

A Fair Score-Based Scheduler for Spatial Transmission Mode Selection

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Abstract—Multi-antenna radio systems which are capable to select the spatial transmission mode according to the current channel conditions promise to achieve high transmission rates. Considering multiple users, the rates can be further increased if the multi-user diversity is properly utilized. However, fairness constraints have to be taken into account here to ensure that each user will be assigned any resources at all. We present a score-based scheduling solution which enables to adapt the degree of fairness supposed to be provided in the resource allocation process, and which further supports spatial transmission mode selection to attain a high overall throughput.

I. INTRODUCTION

Multiple-input multiple-output (MIMO) radio systems offer spatial diversity, which can be utilized either to improve the quality of a single transmitted spatial data stream (referred to as diversity mode), or to enable the simultaneous transmission of multiple spatial data streams (spatial multiplexing mode, SMUX). In [1] a fundamental tradeoff between these two different modes has been pointed out, revealing that the best mode to be selected in order to maximize the capacity depends on the actual channel state. This fact motivated the development of an adaptive transmission system which is capable to select the transmission mode based on (limited) feedback on the actual channel quality at the receiving stations [2]–[5]. The system concepts herein consider single user links ([5] additionally considers a basic multi user link with two users); however, the basic idea may also be applied in multi user systems, offering additionally the possibility to benefit from multi user diversity. In such a system, the simultaneously transmitted streams in the SMUX mode may be assigned to different users, enabling space division multiple access (SDMA). The switching option then translates to transmitting either a single stream exclusively to one user (diversity mode) or transmitting multiple streams to arbitrary users (SDMA). In [6] a multi user system with single-antenna terminals is considered, and it has been shown that in the low SNR regime it is in the information theoretic sense optimal to transmit a single stream to a single user only, while with increasing SNR additional SDMA users should be supported. This finding suggests that the concept of transmission mode switching may also have a high potential in a multi user scenario.

While in a single user system a suitable metric enabling the selection of the transmission mode is the maximum achievable

throughput, in a multi user system this metric might lead to an unfair assignment of resources, as users experiencing bad channel conditions might not be assigned any resources at all. To provide fairness within the user selection process, a proportional fair scheduling policy can be applied, which enables each user to realize a constant fraction of his total achievable rate [7]. A scheduler yielding (asymptotically) proportional fairness is the score-based scheduler [8], which is favoured for implementation due to its simple structure and its efficiency.

In this paper, we combine the concept of mode switching with the score-based scheduling approach to realize a concept for the downlink of a multi-user MIMO-OFDM system aiming at a high throughput while meeting desired fairness constraints. The system concept and its basic fundamentals are sketched in section II. Section III presents the score-based scheduler with transmission mode switching. Investigations on link-level have been carried out exemplarily for a 2×2 MIMO configuration, found in section IV. Section V ends with the conclusions.

II. SYSTEM CONCEPT

Consider the downlink of a multi-user MIMO-OFDM system, where base station (BS) and terminals both are equipped with multiple antennas. Let the system bandwidth be subdivided into single sub-bands called chunks, each one consisting of a fixed number of contiguous subcarriers. The chunks form the basic scheduling resources that can be individually assigned to distinct users. Each chunk is processed separately and thus may support an individual spatial transmission mode. The spatial transmission modes supported in the chunks are termed as single stream (diversity mode) and multi stream mode (SDMA). Thanks to the multiple antennas at the terminals, the latter mode also comprises transmitting multiple streams to a single user now.

We further consider the system to operate in frequency division duplex (FDD) mode, hence the channel is assumed to be perfectly known at the receiving terminals only. To establish a system where partial CSI at the BS can be obtained with a comparably low amount of feedback, we resort to the concept of opportunistic beamforming proposed in [7]. Here, the BS provides a set of beams and the terminals simply report the beam index and the corresponding SINR

that best fits their actual channel condition. In contrast to the original concept using random beams, we apply the Grid of Beams (GoB) concept presented in [9]. Here, the set of beams provided by the BS is confined to a fixed set of unitary beams. Based on these fixed beams, the terminals can evaluate the channel per chunk and determine the rates they are able to achieve in the different spatial modes with the single beams. Each user conveys information on the achievable rates and the selected beams to the BS which then carries out the user scheduling process.¹ To simplify the concept, we assume linear equalization techniques to be applied at the multi-antenna receivers, which comprise maximum ratio combining (MRC) for single stream mode and minimum mean square error (MMSE) equalization for multi stream mode. For these techniques closed form expressions for the post-detection SINRs of the spatial streams exist, facilitating the evaluation and proper comparison of the rates that can be attained with the different spatial modes.

The scheduling process is based on the score-based scheduling strategy [8], which is a simple heuristic process aiming at assigning each user its best resources from a resource block defined over frequency and time: The resources of each user within the resource block are ranked by their quality, and corresponding scores are assigned. The BS then assigns a resource to the user providing the best score. In the mean, this scheduling strategy assigns an equal amount of resources to each user, enabling them to realize a constant fraction of their total achievable rate and thus yielding (asymptotically) a performance similar to the one of the proportional fair scheduler [7]. In our system, we confine the resource block to the frequency domain only, hence all users will be scheduled within one time-slot, establishing instantaneous fairness on time-slot level.

III. SCHEDULER WITH SPATIAL MODE SELECTION

Let the BS be equipped with N antennas and provide a set of $B = rN$ fixed beams, where r is an integer number specifying the number of available unitary beam sets. The user terminals are equipped with M receive antennas, enabling the simultaneous reception of as many spatial streams in the SMUX mode. Channel evaluation and transmission mode selection are performed in a 2-step algorithm depicted in Fig. 1. The first step (top figure) is carried out at the terminals. In each chunk, represented by the different layers in the figure, the users evaluate their channel H and determine the rates they are able to achieve by applying the different spatial transmission modes: For the single stream (ss) GoB mode, each beam \mathbf{b}_i from the B total available beams is picked and the corresponding post-detection SINR based on MRC is determined as

$$\text{SINR}_{ss,i} = \frac{P_s}{N_0} \|H\mathbf{b}_i\|^2, \quad i \in \{1, \dots, B\} \quad (1)$$

¹A system concept based on a similar setting has been investigated and analyzed in [10]. However, the authors did neither consider mode switching nor took any fairness-sensitive scheduling into account.

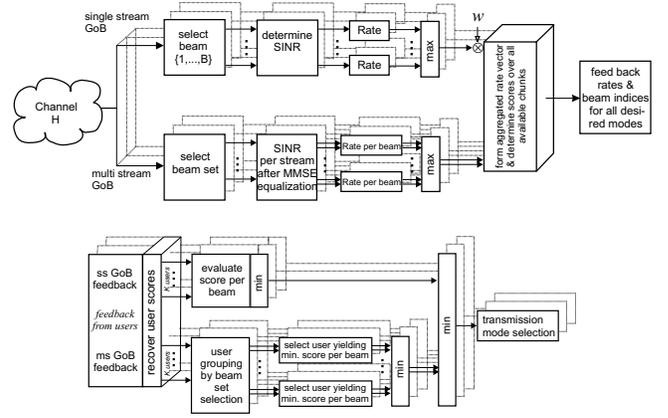


Fig. 1. Top: Step 1 - Determination of the scores at the user terminals. Bottom: Step 2 - Transmission mode selection at the base station

where $\|\cdot\|^2$ is the Euclidean norm, P_s is the total available transmission power per chunk and N_0 is the power of a white Gaussian noise process. From these SINR values the achievable rate is determined per beam; the maximum specifies the favoured beam for this transmission mode.

For multi stream (ms) GoB mode, we assume that Q unitary beams are served in parallel with equal transmit power P_s/Q per beam. If $Q < N$, there is a total of $n = \binom{N}{Q}$ sets of unitary beams. The following evaluation is done for each of the n sets of beams separately. For the equalization of the beams $\mathbf{b}_i, i \in \{1, \dots, Q\}$ in one set, we use the MMSE equalizer, which is defined by

$$\mathbf{w}_i = Z^{-1}H\mathbf{b}_i, \quad Z = \frac{QN_0}{P_s} \cdot I + \sum_{k=1}^Q H\mathbf{b}_k\mathbf{b}_k^H H^H \quad (2)$$

where $(\cdot)^H$ is the conjugate transpose operator and I is the identity matrix. The post-detection SINR for each beam \mathbf{b}_i then is given by

$$\text{SINR}_{ms,i} = \frac{\|\mathbf{w}_i^H H\mathbf{b}_i\|^2}{\mathbf{w}_i^H Z \mathbf{w}_i - \|\mathbf{w}_i^H H\mathbf{b}_i\|^2} \quad (3)$$

From the obtained SINRs, we can once again determine the achievable rate for each beam. To find the M beams which are best suited for SMUX transmission for this user, we determine first the M beams achieving the highest rate in each of the n sets and finally select the beam set where the sum rate of all M selected beams is maximum.

Next, the scores for all available resources have to be determined from the rates, which are later used for the resource assignment at the BS. Within this resource assignment process, the spatial transmission mode per chunk should be selected implicitly; hence a single score set is used to rank the user rates from all possible transmission modes over all chunks. For the implicit mode selection aiming at a high throughput for that user, a direct comparison of the single rates achievable with the different transmission modes needs to be enabled. That means, we have to account for the fact that each mode supports a different number of simultaneously active streams. We thus introduce a penalty factor w used to weight the

rates of single stream mode. The value at hand to be used for w is $w = 1/Q$, which is indeed a good choice if we aim at maximizing the achievable user and system throughput for the case that all users applying for resources have the same mean SNR. However, in general tuning the penalty factor directly influences the selection probability of the single stream mode, and hence it can be optimized with respect to any desired measure, where the result will strongly depend on the considered application scenario.

The rates from all chunks are aggregated into one vector, which is sorted by magnitude in descending order. The index within the sorted vector represents the score of each rate. Optionally, the user may now make a selection of the best resources based on the determined scores, which could be used to further reduce the amount of feedback. For all selected chunks, the user finally feeds back the achievable rates for the desired transmission modes as well as the corresponding beam indices.

The second step of the process comprises the scheduling and is carried out at the BS (Fig. 1 bottom), which collects the feedback information from K users. First, it recovers the user scores from the provided rates for the selected chunks. The resource allocation with transmission mode selection then is carried out for each chunk separately: For single stream mode, the favoured user is the one providing the minimum score. For multi stream mode, users that chose the same beam set are put into one group, which is evaluated separately. Each of the Q available beams is assigned to the user in the group providing the minimum score for that beam. We then calculate the sum scores per group and pick the group with the minimum sum. Finally we compare the minimum score of the Q users in the selected group with the minimum score from the single stream user and select the transmission mode yielding the absolute minimum. The decision on the mode and the user allocation per chunk is then signalled forward to the user terminals, who may then configure their receiver accordingly.

A. Fairness steering

The score-based scheduler described above aims at assigning each user the same amount of resources, where it focusses on the ones with highest quality. Hence, each user will be able to realize about the same fraction of his total achievable rate. By introducing a weighting of the user scores at the base station (step 2), we can directly influence the degree of fairness the scheduler will aim for. As an example, let us consider an equal rate scheduling target here. To direct the scheduler towards this target, we can force it to apply a resource assignment according to the 'Robin-Hood principle', where resources are taken from high rate users and given to low rate users in order to improve their realizable rate. Specifically, this can be achieved by weighting the scores of the users by a factor proportional to the achievable rate of each user. This yields an assignment of more resources to users with lower rate at the cost of high-rate users. The proposed weighting follows not only from an intuitive perspective, but also as the solution from an adequately defined (however

simplified) MMSE problem given as follows: Let R_k be the mean achievable rate per chunk for user k and u_k the number of resources assigned to that user, then the realizable rate r_k per user can be approximated by $r_k = R_k \cdot u_k$. Further, let u_1 be the resources assigned to user 1, whose scores remain unweighted (weighting factor 1). Then the resources assigned to user k , whose scores were weighted with w_k , result in the mean in $u_k = w_k^{-1} \cdot u_1$. The sum of the resources from all K users is constrained to U , hence $u_1 \cdot \sum_{k=1}^K w_k^{-1} = U$ must hold (with $w_1 = 1$ by definition). The equal rate requirement for the realizable user rates can be given in form of an MSE expression that is to be minimized, $\|r_k - c\|^2 \forall k$, where c is a constant expressing the equal rate target. The MMSE problem thus is given as

$$\min_{w_k} \sum_{k=1}^K \|R_k \cdot w_k^{-1} u_1 - c\|^2 \quad \text{s.t.} \quad u_1 \cdot \sum_{k=1}^K w_k^{-1} = U \quad (4)$$

where we seek for w_k , $k \in \{1, \dots, K\}$, yielding the solution $w_k \sim R_k$.

To apply the weighting yielding the equal rate target within our scheduling process, we define an iterative approach: The scheduling routine is carried out once with the original (i.e. unweighted) scores, yielding the realizable rates r_k for each user. These rates are normalized to the minimum rate in the time slot, $r_{min} = \min_k r_k$, and then used to determine the user-specific weighting factors. Introducing another tuning parameter $q \in [0, 1]$ enables to specify the intensity of the fairness steering, so that the weighting factors finally yield:

$$w_k = q \cdot r_k / r_{min} + (1 - q) \quad (5)$$

Each user score vector is then multiplied with the corresponding weighting factor w_k and the scheduling process is rerun. After obtaining the new result, the entire weighting process could be repeated to achieve further improvements, thus establishing an iterative scheduling procedure. The final result as well as the speed of convergence will depend on the tuning parameter q , which could be optimized for any specific application scenario considered (i.e. number of users, user distribution in cell, SINR distribution etc.).

IV. INVESTIGATIONS ON LINK-LEVEL

A. Link-level assumptions

The properties of the modified score-based scheduler are investigated in a single-cell link-level simulation environment. Exemplarily, we focus on a system setup with K user terminals being equipped with $M = 2$ antennas each and a BS with $N = 2$ antennas, which provides one unitary beam set with $B = 2$ beams, defined as $\mathbf{b}_1 = 1/\sqrt{2} \cdot [1 \ i]^H$ and $\mathbf{b}_2 = 1/\sqrt{2} \cdot [1 \ -i]^H$. Possible multi stream modes thus are 2-user SDMA or dual stream SU-MUX. All users are assumed to experience independent channels with mean energy of unity; hence the mean reception SNR is equal to P_s/N_0 for all users. For the channel modelling we use the channel model provided by the European WINNER project (WIM) in its configuration for wide area urban macro scenario. This model assumes

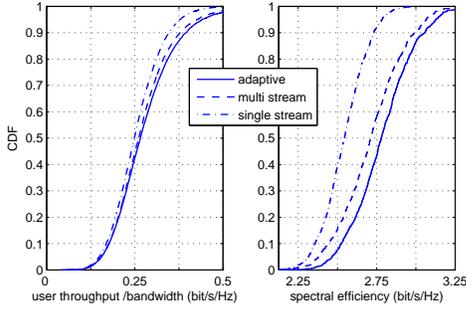


Fig. 2. CDFs of the achievable user throughput (left) and spectral efficiency in cell (right) based on Shannon information rates. $K=10$ users, $\text{SNR} = 0$ dB.

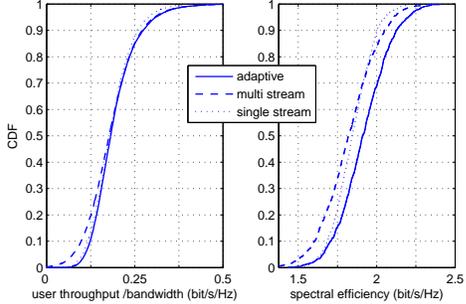


Fig. 3. System performance based on quantized rate mapping function.

a uniform linear antenna array; antenna spacing was set to 4λ , yielding a low degree of correlation between the antenna paths. An OFDM system with 1024 subcarriers spanning a bandwidth of 40 MHz is assumed, accommodating 128 chunks of 8 subcarriers width. The per-stream SINR ρ for the different transmission modes obtained from (1) and (3), respectively, are averaged over the chunk as described in [5]. The corresponding achievable rates are then determined via the Shannon information rate $\log_2(1 + \rho)$. Alternatively, to obtain rates that are closer to the ones achievable in practice, via a quantized rate mapping function presented in [11]. This rate mapping function is based on a puncturable LDPC code with constant blocklength of 1152 bits and supports the fixed symmetric modulation formats up to 64QAM. The discrete steps of the mapping function are derived from the SINR values required to meet a block error rate performance of 10^{-2} in an equivalent AWGN channel. Due to the limited blocklength of the code as well as the modulation formats, the rates supported by the mapping function are also limited to a minimum of 0.5, corresponding to a BPSK modulation with code rate 0.5, and a maximum of 5.538, achieved by 64QAM modulation with code rate 24/26. Simulation results are obtained from a total of 10,000 independent channel realizations.

B. Performance of spatial mode switching

First we examine the system performance of the adaptive system described above in the low SNR regime $P_s/N_0 = 0$ dB, which is relevant for cell-edge users. We expect the benefits from switching to single stream mode to become prominent here. Fig. 2 presents cumulative distribution functions (CDF) of the achievable user throughput divided by the

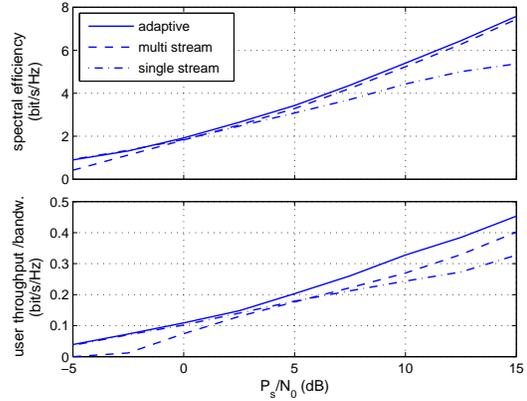


Fig. 4. Throughput performance vs. SNR. Top: mean spectral efficiency in cell, bottom: 5-percentile of user throughput. Quantized rates, $K=10$ users.

signal bandwidth (left) and the spectral efficiency within the cell (right) for $P_s/N_0 = 0$ dB for $K = 10$ users. We compare the adaptive system described above to a system supporting solely either single stream or multi stream transmission. For the user throughput (left), we observe that the performance benefits from switching in the region where the CDF is above 0.5. Further, for the CDF region below 0.2, the single stream curve is nearly identical to the multi-stream curve; hence no gains from switching can be realized here. This observation can be explained as follows: In the low SNR regime, we can expect that the SINR of the selected beam for single stream mode is about twice as large as the SINR ρ for the corresponding beam in multi stream mode. Moreover, in multi stream mode the amount of beams assigned to each user is twice as large as in single stream mode. As for $\rho \ll 1$ the relation $\log_2(1+2\rho) \approx 2 \log_2(1+\rho)$ holds, the rates achievable with the two different modes are nearly identical. Considering the spectral efficiency within the cell (right subfigure), we observe that the adaptive system benefits significantly from the mode switching over the entire CDF region.

Fig. 3 depicts performance curves for the same setting, but this time the quantized rate mapping function is used. For the user throughput (left), we observe here that the CDF of the adaptive system represents a hull curve of the two others supporting a single mode only. As the minimum supported rate to be assigned is now bound to 0.5, the adaptive system now significantly gains from switching to single stream mode if the SINR conditions are low (left region of the CDF curve). The CDF of the adaptive system is quite close to the one supporting single stream mode only, suggesting that this mode is predominantly chosen at low SNR. Considering the spectral efficiency in the cell (right figure), only the left tail of the adaptive system's CDF approaches the curve of the pure single stream mode. In the remaining region, substantial gains from mode switching become visible.

To examine the performance for varying SNR, we focus on the mean spectral efficiency in the cell as well as on the 5-percentile of the user throughput CDF, which represents the rate achievable by users experiencing relatively bad SINR conditions. For quantized rate mapping and $K = 10$ users,

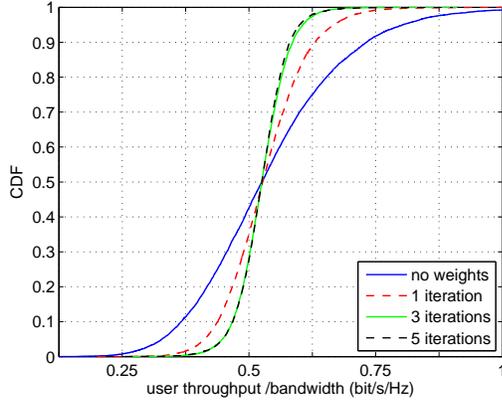


Fig. 5. Fairness steering with $q = 0.5$ for $K = 10$ users and $\text{SNR} = 10$ dB.

these measures are depicted versus P_s/N_0 in Fig. 4. From both figures, we observe that in the low SNR region the single stream mode is predominantly chosen. At about 0 dB, the adaptive system frequently switches to multi stream mode and thus improves the overall system performance significantly compared to the single mode systems. This improvement above 0 dB SNR is most prominent in the 5-percentile user throughput.

C. Steering the fairness to equal rate

We examine here the behaviour of the scheduler if we apply the fairness steering option to achieve an equal rate scheduling target as described in section III-A. For the tuning factor, we chose $q = 0.5$ to enable a rather smooth redistribution of the resources in each iteration step. Investigations have been carried out for a mean SNR of 10 dB and $K = 10$ users applying for the resources of one time-slot. The results in terms of the CDF of the finally realized user rates are depicted in Fig. 5. We observe that after the first iteration the CDF significantly gains in steepness and thus conveniently approaches the equal rate target. Furthermore, we observe that the characteristics can indeed be improved further if additional iterations are performed. With the chosen tuning factor, the routine seems to converge quite rapidly, as we cannot identify further improvements after 5 iterations. Most interestingly, note that median user throughput (achieved at the point where the CDF has the value 0.5, for symmetrical distributions equal to the mean) does not change due to the applied weighting, highlighting the convenient redistribution of the resources.

D. Capacity scaling of the adaptive system

We examine the capacity achievable with the adaptive system and compare it to the upper bound, which is the capacity of the 2×2 broadcast channel (BC) when full CSI is available at the receivers as well as the transmitter. In [12], [13] it was shown that the capacity of the BC can be achieved with the dirty paper coding technique (DPC), and in [14] an algorithm was presented to compute it in an iterative fashion for any given set of user channels. We have used this algorithm to obtain the upper bound, which is depicted in Fig. 6 versus the SNR for $K = 10$ users. To obtain the achievable capacity

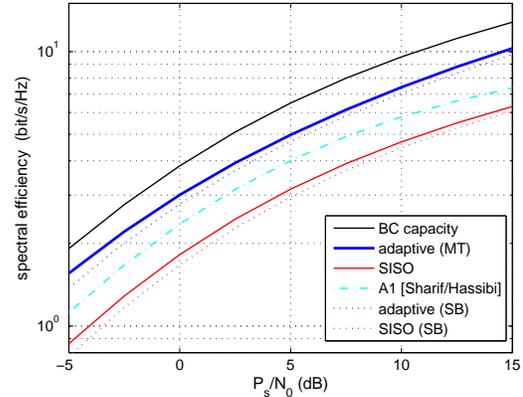


Fig. 6. Comparison of the capacity for various systems vs. SNR. $K=10$ users, Shannon information rates.

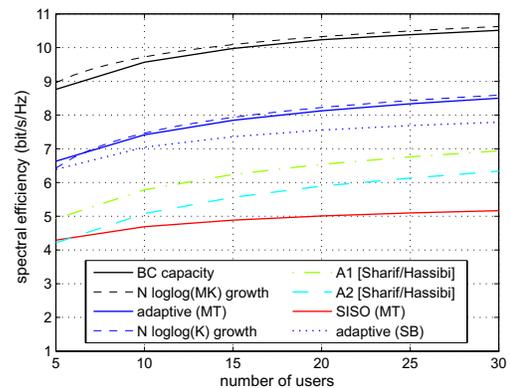


Fig. 7. Capacity scaling with number of users at $\text{SNR} = 10$ dB.

of our adaptive system, we applied Shannon's information rates and carried out a maximum throughput (MT) scheduling based on the reported rates at the BS, which selects for each chunk the user (single stream) or user constellation (multi stream) that achieves the highest throughput in that resource. In Fig. 6 we observe that for an SNR above 0 dB, the capacity of our adaptive system achieves a constant fraction of the capacity of the BC, which amounts to about 80%. Additionally, we included the capacity of the SISO channel achieved in an equivalent scenario. While we observe here that the capacity of the BC scales with factor 2 (corresponding to $\min(M, N)$) compared to the capacity of the SISO channel in the high SNR range, the capacity of our adaptive system scales with factor 1.6. For comparison, we also added the spectral efficiency achievable with the fair score-based (SB) scheduling technique. It can be seen that the price we have to pay to obtain instantaneous fairness for all users is only marginal, as the loss in spectral efficiency is only about 5%.²

Finally, in Fig. 7 we examine the scaling of the capacity of the adaptive system with the number of users and compare it to several other systems. At first glance, the capacity seems to scale similarly as the BC capacity achieved with DPC. However, a closer look reveals slight differences, as the BC

²Note that this loss may increase substantially if users with different mean SNRs are considered.

capacity grows with a slope equivalent to $N \log \log(MK)$, which actually represents the scaling law for the BC capacity for large number of users as shown in [10], while the capacity of the adaptive system grows with a slope equivalent to $N \log \log(K)$. This observation suggests that compared to the BC capacity scaling, the scaling of the adaptive system is reduced by M degrees of freedom. This is also reasonable as we consider the $(M-1)$ additional receive antennas to be used for suppressing the interference from simultaneously active beams.

For comparison, we also show the capacity of the SISO system, which grows roughly with a slope of $\log \log(K)$ and thus less steep than the adaptive system. We also compare the achievable capacity of the adaptive system to two multi stream approaches with Q simultaneously active beams, which have been suggested and investigated for a similar system setup as the one presented here in [10]. The authors claimed that the first approach A1 achieves a capacity scaling similar to the BC channel if the number of users grows to infinity. The two approaches are as follows: A1) Each receive antenna at the mobile terminal is treated as an independent receiver. Hence, the per-antenna reception SINR is calculated for each beam, assuming that the other $(Q-1)$ active beams interfere. For each antenna, the terminal feeds back the best beam together with the corresponding SINR, and the BS assigns each beam to the user having provided highest SINR value for it. A2) The terminals carry out MRC for each received beam and determine the post-detection SINR afterwards; feedback and beam assignment as in A1. As nothing is done to combat the interference, the SINR conditions might become quite poor in this approach.

As derived analytically in [10], we observe from Fig. 7 that A1 performs significantly better than A2. We thus can confirm that it cannot be recommended to use MRC reception technique at a multi antenna terminal in case multiple beams are active within a cell. Comparing A1 to the adaptive system, we observe that the adaptive system achieves a significantly higher capacity, highlighting impressively the gains that can be achieved by using the additional receive antennas to actively suppress the interference from other active beams.

Finally we plotted the achievable spectral efficiency when applying the score-based scheduling. Although the loss in throughput to provide the desired fairness is not exceptionally high, we observe that the gap between MT and SB scheduling increases with increasing number of users. This is not very surprising, as with a growing number of users, the probability that a user experiencing bad channel conditions is present increases. The support of these users by the fair scheduler thus costs a growing share of the maximum sum capacity.

V. CONCLUSIONS

We have presented a concept for the downlink of a multi-user MIMO-OFDM system combining spatial transmission mode switching with a fair scheduling approach. Based on unitary fixed beamforming, the users report information on the achievable rates on distinct beams with the different modes

via a low-rate feedback channel. Performance evaluation has been carried out exemplarily for a 2×2 MIMO configuration, revealing significant gains in spectral efficiency as well as the user throughput due to the mode switching. We introduced a fairness steering, which can be tuned with respect to any desired fairness target the scheduler is supposed to provide, and showed its potential exemplarily for an equal rate target. The achievable capacity of the adaptive system has finally been compared to the capacity of the SISO, the MIMO broadcast channel and the reference systems given in [10], showing that the system effectively achieves a high performance with moderate complexity. The scheduling concept can also effectively be employed in a multi-cell environment, which has been investigated in [15].

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