate user must have an achievable throughput that is not below a certain minimum. This version of ROF enhances the throughput while achieving excellent air time fairness.

The remainder of this paper is organized as follows. Section II presents the channel model and outlines the main assumptions. The proposed modification to ROF is introduced in section III. Simulation results are presented in section IV, along with performance comparisons to other scheduling algorithms. Section V concludes the paper.

II. CHANNEL AND SYSTEM MODELING

Downlink transmission over a rich scattering flat Rayleigh fading channel in a single cell of a cellular system is assumed.

In addition to small scale Rayleigh fading, the channel is assumed to introduce large-scale fading in the form of path loss and log normal shadowing. Since the system consists of one cell; co-channel interference is not included in the channel and signal models. The signal-to-noise ratio (SNR) will, therefore, be used as a measure of channel quality. The base station (BS) is assumed to be located at the center of the cell. The BS is assumed to serve, in a time-slotted manner, U fixed (non-mobile) users, each equipped with one receiving antenna. In other words, time is the system resource that is shared among the users. Details of the channel model, as well as SNR analysis are as in [1].

A full-buffer model is used, i.e., the BS is assumed to always have data to send to all users over the downlink. BS transmissions (BSTs) are assumed to happen at the ith multiples of the channel coherence time (to make sure that channel conditions do not change during a BST), where i is a non-negative integer. As in ROF, and as explained briefly below, the scheduled user at any time instant is a member of the candidate users set. At the beginning of each time slot, the scheduler determines the best candidate user that should receive a BST.

At time instant $i \geq 0$, each user u has a wait figure $w_u(i)$, which controls the number of time slots the user has to wait before competing for a BST. During the operation of the algorithm, smaller wait figures indicate longer already elapsed waiting times. Initial wait figures can be all set to zero. However, this would not provide any straightforward means to select the initial set of users that are candidates to get a BST. Therefore, wait figures of all users are initialized with very small random values. Users are ordered ascendingly according to their wait figures. The U_x users with smallest wait figures form the set of candidate users, where $1 \leq U_x \leq U$. The BS schedules a BST to the candidate user with the highest achievable throughput. This is equivalent to scheduling a BST to the user with the highest instantaneous received SNR. Since, at any time instant, there could be non-candidate users with better channel conditions than those of all candidate users; assigning BSTs to only candidate users does not always produce the highest possible throughput. This throughput sacrifice can be justified on the ground that candidate users are the ones that have waited the longest times to receive BSTs.

The number of candidate users U_x is an important parameter in the trade-off between fairness and achievable throughput. For example, when $U_x = 1$ ROF becomes equivalent to round-robin scheduling, which creates maximum air time fairness among all users. This is because at every time instant there is only one candidate user, and that user is the one that has waited the longest time before receiving a BST. In contrast, when $U_x = U$ ROF performs purely opportunistic scheduling, and achieves the highest possible throughput. This is because at every time instant all users are candidates, and the one that receives a BST is necessarily the one that has the best channel conditions. In general, smaller values of U produce more fairness, whereas higher values of U produce higher throughputs.

When user u receives a BST at time i, a quantity ρ_u is added to its previous wait figure $w_u(i-1)$ to form the new wait figure $w_u(i)$, i.e.,

$$w_u(i) = w_u(i-1) + \rho_u \tag{1}$$

where ρ_u is a (usually small) constant value. In the long term, this is equivalent to moving user u to the end of the waiting figure queue. At this time instant, the non-candidate user with the smallest wait figure replaces users u in the subset of candidate users.

III. ROF SCHEDULING WITH PERFORMANCE GUARANTEES (MPG)

ROF is a heuristic opportunistic scheduling algorithm that maximizes the network throughput under fairness restrictions. The main idea of ROF is to limit assigning BSTs to a dynamic subset of candidate users [1]. The objective of this restriction is to improve chances of users with generally bad channels qualities to get BST allocations. It has been shown in [1] that good levels of fairness in BST assignment to users can be achieved.

The scheduling algorithm decides which candidate user is to receive data from the BS in a given time slot, based on channel conditions of the users. It is assumed that the BS knows the channel conditions of all users. How this information is made available to the BS is beyond the scope of this paper.

It is assumed that a BST consists of a number of symbols that is proportional to the achievable throughput. This can be done by setting the modulation order (signal constellation size) using adaptive bit loading. Throughout this process, the duration of a BST is kept fixed, regardless of the number of transmitted symbols. It is assumed that fading is sufficiently slow such that channel conditions do not change during a BST. However, the channel is assumed to vary independently from one BST to another. Quantization to integer numbers of bits is not considered in this paper; and hence whenever throughput is mentioned, what is meant is actually achievable throughput. In the simulation experiments, we measure the achievable throughput normalized to a unit bandwidth.

To impose an MPG condition, a candidate user is chosen to receive a BST only if the user has an instantaneous achievable throughput that is not below a given threshold. The objective here is to increase the overall achievable network throughput. If no candidate user satisfies the MPG condition, the set of candidate users is extended gradually until one of the candidates satisfies the MPG condition. Non-candidate users are added, one at a time, to the set of candidate users following their ascending order of wait figures. It should be clarified here that the threshold under consideration is an instantaneous one; maeaning that users who do not satisfy it at one BST may satisfy it at following BSTs. Intuitively, and as will be seen through simulation results, higher MPG threshold values are expected to increase the average achievable network throughput.

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IV. SIMULATION AND RESULTS

To produce the simulation results that are presented below, we have assumed a single-cell cellular system with one BS at the cell center. The system suffers no co-channel interference, meaning that the system is noise-limited, and that throughput computations are based on the SNR. Small-scale Rayleigh fading, and large-scale fading consisting of path loss and log-normal shadowing are assumed to affect the signals transmitted over the communication channel. A path loss exponent of 4 and a shadowing standard deviation of 8 dB are assumed. The cell radius is 1000 m. The number of users U is 40. User u is assumed to be separated from the BST by a distance equal to

$$d_u = 0.1 + 0.8\left(1 - \frac{u}{U}\right) \tag{2}$$

In other words, user U is closest to the BS and user 1 is farthest, with equal distance increments for the users in between. The achievable normalized throughput has been calculated using [12]

$$\xi_u = \log_2\left(1 + \frac{Z_u}{K}\right) \tag{3}$$

where K is a constant system-efficiency factor that depends on the system design and the target bit error rate, and Z_u is an exponentially distributed random variable representing the the received SNR of user u. The details of generating Z_u, including how the different fading mechanisms are involved can be found in [1]. Following [12], K is chosen equal to 8.

The number of candidate users that compete for a BST is $U_x = 10$. Each simulation experiment includes 50 runs of 400,000 BSTs (or time slots). In each run, measurements like throughput and air time share are taken every 1000 BSTs. This means that 400 readings are taken in every run. Readings are averaged over the 50 runs to produce the experiment results.

Although many fairness indicators have been proposed and used in the literature, we choose to use the variance of the measurements to quantify fairness in the measured quantity. This is motivated mainly by the well-known fact that the variance measures the extent of variation of the measured quantity. When the variance of a measured quantity is lower, the measurements are closer to their average value, and hence the fairness is higher. Obviously, the converse is true too.

Fig. 1 shows the average normalized throughput, as function of the minimum acceptable achievable throughput while the latter is varied from 0 (ROF with no MPG) to 4 b/s/Hz. As can be seen in the figure, increasing the minimum acceptable achievable throughput can substantially improve the average normalized throughput of the system. The throughput improvement obtained by introducing the MPG condition comes at the cost of worsening the air time fairness.

Fig. 2 shows how increasing the minimum acceptable throughput increases the air time variance. However, users are scheduled to receive BSTs only when their achievable throughput is above the MPG threshold. As discussed below, this is why air time fairness is not a big concern.
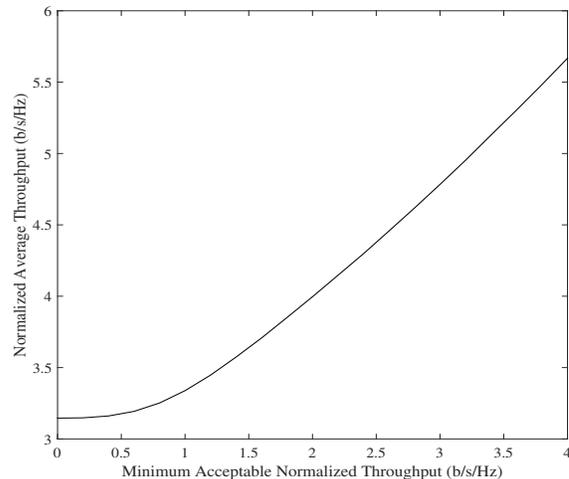

Fig. 1. Normalized average throughput as function of the minimum acceptable throughput
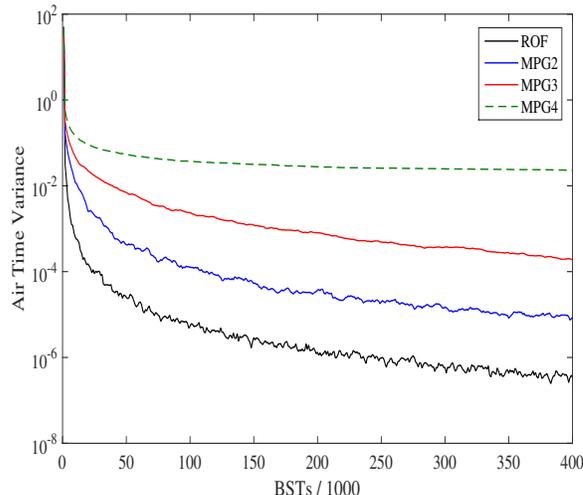

Fig. 2. Airtime variance of ROF with MPGx (where x is the required minimum achievable throughput in b/s/Hz)

In Figure 3 we have plotted the variance of the average normalized throughput achievable by users using ROF and MPG. The required minimum achievable throughput is assumed to be 2 b/s/Hz. Except when the number of users is very small (which is not the common case) MPG outperforms ROF by orders of magnitude in terms of throughput fairness. The MPG throughput fairness advantage over ROF is, in fact, more significant than the airtime time fairness cost. This is because even if a user gets fewer occasions to use the system resources with MPG than with ROF, the user is able to achieve higher overall average throughput with MPG.

Fig. 4 shows the average normalized throughputs of all users under ROF and MPG (where the latter has a required minimum achievable throughput of 2 b/s/Hz). Obviously, MPG can achieve an improved throughput fairness among users,

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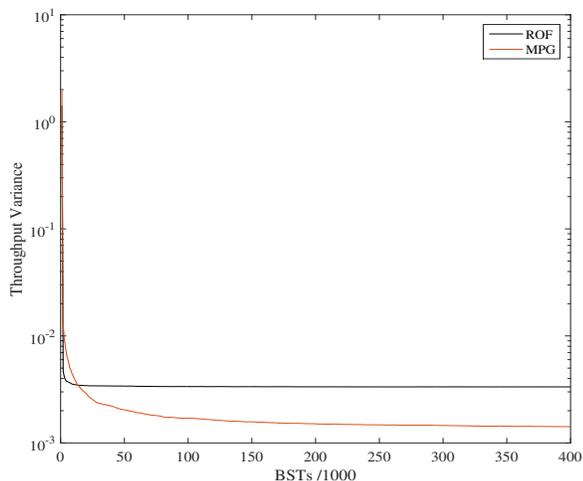normalized throughput of all users are higher with the new algorithm that with ROF.

Fig. 3. Throughput variances of ROF and MPG (where the latter has a required minimum achievable throughput of 2 b/s/Hz)
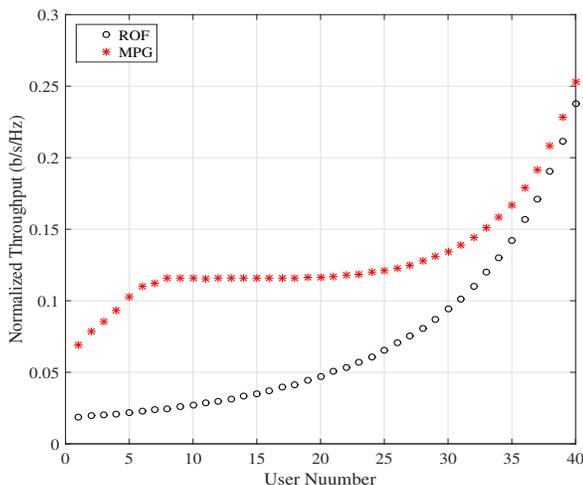

Fig. 4. User normalized throughputs of ROF and MPG (where the latter has a required minimum achievable throughput of 2 b/s/Hz)

compared to ROF. It can also be seen in Fig. 4 the the average normalized throughput of all users is higher than possible with ROF.

V. Conclusion

A modified ROF scheduling algorithm has been proposed and studied. The proposed algorithm imposes a minimum performance guarantee (MPG) based on a an acceptable achievable throughput threshold. The new algorithm improves on the original ROF algorithms in several aspects. It has been found through simulations that the average normalized throughput of the system can be substantially increased, compared to that of ROF. It has also been found that users enjoy higher throughput fairness than with ROF. Finally, the average

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