MU-MIMO with Localized Downlink Base Station Cooperation and Downtilted Antennas

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***Abstract*—Multi-cellular radio systems are often limited due to the presence of cochannel interference. Proposed physical layer concepts, e.g. coordinated joint transmission and interference rejection combining, try to strengthen the signal while combating the interference. It is well known that base station cooperation yields great capacity improvement for downlink multi-antenna cellular networks. However, the proposed solutions assume a central processing unit, coordinating the information exchange and thus determining the optimal resource allocation of the overall cellular network. Recently multi-user eigenmode transmission was proposed to relax the constraint of channel state information at the transmitter. It requires the terminals to feed back their dominant eigenmodes only. To reduce the computational costs and the information exchange further, we consider limited localized base station cooperation. We demonstrate potential capacity gains in a cellular orthogonal frequency division multiplexing system using real 3D measured antenna patterns and the scaling with the number of cooperating antenna arrays. Additionally, we use minimum mean square error equalization at the terminal side to combat residual cochannel interference.**

I. Introduction

Recent advances valid for an isolated cell indicate huge 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] and thus utilizing multi-user MIMO (MU-MIMO). As optimum transmission strategy in an isolated cell or cell cluster, joint dirty paper coding (DPC) is known to achieve the capacity of the broadcast channel [5] and it is therefore usually considered as an upper bound for multi-user transmission. However, cellular systems would suffer from multi-cell interference from other clusters, i.e. inter-cluster interference. In order to develop advanced multi-antenna techniques, such as MU-MIMO or cooperative transmission [6], we have to ensure a realistic modeling of multi-cell interference. This enables us to investigate their performance more realistically. Performance evaluation is commonly based on multi-cell simulations using 2D models as e.g. 3GPP's extended spatial channel model (SCME). However, in this work we consider an extension to the 3D case using real 3D measured antenna patterns [7]. The used antenna is one of the standard antennas, which will be used for future 3G Long Term Evolution (3G-LTE) sectorized cellular urban deployments.

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 [8] with $N_T = N_R$ transmit and receive antennas. This work focused on static DFT-based pre-coding, interference rejection combining (IRC) at the mobile terminals (MTs) and heuristic optimization in the sense of frequency-selective resource allocation, which tends to assign an equal amount of resources to all users. However, in this context, transmission shows interference limited behavior. Especially 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 a great performance gain.

In this work we focus on how to realize limited localized cooperative transmission in a multi-cellular network. Therefore, we employ multi-user eigenmode transmission (MET), known to realize 90% of the DPC capacity in an isolated cell context [6], based on the dominant eigenmodes of the MTs in the serving area. This work indicates potential performance gains in an orthogonal frequency division multiplexing (OFDM) downlink with $N_T \in \{2, 4\}$ transmit and $N_R = 2$ receive antennas and a variable size of the cooperation area. We limit our analysis to a sparse user distribution, which ensures to evaluate gains from cooperative transmission independent from multi-user diversity gains. To combat residual CCI we employ MMSE equalization, known as optimum combining (OC) [9], at the terminal side. Under consideration of residual multi-cell interference from the cellular system, the MMSE receiver helps to restrict the residual inter-beam interference in the cooperation area and the inter-cell interference to a minimum. Our results are obtained from multi-cell simulations based on 3GPP's SCME and its extension to inlude the 3D antenna characteristics.

II. Downlink system model

The downlink MIMO-OFDM transmission system with N_T transmit and N_R receive antennas per MT is described on per subcarrier basis

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

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

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Assume that a group of α cooperating base station (BS) sectors provides a beam set $\mathbf{C}_i$. The beam set 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 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

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

The desired data stream $x_{i,u}$ transmitted on the u-th beam 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 for user m formed by the cluster i. Thus, $\zeta_{i,u}$ denotes the interference generated in the cooperation area. In the scope of this paper, it is assumed that all αN_T beams in the beam set $\mathbf{C}_i$ are simultaneously active, whereby the total available power p_i is assumed to be uniformly distributed over the αN_T beams. Thus, $E\left\{|x_{i,j}|^2\right\} = p_i/(\alpha N_T)$ holds, and $p_i = \sum_{j=1}^{\alpha N_T} \mathrm{E}\left\{|x_{i,j}|^2\right\} = \alpha p_s$ with p_s being the transmit power per sector.

A. Determine BS cluster for cooperation

The choice of collaboration area (CA) can be done network-centric or user assisted (user-centric). The user-centric choice may be found by measuring the broadband channels to all nearby BSs and reporting a set of strongest BS antennas to its serving BS. The serving BS may initialize the setup of a new CA or allocate this particular MT into a user group served inside a predefined CA. To determine the upper limit, which may be achieved by the of use of distributed cooperative MU-MIMO transmission, we assume all users within this group to report the same set of strongest BS antennas. However, the users are arranged such that the index order of these BS antennas is obtained by a unique permutation. Since it is likely to assume that there is a strongly limited number of users, i.e. sparse user distribution, meeting these requirements, we do not consider multi-user diversity in the process of user grouping.

III. 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. A basic concept to achieve this kind of synchronization has been presented in [10].

As a reference design for downlink cooperation in cellular systems, we use an approach based on MET, which is known to achieve a near-optimum pre-coding performance for an isolated cell cluster [6]. For MET, the MTs report the $\lambda \leq N_R$ dominant eigenmodes of their channel to the cell cluster together with the corresponding eigenvalues. MET supports to simultaneously transmit up to αN_T data streams via unitary precoding beams, while up to N_R beams may be assigned to a single MT. However, it has been indicated in [6] that MU-MIMO service for distinct terminals using MET is more efficient than time-multiplexing multi-stream transmission to a single user. Thus, for our investigations, we let all MTs report their dominant eigenmode only ($\lambda = 1$), which keeps the required amount of feedback per user limited. Determination of the MET-based pre-coding beams in matrix $\mathbf{C}$ is briefly sketched as follows.

A. User assisted pre-selection of feedback information

Consider a fixed set $\mathcal{M}$ of users, which should be served in a resource block (RB). Each user m decomposes its $N_R \times \alpha N_T$ channel matrix $\mathbf{H}_i^m$ according to the singular value decomposition (SVD), yielding $\mathbf{H}_i^m = \mathbf{U}_i \mathbf{\Sigma}_i \mathbf{V}_i^H$. We assume each user to apply for service on a single data stream only, i.e. MU-MIMO transmission to different MTs. Thus, it is favorable to select the dominant eigenmode for each user, i.e. the eigenvector corresponding to the highest eigenvalue. The user's effective eigenmode channel after equalization is given by

$$\begin{aligned}\mathbf{\Gamma}_m &= \mathbf{u}_{i,1}^H \mathbf{H}_i^m \\ &= \mathbf{u}_{i,1}^H \mathbf{U}_i \mathbf{\Sigma}_i \mathbf{V}_i^H \\ &= \Sigma_{i,1} \mathbf{v}_{i,1}^H \qquad (3)\end{aligned}$$

Each user has to report the effective channel $\mathbf{\Gamma}_m$ to its serving BS.

B. 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 $(\alpha N_T - 1) \times \alpha N_T$

$$\tilde{\mathbf{\Gamma}}_m = [\mathbf{\Gamma}_1^H \ldots \mathbf{\Gamma}_{m-1}^H \, \mathbf{\Gamma}_{m+1}^H \ldots \mathbf{\Gamma}_{\alpha N_T}^H]^H \qquad (4)$$

According to the block diagonalization (BD) solution [11], we perform the SVD of $\tilde{\mathbf{\Gamma}}_m$, which yields

$$\tilde{\mathbf{\Gamma}}_m = \tilde{\mathbf{U}}_m \left[\begin{array}{cc} \tilde{\mathbf{\Sigma}}_m & \mathbf{0} \end{array} \right] \left[\begin{array}{cc} \tilde{\mathbf{V}}_m^1 & \tilde{\mathbf{v}}_m^0 \end{array} \right]^H, \qquad (5)$$

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 $\alpha N_T \geq \sum_{\forall m \in \mathcal{M}} N_R(m)$ is relaxed by the use of dominant eigenmodes, resulting in $\alpha N_T \geq |\mathcal{M}|$ instead [6].

$$
\begin{aligned}
\mathbf{r}_m &= \mathbf{w}_m^H \mathbf{y}^m \\
&= \left[\frac{p_i \mathbf{R}_{yy}^{-1} \mathbf{H}_i^m \tilde{\mathbf{v}}_m^0}{\alpha N_T}\right]^H \left[\mathbf{H}_i^m \tilde{\mathbf{v}}_m^0 x_{i,m} + \underbrace{\sum_{\substack{n=1 \\ n \neq m}}^{\alpha N_T} \mathbf{H}_i^m \tilde{\mathbf{v}}_n^0 x_{i,n}}_{\zeta_{i,m}} + \mathbf{z}_{i,u} + \underbrace{\sum_{\substack{\forall l \\ l \neq i}} \sum_{j=1}^{N_T} \mathbf{H}_l^m \mathbf{b}_{l,j} x_{l,j} + \mathbf{n}}_{\mathbf{z}_{i,u}} \right]
\end{aligned}
\quad (8)
$$

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

$$\mathbf{C} = \left[\tilde{\mathbf{v}}_1^0 \ldots \tilde{\mathbf{v}}_m^0 \ldots \tilde{\mathbf{v}}_{\alpha N_T}^0\right], \quad (6)$$

where $\mathrm{tr}\left[\mathbf{C}\mathbf{C}^H\right] = p_i$. As the beamforming vectors are unitary, $\mathbf{C}$ implicitly includes the constraint of equal transmit power per beam and sum power per cell cluster.[1]

C. Linear Receivers

Assuming a linear equalizer $\mathbf{w}_u$ at the MTs, which is required to extract the useful signal $x_{i,u}$ from $\mathbf{y}^m$ according to (2), yields a post-equalization signal to interference and noise ratio (SINR) at the MT for stream $x_{i,u}$ given by

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

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

In case of a maximum ratio combining (MRC) like receiver, each terminal has to store the linear detectors for each RB, given by the Hermitian transpose of the leftmost column in $\mathbf{U}_i$. In this case under idealistic assumption, i.e. no quantization effects and a static channel, there would be no inter-beam interference in the cell cluster i. In this work, we consider minimum mean square error (MMSE) equalization for the purpose of inter-cell interference suppression at the receiver side according to

$$\mathbf{w}_m^{\mathrm{MMSE}} = \frac{p_i \mathbf{R}_{yy}^{-1} \mathbf{H}_i^m \mathbf{b}_{i,u}}{\alpha N_T}, \quad (8)$$

where $\mathbf{R}_{yy}$ denotes the covariance matrix of $\mathbf{y}^m$ from (2), i.e. $\mathbf{R}_{yy} = \mathrm{E}\left[\mathbf{y}^m \left(\mathbf{y}^m\right)^H\right]$. This receiver yields a post-equalization SINR on a given RB for user m

$$\mathrm{SINR}_m = \frac{p_i}{\alpha N_T} \left[\mathbf{H}_i^m \mathbf{b}_{i,u}\right]^H \mathbf{Z}_u^{-1} \mathbf{H}_i^m \mathbf{b}_{i,u} \quad (9)$$

In a practical context, the covariance matrix

$$\mathbf{R}_{yy} = \mathbf{Z}_u + \mathbf{H}_i^m \mathbf{b}_{i,u} \left(\mathbf{H}_i^m \mathbf{b}_{i,u}\right)^H \quad (10)$$

may be obtained by using multi-cell channel estimates based on common and dedicated reference signals [12]. Thus, each terminal is able to combat residual CCI from surrounding cells aggregated in $\mathbf{z}_{i,u}$ from (2).

The received signal vector $\mathbf{r}_m$ behind the linear detector at the m-th MT is given in (8). Thus, each terminal is able to combat residual CCI denoted as $\mathbf{z}_{i,u}$ in (2). In addition errors made due quantization effects and a time-varying channel may be restricted to minimum. For the purpose of channel estimation, we assume the BSs to transmit common pilots and dedicated pilots for estimation of selected pre-coding weights at the MT. Thus the MTs are able to estimate the linear detector itself from the reference signals without the requirement of feed forward information or huge buffers for storage of filter coefficients as necessary for MRC like equalization.

TABLE I
SIMULATION ASSUMPTIONS.

parameter	value
channel model	3GPP SCME
type	Monte Carlo
scenario	urban-macro
additional modifications	scenario-mix[2]
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	1,2,4 ; 4λ
transmit power	46 dBm
sectorization	triple, with FWHM of 68°
elevation pattern[3]	FWHM of 6.2°, elec. downtlit 10°
BS height	32m
N_T ; spacing	1,2 ; λ/2
MT height	2m

IV. SIMULATION ENVIRONMENT

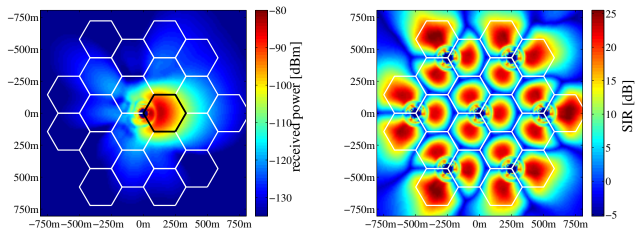
The performance is investigated in a triple-sectored hexagonal cellular network with 19 BSs in total, refer to Fig. 2 (left). The SCME with urban macro scenario parameters is used [13], yielding an user's geometry as shown in Fig. 2 (right). The basic system settings for simulations are summarized in Table I.

Effect of downtilted BS antennas:
Simulation results are given for two different antenna settings:

[1] We are not considering any optimal power allocation scheme here.

[2] i.e. each cell, consisting of 3 sectors, may have different channel conditions, e.g. line of sight (LOS) or non line of sight (NLOS).

[3] using a 3D measured radiation pattern, KAHTREIN 80010541.



(a) received power (b) SIR

Fig. 1. Modeling of 3D antennas and influence on cellular deployment.

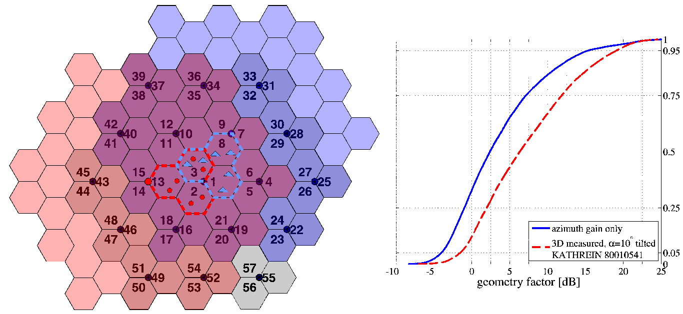


Fig. 2. Left: Triple-sectored cellular setup. The region bounded by the red and blue dashed line indicates a cooperative cell cluster jointly serving their terminals on different RBs. Right: User geometries obtained from that cell layout and given parameters.

First, only the azimuth radiation pattern is used, which is the widely used approach for performance analysis in a cellular deployment. Second, we extend the simulation environment to include the elevation characteristics of real-world antennas [7]. Therefore, we use real 3D measured antenna patterns from a KATHREIN 80010541 antenna, which is one of the standard antennas used for future 3G-LTE sectorized cellular urban deployments. Fig. 1(a) shows the received power experienced by a MT based on an urban path loss in combination with 3D measured antenna pattern. The BS antenna is mounted at 32 m above ground level and uses an electrical downtilt of 10°. Fig. 1(b) depicts the achievable signal to interference ratios (SIRs) in this setup, where the inner 3 sectors may serve as representatives in a cellular deployment. It can be observed that the SIR ranges from 0 dB at the cell edge up to 25 dB in the cell center. From [7] we know that downtilted antennas not only change achievable SIRs, but additionally ensure that the origin of strong interference is close to the user's position.

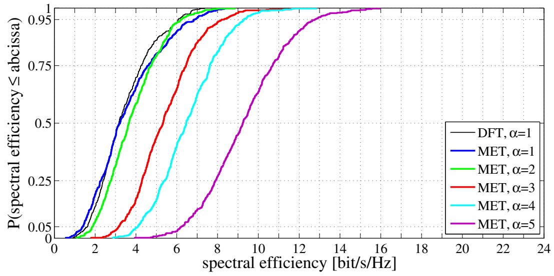
Wrap-around technique:
For a reliable performance evaluation we are using a wrap-around, which ensures that the interference scenario is complete and follows independent identically distributed (i.i.d.) statistics for all users. As an initial step we place N_T terminals per sector inside the inner cell with id={1,2,3}. In this work, N_T corresponds to the available spatial dimensions per sector antenna array. For each time and frequency resource all available MTs are served with MU-MIMO. 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 of the cell topology into the desired direction. In particular, if cells 1,3 and 8 (indicated by the blue framed region in Fig. 2 (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 by the light blue region in Fig. 2 (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 both the sum throughput in a specific cell cluster of size α and the throughput for individual users assigned to the BSs. Both values are normalized by the signal bandwidth, while the sum throughput is additionally divided by α, yielding an effective spectral efficiency per sector. The achievable rates are determined from Shannon's formula, which represent theoretical limits in a practical system. The receiver is assumed to to have perfect channel state information (CSI) from all BSs, and feedback given by the MTs is considered to be error free and not affected by any delays.

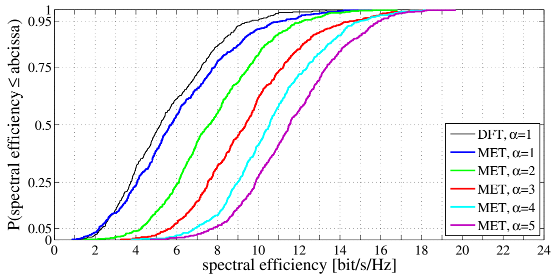
V. Performance Evaluation

Fig. 3 shows the achievable spectral efficiency for a MIMO system with $N_T \in \{2,4\}$ and $N_R = 2$. For reference purpose we include throughput cumulative distribution functions (CDFs) for a non-cooperative MU-MIMO system using DFT-based pre-coding under sparse user distribution, i.e. $|\mathcal{M}| = 2$. Fig. 3(a) depicts the achievable performance for the MET-based pre-coded system with variable cluster size with $\alpha \in \{1,2,3,4,5\}$ under widely used simulation assumptions, i.e. BS antennas are modeled in azimuth direction only. In contrast, the achievable performance using real-world antenna characteristics with an electrical downtilt angle set to 10° is shown in Fig. 3(b). Here the use of downtilted antennas already show a high gain in spectral efficiency. In this case, the CSIT based pre-coding technique brings an additional 10% gain over the DFT-based pre-coded downlink transmission. Thus, we may conclude that codebook based pre-coding approaches the performance of the CSIT based concept for $N_T = N_R$. The gain over the reference system increases by factors of 1.46, 1.81, 2.04 and 2.2 for step-wise increasing α. Turning the focus to cellular systems having $N_T =$ transmit antennas per BS, we oberve in Fig. 3(c) an enhanced performance compared to the MIMO 2×2 case. The scaling factors with respect to the reference system amount to 1.5, 2.04, 2.65, 3.02, 3.29 for $\alpha \in \{1,2,3,4,5\}$. Finally we remark that additional gains decrease with increasing cluster size α.

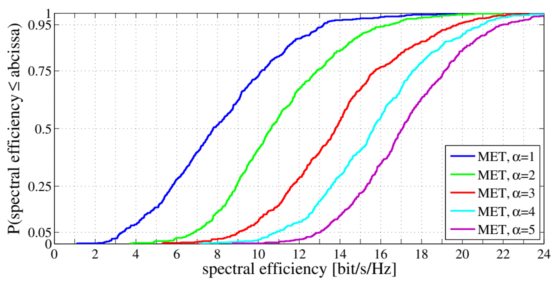
Fig. 4 depicts the scaling for the user's 5-percentile normalized throughput versus the median spectral efficiency of each sector for different cluster sizes. Note, the 5-percentile of the normalized user throughput may serve as a measure to represent the throughput of cell-edge users, while the sectors's median spectral efficiency is commonly used as cell benchmark. In general the 2×2 system shows a higher user throughput, while the 4×2 increases the median spectral effi-



(a) 2x2, azimuth pattern only



(b) 2x2, 10° downtilt, real 3D measured antenna pattern



(c) 4x2, 10° downtilt, real 3D measured antenna pattern

Fig. 3. Modeling of 3D antennas and influence on cellular deployment.

ciency of the sector. Since we do not consider the performance of an isolated cluster, inter-cluster interference is still limiting the throughput performance of the users.

VI. Conclusion

This work shows results for a cooperative downlink transmission in cellular MIMO OFDM, obtained from system level simulations. The performance analysis was carried out for $N_T \in \{2, 4\}$ transmit antennas with a variable size α for the cooperative cluster. To increase spectral efficiency, especially in metropolitan and urban macro areas, 3G-LTE and its successors will use highly directive antennas. With downtilt angles adjusted to the desired cell size, inter-cell interference can directly be mitigated. Downlink cooperation was shown to further increase the system's spectral efficiency by 200% ($N_T = 2$) and 300% ($N_T = 4$) for $\alpha = 4$ compared to the non-cooperative codebook-based pre-coded system with $N_T = N_R = 2$. Thus, limited localized base station cooperation based on multi-user eigenmode transmission in combination with MMSE equalization at the receiver was shown to increase the system and user performance significantly.

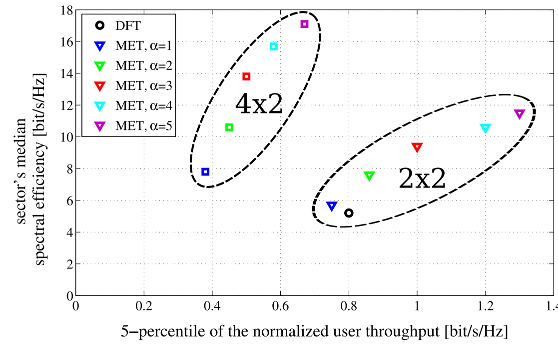


Fig. 4. User's 5-percentile spectral efficiency vs. sector's median spectral efficiency for $N_T \in \{2, 4\}$ and $N_R = 2$.

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