Capacity Scaling of Multi-User MIMO with Limited Feedback in a Multi-Cell Environment

(Invited Paper)

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Abstract—We demonstrate that the fundamental capacity scaling law of multiple-input multiple-output radio systems, being proportional to the minimum of the number of receive and transmit antennas, holds also for the interference-limited multi-user multi-cell downlink scenario. It can be realized by using a sophisticated combination of physical and medium access control layer algorithms.

The algorithms have low complexity and require no coherent channel state information at the transmitter. Instead, limited feedback on the effective channel quality is provided via a low-rate control channel. Our set of algorithms offers a fixed grid of beams at the transmitter, where the terminals can select the best beam set. Further, we use receivers exploiting the instantaneous knowledge of the interference at the terminal side. A score-based scheduler, which asymptotically reaches proportional fairness, is used to switch adaptively between multi-user diversity and multi-user multiplexing, in a frequency-selective manner. We provide many insights into the synergy between these algorithms from multi-cell simulations in a hexagonal cellular deployment.

I. INTRODUCTION

The use of multiple antennas both at the transmitting and receiving ends of a wireless link has become increasingly mature in recent years. The fundamental capacity gain in the multiple-input multiple-output (MIMO) radio link, being proportional to the minimum of the number of transmit and receive antennas, is well understood for an isolated point-to-point link [1]. Existing and future wireless standards, as 802.11n, WiMax, 3G HSDPA and its long-term evolution (3G-LTE) have built-in means for MIMO signaling.

In order to offer broadband wireless access everywhere, MIMO transmission must be made robust in the interference-limited scenario. However, it is not yet fully evident how the potential capacity gains of MIMO can be realized under these conditions. In fact, early results indicate that the capacity gain of spatial multiplexing (SMUX) may not pay off compared to the classical spatial diversity (SDIV) in the interference-limited case. The additional intra-cell interference introduced by SMUX tends to reduce the spatial degrees of freedom to combat interference from other cells [2]. Further work illustrated that SMUX increases peak rates close to the cell center, while SDIV enhances the cell edge throughput. Hence, it might be helpful to switch between these two transmission modes, depending on the actual channel condition, as it has been previously proposed for noise-limited environments [3]–[7].

Joint "dirty-paper" pre-equalization achieves the capacity of the broadcast channel and it is considered an upper bound for multi-user transmission [8], [9]. For multi-cell applications, however, the base station would need coherent intra-cell channel state information, and also the inter-cell interference must be known in advance. Unfortunately, this information is available at the other side of the radio link. A distant mobile terminal, measuring these quantities at vehicular velocities in the downlink, may have limited power and hence a limited uplink capacity to feed back such complex information instantaneously to the base station. Consequently, in this paper, we consider MIMO equalization at the terminal side and feedback of post-equalization SINRs is provided. This approach reduces bandwidth and latency requirements for control channels.

SINR feedback is provided in a frequency selective fashion for all possible single- and multi-stream transmission modes as indicated in Fig. 1. The mode itself is always selected at the base station, using a score-based scheduling algorithm. This approach may easily be implemented and reaches the performance of the proportional fair scheduler asymptotically [10]. The original algorithm has been extended here to support multiple mode transmission, see also [11]. At the terminal, the most appropriate receiver algorithm is used.

The performance is investigated in a triple-sectored hexagonal cellular network, and the widely used spatial channel model (SCME) with urban macro scenario parameters is used [12]. This choice has been confirmed by measurements [13].
We have also compared the simulated interference scenario with drive-tests in real 3G networks where good agreement is found for dense urban network deployments.

Our results illustrate the advantages of frequency-selective scheduling. However, we point out that proportional fair scheduling policies are rather costly in a cellular network, compared to the throughput-maximizing approach. We illustrate the benefit of multi-antenna receiver algorithms that are aware of the interference (refer to optimal or interference rejection combining [14], [15]) and extend these algorithms to the case of multiple stream (ms) transmission. Compared to the single-input single-output (SISO) system, the capacity gain due to single stream (ss) transmission may be significant for cell-edge users and for users with singular channels. However, in this case there is hardly any further gain when using SMUX, where multiple streams are assigned to a single user, similar to [2]. Nonetheless, multi-stream transmission is valuable. It enables a new kind of multi-user transmission where parallel streams are transmitted from the base station intended for distinct users, which can separate these streams. These streams may be scheduled to distinct users, based on their feedback information. This mode is called multi-user spatial multiplexing (MU-MUX) [7]. It is selected frequently by the scheduler, even close to the cell edge, and it can be identified as one of the major driving forces enabling the multi-antenna capacity gain also for cellular networks. Highest gains and lowest outage are achieved when switching between all modes is allowed. In this way, the fundamental MIMO capacity scaling law, proportional to the minimum number of receive and transmit antennas, can be realized in a proportional fair sense for all users within a cell. Of course, there might be a small penalty attributed to the limited feedback.

The paper is organized as follows. In section II and III, the transmission and detection schemes of the physical layer are briefly described. Section IV sketches the fair score-based scheduling algorithm. Our multi-cell simulation environment and its validation by measurements are described in section V. Results are presented and discussed in section VI.

II. SYSTEM MODEL

Vectors are indicated by bold face small letters, e.g. \( \mathbf{h} \) is a column vector. Bold face capital letters are used to indicate matrices, e.g. channel matrix \( \mathbf{H} \). The Hermitian transpose of a vector or matrix, i.e. the complex conjugate transpose, is given by \( \mathbf{v}^H \).

Transmission over a frequency selective channel in the discrete time domain may be described by

\[
\tilde{y}(k) = \sum_{l=0}^{L-1} \mathbf{H}(l) x(k-l) + \tilde{\mathbf{n}}(k),
\]

where \( \mathbf{H}(l) \) is the channel matrix of tap \( l \), \( x(k) \) is the transmit symbol vector and \( \tilde{\mathbf{n}}(k) \) is the additive white Gaussian noise vector. The frequency equivalent channel matrix for each subcarrier \( \Omega \) in an orthogonal frequency division multiple access (OFDMA) system is given by

\[
\mathbf{H}(\Omega) = \sum_{l=0}^{L-1} \mathbf{H}(l) \exp(-j2\pi\Omega l/N),
\]

where \( L \) and \( N \) are the number of resolvable taps in the time domain and used subcarriers, respectively. This leads to

\[
y(\Omega) = \mathbf{H}(\Omega) x(\Omega) + \mathbf{n}(\Omega)
\]

In the following, we drop the frequency index \( \Omega \) and consider the multi-cellular and single-input multiple-output (SIMO) channels in the downlink with \( N_T = 1 \) and \( N_K = 2 \), for simplicity. Thus, the transmission system may be given by

\[
y_i^m = h_i x_i + \sum_{k \neq i} h_k x_k + \mathbf{n},
\]

where \( h_i \) and \( h_k \) are the channel vectors (SIMO) of the desired base station (BS) \( i \) and all interfering BSs for a specific user \( m \).

III. PHYSICAL LAYER ALGORITHMS

A. Overview of Spatial Modes

As a base line, single-antenna mobile terminals (MTs) and BSs are considered, refer to Fig. 2a. Note that a single-antenna MT is not capable to combat any cochannel interference (CCI).

As a next step, shown in Fig. 2b, multiple antennas are introduced at transmitter and receiver sides. The link now gains from signal combining of receive antennas, which can be either maximum ratio combining (MRC), as a simple technique applicable for all user scenarios, or interference rejection combining (IRC) with a higher complexity at the terminal side. At this point, single stream (ss) service is assumed. By introducing an adaptive single stream grid of beams (GoB) approach, one can serve a specific user out of \( M \) users with a specific beam chosen from a discrete set of \( B \) fixed beams. Assuming a low-rate control channel, the MT may select the most suitable beam.

Extending this approach to adaptive multiple stream (ms) GoB transmission, one can serve multiple users from the same BS on different spatial streams. This is the MU-MUX technique and is illustrated in Fig. 2c. MU-MUX includes single user spatial multiplexing (SU-MUX) as a special case, where all streams in a cell are assigned to the same MT.

Different users’ channel conditions result in different requirements for the receiver technique applied at the MT. In appendix I we discuss several receiver structures mathematically, while their application in the adaptive transmission system is described in the following.

B. Fixed Unitary Beamforming

Consider a BSs having a number of \( N_T \) transmit antennas. The coverage area may be served by a set \( B \) consisting of fixed unitary beams (GoB concept), formed at the BSs. Here
Fig. 2. a) single-input single-output system, b) multi-antenna terminals can use interference rejection combining to improve their performance, single stream GoB concept, c) multiple stream GoB serving mode, multiple users may be served within the same cell, i.e. MU-MUX.

Fig. 3. Block diagram for the adaptive transmission strategy. The terminals need to determine the achievable SINRs for single stream and multiple stream transmission.

we apply unitary beam vectors $\mathbf{b}_j \in \mathcal{B}$ derived from the DFT matrix.

By using beamforming at the BSs and assuming a low-rate feedback channel, the MT within the current sector may choose the set $\mathcal{B}_i \subseteq \mathcal{B}$, which maximizes the data rate. Depending on the scheduling algorithm, the BS may decide to serve a MT in single- or multi-stream mode on a specific resource. The number of active beams is indicated with $|\mathcal{B}_i|$, where the total number of unitary active beams must not exceed $N_T$. In order to model independent scheduling in adjacent cells, beam sets $\mathcal{B}_i \subseteq \mathcal{B}$ in other cells are chosen randomly. According to (5), effective channels are obtained to form the received signal $y_{j}^{(n)}$ belonging to the $n$-th MT, the $i$-th BS and $j$-th data stream. Hence, the MIMO system reduces to a SIMO system for each data stream $j$ transmitted from the $i$-th BS.

$$
y_{j}^{(n)} = \sum_{h_{n,i}} \mathbf{H}_{i,n} \mathbf{b}_j \mathbf{x}_i + \sum_{k \neq j} \mathbf{H}_{i,k} \mathbf{b}_k \mathbf{x}_k + \mathbf{n} \tag{5}
$$

C. Channel Quality Evaluation at the Terminal

Since the multi-cell performance of each transmission mode is user-, time- and frequency-dependent, it is reasonable to consider a fully adaptive spatial transmission mode selection, refer to Fig. 3. Each terminal determines the achievable transmission rate for single stream and multiple stream GoB transmission for each resource, based on the per-stream SINRs obtained from (8) (MRC) or (11) (IRC) for single stream GoB (SDV) and (14) for multiple stream GoB (SMUX), respectively.

The best receiver mode is determined at the MT, which reduces the feedback. In case of single stream transmission, the MTs may increase their data rates by choosing from IRC and MRC. For multiple stream transmission, the terminal uses IRC for each offered stream, separately, illustrated in Fig. 3. The use of successive interference cancellation (SIC) may be permitted by the BS and requires additional feedback (refer to section VI). Thus each user has to feed back the achievable rate for single stream and multiple stream transmission for each resource, i.e. the required feedback is $3 \times CQI \times$ number of resources with 2 transmit and 2 receive antennas.

The channel quality identifier (CQI) may be represented by quantized SINRs or the corresponding achievable rates.

IV. MAC LAYER ALGORITHMS

As a resource block (chunk), we define a fraction of the system bandwidth which may be assigned to distinct users during a given time period, e.g. a time slot has 0.5 ms in case of 3G-LTE. For a chunk, a fixed number of contiguous OFDM subcarriers is combined.

Consider now a number of $M = |\mathcal{M}|$ MTs assigned to a BS. To decide on the best transmission mode and resource assignment, the BS has to evaluate the entire feedback reported by the MTs. This may be done using different scheduling algorithms. A simple algorithm is to serve the users in a time-division multiple access (TDMA) round robin (RR) fashion, where all frequency resources are assigned to a single user for the duration of a time slot. After $M$ time slots, the same user is served again. This is a simple way to ensure fairness, however it is not optimal in terms of throughput. Since the channel conditions of users may change over frequency, i.e. the individual channels fade independently, a frequency-dependent resource assignment is more promising in order to maximize the throughput.

The system’s throughput is maximized by assigning a given resource solely to the user having the best channel quality on that resource, which is often referred to as frequency-division multiple access (FDMA) based maximum throughput scheduling.

On the other hand, maximizing the throughput alone does not meet fairness requirements defined by network operators. In a multi-cell environment, there is a certain spread of the effective SINRs at the MTs and hence the rates vary considerably. In this paper, we use a heuristic scheduling algorithm tending to assign distinct users to their best resource blocks, i.e. chunks, while simultaneously ensuring instantaneous fairness in each time slot. Each user ranks independently all chunks in terms of the achievable throughput, in a descending manner, based on a chunk-wise evaluation of the post-equalization SINRs for all physical layer modes. Corresponding scores chosen from a unique set are assigned (refer algorithm 1). To ensure that the rates from different transmission modes are comparable, the achievable rates for the single stream transmission mode are further weighted with a so-called penalty factor $w$. The penalty factor for a specific mode is set to $w = |\mathcal{B}_i| / N_T$, the number of active beams.

1 If the interference cannot be distinguished from the received signal, decisions are based on the achievable SINR with each receiver algorithm.

2 See 3GPP TS 36.211 (Release 8)
The BS selects the user providing the best score for each chunk, i.e. the lowest value among all users. In the mean, this scheduling algorithm results assigns an equal fraction of resources to the users served by the same BS. Thus each user may realize an equivalent fraction of his total achievable user rate. The score-based scheduler (SB scheduler) realizes asymptotically a performance similar to the proportional fair scheduler [16], see [10]. For more details, refer to [11].

Algorithm 1 Matlab pseudo code for score-based scheduling in a 2x2 MIMO system.

\[
\begin{align*}
1: & \text{ for each user } m \in M \\
2: & \text{ for } m = 1: M \text{ do } \\
3: & \quad w_{ss} = 1/2; \quad \% \text{ penalty for ss usage} \\
4: & \quad R_m(\cdot) = []; \quad \% \text{ define a rate array} \\
5: & \quad R_m = \text{ceil}(1, R_m, w_{ss} \cdot \text{rate}_{\text{res}}); \quad \% \text{ include ss rates} \\
6: & \quad R_m = \text{ceil}(1, R_m, \text{rate}_{\text{res}}); \quad \% \text{ include each ms rate} \\
7: & \quad [a idx] = \text{sort}(R_m, 'descend'); \quad \% \text{ sort } R_m \\
8: & \quad S_m(a) = \lfloor 1 : \text{length}(R_m) \rfloor; \quad \% \text{ get scores} \\
9: & \quad \text{score}_{ss} = S_m(1 : \text{chunks}); \quad \% \text{ get scores for ss} \\
10: & \quad \text{score}_{ms} = S_m(\text{chunks} : \text{end}); \quad \% \text{ get scores for ms} \\
11: & \text{ end for } \\
12: & \text{ for each chunk over all users find the minimum score} \\
13: & \quad \text{ss user}_{ms} = \min_{v_{ms}} (\text{score}_{ms}); \quad \% \text{ select ss user/chunk} \\
14: & \quad \text{ms user}_{ms} = \min_{v_{ms}} (\text{score}_{ms}); \quad \% \text{ ms user/chunk/stream} \\
15: & \quad \% \text{ decide whether to do ss or ms on each chunk} \\
16: & \quad \text{score mode} = \min(\text{ss}, \text{min}(\text{ms})); \\
17: & \quad \text{do mode selection based on mode, then do resource assignment} \\
\end{align*}
\]

V. MULTICELL SIMULATIONS

The simulation assumptions used in this work are given in Table I. Applied is the 3GPP SCME with some modifications discussed below. For the sectorization, the simulation scenario is initialized cell-wise, i.e. independently for each BS. The large scale parameters are kept fixed for all three sectors belonging to the same BS, while the small scale parameters are randomized as indicated in [17]. Based on channel measurements in an urban macro cellular deployment [18], a so-called scenario-mix has been introduced. For distinct MT positions, different channel conditions may be experienced, e.g. line of sight (LOS) or non line of sight (NLOS) propagation to different BSs, which is more realistic than assuming the same conditions for all channels. The state is changed for different channel realizations in a simulation run, following a distance dependent stochastic process based on experimental results. This scenario mix has a positive effect on the interference statistics, and leads to higher average cell capacities.

A. Verification by Measurements

Assume that a MT may be able to detect the $N = |\mathcal{N}|$ strongest BS signals, i.e. a set of BSs $\mathcal{N} \subset \mathcal{K}$ of all BSs within the deployment. Based on the user-specific channels to all base stations, a so-called Top-$N$ power distribution is generated by instantaneously sorting the power distributions. The sorted powers are put in one overall statistic, enabling us to observe the power distributions for all channels seen by a MT on average (Fig. 5). Note that each cumulative distribution function (cdf) curve is generated from uncorrelated sample points for single user locations, but e.g. the second-strongest signal may belong geographically to a different BS and sector, in each individual channel realization.

To verify our simulation assumptions, we have performed so-called drive tests in commercial 3G networks using the TSMU radio network analyzer from Rohde&Schwarz. A 10 km track has been measured through the city area in Berlin, Germany. Results are based on the downlink common pilot channel (CPICH), which is always transmitted in each sector with 10% of power. It has a spreading factor of 256 and sector-selective scrambling. The CPICH of other sectors can be suppressed by at most $10\log_{10}256 = 24$ dB in the absence of data, hence we cannot observe most of the dense weaker signals present in simulation results. In Fig. 5, the measured Top-$N$ power statistics are given for a operator with a relatively dense network deployment. It matches very well

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>SIMULATION ASSUMPTIONS.</th>
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<tbody>
<tr>
<td>parameter</td>
<td>value</td>
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<tr>
<td>channel model</td>
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<td>scenario</td>
<td>urban-macro&lt;sup&gt;5&lt;/sup&gt;</td>
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<td>additional modifications</td>
<td>scenario-mix&lt;sup&gt;6&lt;/sup&gt;</td>
</tr>
<tr>
<td>$f_c$</td>
<td>2 GHz</td>
</tr>
<tr>
<td>system bandwidth</td>
<td>31.72 MHz, 128 chunks</td>
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<tr>
<td>signal bandwidth</td>
<td>18 MHz</td>
</tr>
<tr>
<td>antisection distance</td>
<td>500m</td>
</tr>
<tr>
<td>number of BSs</td>
<td>19 having 3 sectors each</td>
</tr>
<tr>
<td>antenna elements : spacing transmit power</td>
<td>1,2,4 : 4\lambda</td>
</tr>
<tr>
<td>BS height</td>
<td>46 dBi</td>
</tr>
<tr>
<td>antenna elements : spacing MT height</td>
<td>triple, with FWHM of 68°</td>
</tr>
<tr>
<td></td>
<td>1.2,4 : $\lambda/2$</td>
</tr>
<tr>
<td></td>
<td>2m</td>
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</table>
VI. PERFORMANCE EVALUATION RESULTS

Performance evaluation is conducted for both the sum throughput in a sector and the throughput of a specific user. Both values are normalized by the signal bandwidth, yielding a sector's spectral efficiency and normalized user throughput, respectively. Note that the normalized user throughput is decreasing with increasing number of served users sharing the signal bandwidth. The achievable rates are determined from SINRs using Shannon's formula for the information theoretic capacity $C_{\text{Shannon}} = \log_2(1 + \text{SINR})$. For certain results, which represent achievable rates in a practical system, we apply a quantized rate mapping function given in [19]. This mapping function supports different modulation and coding schemes, ranging from BPSK up to 64QAM with code rates from 1/2 up to 24/26. The corresponding switching steps are obtained from the performance in an equivalent AWGN channel meeting a packet error rate of $10^{-2}$ with a blocklength $L = 1152$ bits.

One part of Fig. 6 (red and black lines) demonstrates the effect of scheduling using both TDMA and FDMA with fairness constraints. The frequency dependent scheduling clearly outperforms the system scheduled in the time domain. The FDMA approach has reduced outage probability. For intuition, it fills the gaps which cannot be used by cell-edge users in TDMA mode by assigning these resources to other users, which increases the mean user and cell throughput rates. Only at the cell edge, represented by the low-percentile part of the user throughput, there is little gain due to FDMA. A cell-edge user may have only a few chunks where it can decode any signal at all, and these chunks are assigned in any case by the score-based scheduler. The rate at cell edge can be improved by so-called fairness steering at the cost of users with better channel conditions, refer to [11].

In addition, Fig. 6 shows the price to be paid in a multi-cell environment when fair resource assignment is required. The loss in sector throughput is enormous compared to maximum throughput scheduling (left). On the other hand, there is a significant improvement for the score-based scheduling when taking the user rate into account. Fair scheduling removes user outage completely. In contrast, maximum throughput scheduling has more than 75% outage. Note that many single-cell results indicate much smaller throughput loss. In these cases, equal SINR for the MTs is usually assumed. This is not realistic in a multi-cell environment, where a certain spread of the SINRs is always present at the receiver.

By introducing IRC at the terminal side, the SINR and thus both the sector as well as the user throughput is increased (Fig. 7), compared to MRC, see (11). The 5-percentile of the user rate is almost doubled with respect to the SISO reference case. Note that for IRC the covariance matrix of interference plus noise needs to be estimated at the MT. This knowledge may be obtained by using a multi-cell channel estimation based on orthogonal pilots or by averaging the covariance of the received signal $y_m$ over a sufficient number of consecutive transmitted data symbols [15].

In Fig. 7 (left), we additionally compare the performance of spatial diversity and spatial multiplexing using interference rejection combining, according to (12) and (14), where all available data streams are assigned to a single user. As already observed in [2], spatial multiplexing can only show minor gain over spatial diversity. Gains can only be achieved using SU-MUX with non-linear interference rejection combining (SIC) which outperforms the SDIV system in terms of cell throughput. However, the achievable 5-percentile of the user rate is still better with SDIV compared to both SMUX receiver algorithms, see Fig. 7 (right).

Nevertheless, this must not lead to the conclusion that the multi-stream transmission mode is not useful in a multi-cell environment. Rather, it opens the way for a new transmission scheme called multi-user multiplexing (MU-MUX) [7]. It can be regarded as a generalization of the multi-user diversity concept when using parallel data streams in a given sector. Note that the resources on these parallel streams may be assigned to different users, owing to the above described score-based scheduling algorithm. This can be very efficient in terms of both sector throughput and individual user rates. Fig. 7 indicates significant gains compared to SU-MUX, already in case of linear IRC when the MU-MUX mode is enabled. There are groups of users, served on different parallel spatial streams, for which the sum rate is indeed much higher than for serving a single user on all the streams. On the other hand, multi-user SIC can hardly provide additional gains compared to linear.
IRC for a large number of users, e.g. 20. Thus the rate is only plotted for the IRC case.

When applying SIC in the multi-user case, there are additional constraints for the scheduler related to error propagation. Consider a first user scheduled on stream 1 and a second user on stream 2. We assume that the first user decodes stream 1 at first, and thus it takes no advantage from using SIC. The second user should now be able to decode the data of the first user first, before reducing the interference on the data signal actually assigned. Hence, the rate for the first user must not be larger than the rate which can be supported by the second user on the first stream, due to error propagation. Next, the second user should realize a higher rate on the second stream that it could achieve using linear IRC. According to our experience, both conditions are infrequently met simultaneously even if the number of users is large. Thus a minor gain from SIC is observed in the MU-MUX mode.

In Fig. 8 we compare the performance of adaptive switching between all transmission modes (single-and multi-stream) with the fixed MU-MUX and SISO reference systems. The adaptive system outperforms the fixed MU-MUX in case of sector throughput (left). For the low percentile region of the user throughput (right), the gain is small. This is related to the SINR to rate mapping using Shannon’s formula. The logarithm is almost linear in the low SINR regime. If a user is served in the multiple stream (ms) mode, the SINR and thus the rate is approx. halved, compared to the single stream (ss) mode. Hence, each user may be assigned to multiple streams, yielding the same rate as in single stream mode. When employing a discrete modulation and coding scheme (MCS) for SINR to rate mapping, we observe effects which are closer to reality, where the the minimum supported rate is limited to some small value, e.g. 0.5 bit/s/Hz, referring to BPSK with code rate 1/2. With discrete mapping, outage occurs if the achievable post-equalization SINR is below some threshold. In fact, we observe outage if we limit the transmission mode to MU-MUX, while in the adaptive mode, switching back to the single stream mode can benefit from the increased SINR. Hence, the adaptive transmission system outperforms the fixed MU-MUX system in both, sector and user throughput under realistic conditions. For 20 users and the MIMO 2×2 case with discrete MCS, the system selects MU-MUX in 80%, SU-MUX in 2% and SDIV in 18% of all cases. Outage is even more avoided if the number of users is reduced.

Finally, we compare the achievable capacity gains for the MIMO 2×2 and 4×4 system with respect to the SISO reference case, Fig. 9. Again, 20 users are assigned to a single BS, the adaptive transmission mode selection is used and the FDMA score-based scheduler is applied. We observe almost the same factor for capacity scaling, independent from the used SINR rate mapping. With increasing number of antennas from SISO to MIMO 2×2 and 4×4, the mean sector capacity scales linearly with a factor of 1.9 and 3.5, respectively. The 5-percentile of the normalized user throughput, i.e. throughput of cell-edge users, scales with a factor of 2.1 and 4.1 for \( N_T = N_R = 2 \) and \( N_T = N_R = 4 \), respectively. In Fig. 10, the number of users is changed from 5, 10 to 20 MTs served in a single sector. We observe that the average capacity is increased with the number of users, but with only small gains in the last step from 10 to 20 MTs. As expected, the normalized user throughput is decreasing with increasing number of MTs, since the users have to share the system’s bandwidth. The 5-percentile of the normalized user throughput scales better with the number of antennas if the number of terminals is sufficiently large, which improves the statistics and ensures that each user gets only his best resources. The minor penalty of scaling factors are attributed to two reasons: First, we have used limited feedback instead of perfect channel state information at the transmitter. Second, we have used only one possible set of unitary precoding vectors, to reduce the computational complexity of evaluating the various SINRs.

VII. CONCLUSIONS

We have considered the performance of an adaptive broadband MIMO transmission system for the next generation of cellular radio. The system concept is based on limited feedback from the terminals to the base station, using post-equalization SINRs, and decentralized scheduling of resources in each sector. Our set of algorithms has low complexity at the terminal side and requires no coherent channel state.
Fig. 9. Compares the sector and user throughput for the SISO, MIMO 2x2 and MIMO 4x4 system, while meeting fairness constraints for 20 users assigned to the BS. The solid lines are for Shannon rates and the dashed are given for a discrete modulation and coding scheme (MCS).

Fig. 10. Compares the capacity scaling with min(Nr, Ns) for a variable number of terminals assigned to the base station, while meeting fairness constraints.

limited multi-user multi-cell scenario: Being proportional to the minimum of the number of receive and transmit antennas and for all users in the cell while meeting fairness.

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APPENDIX I

RECEIVER TECHNIQUES

A. Maximum Ratio Combining (MRC)

The MRC receiver is a simple algorithm which exploits the spatial diversity of multiple receive antennas. Here it is employed for reference purpose. Under the assumption of circular symmetric Gaussian noise at the receiver (Rx) antennas, the channel may be equalized using the hermitean transpose of the desired user channel i. Thus, using (4) leads to

\[ \hat{X} = h_i^H [h_i x_i + z_i] \]  

The SINR of the desired channel i is given by

\[ \text{SINR}_i = E \left\{ \frac{|h_i^H x_i|^2}{|h_i^H z_i|^2} \right\} \geq E \left\{ \frac{|h_i^H h_i x_i|^2}{|h_i^H z_i|^2} \right\} \]  

(7)

Applying the Jensen's inequality for convex functions leads to the lower bound of the instantaneous SINR. Simplification results in

\[ \text{SINR}_i \geq \frac{\sigma_i^2}{\sigma_n^2 + \sum_{k \neq i} \sigma_k^2 (h_k^H h_i)^{-1} h_i^H h_k h_k^H h_i} \]  

(8)

Note, that the interference is weighted by the inverse of the summed energy of the desired channel h_i.

B. Interference Rejection Combining (IRC)

In general, the SINR can be given similar to (7) as

\[ \text{SINR}_i \geq p_i w_i^H h_i h_i^H w_i \frac{h_i^H Z_i w_i}{w_i^H Z_i w_i}, \]  

(9)

where w_i is the equalization vector and Z_i is the covariance matrix of the residual radio network excluding the own signal's contribution h_i, i.e. \[ Z_i = \sigma_n^2 I + \sum_{k \neq i} p_k h_k h_k^H. \]
1) maximum SINR Receiver: First we concentrate on the maximum SINR (maxSINR) receiver as a suitable technique for IRC. By employing multiple receive antennas and using sophisticated signal processing it is possible to strengthen the desired signal while suppressing the residual interference. (9) is individually maximized by using the normalized minimum mean square error (MMSE) solution [20], where

$$w_i^{\text{maxSINR}} = \alpha Z_i^{-1} h_i,$$

(10)

where $Z_i^{-1}$ is the inverse of of $Z_i$ and $\alpha$ is constant factor. Since $\alpha$ does not affect the SINR we do not consider its value here. Hence, the achievable SINR with full channel knowledge for all interfering BSs simplifies to [21]

$$\text{SINR}_i \geq p_i h_i^H Z_i^{-1} h_i.$$ 

(11)

2) Minimum Mean Square Error Receiver: Due to the fact that the MMSE receiver is a special case of the before mentioned maxSINR algorithm it still maximizes the received SINR. In addition it minimizes the mean square error (MSE) at the detector output. Thus the covariance matrix of the entire radio system $R_{xx}$ is included in the MMSE solution

$$w_i^{\text{MMSE}} = p_i R_{xx}^{-1} h_i,$$

(12)

with $R_{xx}$ containing all channel vectors of the system, i.e. $R_{xx} = \sigma_n^2 I + \sum_{k \neq i} p_k h_k h_k^H$.

Since both receivers lead to the same SINR, it is possible to use both expressions to get the achievable SINR at the MT dependent on the receiving strategy, yielding lower complexity.

$$\text{SINR}_i^{\text{maxSINR}} = \text{SINR}_i^{\text{MMSE}}$$

(13)

$$p_i h_i^H Z_i^{-1} h_i = p_i \left( \frac{(R_{xx}^{-1} h_i)^H h_i h_i R_{xx}^{-1} h_i}{(R_{xx}^{-1} h_i)^H Z_i R_{xx}^{-1} h_i} \right) = p_i h_i^H R_{xx}^{-1} h_i - p_i h_i^H R_{xx}^{-1} h_i$$

(14)

3) Successive Interference Cancellation (SIC): As an additional receiver technique we consider the SIC receiver as suggest in [22]. We keep the equalization order fixed for each terminal independently, based on the descending sorted signal strength. In this work SIC is extended by the functionality of an IRC algorithm. Hence, the strongest data stream is equalized by the algorithm described in 1-B.2. Succeeding the reconstructed data stream is ideally removed from the set of intra-sector interference. Subsequently all residual data streams, transmitted from the identical BS are equalized by the same algorithm with reduced number of streams. Using SIC in combination with SU-MUX, no further constraints must be met. The case of MU-MUX and SIC is more critical and is discussed in section VI.

$$\gamma = \frac{R_{xx}^{\text{maxSINR}}}{\lambda_{\text{max}}} \quad \text{and} \quad \|w_i^{\text{maxSINR}}\|_2 = 1$$

REFERENCES


