Interference-Aware Scheduling in the Synchronous Cellular Multi-Antenna Downlink

Invited Paper

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***Abstract*—We consider the downlink of a multi-user MIMO OFDM system in a cellular environment, where users are scheduled to the transmission resources in frequency and space. Targeting a practical solution, we assume the use of fixed DFT-based pre-coding beams at the base stations and linear receivers at the multi-antenna terminals. After having received feedback on the frequency-selective interference conditions from all terminals, each base station schedules the terminals to their resources of highest quality while following a fair scheduling policy. It is shown that this rather simple practical concept enables spatial multiplexing transmission for all users in the system, in particular even for users at cell edge. This results in a capacity scaling that is similar to the one known for isolated point-to-point links. Finally, the system is shown to achieve a performance close to the ideal case if proper techniques to estimate the desired and interfering channels are applied.**

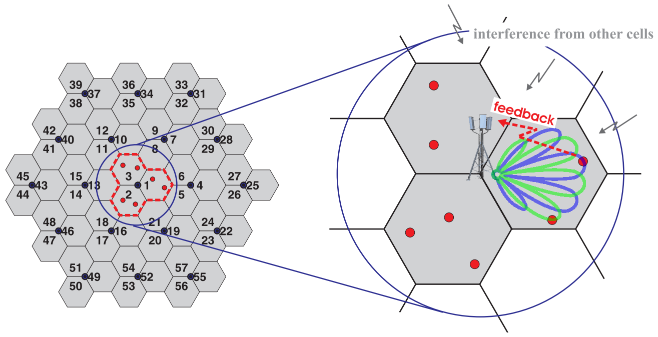

Fig. 1. System concept assuming multiple antennas at the base station for the purpose unitary fixed DFT-based pre-coded beamforming. SINR feedback is provided by the terminal for possible transmission modes using a narrow band feedback channel.

I. INTRODUCTION

Transmission with multiple antennas both at the transmitting and receiving ends of a wireless link has become increasingly mature in recent years. From theory, 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. A fundamental trade-off between different transmission modes has been pointed out in [1], which are spatial multiplexing (SMUX) and spatial diversity (SDIV), revealing that the mode maximizing the capacity depends on the actual channel state. This fact motivated the development of an adaptive transmission system, selecting the transmission mode depending on the actual channel quality in order to improve the error rate performance for fixed data rate transmission [2] or to increase the spectral efficiency [3].

To enable ubiquitous broadband wireless access, MIMO transmission must be made robust against multi-cell interference. However, it has not been fully evident yet how the potential capacity gains of MIMO can be realized under these conditions. In fact, early results obtained for a small set of linear transceiver setups, indicate only small gains for SMUX over SDIV systems [4]. The achievable spectral efficiency may be enhanced by enabling multi-user MIMO (MU-MIMO) into system design and thus turning the focus to multi-user links [5]. However, base stations (BSs) would require coherent channel state information to optimally serve their users in MU-MIMO, which is difficult to obtain in frequency division duplex (FDD) systems, as a high rate feedback link would be required.

Further, fair resource assignment is mandatory in cellular networks in order to guarantee radio access for all users. The multi-path structure of signal and interference channels may be used beneficially in this interference-aware scheduling process. Supplemental to the time-domain scheduling already used in todays radio systems, groups of frequency resources may be assigned to the users according to frequency-selective SINR conditions. In this case users may beneficially be assigned to their best resources.

Targeting a practical solution, we consider to use fixed beams for transmission as depicted in Fig. 1. Terminals are assumed to report their preferred pre-coding indices in combination with corresponding post-equalization SINRs via a low-rate feedback channel. For the equalization at the mobile terminal (MT), comprehensive channel knowledge of the radio system is required, which may be obtained by multi-cell channel estimation based on pilot symbols. Therefore downlink transmission has to be synchronized [6]. With this approach we demonstrate substantial capacity gains for MIMO systems in multi-cell environments, similar to those known for point-to-point links. We further indicate potential performance gains under the influence of imperfect channel estimation in systems with non-synchronized and synchronized BSs.

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II. DOWNLINK SYSTEM MODEL

The downlink MIMO-OFDM transmission system for an isolated sector with N_T transmit and N_R receive antennas per MT is described on each subcarrier by

$$\mathbf{y} = \mathbf{HCx} + \mathbf{n}\,, \quad (1)$$

where $\mathbf{H}$ is the $N_R \times N_T$ channel matrix and $\mathbf{C}$ the unitary $N_T \times N_T$ pre-coding matrix; $\mathbf{x}$ denotes the $N_T \times 1$ vector of transmit symbols; $\mathbf{y}$ and $\mathbf{n}$ denote the $N_R \times 1$ vectors of the received signals and of the additive white Gaussian noise (AWGN) samples, respectively, with covariance $\mathrm{E}\{\mathbf{nn}^H\} = \sigma^2\mathbf{I}$.

The evaluation process is briefly sketched as follows: Assume that all BSs provide Ω fixed unitary beam sets $\mathbf{C}_\omega$, $\omega \in \{1, ..., \Omega\}$. For the case of $N_T = 2$ and $\Omega = 2$ the beam sets based on the DFT-matrix are given as

$$\mathbf{C}_1 = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ i & -i \end{bmatrix} \quad \mathbf{C}_2 = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \quad (2)$$

In general, each beam set contains N_T fixed pre-coding vectors (beams) $\mathbf{b}_{\omega,u}$ with $u \in \{1, ..., N_T\}$. Each BS i independently selects one of these sets. In the following we denote $\mathbf{b}_{i,u}$ as the u-th pre-coding vector used by BS i. The received downlink signal $\mathbf{y}^m$ at the MT m in the cellular environment is given by

$$\mathbf{y}^m = \underbrace{\mathbf{H}_i^m \mathbf{b}_{i,u}}_{\overline{\mathbf{h}}_{i,u}} x_{i,u} + \underbrace{\sum_{\substack{j=1 \\ j\neq u}}^{N_T} \mathbf{H}_i^m \mathbf{b}_{i,j} x_{i,j}}_{\zeta_{i,u}} + \underbrace{\sum_{\substack{\forall l \\ l\neq i}} \sum_{j=1}^{N_T} \mathbf{H}_l^m \mathbf{b}_{l,j} x_{l,j} + \mathbf{n}}_{\mathbf{z}_{i,u}}\,, \quad (3)$$

The desired data stream $x_{i,u}$ transmitted on the u-th beam from the i-th sector is distorted by the intra-sector and inter-sector interference aggregated in $\zeta_{i,u}$ and $\mathbf{z}_{i,u}$, respectively. Each BS may select a limited number $Q_i < N_T$ of active beams in the chosen set to serve the users simultaneously. Thus, the transmit power per beam is uniformly distributed over all non-zero transmit symbols $x_{i,j}$ with p_i/Q_i, where $p_i = \sum_{j=1}^{N_T} \mathrm{E}\left\{|x_{i,j}|^2\right\}$ is the total available power for BS i. If only one beam is active, i.e. $Q_i = 1$, we name it single-stream (ss) mode, while for $Q_i > 1$, we refer to it as multi-stream (ms) mode.

To enable interference-aware scheduling in a cellular system, cochannel interference (CCI) has to be predictable. This can be achieved by limiting the available beams to a single set, i.e. $\Omega = 1$, yielding a static pre-coding.

III. LINEAR RECEIVERS

Assuming a linear equalizer $\mathbf{w}_u$, which is required to extract the useful signal from $\mathbf{y}^m$, yields a post-equalization SINR at the MT for stream $x_{i,u}$ given by

$$\mathrm{SINR}_u = p_i \frac{\mathbf{w}_u^H \overline{\mathbf{h}}_{i,u} \overline{\mathbf{h}}_{i,u}^H \mathbf{w}_u}{\mathbf{w}_u^H \mathbf{Z}_u \mathbf{w}_u}\,, \quad (4)$$

where $\mathbf{Z}_u$ is the covariance matrix of the interfering signals aggregated in $\zeta_{i,u}$ and $\mathbf{z}_{i,u}$, i.e. $\mathbf{Z}_u = \mathrm{E}\left[(\zeta_{i,u} + \mathbf{z}_{i,u})(\zeta_{i,u} + \mathbf{z}_{i,u})^H\right]$, with $E[.]$ being the expectation operator.

For interference rejection combining (IRC) [7], the interference-aware minimum mean square error (MMSE) receiver is used:

$$\mathbf{w}_u^{\mathrm{MMSE}} = \frac{p_i \mathbf{R}_{yy}^{-1} \overline{\mathbf{h}}_{i,u}}{Q_i} \quad (5)$$

where $\mathbf{R}_{yy}$ denotes the covariance matrix of the received signal $\mathbf{y}^m$, i.e.

$$\mathbf{R}_{yy} = \mathrm{E}\left[\mathbf{y}^m (\mathbf{y}^m)^H\right] = \mathbf{Z}_u + \overline{\mathbf{h}}_{i,u} \overline{\mathbf{h}}_{i,u}^H \quad (6)$$

According to [8], the MMSE receiver yields a post-equalization SINR

$$\mathrm{SINR}_u^{\mathrm{MMSE}} = \frac{p_i}{Q_i} \overline{\mathbf{h}}_{i,u}^H \mathbf{Z}_u^{-1} \overline{\mathbf{h}}_{i,u} \quad (7)$$

Based on this SINR, the achievable spectral efficiency is evaluated in a downlink OFDMA multi-cellular simulation environment. For reference purpose, we compare these results with the performance achievable by using a maximum ratio combining (MRC) receiver

$$\mathbf{w}_u^{\mathrm{MRC}} = \overline{\mathbf{h}}_{i,u} \quad (8)$$

yielding a post-equalization SINR

$$\mathrm{SINR}_u^{\mathrm{MRC}} = \frac{\frac{p_i}{Q_i} \left\| \overline{\mathbf{h}}_{i,u}^H \overline{\mathbf{h}}_{i,u} \right\|^2}{\overline{\mathbf{h}}_{i,u}^H \mathbf{Z}_i \overline{\mathbf{h}}_{i,u}} \quad (9)$$

A. Imperfect channel estimation

While for theoretical investigations full channel state information at the receiver (CSIR) may be assumed, the challenge for practical systems is the robustness against channel estimation errors. In [9], IRC was shown to be highly sensitive to estimation errors, since the spatial structure of the system's covariance matrix is utilized for equalization. In the following we assume quasi-static channel conditions over the observation interval.

Non-synchronized BSs, i.e. BSs are not synchronized to each other with respect to carrier frequencies and frame start. Therefore, we introduce channel estimation errors according to $\widehat{\overline{\mathbf{h}}}_{i,u} = \overline{\mathbf{h}}_{i,u} + \delta_{i,u}$. $\widehat{\overline{\mathbf{h}}}_{i,u}$ denotes the estimate of variable $\overline{\mathbf{h}}_{i,u}$, and $\delta_{i,u}$ denotes the zero-mean Gaussian distributed error with variance μ, being the normalized mean square error (MSE) for channel estimation. For SINR estimation, we consider knowledge on frequency-flat and frequency-selective independent identically distributed (i.i.d.) interference powers σ_{IF}^2 according to (10) and (11), respectively. Further, we consider the case of full frequency-selective covariance knowledge based on received data signals $\mathbf{y}^m$. In the following, f and n denote the discrete frequency index and the discrete time index, respectively.

Frequency-flat i.i.d. interference power σ_{IF}^2

$$\widehat{\mathbf{Z}}_u = \mathbf{I}\left(\mathrm{E}_f\left[\left(\sum_{\forall l,j}|\overline{\mathbf{h}}_{l,j}(f)|^2\right) - |\widehat{\overline{\mathbf{h}}}_{i,u}(f)|^2\right] + \sigma^2\right) \quad (10)$$

Frequency-selective i.i.d. interference power σ_{IF}^2

$$\widehat{\mathbf{Z}}_u(f) = \mathbf{I}\left(\left(\sum_{\forall l,j}|\overline{\mathbf{h}}_{l,j}(f)|^2\right) - |\widehat{\overline{\mathbf{h}}}_{i,u}(f)|^2 + \sigma^2\right) \quad (11)$$

Frequency-selective covariance $\mathbf{Z}_u$

$$\widehat{\mathbf{Z}}_u(f) = \mathrm{E}_n\left[\mathbf{y}^m(f,n)\mathbf{y}^m(f,n)^{\mathrm{H}}\right] - \widehat{\overline{\mathbf{h}}}_{i,u}(f)\widehat{\overline{\mathbf{h}}}_{i,u}(f)^{\mathrm{H}} \quad (12)$$

Synchronized BSs, using multi-cell channel estimation based on virtual pilot sequences [10]. These sequences are block-orthogonal and are defined over time-domain. For channel estimation, the receiver is based on a simple correlator. For simplicity we drop the frequency index f.

Correlation approach

$$\widehat{\overline{\mathbf{h}}}_{i,u} = \frac{1}{N}\sum_{n=0}^{N-1} c_{i,u}^*(n)\mathbf{y}^m(n) \quad (13)$$

$$\widehat{\mathbf{Z}}_u = \sum_{\forall l,j}\widehat{\overline{\mathbf{h}}}_{l,j}\widehat{\overline{\mathbf{h}}}_{l,j}^{\mathrm{H}} - \widehat{\overline{\mathbf{h}}}_{i,u}\widehat{\overline{\mathbf{h}}}_{i,u}^{H} \quad (14)$$

IV. Resource allocation and fair user selection

Resource allocation and selection of the proper spatial transmission mode (i.e. ss or ms, see section II) is carried out by a score-based scheduling process developed in [11], which is briefly described as follows: In a first step, the user terminals evaluate the current channel conditions per resource block (RB) in terms of their achievable SINR conditions. By using equations (7) and (9) and a suitable SINR-to-rate mapping function, they can determine for each transmission mode the achievable rate per supported beam. This information is conveyed to the base station, where a score-based resource scheduling algorithm is performed: To enable direct comparison of the single per-beam rates from different spatial modes, the stream-stream rates are weighted by a so-called penalty factor, which accounts for the higher power allocated to the ss beam compared to ms mode. In particular, if Q is the number of simultaneously active streams in ms mode, the penalty factor is chosen as Q^{-1}. For each user, the (weighted) per-beam rates from all modes over all RBs are ranked by their quality, and corresponding scores are assigned. Mode selection and resource assignment is then done for each RB individually: Firstly, each beam available per transmission mode is assigned to the user providing minimum score for that beam. Thereafter, the mode is selected which comprises the minimum overall user score.

The objective of this score-based resource allocation process is to assign each user his best resources, and the decision on the spatial mode is taken under the premise of achieving a high throughput for each user. Clearly, the process is of heuristic nature, and hence the global scheduling target of assigning each user an equal amount of resources is achieved on average only or if the number of available resources tends to infinity. However, its convenient property for practical applications is its flexible utilization, as the set of resources can be defined over arbitrary dimensions (time/frequency/space). Thus, fairness can be established on a small time scale, e.g. even for the scheduling of resources contained within a single OFDM symbol.

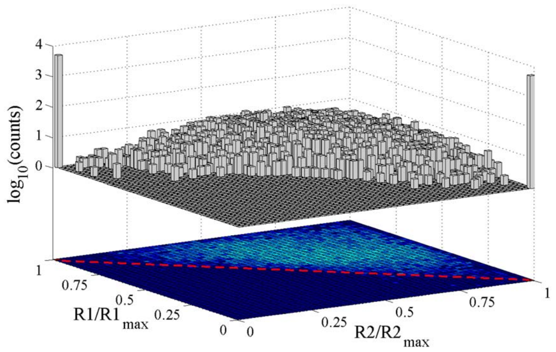
An illustration of the performance achievable by the score-based scheduler is given in Fig. 2. It depicts the histogram of normalized achievable user rates in the rate region plane for two users, which may be scheduled in each RB. In particular, we assume two spatial layers to be available in each RB (i.e. $N_T = 2$), allowing two users to be served simultaneously in MU-MIMO mode. The rate allocated to each of these two users is normalized to the rate it would achieve if the RB was assigned exclusively to it. Fig. 2(a) shows the distribution of normalized rates if the total set of users to select from is limited to $K = 2$, while Fig. 2(b) refers to the case $K = 20$. From both figures, it is clearly seen that the achievable rates lie beyond the time division multiple access (TDMA) rate region (indicated by the dashed red line in the rate region plane). For increasing number of users K, the histograms is more and more concentrated in the upper right corner of the rate region. This illustration indicates that the heuristic score-based scheduling approach significantly outperforms TDMA scheduling and conveniently achieves high user rates by properly utilizing the MU-MIMO mode.

V. Single-cell performance

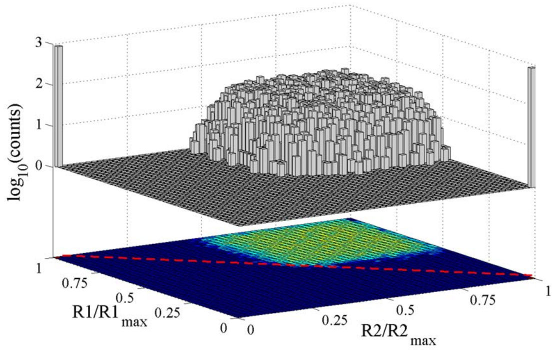
Initial performance evaluation is carried out for a fixed system setting in an isolated cell ($\mathbf{z}_{i,u} = \mathbf{n}$ in (2)), where K MTs, each equipped with $N_R = 2$ receive antennas, communicate with a dual-antenna BS, ($N_T = 2$). The evaluation environment is based on the extended spatial channel model (SCME) [12] and full CSIR is assumed. We investigate the probabilities of mode selection depending on the mean SNR conditions, which are depicted in Fig. 3 for 2 users (a)[1] as well as for 10 users (b). Three different configurations of the adaptive mode switching system are considered here:

1) *adaptive*: Adaptive MU-MIMO system as described in section IV with beam set $\mathbf{C}_1$ from (2) being available. Simultaneously active beams can be assigned independently to different users. The mode per user is selected per RB, i.e. a user may be served in different modes simultaneously.
2) *adaptive SU-MIMO*: MU-MIMO option is switched off, i.e. ms mode reduces to single-user MIMO (SU-MIMO).

[1] Note that resources where a rate cannot be supported by any user are not assigned by the scheduler. For that reason, the selection probability of ss mode drops down to 75% at $P_s/N_0 = -5\,dB$ in Fig. (a).

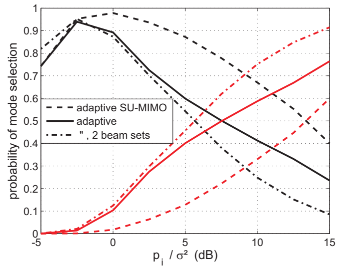


(a) $K = 2$ users

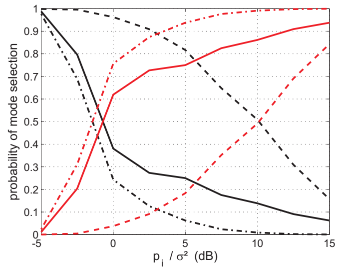


(b) $K = 20$ users

Fig. 2. Rate allocation across two data streams



(a) $K = 2$ users



(b) $K = 10$ users

Fig. 3. Probability of mode selection vs. SNR $= p_i/\sigma^2$. Black: ss mode, red: ms mode.

TABLE I
SIMULATION ASSUMPTIONS.

parameter	value
channel model	3GPP SCME
type	Monte Carlo
traffic model	full buffer
f_c	2 GHz
frequency reuse	1
signal bandwidth	18 MHz, 100 RBs
intersite distance	500m
transmit power	46 dBm
sectorization	triple, with FWHM of 68°

Now only one user is served per RB either in diversity or SU-MIMO mode.

3) *adaptive,* $\Omega = 2$ *beam sets*: Adaptive MU-MIMO system with the two beam sets $\mathbf{C}_1$ and $\mathbf{C}_2$ from (2) being available.

The crossing point of the curves for ss and ms mode in Fig. 3 highlights the point in the SNR region where the ms mode becomes the dominantly selected one. From both figures, we observe that going from SU-MIMO to MU-MIMO promotes selection of the ms mode substantially, as the crossing point is shifted by 5 dB in case of 2 users and by more than 10 dB in case of 10 users down towards the low SNR regime. For 10 users, the crossing point falls below an SNR of 0 dB. The support for MU-MIMO mode also results in significant gains in the spectral efficiencies (refer to Fig. 6 in the next section). These results strongly emphasize that MU-MIMO is the key for the efficient use of spatial multiplexing transmission even at low SNR conditions.

Providing an additional beam set shifts the crossing point even further down, which can be attributed to the finer granularity in the quantization of the transmit vector space. For 10 users, the crossing point in Fig. 3(b) can be shifted down to about -1.5dB now. Further, it can be observed that the shape of the probability curves for that case approach the one of a step function, highlighting that the system behaviour tends towards a hard mode switching at a fixed SNR value.

VI. MULTI-CELL PERFORMANCE

Turning the focus to a multi-cell system, we investigate the performance is investigated in a triple-sectored hexagonal cellular network with 19 BSs in total, i.e. a center cell surrounded by two tiers of interfering cells, as indicated in Fig. 1. Simulation parameters are given in Table I. Initial results are based under the assumption of full and perfect CSIR. The SCME with urban macro scenario parameters is used [12], yielding an equivalent user's geometry as reported in [13]. The MTs are always served by the BS whose signal is received with highest average power over the entire frequency band. For capacity evaluation, only MTs being placed inside of the center cell will be considered. In this way, BS signals transmitted from 1st and 2nd tier model the inter-cell interference [8]. Performance is evaluated for both the sum throughput in a sector and the throughput for individual users. Both values are normalized to the signal bandwidth, yielding a sector's overall spectral efficiency and normalized user throughput, respectively. The achievable rates are determined from the SINRs calculated according to expression (7) by using a quantized rate mapping function [14], representing achievable rates in a practical system. From these results, cumulative distribution function (CDF) plots are obtained.

Case 1: All BSs provide $\Omega = 1$ fixed unitary beam set. With respect to the single-input single-output (SISO) reference case, our results in Fig. 4 (solid lines) indicate a capacity increase of the median sector's spectral efficiency by a factor of $\alpha = 1.95$, $\alpha = 2.88$ and $\alpha = 3.43$ for the MIMO 2×2 ($N_T \times N_R$), 2×4 and 4×4 system. We can observe only small additional capacity gains for systems with $N_T > N_R$ compared to radio system with $N_T = N_R$. This is mainly

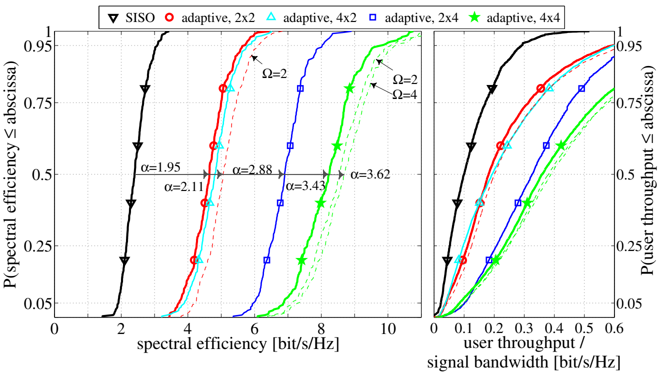


Fig. 4. Idealistic system performance for the SISO, MIMO 2×2 ($N_T \times N_R$), 4×2, 2×4 and 4×4 system for 20 users assigned to the BS. Dashed lines indicate the performance achievable with $\Omega = \{2, 4\}$ beam sets $\mathbf{B}_\omega$.

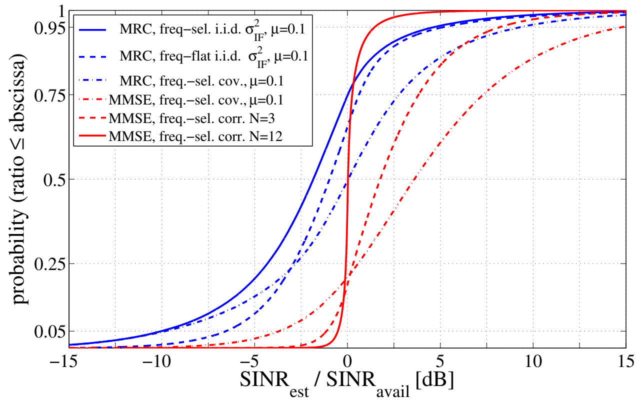


Fig. 5. Estimation error for the estimated $\mathrm{SINR}_{\mathrm{est}}$ in ss mode compared to the available $\mathrm{SINR}_{\mathrm{avail}}$.

caused by the constraint of DFT-based pre-coding, where the total transmit power is distributed evenly over all transmit antennas. In contrast, the system with $N_T < N_R$ benefits from advanced capabilities for interference suppression, as well as higher receive diversity. This enables the system to achieve larger scaling factors, e.g. $\alpha = 2.88$ for MIMO 2×4. The 5-percentile of the normalized user throughput, which may serve as a measure to represent the throughput of cell-edge users, shows similar scaling.

Case 2: All BSs provide $\Omega > 1$ fixed unitary beam sets. Fig. 4 (dashed lines) further indicates the potential capacity gains for allowing the users to choose from multiple beam sets $\mathbf{B}_\omega$, $\omega \in \{2, 4\}$. On the one hand, the system may profit from additional beamforming gains yielding a capacity increase of $\alpha = 2.11$ for MIMO 2×2 with $\Omega = 2$ beam sets. However, note that considering independent adaptation of $\mathbf{B}_\omega$ for all BSs results in a system where $\mathbf{Z}_u$ is no longer predictable, which decreases the capacities promised in Fig. 4 in practice. Hence, the results with $\Omega > 1$ may rather serve as an upper bound for the capacity achievable by the concept described in this work, and it helps to qualify the performance of MU-MIMO with $\Omega = 1$.

VII. Multi-cell performance including channel estimation errors

In the following, we take channel estimation errors into account. Therefore we use (10)-(14). Fig. 5 indicates the estimation error of the ss SINR at the terminal. We compare the ratio of the estimated $\mathrm{SINR}_{\mathrm{est}}$ to the achievable $\mathrm{SINR}_{\mathrm{avail}}$ under perfect CSIR and estimated equalization weights. Employing either MRC in an asynchronous network or IRC in a synchronized one, leads to significantly different estimation errors. For MRC, based on (11), the estimation suffers in two ways: There is a median shift of -1.9 dB, i.e. $\mathrm{SINR}_{\mathrm{est}}$ is systematically too low. In addition the estimation error has a considerable variance. With overestimated SINR conditions, the channel may be overloaded, resulting in substantial performance degradation. Assuming that strong channel codes as well as hybrid automatic repeat request (HARQ) mechanisms are able to correct errors if 10% of the resources are overloaded, we have to ensure that the 90-percentile of $\mathrm{SINR}_{\mathrm{est}}/\mathrm{SINR}_{\mathrm{avail}}$ is below 0 dB. This can be achieved by introducing a safety factor $S < 1$, which shifts all $\mathrm{SINR}_{\mathrm{est}}$ correspondingly.

For MRC based on (11), we can estimate $S = 2.3$ dB from Fig. 5. Focusing on the median value, there is an overall penalty (offset) of approx. $\mathrm{SINR}_{\mathrm{pen}} = 4.2$ dB at the medium access control layer (MAC layer) compared to $\mathrm{SINR}_{\mathrm{avail}}$. Averaging the interference power σ^2_{IF} over the entire frequency band, i.e. using (10), reduces the penalty to $\mathrm{SINR}_{\mathrm{pen}} = 3.7$ dB. Covariance estimation, i.e. (12), leads to unbiased $\mathrm{SINR}_{\mathrm{est}}$, but the S-factor is higher due to the larger variance, resulting in $\mathrm{SINR}_{\mathrm{pen}} = 6.3$ dB. Concentrating on asynchronous downlink transmission, we conclude, that frequency-flat i.i.d. σ^2_{IF} results in highest performance.

The penalties can be reduced further, if the interference is estimated more precisely, e.g. in a synchronous system using MMSE receiver and the correlation approach as given in (13)-(14). For a correlation window spanning $N = 3$ pilot symbols, we assume to be able to distinguish between the channels belonging to 3 out of 57 sectors. Hence, interference cannot be separated sufficiently, and thus SINR is systematically overestimated. However, already with a correlation window spanning $N = 12$ pilot symbols, 12 sectors and thus more interferers can be identified, and the SINR is determined more precisely [9]. The safety factor is then $S = 0.9$ dB, and the median shift becomes negligible.

Fig. 6 shows the achievable sum rates in the multi-cell system including $\mathrm{SINR}_{\mathrm{pen}}$. As lower bounds we use the performance in SISO case including the effects of estimation errors for the desired channel $\widehat{\mathbf{h}}_{i,u}$. The upper bound is given by the adaptive transmission system assuming perfect CSIR. Assuming the MT is able to estimate its dedicated channel with $\mu = 0.1$ and $\mathbf{Z}_u$ according to (11) and the system is forced to SU-MIMO mode only, results in an inferior performance compared to the ss transmission using MRC. The reason is that the estimation error leads to inter-stream interference in the SU-MIMO case, which is not present with ss transmission.

The next three CDF curves are all based on the estimates

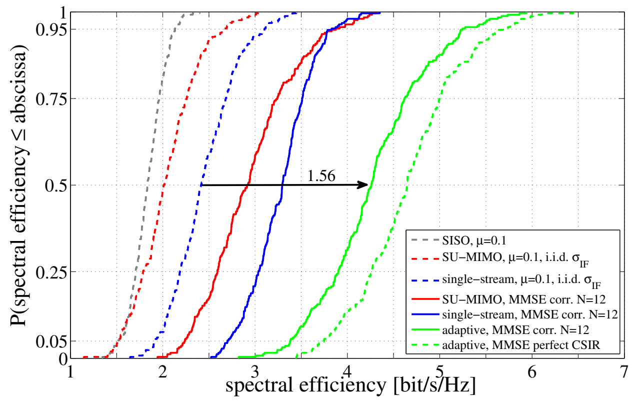


Fig. 6. Spectral efficiency of various transmission schemes including estimation errors.

(13)-(14). Although the use of the MMSE receiver can exploit the knowledge of interference, the ss mode using the MMSE receiver outperforms the SU-MIMO transmission. Allowing the fully adaptive transmission yields a significant throughput gain for the system. This gain is mostly related to the MU-MIMO scheduling. Note that the gap to the adaptive system with perfect CSIR amounts to 8% only, indicating the robustness of the proposed scheme. Finally we come to the following conclusion: Synchronized downlink transmission from all BSs in combination with the MMSE receiver based on estimates (13)-(14) outperforms the asynchronous case. However, if the system design would be constrained to non-sychronized BSs, ss transmission in combination with the MRC receiver would be a suitable choice. The difference in the average throughput between both cases is significant and amounts to 56% in our results. Thus, the overall throughput gain achievable with synchronized base stations is still significant even under practical considerations.

VIII. Conclusion

This work evaluates the gains from using interference-aware, frequency-selective MU-MIMO scheduling in a cellular network with synchronized BSs. Terminals are assumed to be able to estimate their dedicated and interfering channel coefficients. With the suggested scheduling approach, we can conclude with two important observations: Efficient MU-MIMO transmission can be achieved by using fixed DFT-based unitary pre-coding, i.e. without the requirement of full channel state information at the transmitter. Further, proper application of the MU-MIMO mode enables to conveniently serve even users in the ms mode who experience relatively poor SNR conditions. Thus, the MU-MIMO mode establishes a win/win situation for low- and high-rate users competing for a resource: Low-rate user can be served without blocking a given resource for any high-rate users, who can support a rate on any of the available beams. We further studied the suggested concept in an interference-limited environment and observed that knowledge of the interference channels yields a more precise estimation of the achievable SINR compared to the traditional approach, where interference is assumed white.

We implemented essential functions of this scheme in an experimental urban macro scenario, Testbed Berlin, and confirmed the significantly increased probability to select the ms mode also for realistic propagation conditions [15], [16]. The experimental proof of the gain from MU-MIMO transmission in the interference-limited scenario is subject of our ongoing research.

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