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Complexity Performance Trade-off for Proportional Fair Scheduling in a Multiple Antenna OFDMA System

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Abstract: We study the performance of a Proportional Fair (PF) scheduler for the uplink of an OFDMA system with multiple antennas at the Base Station (BS). We consider a BS performing Successive Interference Cancellation (SIC), as well as two simpler solutions: i) orthogonal multiple access; ii) a heuristic based on the assumption that the BS can perform SIC for up to ν users. In order to reduce the intercell interference, we introduce a sum-power constraint for users transmitting on the same frequency sub-band. Results show that the optimal power allocation with the PF scheduler involves allowing many users to simultaneously transmit on the same frequency band; the orthogonal approach, therefore, leads to a substantial performance loss, particularly at high SNR. The proposed SIC heuristic represents a good tradeoff between performance and complexity.

Keywords: multiaccess communication, scheduling, resource allocation, OFDMA, power control, multiple antennas

1. Introduction

In this paper, we consider the design of a Proportional Fair (PF) scheduler for the uplink of an Orthogonal Frequency Division Multiple Access (OFDMA) cellular system, in which the Base Station (BS) has multiple antennas. We compare the performance obtained with a receiver with Successive Interference Cancellation (SIC) at the BS, with that obtained with two simpler schemes: a limited complexity SIC receiver, such that only a limited number of users can share the same subchannel, and an orthogonal multiplexing scheme, where each OFDM subchannel is assigned to a single user.

It is well known that multiple antennas can have a beneficial impact on the link layer performance of wireless networks; in particular, they reduce the influence of channel statistics on fairness and buffer load balance [1]. In broadband systems, which are characterized by frequency-selective fading and thus intersymbol interference (ISI), MIMO technologies are usually combined with OFDM modulation, which turns the frequency-selective channel into a set of parallel flat fading channels [2]. A survey on existing MIMO-OFDM systems, together with a discussion of their limitations and with proposed practical solutions, can be found in [3].

In order to reduce the complexity of receivers, it may be necessary to limit the number of users simultaneously transmitting on an OFDM tone. In [4] the authors study the impact of a variable amount of collision in MIMO-OFDM multiple access schemes. They found that the capacity region obtained for any amount of collision is outer-bounded by the capacity region obtained for a fully collision-based multiple-access scheme, referred to as simply SIC in this paper. In practice, however, it is desirable to reduce the amount of collision in frequency, as this reduces the receiver complexity. The authors also show that in the low-SNR regime the amount of collision has a negligible impact on the capacity region. In the high-SNR regime, collision in frequency is crucial to maximize the capacity if the users are spatially well separated and if there is a large number of antennas at the BS.

Proportional fair scheduling algorithms are analysed in [5], where their convergence is proved under general conditions; extensions to the basic algorithm (simultaneously transmitting users, minimum throughput requirements, etc.) are discussed in [6]. In [7] the PF algorithm is extended to systems with multiple antennas at the BS; in this scenario, PF scheduling is formulated as a convex optimization problem; the author derives an asymptotically optimal solution to the problem. A stability-optimal scheduling policy for SIMO MAC (Multiple Access Channel) systems, based on the maximization of the sum of the rates weighted by the queue lengths, is proposed in [8]. The BS is assumed to perform SIC; the optimal SIC order is determined by the weights and does not depend on the channel. These results are extended to the case of mobile terminals with multiple antennas (MIMO systems) in [9], which also introduces a converging iterative optimization algorithm.

In the present work we do not make reference to any specific radio interface. However, the solutions we investigated can be deployed in many existing systems, and the results we obtained can provide information on the performance and QoS tradeoffs involved in such systems. In fact, all 4G air interfaces (e.g., WiMAX [10], UTRAN Long Term Evolution [11], IEEE 802.20 [12], etc.) are based on OFDMA access, and envisage the use of multiple antennas at the BS. In particular, MIMO-OFDM has been selected as one of the possible uplink transmission schemes in the UTRAN Long Term Evolution in 3GPP [11].

Some of these systems make it possible to vary the amount of user collision. E.g., in [11] two concepts are discussed: Single User (SU-) MIMO, in which a time-frequency resource is assigned to a single user, and Multi User (MU-) MIMO, in which different users are spatially multiplexed on the same frequency resource. Various opportunistic scheduling algorithms have been proposed for 4G wireless networks; in particular, a PF scheduler for the UTRAN LTE is discussed in [13], where the authors compare the performance obtained with SU- and MU-MIMO.

2. System model

We consider an uplink SIMO system, in which K users are transmitting to a Base Station (BS). Users are assumed to be randomly scattered with uniform probability distribution over a disk of radius D centred at the BS. There are n_R antennas at the BS and the overall available bandwidth B is divided into N frequency bins. Time is slotted into frames of duration T_a and radio resources (power allocated to antennas and sub-bands) are allocated to users every frame for the whole frame duration.

OFDM carriers are grouped into the N frequency sub-bands, so that within each sub-band the channel can be reasonably approximated as flat fading (sub-band bandwidth $<$ coherence bandwidth). The radio channel model comprises a deterministic non selective attenuation inversely proportional to a power α of the distance between a user and the BS, and a frequency selective multi-path Rayleigh fading with coherence bandwidth B_c, correlation over time with coherence time $T_c > T_a$. Further details along with parameter numerical values are given in Section 5.

3. Proportional fairness

Given a set of K contending information flows that share a same link (wireless access to the BS in our case), a rate allocation $R_i, i = 1, \dots, K$ is said to be proportionally fair if for any other allocation $\tilde{R}_i, i = 1, \dots, K$ we have

$$\sum_{i=1}^{K} \frac{\tilde{R}_i - R_i}{R_i} \leq 0$$

i.e. the sum of the relative increments of flow rate is non positive. Even if for some flow there might be an advantage in terms of relative rate with the allocation $\tilde{R}_i$, there is no overall gain (at best). It can be shown that Proportional Fair (PF) allocation maximizes $\sum_i \log(R_i)$ under the constraint imposed by the overall capacity of the shared link.

In the context of wireless access to a BS, finding proportionally fair rates for the K users contending the access to the channel with overall power constraint P can be stated as the following optimization problem:

$$\begin{aligned} & \max \textstyle\sum_{k=1}^{K} \log R_k \\ & [R_1, \dots, R_K] \in \mathcal{C}(P) \\ & R_k \geq 0, \quad k = 1, \dots, K \end{aligned} \tag{3.1}$$

where $R_k = \mathbb{E}[r_k(t)], k = 1, \dots, K$, are the long-term average rates, $(r_1(t), \dots, r_K(t)) \in \mathcal{C}(t, P)$ are the instantaneous rates at time t, $\mathcal{C}(t, P)$ is the capacity region at time t (determined by the power constraints and the current channel state), $\mathcal{C}(P)$ is the ergodic capacity region.

It can be shown (see [7]) that a scheduler is PF if the instantaneous rate $\{r_1(t), \dots, r_K(t)\}$ maximizes:

$$\sum_{k=1}^{K} \frac{r_k(t)}{R_k} \tag{3.2}$$

Hence, our goal is to maximize the weighted sum rate $\sum_k w_k r_k$, where the weight w_k assigned to user k is an estimate of $1/\mathbb{E}[r_k(t)]$.

In the following we estimate R_k at frame $t+1$ by means of a simple exponentially weighted smoothing to deal with a time varying channel, i.e. $\hat{R}_k(t+1) = \beta \hat{R}_k(t) + (1-\beta) r_k(t)$, where $r_k(t)$ is the rate assigned at frame t to the k-th flow and $\hat{R}(\cdot)$ denotes the estimate of the long term average rate of the k-th flow.

So, the optimization problem solved in each allocation interval is of the general form:

$$\begin{aligned} & \max_{\mathbf{p}} \sum_{k=1}^{K} \frac{r_k}{\hat{R}_k} \\ & [r_1, \dots, r_K] \in \mathcal{C}(t, \mathbf{p}) \\ & \sum_{k=1}^{K} p_k \leq P \\ & r_k \geq 0, \quad k = 1, \dots, K \end{aligned} \tag{3.3}$$

where $\mathbf{p} = [p_1, \dots, p_K]$ are the transmission powers of the individual users.

4. Proportional Fair Scheduling algorithm

The resource allocation algorithm is based on an optimization problem statement, referred to each allocation interval of duration T_a. At the beginning of the j-th allocation interval the BS is assumed to have collected channel measurements of the K uplink paths from each user to the BS (Channel State Information, CSI) and the mean rate achieved by each user link $R_k(j), k = 1, \dots, K$.

Let $p_{k,n}(j)$ and $r_{k,n}(j)$ denote the allocated power and the corresponding achieved information rate for user k on frequency band n during allocation interval j ($k = 1, \ldots, K; n = 1, \ldots, N$). Let also $\mathbf{h}_{k,n}(j)$ be the channel coefficient vector of user k on frequency band n and time interval j; it is of size n_R and collects channel coefficients of the n_R paths from the transmitting antenna of the user terminal to each of the n_R antennas of the BS. Finally, let $w_k(j)$ be the weight of the k-th user, i.e. $w_k(j) = 1/R_k(j)$, according to the result in Section 3. In the following we drop the time argument j, unless more than a single interval is considered.

In the optimization problem we aim at guaranteeing proportional fairness as discussed in Section 3, so the objective function is defined as in (3.2). The assigned rates must lie in the capacity region of the multi-access system, given the power allocation and the channel state; moreover, we introduce a sum power constraint. The rationale for doing so in an uplink scenario is to control the interference due to the transmission of the tagged cell on other nearby cells [15]. So, we require that the amount of power used by all users operating in a given frequency band be no more than a given share of an overall power budget P. In the following we assume that the sum power over each frequency band is upper limited by P/N. The physical motivation for this kind of constraint is the limitation of the power spectral density of the interference induced by communications going on in the tagged cell towards other nearby cells[1].

Hence, the optimization problem can be stated as

$$\begin{aligned} &\max_{\mathbf{p}} \sum_{k=1}^{K} w_k \sum_{n=1}^{N} r_{k,n} \\ &\sum_{k=1}^{K} p_{k,n} \leq P/N, \quad n = 1, \ldots, N \\ &r_{k,n} \in \mathcal{C}(\mathbf{p}_n, \mathbf{H}_n) \\ &p_{k,n} \geq 0 \end{aligned} \tag{4.1}$$

where $\mathbf{p}_n$ is a vector made up of the powers $p_{k,n}$'s for a given n, $\mathbf{H}_n$ is a matrix whose columns are the channel coefficient vectors $\mathbf{h}_{k,n}$, $k = 1, \ldots, K$, and $\mathcal{C}(\mathbf{p}_n.\mathbf{H}_n)$ denotes the capacity region of the n-th frequency channel, depending on the assumed receiver structure.

In the following we compare three approaches:

- Orthogonal multiplexing, where at most a single user is allocated on a given frequency band (similar to SU-MIMO in the UTRAN LTE);
- Successive Interference Cancellation (SIC) receiver
- A heuristic based on a limited complexity SIC receiver, where at most ν users can share a given frequency band.

In the first case, we have $r_{k,n} = \log_2 (1 + p_{k,n} \|\mathbf{h}_{k,n}\|^2/\eta)$, for $k = 1, \ldots, K$, where η is the noise power in each frequency band. Therefore, in the orthogonal multiplexing approach, the optimization problem in (4.1) reduces to allocating the n-th frequency band to user k_n^* ($n = 1, \ldots, N$), where

$$k_n^* = \arg \max_{1 \leq k \leq K} w_k \log_2 \left(1 + \frac{\|\mathbf{h}_{k,n}\|^2 P}{N\eta} \right) \tag{4.2}$$

Note that $N\eta = N_0 B$, where N_0 is the noise power spectral density and B is the overall bandwidth available in the multiple access system.

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[1] In the uplink another natural constraint is on the power budget of individual users, i.e. $\sum_{n=1}^{N} p_{k,n} \leq P_k$; we do not take account of this constraint, so as to keep the analysis simple and focused on the overall performance/complexity trade-off under a fairness constraint; for similar approaches see [8] [9]

In the SIC receiver case, the capacity region is given by

$$\mathcal{C}\left(\mathbf{p}_n, \mathbf{H}_n\right) = \left\{ \mathbf{r} : \sum_{k\in\mathcal{S}} r_{k,n} \leq C_n(\mathcal{S}), \forall\mathcal{S} \subset \{1,\ldots,K\} \right\} \tag{4.3}$$

with $C_n(\mathcal{S})$ defined by

$$C_n(\mathcal{S}) = \log_2 \det\left(\mathbf{I} + \frac{1}{\eta}\sum_{k\in S} p_{k,n}\mathbf{h}_{k,n}\mathbf{h}_{k,n}^H\right) \tag{4.4}$$

where a superscript H denotes transposition and complex conjugate.

For a given user decoding order, let $\mathcal{A}_k$ denote the set of the first k decoded users and $\mathcal{B}_k = \{1,\ldots,K\} - \mathcal{A}_k$ the set of the last $K-k$ decoded users. Then $r_{k,n} = C_n(\mathcal{B}_{k-1}) - C_n(\mathcal{B}_k)$ for $k = 2,\ldots,K$ and $r_{1,n} = C_n(\{1,\ldots,K\}) - C_n(\mathcal{B}_1)$.

For the objective function considered in (4.1) it can be shown that the optimal decoding order is by increasing weight order (e.g. see [14]). In the following we assume users are numbered so that $w_1 \leq w_2 \leq \cdots \leq w_K$ in the tagged allocation time interval. Then, the optimal decoding order is $\{1,2,\ldots,K\}$ and the optimization problem can be re-stated as follows:

$$\begin{aligned} &\max_{\mathbf{p}} \sum_{k=1}^{K} \tilde{w}_k \sum_{n=1}^{N} \log_2\left(\mathbf{I} + \frac{1}{\eta}\sum_{j=k}^{K} p_{j,n}\mathbf{h}_{j,n}\mathbf{h}_{j,n}^H\right) \\ &\sum_{k=1}^{K} p_{k,n} \leq P/N, \quad n = 1,\ldots,N \\ &p_{k,n} \geq 0 \end{aligned} \tag{4.5}$$

where $\tilde{w}_k = w_k - w_{k-1} \geq 0$ for $k = 2,\ldots,K$ and $\tilde{w}_1 = w_1$. Thanks to the non-negativity of the $\tilde{w}_k$'s this can be shown to be a convex problem [16], so it can be reliably solved numerically. The problem can be also re-stated by introducing normalized powers $\hat{p}_{k,n} = p_{k,n}/\left(P/N\right)$:

$$\begin{aligned} &\max_{\mathbf{p}} \sum_{n=1}^{N}\sum_{k=1}^{K} \tilde{w}_k \log_2\left(\mathbf{I} + \frac{P}{N_0 B}\sum_{j=k}^{K} \hat{p}_{j,n}\mathbf{h}_{j,n}\mathbf{h}_{j,n}^H\right) \\ &\sum_{k=1}^{K} \hat{p}_{k,n} \leq 1, \quad n = 1,\ldots,N \\ &\hat{p}_{k,n} \geq 0 \end{aligned} \tag{4.6}$$

which makes it evident that the numerical evaluation of the optimal power assignment can be decomposed into N parallel optimization sub-problems, each one for a single frequency bandwidth.

A special case of these problems is obtained when the weights are set all equal to 1, i.e. no care is taken of fairness. In that case we refer to Maximum Throughput (MT) optimization problem, since the objective function is the sum rate. The problem decouples over the frequency bands, specifically:

$$\bar{R}_k^{MT}(N,P) = \mathbb{E}\left[\sum_{n=1}^{N} r_{k,n}(t)\right] = N \cdot \bar{R}_k^{MT}(1, P/N)$$

where $\bar{R}_k^{MT}(N,P)$ is the long-term average throughput of link k with MT optimization, N frequency bands and overall power budget P and the expectation is taken over radio channel realizations. This simple relationship does not carry over to the case where fairness (PF) is tackled by introducing adaptive weights. In fact, those weights are updated according to the rate obtained by each user on *all* frequency bands.

As for the limited complexity SIC, we assume that up ν users can be separated by the receiver by means of cancellations. So, each frequency band can host up to ν concurrent user links in each allocation time interval. The transmission powers of the users sharing a same frequency band are set according to SIC optimization. The heuristics comes into play to select which users should transmit in each frequency band. To this end, we find the ν users that would attain the best capacity in the frequency band n, given their radio channel coefficients and the available power budget. Let $C_{k,n}(p) = w_{k,n} \log_2(1 + \|\mathbf{h}_{k,n}\|^2 p/\eta)$ and $C_{\kappa_1(n),n}(P/N) \geq C_{\kappa_2(n),n}(P/N) \geq, \ldots, \geq C_{\kappa_K(n),n}(P/N)$. Then we allocate users indexed as $\kappa_1(n), \ldots, \kappa_\nu(n)$ to frequency band n. Let $\mathcal{S}_n(\nu)$ be the set of selected users for frequency band n. The optimization problem solved for each frequency band is the same as full SIC in (4.5) except that the set of involved users to be used is $\mathcal{S}_n(\nu)$ instead of $\{1, \ldots, K\}$.

5. Results

We present simulation results to show the performance of the Proportional Fair scheduling algorithm with the three approaches discussed in Section 4: orthogonal multiplexing, SIC receiver, heuristics based on a limited complexity SIC receiver. In the latter case we assume $\nu = 4$, i.e, up to 4 users can be separated by the receiver; this approach will be denoted as SIC4 in the following. We simulated a single-cell system, in which $K = 10$ Mobile Terminals (MTs) are uniformly scattered over a cell with radius $D = 400\ m$. The simulations have been carried out with traffic in saturation (i.e., the MTs always have data to send). The BS has perfect knowledge of Channel State Information (CSI). A resource allocation frame has a duration $T_a = 10\ ms$. The OFDM signal spans a bandwidth $B = 20\ MHz$ at a carrier frequency $f_0 = 2.4\ GHz$.

The wireless channel is modelled as a Rayleigh fading channel, consisting of L independent Rayleigh multipaths. The rms delay spread is $\sigma_\tau = 0.25\ \mu s$, typical of an urban environment; thus the coherence bandwidth is $B_c \approx 1/(2\sigma_\tau) = 2\ MHz$. The power delay profile is exponentially decaying; the power of the l-th path is $\sigma_l^2 = \sigma_h^2 \exp(-l/\sigma_n)$, $l = 1, \ldots, L$ where σ_h^2 is a normalization factor, chosen such that the average power of the channel is normalized to the value of the path loss, $\sigma_n = \sigma_\tau / T_s$ is the normalized delay spread, $T_s = 50\ ns$ is the OFDM sampling time, and $L = \lfloor 3\sigma_n \rfloor$ is the number of paths taken into account. The time-variant nature of the fading channel has been obtained by shaping its power spectral density $S(f)$ with an elliptic filter that approximates the Jakes function filter response: $S(f) = 1/\left(\pi f_D \sqrt{1 - (f/f_D)^2}\right)$, $|f| \leq f_D$; here f_D is the Doppler spread, $f_D = v/\lambda$, where v is the speed of the mobile terminal and λ is the signal wavelength. Simulations have been carried out for terminals moving at a speed $v = 3.6\ km/h$; thus the coherence time is $T_c = 1/(4f_D) = 31.25\ ms$, corresponding to 3 allocation intervals. Channels are assumed to be uncorrelated across users and across receive antennas. Deterministic path loss has been taken into account, with a path loss exponent $\alpha = 4$.

Figures 1(a) and 1(b) show the total system throughput versus the sum power P, for 1 and 4 receive antennas respectively. With 1 antenna the system capacity is maximized by having only the best user transmit on each sub-band; thus the SIC and orthogonal approaches coincide. This is not the case with 4 receive antennas: the orthogonal multiple access is always suboptimal, since it suffers from its inability to exploit the available spatial degrees of freedom, i.e. it cannot trade-off diversity gain offered by multiple antennas for multiplexing gain on each subchannel. This is evident at high SNR, while for low SNR the

SIC receiver provides very little capacity gain over the orthogonal approach. Note that the heuristic approach with a limited-complexity SIC receiver is almost optimal. In fact, as shown in Figure 3(a), the average number of users simultaneously transmitting on the same frequency channel with SIC4 and the MT scheduler is very close to the number of users selected with SIC; this suggests that limiting the number of separable users to 4 has a negligible impact on performance. Note that, although the Maximum Throughput policy is inherently unfair, with multiple antennas and a SIC receiver the fraction of starved users (i.e., users never scheduled to transmit) decreases as the power budget increases (see Figure 2(b)). In other words, having multiple antennas at the BS has a positive impact on fairness, provided that we manage to exploit their ability to multiplex users.

As expected, the PF scheduler suffers from a performance penalty with respect to the MT scheduler; this is the price to pay in order to achieve some level of fairness among users. Adopting an orthogonal multiple access causes a more severe performance loss than with the MT scheduler; this arises from the fact that, as shown in Figure 3(b), with the SIC receiver a larger number of users are simultaneously selected for transmission.

A further insight is offered by Figure 2(a), which shows Jain's throughput fairness index[2] versus the sum power constraint, with the PF scheduler. The orthogonal multiplexing achieves a fairer throughput distribution among users than the solution based on limited complexity SIC; the latter is in turn fairer than SIC. This is due to the PF enforcement, which makes the BS assign capacity also to users with inferior channels; if a high degree of parallelism is enabled by the receiver complexity (i.e. SIC), then best channel users keep transmitting anyways; in the case of orthogonal multiplexing (at most one user per sub-band), the performance improvement of users with a poor channel is obtained to the expense of users experiencing a good channel, thus limiting performance. Jain's fairness index in Figure 2(a) should be compared to the results in Figure 2(b) to get a full picture of the unfairness of the MT scheduler.

It is interesting to compare the performance of the limited complexity algorithms with that of the full SIC. The throughput loss experienced with the orthogonal approach is maximal with 4 antennas and at high SNR, with both schedulers. At low SNR and with the MT scheduler the orthogonal multiple access approaches the capacity provided by the more complex schemes; however, with the PF scheduler the loss remains significant even at low SNR. The heuristic based on a limited complexity SIC receiver is almost optimal when used with the MT scheduler; in this case the optimal solution with the SIC receiver concentrates transmission power on a few users, and the choice made by our heuristic appears to be very good. With the PF scheduler the limited complexity SIC heuristic shows some performance loss, but it behaves significantly better than the orthogonal approach, especially at high SNR.

Another interesting result pointed out by Figure 3(b) is that the SIC receiver (even in the limited complexity SIC4 version) with multiple antennas tends to make all users transmit simultaneously, even at relatively low power budgets. This points out the pathway to high capacity systems, even under fairness constraints; it also indicates that wireless access can be modelled as a weighted processor sharing server from the point of view of upper layers.

6. Conclusion

In this paper we considered the design of a Proportional Fair (PF) scheduler for the uplink of an OFDMA cellular system, with multiple antennas at the BS, and compared the performance obtained with a receiver with Successive Interference Cancellation (SIC) at

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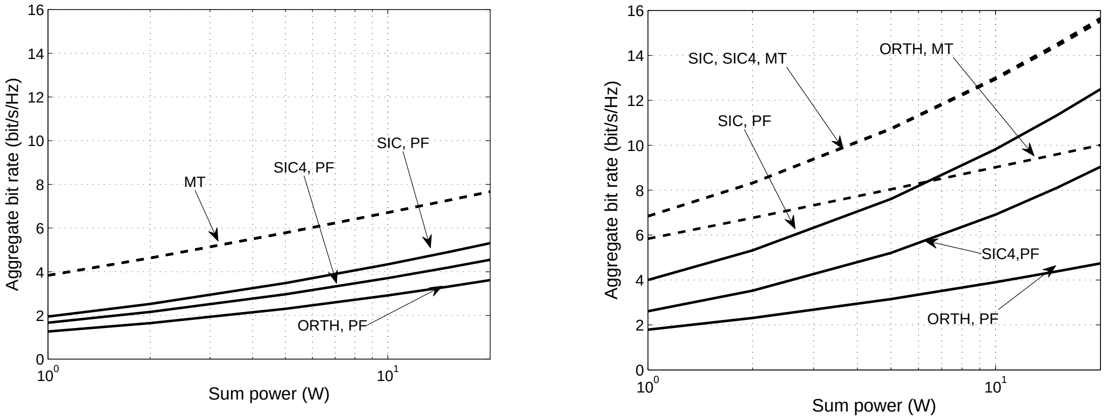
[2] Computed as $\left(\sum_{i=1}^{K} x_i\right)^2 / \left(n \sum_{i=1}^{K} x_i^2\right)$, where x_i is the average throughput of user i.

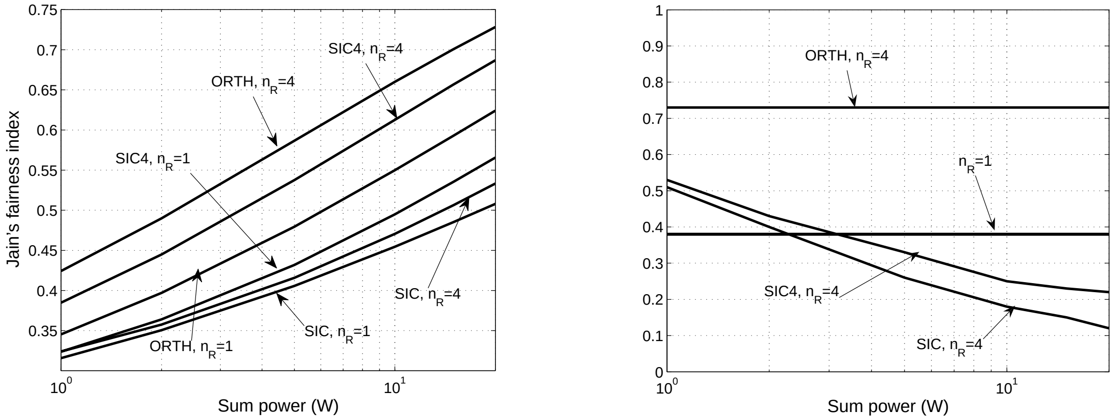
the BS, with that obtained with two simpler schemes: a limited complexity SIC receiver and an orthogonal multiplexing scheme. In order to reduce the intercell interference, we introduced a sum-power constraint for users transmitting on the same frequency sub-band. Results have shown that the orthogonal approach leads to a substantial performance loss, particularly at high SNR, while the proposed SIC heuristic represents a good tradeoff between performance and complexity. This suggests that orthogonal solutions (e.g., SU-MIMO in the UTRAN LTE) are ineffective at leveraging the benefits of multiple antennas, particularly when the scheduler aims at achieving fairness among users. In the future we intend to study the power allocation strategies resulting from introducing individual power constraints, in addition to the sum power constraint already taken into account in the present work. We also aim at deriving analytic expressions for the optimal allocated powers with the PF scheduler, based on asymptotic analysis. Finally, we are currently investigating how the introduction of a sum power constraint can be used to manage the interference and to achieve a fair allocation of resources in a multicell system.



(a) 1 antenna

(b) 4 antennas

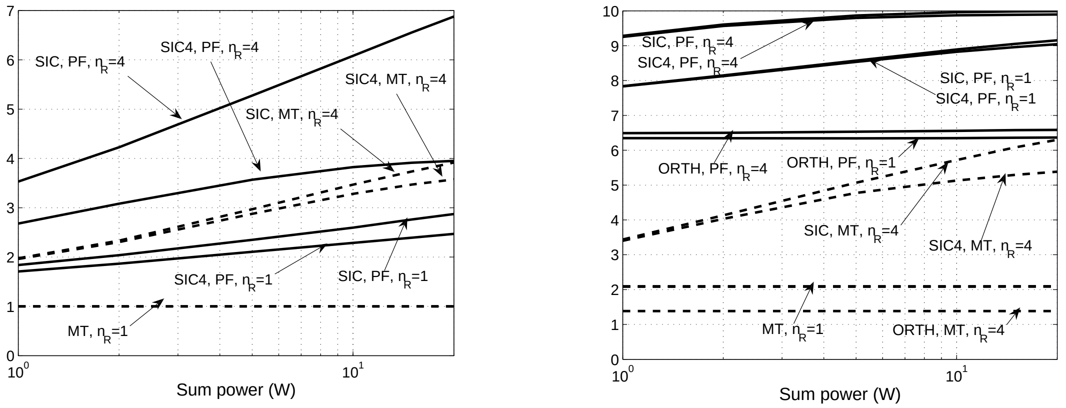
Figure 1. Sum rate vs sum power for MT and PF schedulers



(a) Jain's fairness index on user rates vs sum power, PF scheduler

(b) Fraction of starved users vs sum power, MT scheduler

Figure 2. Measures of fairness for the PF and MT schedulers



(a) Per frequency channel *(b) Per allocation interval*

Figure 3. Average number of served users

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