Cooperative Multi-User MIMO Based on Limited Feedback in Downlink OFDM Systems

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Abstract—**Multi-cellular radio systems are often limited due to the presence of cochannel interference. Physical layer concepts as e.g. interference rejection combining, optimize the receiver side and thus strengthen the signal while combating the interference at the terminal side only. It is well known that joint transceiver optimization, i.e. coordinated joint transmission from several base stations, yields large capacity improvement for downlink transmission. However, the performance highly depends on the available channel knowledge. We focus on how to realize a decentralized and limited cooperative downlink transmission in a multi-cellular network. This yields the crucial question: Is an efficient cooperative transmission possible by using simple channel quality identifiers, or is channel state information at the transmitter mandatory? Further, we use minimum mean square error equalization at the terminal side to combat residual cochannel interference. For baseline we apply receiver optimization only and compare these results with those obtained from cooperative transmission. We demonstrate potential capacity gains in a cellular orthogonal frequency division multiplexing system and their scaling with the number of cooperating antenna arrays.**

I. INTRODUCTION

Transmission with multiple antennas both at the transmitting and receiving ends of a wireless link has become increasingly mature in recent years. Recent advances valid for an isolated cell indicate large performance gains obtained from multiple-input multiple-output (MIMO) communications [1]–[3]. The achievable spectral efficiency may be further enhanced by shifting the focus to multi-user links [4], i.e. by using multi-user MIMO (MU-MIMO). As optimum transmission strategy, joint dirty paper coding (DPC) is known to achieve the capacity of the broadcast channel [5] and it is therefore considered as an upper bound for multi-user transmission. However, in this case, the base station (BS) needs coherent channel state information at the transmitter (CSIT) from all mobile terminals (MTs).

To enable ubiquitous and efficient broadband wireless access in cellular systems, MIMO algorithms in addition must be made robust against multi-cell interference. Recently, it was shown that the capacity scaling law, known from an isolated cell, also holds for the interference limited case of a multi-cellular radio system with $N_T = N_R$ transmit and receive antennas [6]. This work mainly focused on the optimization at the receiver side. It turned out, if $N_T > N_R$, cochannel interference (CCI) is still the dominant source of performance degradation in the cellular network. Thus, removing CCI may lead to large performance gains.

In this work we focus on how to realize limited localized cooperative transmission in a multi-cellular network, which yields the crucial question: Is an efficient cooperative downlink transmission possible by using simple channel quality identifiers (CQIs), or is CSIT mandatory? Targeting a practical solution, it would be favorable to report indices from a fixed set of unitary pre-coding vectors and their corresponding post-equalization SINRs via a low-rate feedback channel, as suggested for non-cooperative transmission in a multi-cellular environment. Thus, the terminals may choose between standard and joint pre-coded beamforming algorithms spread over a single or several sectors in the multi-cellular network, respectively. As an upper bound we employ multi-user eigenmode transmission (MET), known to realize 90% of the DPC capacity [7], based on the dominant eigenmodes of the MTs in the serving area.

Our work indicates potential performance gains in an orthogonal frequency division multiplexing (OFDM) downlink with $N_T = N_R = 2$ transmit and receive antennas and a variable size of the cooperation area. Our analysis covers dense and sparse user distribution, where the latter enables an isolated view on gains from cooperative transmission, i.e. independent from selection diversity gains among multiple users. To combat residual CCI caused by surrounding cells and imperfect feedback, we employ MMSE equalization, known as interference rejection combining (IRC) [8], at the terminal side. Our results are obtained from multi-cell simulations based on 3GPP's extended spatial channel model (SCME).

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

$$\mathbf{y} = \mathbf{H}\mathbf{C}\mathbf{x} + \mathbf{n}\,, \tag{1}$$

where $\mathbf{H}$ is the $N_R \times N_T$ channel matrix and $\mathbf{C}$ the unitary $N_T \times N_R$ 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 with covariance $E\{\mathbf{n}\mathbf{n}^H\} = \sigma^2\mathbf{I}$.

The evaluation process is briefly sketched as follows: Assume that a group of α cooperating BS sectors provide a beam

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set $\mathbf{C}_i$. Each beam set is allowed to change on each time-frequency resource and contains αN_T pre-coding beams $\mathbf{b}_{i,u}$ with $u \in \{1, ..., \alpha N_T\}$. In the following we denote $\mathbf{b}_{i,u}$ as the u-th used pre-coding vector provided by the i-th cell cluster. The received downlink signal $\mathbf{y}^m$ at the MT m in the cellular environment is given by

$$\begin{aligned}\mathbf{y}^m = \; & \underbrace{\mathbf{H}_i^m \mathbf{b}_{i,u}}_{\bar{\mathbf{h}}_{i,u}} x_{i,u} + \underbrace{\sum_{\substack{j=1 \\ j \neq u}}^{N_T} \mathbf{H}_i^m \mathbf{b}_{i,j} x_{i,j}}_{\zeta_{i,u}} \\ & + \underbrace{\sum_{\substack{\forall l \\ l \neq i}} \sum_{j=1}^{N_T} \mathbf{H}_l^m \mathbf{b}_{l,j} x_{l,j} + \mathbf{n}}_{\mathbf{z}_{i,u}}, \qquad (2)\end{aligned}$$

The desired u-th data stream transmitted from the i-th cluster is distorted by the intra-cluster and inter-cluster interference aggregated in $\zeta_{i,u}$ and $\mathbf{z}_{i,u}$, respectively. $\mathbf{H}_i^m$ spans the $N_R \times \alpha N_T$ channel matrix formed by the cluster. Thus $\zeta_{i,u}$ denotes the interference generated in the cooperation area, which is intended to be reduced by joint transmission techniques. The transmit power per beam is uniformly distributed over all αN_T transmit symbols $x_{i,j}$ with $p_i/(\alpha N_T)$, where $p_i = \sum_{j=1}^{\alpha N_T} \mathrm{E}\left\{|x_{i,j}|^2\right\} = \alpha p_s$ is the total available power for α cooperating BS sectors. p_s is the transmit power per sector.

A. Determine serving BS or cooperative BS cluster

The general assumption for single-cell operation is that each MT is assigned to the BS sector providing the highest receive power, denoted as top-1 signal over the total available frequency band. Thus, the BS assignment is based on broadband conditions in a fast cell handover manner. For downlink cooperation we extend this scheme by evaluating the top-α strongest signals and grouping the users selecting the same set of α BSs for joint signal transmission. It is likely to assume that there is a small number of users signaling the same desired cluster i for joint downlink transmission. As a first starting point for our evaluations, we turn the focus to a sparse user distribution for $\alpha > 2$, where additional gains from selection diversity among multiple users are not available.

On the next fraction of the system bandwidth of the OFDM system, denoted as a resource block (RB), another group of MTs is served and thus the BS clustering may change over the frequency band.

III. COHERENT DOWNLINK TRANSMISSION

As a baseline we consider a system concept from [6] based on receiver side optimization. This work indicated potential gains from MU-MIMO using fixed DFT-based beamforming according to (3) operating on a single-cell basis, which keeps CCI predictable.

$$\mathbf{C}_1 = \begin{bmatrix} 1 & 1 \\ i & -i \end{bmatrix} \qquad (3)$$

In combination with fair, interference-aware scheduling policies, users profit from almost doubled spectral efficiencies in the MIMO 2 × 2 system, as compared to the SISO setup [6]. The resource scheduling is based on the score-based policy described in [9]. It aims at assigning users their best resources and ensures a fair resource allocation on a short time scale. In particular this allocation tends to an equal amount of resources for all users. The scheduler was extended in [10] to support adaptive mode switching in order to increase the spectral efficiency. The supported modes are single-stream mode, if only one beam is active and multi-stream mode otherwise. In case of multi-stream transmission MU-MIMO is the most prominent transmission scheme [6], i.e. each user is served by $\lambda = 1$ spatial stream.

Recently, it was shown that interference-aware minimum mean square error (MMSE) equalization helps to reduce the gap between system performance under ideal and practical conditions [11]. Equalization weights were determined from multi-cell channel estimates obtained in a synchronous 3G Long Term Evolution (3G-LTE) downlink.

IV. DOWNLINK COOPERATION

There are several concepts for cooperative downlink transmission, all imposing different demands on the system architecture. As a basic requirement coherent downlink transmission is mandatory. Thus, downlink transmission from all BSs has to be synchronized with respect to the carrier frequency and the frame start [12].

A. Coordinated fixed beamforming

A simple way for inter-cell interference mitigation is the concept of beam coordination among several cells. (4) indicates the pre-coding matrix for $\alpha = 2$ cooperating cells by employing fixed DFT-based beams. $\mathbf{C}_2$ is derived from (3) and does not include joint beamforming among multiple BS arrays. The concept represents a simple form of joint scheduling for several cooperating BSs and thus relaxes the constraints on the cell handover process. In addition a frequency-selective handover may be permitted and thus the MTs may choose from transmission resources offered from different BSs at the same time.

$$\mathbf{C}_2 = \begin{bmatrix} 1 & 1 & 0 & 0 \\ i & -i & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & i & -i \end{bmatrix} \qquad (4)$$

B. Cooperative fixed beamforming

As a next step we will examine the gains from cooperative downlink transmission based on joint, fixed DFT-based beamforming. The pre-coding vectors in (5) are spread over all transmit antennas from $\alpha = 2$ BS arrays. For proper functionality, equal gain transmission assumes independent identically distributed (i.i.d.) pathloss to all antennas which are used for pre-coded beamforming. Due to the fact that users in a cellular system experience different pathloss to the BSs, we expect marginal gains from cooperative fixed beamforming based on $\mathbf{C}_3$.

$$\mathbf{C}_3 = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -i & -1 & i \\ 1 & -1 & 1 & -1 \\ 1 & i & -1 & -i \end{bmatrix} \tag{5}$$

C. MET based cooperation

To determine a near-optimum linear pre-coding matrix for MU-MIMO service for a group of MTs in the cooperation area, we employ MET. [7] describes the MET concept in more details and indicates that MU-MIMO service for distinct terminals using MET is more efficient than time-multiplexing multi-stream transmission to a single user. Thus, we limit all terminals to apply for $\lambda = 1$ spatial stream only. For this purpose, each MT is assumed to feed back its dominant eigenmode only, which reduces the required amount of feedback per user.

Consider a fixed set $\mathcal{M}$ of users, which should be served in a RB. Each user m decomposes its $N_R \times \alpha N_T$ channel matrix $\mathbf{H}_i^m$ using the singular value decomposition (SVD) yielding $\mathbf{H}_i^m = \mathbf{U}_i \mathbf{\Sigma}_i \mathbf{V}_i^H$, where the strongest eigenvalue in $\mathbf{\Sigma}_i$ corresponds to the dominant eigenmode in $\mathbf{v}_{i,1}$. The dominant eigenmode weighted by the eigenvalue, i.e. $\mathbf{\Gamma}_m = \Sigma_{i,1}\mathbf{v}_{i,1}^H$, needs to be fed back from each MT to the cell cluster.

User orthogonalization at the BS: To obtain the pre-coding vector for the m-th user, the BS cluster aggregates the interfering eigenmodes $\mathbf{\Gamma}_n$ with $n \in \{1, ..., (m-1), (m+1), ..., \alpha N_T\}$ from the other terminals in the active set $\mathcal{M}$, yielding a matrix of dimension $(\alpha N_T - 1) \times \alpha N_T$

$$\tilde{\mathbf{\Gamma}}_m = [\mathbf{\Gamma}_1^H \dots \mathbf{\Gamma}_{m-1}^H \, \mathbf{\Gamma}_{m+1}^H \dots \mathbf{\Gamma}_{\alpha N_T}^H]^H \tag{6}$$

Performing the SVD of $\tilde{\mathbf{\Gamma}}_m$ yields

$$\tilde{\mathbf{\Gamma}}_m = \tilde{\mathbf{U}}_m \begin{bmatrix} \tilde{\mathbf{\Sigma}}_m & \mathbf{0} \end{bmatrix} \begin{bmatrix} \tilde{\mathbf{V}}_m^1 & \tilde{\mathbf{v}}_m^0 \end{bmatrix}^H , \tag{7}$$

where $\tilde{\mathbf{v}}_m^0$ corresponds to the eigenvector associated with the null space of $\tilde{\mathbf{\Gamma}}_m$. Note, in principle the null space is represented by a matrix of dimensions $\lambda \times \alpha N_T$. Since we limit each user to be served on its dominant eigenmode only, i.e. $\lambda = 1$, $\tilde{\mathbf{v}}_m^0$ is of dimension $1 \times \alpha N_T$ and thus a vector.

This vector is used for pre-coded transmission to user m, which ensures that all other users in $\mathcal{M}$ do not experience any interference from this beam under ideal conditions. Note, that the block-diagonalization constraint, which is $\alpha N_T \geq \sum_{\forall m \in \mathcal{M}} N_R(m)$ is relaxed by the use of dominant eigenmodes satisfying $|\mathcal{M}| \leq \alpha N_T$ [7].

The selected pre-coding matrix on a RB and time slot is given by

$$\mathbf{C}_4 = [\tilde{\mathbf{v}}_1^0 \dots \tilde{\mathbf{v}}_m^0 \dots \tilde{\mathbf{v}}_{\alpha N_T}^0] \, , \tag{8}$$

where $\mathrm{tr}\left[\mathbf{C}_4 \mathbf{C}_4^H\right] = p_i$. As the beamforming vectors are unitary, $\mathbf{C}_4$ implicitly includes the constraint of equal transmit power per beam and sum power per BS. Note, that we are not considering any optimal power allocation scheme.

TABLE I

SIMULATION ASSUMPTIONS.

parameter	value
channel model	3GPP SCME
type	Monte Carlo
scenario	urban-macro
additional modifications	LOS-NLOS propagation mix
traffic model	full buffer
f_c	2 GHz
frequency reuse	1
system bandwidth	31.72 MHz
signal bandwidth	18 MHz, 100 RBs
intersite distance	500m
number of BSs	19 having 3 sectors each
N_T ; spacing	1,2 ; 4λ
transmit power	46 dBm
sectorization	triple, with FWHM of 68°
BS height	32m
N_T ; spacing	1,2 ; $\lambda/2$
MT height	2m

V. LINEAR MMSE RECEIVER

In this work we consider MMSE equalization for the purpose of inter-cell interference suppression at the receiver side according to

$$\mathbf{w}_m^{\mathrm{MMSE}} = \frac{p_i \mathbf{R}_{yy}^{-1} \mathbf{H}_i^m \mathbf{b}_{i,u}}{\alpha N_T} \, , \tag{9}$$

where $\mathbf{R}_{yy}$ denotes the covariance matrix of $\mathbf{y}^m$ from (2), i.e. $\mathbf{R}_{yy} = \mathrm{E}\left[\mathbf{y}^m \left(\mathbf{y}^m\right)^H\right]$. $\mathbf{b}_{i,u}$ is the pre-coding chosen from $\mathbf{C}_i$ according to (3), (4), (5) or (8). This receiver yields a post-equalization SINR on a given RB for user m

$$\mathrm{SINR}_m \geq \frac{\frac{p_i}{\alpha N_T} \left[\mathbf{H}_i^m \mathbf{b}_{i,u}\right]^H \mathbf{R}_{yy}^{-1} \mathbf{H}_i^m \mathbf{b}_{i,u}}{1 - \frac{p_i}{\alpha N_T} \left[\mathbf{H}_i^m \mathbf{b}_{i,u}\right]^H \mathbf{R}_{yy}^{-1} \mathbf{H}_i^m \mathbf{b}_{i,u}} \tag{10}$$

The covariance may be obtained by using multi-cell channel estimates based on common and dedicated reference signals [13]. Thus, each terminal is able to combat residual CCI aggregated in $\mathbf{z}_{i,u}$ from (2). In addition errors caused by time-varying channels and CQI or CSIT feedback quantization may be restricted to a minimum.

VI. SIMULATION ENVIRONMENT

The performance is investigated in a triple-sectored hexagonal cellular network with 19 BSs in total. The SCME with urban macro scenario parameters is used [14] yielding an user's geometry for the center cell, refer to Fig. 1 (right), which is equivalent to [15]. The basic system settings for our simulations are summarized in Table I. For the evaluation of cooperative transmission strategies we have to take users from surrounding cells into account. For a reliable performance evaluation of the cellular network we employ a wrap-around, which ensures that the interference scenario follows i.i.d. statistics for all users.

As an initial step we place up to 20 terminals per sector inside the inner cell with cell ID=$\{1,2,3\}$. Since evaluation in

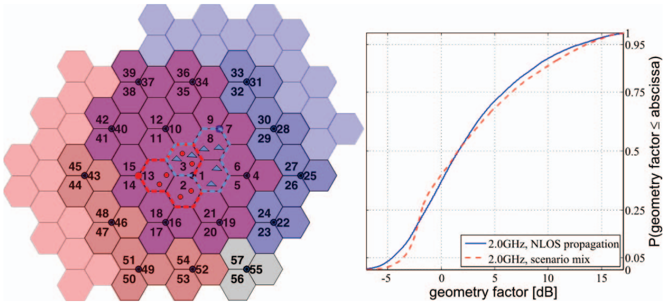

Fig. 1. Left: Triple-sectored cellular setup. The region bounded by the red and blue dashed line indicates a cooperative cell cluster jointly serving their terminals on different RBs. Right: User geometries obtained from the center cell with id={1,2,3} and parameters according to Table I.

this work is limited to linear pre-coded beams, up to αN_T user may be served in the same RB. N_T corresponds to the available spatial dimensions per sector antenna array. If the number of terminals per sector exceeds N_T, interference-aware score-based scheduling is applied, which increases the system throughput further [6]. Note, that results including frequency-selective scheduling are based on fixed beams only, where inter-cell interference remains predictable.

The users in the cooperating cell of a cluster are generated by dropping the users in the center cell constituted from the sectors with ID=$\{1,2,3\}$ and then shifting the origin into the desired direction. In particular, if cells 1,3 and 8 (indicated by the blue framed region in Fig. 1 (left)) form a cooperation cluster, the users distributions in cell 1 and 3 are generated without any shift of the origin, while for the user in cell 8 the center cell is shifted to the north-east direction, as illustrated as the light blue region in Fig. 1 (left). The figure depicts another clustering given as red framed region; the active user set $\mathcal{M}$ in each cluster is indicated as blue triangles and red dots, respectively.

Performance is evaluated for the sum throughput in a specific cell cluster of size α. This value is divided by the signal bandwidth, yielding a clusters's spectral efficiency. The achievable rates are determined from Shannon's formula, which represent theoretical limits in a practical system.

VII. RESULTS

Fig. 2 shows the achievable spectral efficiency for the SISO system for reference purpose. The performance of the coherent MIMO 2×2 system, where each cell is operating independently, is given for a sparse user distribution, i.e. 2 users per cell. It can be observed that the system, which is capable to switch adaptively between single-stream and multi-stream transmission outperforms the one using multi-stream transmission only. The cumulative distribution function (CDF) curves indicating the performance for 5, 10 and 20 users per cell are obtained from simulations using the fair, interference-aware score-based scheduler. The scheduler enables large gains from multi-user diversity, i.e. the median spectral efficiency is growing with a factor of $\gamma = 1.58$ for 20 users with respect to the case of 2 MTs.

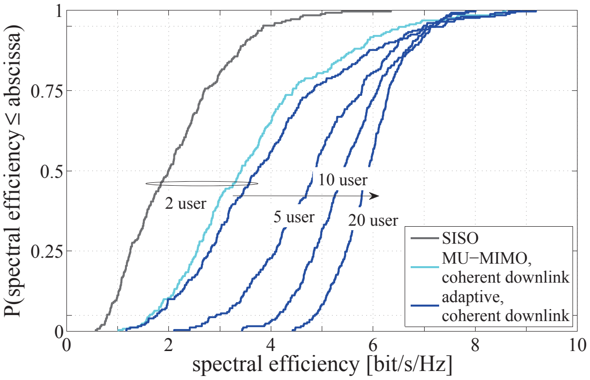

Fig. 2. Compares the spectral efficiency of the single-cell operating SISO, MIMO 2×2 system. If possible fixed DFT-based pre-coded beamforming was used.

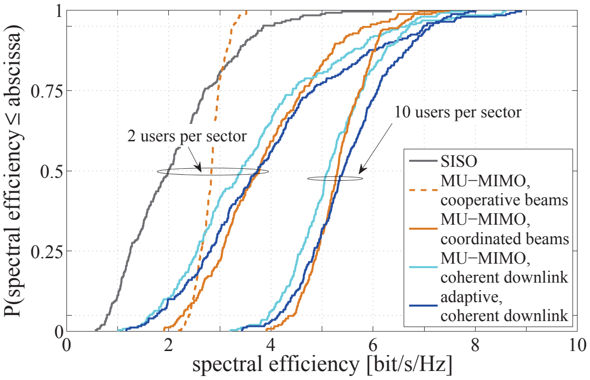

Fig. 3. Compares the spectral efficiency of the coherent downlink system with system using coordinated as well as cooperative beamforming.

The performances of the system using coordinated and cooperative beams for intra-cluster interference mitigation are given in Fig. 3. We additionally include results from the baseline system for comparison. The CDFs are obtained for 2 and 10 users per cell, respectively. The interference mitigation provided from coordinated beams indicates small gains over coherent MU-MIMO in the order of 0-20% for 2 users in 75% of all cases. With higher multi-user diversity, i.e. 10 users per cell, gains are reduced to 0-10%. The concept using cooperative fixed DFT-based beamforming suffer from the equal gain constraint and thus shows inferior performance compared to the baseline in 75% of all situations. However, the CDF is very steep, i.e. spectral effieciencies in the system show only small variations.

Fig. 4 shows the achievable spectral efficiency for the non-cooperative SISO and the coherent MIMO system for reference purpose. The results are limited to a sparse user distribution, i.e. 2 users per cell. The performance of the 2×2 system with $\alpha = \{2, 3\}$ cooperating sectors using MET is given as red and green dashed lines. MET without any multi-user diversity available for the user grouping cannot outperform the coherent downlink transmission for $\alpha = 2$. Thus, joint downlink transmission for a fixed set of users

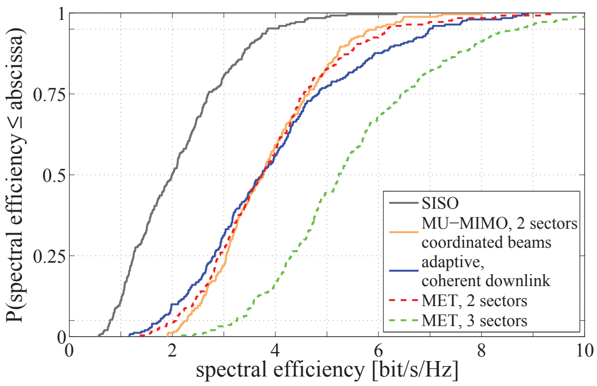

Fig. 4. Compares the spectral efficiency of the coherent downlink system with system using coordinated as well as MET based beamforming.

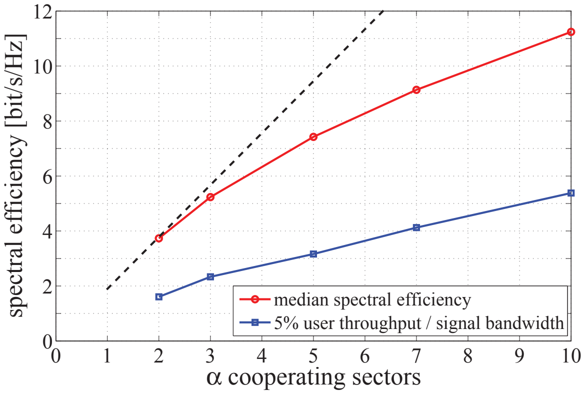

Fig. 5. Indicates the scaling behavior of the spectral efficiency with respect to the cooperation radius α. We included results valid for a MIMO 2 × 2 system.

should be done at least among 3 cooperating cells. Further we observe a similar performance for MET and coordinated beamforming both with a cooperation radius of $\alpha = 2$.

Fig. 5 depicts the scaling behavior for the overall spectral efficiency of the i-th cluster with respect to α cooperating sectors. The spectral efficiency shows a sub-linear increase for a growing size of the cooperation area. The black dotted line represents a growth proportional to α, where the reference point is located at $\alpha = 2$. The scaling factors with respect to the non-cooperative SISO system are $\gamma = \{1.9, 2.6, 3.7, 4.6, 5.6\}$ for $\alpha = \{2, 3, 5, 7, 10\}$. The 5-percentile of the normalized user throughput, which serves as a measure for the throughput of cell-edge users, scales similarly.

VIII. CONCLUSION

This work gives results for limited, distributed cooperative downlink transmission in cellular MIMO OFDM, which were obtained from system level simulations. Simple CQI based joint transmission was enabled by different levels of downlink cooperation which are: coordinated fixed beamforming and cooperative fixed beamforming in combination with MMSE equalization at the receiver. For comparison we include results obtained from a coherent receiver optimized downlink system. As an upper bound, CSIT based cooperation using MET was introduced, which was enhanced by MMSE equalization. It was shown to increase the system and user performance significantly. We demonstrated potential capacity gains under the assumption of CQI and coherent CSIT feedback, respectively, and showed the scaling with the cooperation radius for the latter.

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