Limited Feedback in Multiuser MIMO OFDM Systems Based on Rate Approximation

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Abstract—We propose a new limited feedback scheme for the downlink of multiuser MIMO OFDM systems based on fixed linear beamforming, i.e., the linear beamforming vectors are chosen from a fixed transmit codebook. The proposed feedback method allows the base station to uniformly approximate all multiuser rates for any selection of users and any combination of beamforming vectors defined by the transmit codebook; thus providing all degrees of freedom for the user selection. The approximation of the multiuser rates is enabled by using an additional codebook for the feedback. This has several advantages: the transmit codebook can be designed independent of the feedback codebook, the accuracy of the approximated rates can be scaled by changing the size of the feedback codebook and the feedback codebook can be adapted to the environment. We show how feedback codebooks can be designed for arbitrary environments using the LBG algorithm. Moreover, we show how the computational complexity of the proposed feedback method can be reduced without a significant performance loss. In the simulations we demonstrate that the proposed method outperforms other methods within the LTE context.

I. INTRODUCTION

Multiple antenna downlink technology offers the possibility of sharing the same frequency band at the same time between multiple users. In general nonlinear dirty paper coding (DPC) is capacity achieving [1]. Since in practical systems DPC is difficult to implement, linear beamforming techniques performing close to optimal DPC [2], have been studied extensively. Furthermore, over the last years there have been also a vast number of publications dealing with so-called limited feedback multiuser MIMO systems. In this case the base station obtains partial channel state information (CSI) from the users via a rate–constrained feedback channel. An extensive overview of limited feedback multiuser MIMO systems can be found in [3].

One category of limited feedback multiuser MIMO schemes is based on adaptive beamforming, where the choice of beamforming vectors is not restricted to a specific codebook. Typically, the base station determines the beamforming vectors according to strategies like zero–forcing beamforming [4] or more advanced MMSE–based beamforming techniques [5]. Likewise, the user selection problem can be solved by methods like semi–orthogonal user selection [6]. More advanced feedback concepts are proposed in [7], [8] and [9]. These concepts allow the users to estimate their SINR under the assumption of a specific transmit strategy. However, the problem with adaptive beamforming is that in addition to common pilots, dedicated pilots are necessary to provide the users with a proper phase reference.

A second category is based on the assumption that the transmit beamforming vectors are chosen from a fixed transmit codebook, i.e., fixed beamforming. In particular in LTE [10] a fixed transmit codebook is likely to be selected. Therefore, we focus on this scenario here. When using fixed beamforming no dedicated pilots are necessary. In most of the fixed beamforming approaches each user reports information regarding its preferred codebook index. This feedback information is then used by the base station to select users for transmission. One candidate is the so called per user unitary rate control (PU2RC) introduced in [11]. In [12] it is shown that PU2RC achieves the full multiuser diversity and multiplexing gain asymptotically, i.e. for a large number of users. However as pointed out by [13] the case of a large number of users is actually the opposite of what next generation wireless systems (e.g. LTE) aim at, namely to provide very high data rates to individual users. However for a small number of users the interference situation has to be more accurately predicted. This is not achieved by PU2RC (or others, see e.g. [14]). In addition more accurate information on the interference situation at the base station clearly enlarges the degrees of freedom for user selection.

Making the interference situation available to the base station is exactly the purpose of this paper. We present a new feedback method which allows the base station to uniformly approximate the multiuser rates for any selection of users and any combination of beamforming vectors defined by a transmit codebook. The main idea is to distinguish between a transmit– and a feedback codebook; for the feedback codebook the notion of test channels is introduced which are designed to minimize a certain metric (details given later on). Two striking advantages come with this concept. First, the base station has now all degrees of freedom for user selection and second the rate allocation is more reliable, due to the uniform approximation and the reliability scales with the number of feedback bits. Furthermore, such rate approximations are particularly invaluable if multiple base stations are cooperating. Finally, we demonstrate how feedback codebooks for arbitrary scenarios can be designed using the algorithm proposed by Linde, Buzo...
and Gray in [15]. Hence, using the proposed feedback method different feedback codebooks could be loaded by the users if the environment changes (e.g. moving from indoors to outdoors).

The paper is organized as follows. In section II we describe the system model. Section III introduces the proposed rate approximation limited feedback scheme. The performance of the proposed method is compared to other limited feedback schemes by extensive simulations in section IV. In section V a conclusion is drawn.

Notation: $\|x\|_2 = \sqrt{\langle x, x \rangle}$ denotes the usual euclidian norm of the vector $x$ where $\langle \cdot, \cdot \rangle$ is the inner product. $E[\cdot]$ is the expectation operator. $|\mathcal{A}|$ denotes the size of set $\mathcal{A}$.

II. SYSTEM OVERVIEW

A. System Model

We consider a single cell multiple antenna downlink channel. The base station is equipped with $N$ transmit antennas and each of the $M$ users have a single receive antenna. The OFDM subcarriers are grouped in scheduling blocks (SB), i.e. the smallest scheduling unit. In this paper we will consider a single SB and collect its subcarrier indices in the set $\mathcal{F}$. The corresponding channels of user $m$ are collected in the set $\mathcal{H}_m = \{h_{f,m} \in \mathbb{C}^{N \times 1} : f \in \mathcal{F}\}$. We assume that each user has perfect knowledge of its channels. The signal received by user $m$ on subcarrier $f \in \mathcal{F}$ can be written as:

$$y_{f,m} = \langle h_{f,m}, x_f \rangle + n_{f,m}$$

(1)

where $h_{f,m} \in \mathcal{H}_m$ is the vector of channel coefficients, $x_f \in \mathbb{C}^{N \times 1}$ is the transmitted signal vector and $n_{f,m} \sim \mathcal{CN}(0,1)$ is additive white Gaussian noise. On a given transmission interval the base station selects a set of users $S = \{s_1, s_2, \ldots, s_|S|\} \subseteq \mathcal{M} = \{1, \ldots, M\}$ for transmission and assigns to each user $m \in \mathcal{S}$ a beamforming vector $w_m$. Then the transmitted signal can be written as:

$$x_f = W d_f = \sum_{m \in \mathcal{S}} w_m d_{f,m}$$

(2)

where $d_f = (d_{f,s_1}, \ldots, d_{f,s_|S|})^T$ is the vector of information symbols for user $m \in \mathcal{S}$ and subcarrier $f \in \mathcal{F}$. Notice that the beamforming matrix $W$ does not depend on the subcarrier index $f$, i.e. the base station selects a common beamforming matrix for all subcarriers $f \in \mathcal{F}$ in the SB.

We assume an average sum–power constraint per subcarrier, i.e. the transmitted signal must satisfy $E[|\text{tr} \{x_f x_f^H\}|] \leq 1$. The beamforming vectors $w_m$ are chosen from a transmit codebook $\mathcal{C} = \{c_1, c_2, \ldots, c_|\mathcal{C}|\}$ with unit norm elements $c_i \in \mathbb{C}^{N}$, $\|c_i\|_2 = 1$ for all $i = 1, \ldots, |\mathcal{C}|$. The transmit codebook is generated offline and known to the base station and all users a priori. The set of possible beamforming matrices $W$ for a given number of selected users $|S|$ is defined by:

$$\mathcal{W}(|S|) = \{ W = (w_{s_1}, w_{s_2}, \ldots, w_{s_{|S|}}) \in \mathcal{C}^{|S|}\}$$

That is the set of all beamforming matrices of size $N \times |S|$ that can be generated by the transmit codebook $\mathcal{C}$.

We assume that the base station distributes its available power equally to all beams and that there is no power allocation within a SB. Now the signal–to–noise–and–interference ratio (SINR) of user $m \in \mathcal{S}$ on subcarrier $f \in \mathcal{F}$ is given by:

$$\gamma_{m}(S, W, h_{f,m}) = \frac{|\langle h_{f,m}, w_m \rangle|^2}{\sum_{l \neq m} |\langle h_{f,m}, w_l \rangle|^2 + |S|}$$

(3)

with $W \in \mathcal{W}(|S|)$ the beamforming matrix. In this paper we assume that this SINR correspondence to the achievable rate:

$$r_m(S, W, h_{f,m}) = \log(1 + \gamma_m(S, W, h_{f,m}))$$

(4)

Note that instead of $\log(1+x)$ any other utility mapping can be used. The rate averaged over the set of channels $\mathcal{H}_m$ of user $m \in \mathcal{S}$ is:

$$\bar{r}_m(S, W, \mathcal{H}_m) = \frac{1}{|\mathcal{H}_m|} \sum_{h \in \mathcal{H}_m} \log(1 + \gamma_m(S, W, h))$$

(5)

B. User Selection

Let us assume that the base station wants to select the subset of users $S \subseteq \mathcal{M}$ that maximizes the weighted sum rate:

$$\max_{S \subseteq \mathcal{M}} \max_{W \in \mathcal{W}(|S|)} \sum_{m \in \mathcal{S}} \alpha_m \bar{r}_m(S, W, \mathcal{H}_m)$$

(6)

where $\alpha_m$ is a quality of service weight of user $m \in \mathcal{M}$.

Since we consider a limited feedback model the base station has no perfect CSI from the users $\mathcal{M}$. Instead each user $m \in \mathcal{M}$ sends back partial CSI via a rate constrained feedback channel. The CSI is given by the proposed rate approximation limited feedback approach (given later on). This approach enables the base station to reliably approximate each users average rate $\bar{r}_m(S, W, \mathcal{H}_m)$ for any selection of user $S \subseteq \mathcal{M}$ and all beamforming matrices $W \in \mathcal{W}(|S|)$.

To determine the set of selected users $S$ and the beamforming matrix $W$ we will consider two user selection schemes. A brute force search over all sets $S \subseteq \mathcal{M}$ and all $W \in \mathcal{W}(|S|)$ and the greedy user selection algorithm (GUS) proposed in [16] and [17]. Because of its simplicity the GUS is also applicable in practical systems.

III. RATE APPROXIMATION LIMITED FEEDBACK

The idea of the rate approximation limited feedback scheme is that the feedback is chosen such that the base station can compute an accurate approximation of each users contribution $\bar{r}_m(S, W, \mathcal{H}_m)$ to the multiuser rates (6) for any selection of user $S \subseteq \mathcal{M}$ and all beamforming matrices $W \in \mathcal{W}(|S|)$.

For this purpose we introduce a feedback codebook $\mathcal{V} := \{\nu_1, \ldots, \nu_{|\mathcal{V}|}\}$ which consists of a collection of normalized ($\|\nu_i\|_2 = 1$) test–channels, a priori known to all users and the base station. Now each user must find a single vector $\mu \cdot \nu$, with $\nu \in \mathcal{V}$, that solves:

$$\min_{\mu \in \mathbb{R}} \max_{\nu \in \mathcal{V}} \mathcal{W}(\mathcal{S}|\mathcal{V}) \max_{\nu \in \mathcal{V}} \left| r_m(S, W, \mu \cdot \nu) - \bar{r}_m(S, W, \mathcal{H}_m) \right|$$

subj. to $|S| \leq |\mathcal{M}|$

(7)
Thus the feedback of user $m \in \mathcal{M}$ is chosen such that the maximum error that occurs by approximating the rate $\hat{r}_m(S, W, \mathcal{H}_m)$ by $r_m(S, W, \mu \cdot \nu)$ is minimized. Note that instead of $\max_{W \in \mathcal{W}(|S|)} | \cdot |$, other metrics can be used. After solving (7) user $m \in \mathcal{M}$ feeds back a channel quality information (CQI) $\mu_m$ and a quantized channel direction information (CDI) $\nu_m$. The CDI can be fed back using $\log_2(|V|)$ bits. For simplicity quantization of the CQI is not considered here. This is a typical assumption found in the literature [6], [8].

A. Determining the CQI

To reduce the complexity of problem (7) we introduce a dependency of the CQI on the normalized test-channel $\nu$ and the true channels $\mathcal{H}_m$ of user $m \in \mathcal{M}$, i.e. $\mu_m = g(\nu, \mathcal{H}_m)$. We define this dependency by requiring that $\hat{\mu}_m$ should be the signal-to-noise ratio (SNR) of an additive white Gaussian channel having the same rate as if user $m \in \mathcal{M}$ has the resource exclusively and uses beamforming vector $\nu$, i.e. for a given $\nu$ we define $\hat{\mu}_m$ by:

$$\log(1 + \hat{\mu}_m^2) = \frac{1}{|\mathcal{H}_m|} \sum_{h \in \mathcal{H}_m} \log(1 + |\langle h, \nu \rangle|^2)$$  \hspace{1cm} (8)

This can also be interpreted as the effective channel of user $m \in \mathcal{M}$ over the test–channel $\nu_m$.

B. Determining the CDI

Having established relation (8) the size of problem (7) can be reduced to:

$$\min_{\nu \in \mathcal{V}} \max_{W \in \mathcal{W}(|S|)} \left| r_m(S, W, \hat{\mu}_m \cdot \nu) - \hat{r}_m(S, W, \mathcal{H}_m) \right|$$

subject to $|S| \leq |M|$ \hspace{1cm} (9)

Hence, each user $m \in \mathcal{S}$ solves (9) and feeds back its CDI $\nu_m \in \mathcal{V}$ and CQI $\hat{\mu}_m \in \mathbb{R}$. Using this feedback information the base station can compute the rate $r_m(S, W, \hat{\mu}_m \cdot \nu_m)$ for any user $m \in \mathcal{S}$, any set $\mathcal{S}$ and all beamforming matrices $W \in \mathcal{W}(|S|)$. Using these rates the base station can perform an user selection using the GUS or the brute force user selection.

C. Reduced Complexity CDI Determination

To solve (9) each user has to compute $|\mathcal{V}| \cdot \sum_{i=1}^{M} |C|^i$ rates. This may not be feasible even for small codebook sizes $|\mathcal{V}|$ and $|C|$. One possibility to reduce the number of variations is to consider only user sets of size $a \leq |S| \leq b$, where $a$ and $b$ are two design parameters which should be chosen such that $1 \leq a \leq b \leq |M|$. This would result in $|\mathcal{V}| \cdot \sum_{i=a}^{b} |C|^i$ rates that have to be computed by the user.

Another possibility is to replace the set of beamforming matrices by a smaller set depending on the instantaneous channel realization of user $m$, i.e. $\mathcal{W}_m(S) \subset \mathcal{W}(|S|)$. That is, user $m \in \mathcal{M}$ finds its preferred beamforming vector by solving:

$$\hat{w}_m = \arg \max_{\tilde{w}_m \in C} r_m(\{m\}, \tilde{w}_m, \mathcal{H}_m)$$  \hspace{1cm} (10)

Then the set of beamforming matrices $\mathcal{W}_m(S)$ of user $m \in \mathcal{S}$ is given by: $\mathcal{W}_m(S) = \{ W \in \mathcal{W}(|S|) : \tilde{w}_m = \hat{w}_m \}$. Now problem (9) can be reduced to:

$$\min_{\nu \in \mathcal{V}} \max_{W \in \mathcal{W}_m(S)} \left| r_m(S, W, \hat{\mu}_m \nu) - \hat{r}_m(S, W, \mathcal{H}_m) \right|$$

subject to $a \leq |S| \leq b$ \hspace{1cm} (11)

Hence, each user has to compute $|\mathcal{V}| \sum_{i=a}^{b} |C|^i-1 + 1$ rates.

D. Feedback Codebook Design

In this section we consider the problem of designing a feedback codebook for the rate approximation limited feedback approach. The proposed algorithm is based on an algorithm proposed by Linde, Buzo and Gray (LBG) [15] which is an extension of the generalized Lloyd algorithm [18]. A comprehensive description of different versions of the Lloyd algorithm can be found in [19]. In [8] and [20] the LBG algorithm is applied to generate feedback codebooks for systems under adaptive beamforming.

For a given metric $d_m(\mathcal{H}, \nu, \nu_i)$ the LBG algorithm finds the feedback codebook $\nu = \{\nu_1, \ldots, \nu_{|\mathcal{V}|}\}$ that (at least locally) minimizes the averaged distortion:

$$D = \frac{1}{|T|} \sum_{i=1}^{V} \sum_{\mathcal{H}_i \in \mathcal{R}_i} d_m(\mathcal{H}, \nu_i)$$  \hspace{1cm} (12)

where $T = \{\mathcal{H}_1, \ldots, \mathcal{H}_T\}$ is a large set of channel realizations (training sequence), $m \in \mathcal{M}$ is fixed and $\mathcal{R}_i$ is the quantization region of $\nu_i \in \mathcal{V}$ defined by:

$$\mathcal{R}_i = \{ \mathcal{H} \in T : d_m(\mathcal{H}, \hat{\mu}_i \cdot \nu_i) \leq d_m(\mathcal{H}, \hat{\mu}_j \cdot \nu_j), \forall j \}$$  \hspace{1cm} (13)

For the rate approximation limited feedback approach the metric can be given by:

$$d_m(\mathcal{H}, \nu) = \min_{\nu \in \mathcal{V}} \max_{W \in \mathcal{W}(|S|)} \left| r_m(S, W, \mu \cdot \nu) - \hat{r}_m(S, W, \mathcal{H}) \right|$$

subject to $a \leq |S| \leq b$ \hspace{1cm} (14)

that is the maximal distortion that occurs if $\hat{r}(S, W, \mathcal{H})$ is approximated by $r(S, W, \hat{\mu} \cdot \nu)$ with $\nu \in \mathcal{V}$ and $\hat{\mu} = g(\nu, \mathcal{H})$. The LBG algorithm is known to converge to an optimum that is not guaranteed to be global. However it is a practical way to design a codebook even if the probability density function of the source is unknown.

The described LBG algorithm can be used to generate codebooks for any given training set of sufficient size. For instance the algorithm can be used to adapt the feedback codebook to the environment of a base station.

IV. SIMULATIONS

In this section we demonstrate the performance of the proposed rate approximation limited feedback scheme by extensive simulations.

978-1-4244-4148-8/09/$25.00 ©2009
This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE "GLOBECOM" 2009 proceedings.
A. Considered Limited Feedback Methods

An upper bound on the performance of the rate approximation limited feedback scheme can be obtained by assuming perfect CSI at the base station (CSIT). In this case the selection of users \( S \) and corresponding beamforming vectors \( W \in \mathcal{V}(|S|) \) can be performed by the brute force user selection (at least for small number of users) or by the GUS. The theoretical upper bound is given by the DPC limit for equal power allocation over the subcarriers which is implemented using the algorithm in [21].

A popular limited feedback scheme for scenarios with fixed beams is the so called per user rate limited codebook (PU2RC) proposed in [11]. In which case the transmit codebook consists of multiple unitary groups. Each user feeds back a preferred codebook index and a CQI reflecting the SINR this user expects if all beams within its selected unitary group are used, i.e. its CQI is a worst case SINR.

Another limited feedback scheme was proposed in [14]. This scheme is based on a beam distance criterion and will be termed “beam distance method”. Each user reports a preferred codebook index chosen from a transmit codebook and a CQI reflecting the expected SNR. The base station selects the user with the best CQI first and blocks the beams that are with a predefined distance to this user’s beam. Subsequently the remaining users with the best CQI are selected if their preferred beam is not blocked by a previously selected user.

To obtain a lower bound we apply some simple user selection schemes. Each user feeds back its preferred codebook index and a CQI reflecting its SINR if this beamforming vector is used. The “best users” scheme selects a predefined number of users with the best CQI if they reported different beamforming vectors. The “round robin” user selection selects randomly a predefined number of users that have reported different beamforming vectors.

B. Simulation Setup

The performance is compared using SINR based simulations and link level simulations. The simulation setup is given by a single \( 120^\circ \)-sector of a cellular system. The users are uniformly distributed in \([-60^\circ, 60^\circ]\) and placed at a distance of 200 m to the base station. The SB consists of \(|F| = 36\) subcarriers. The configuration of the OFDM downlink channel is chosen according to the configuration of the LTE downlink [10]. The channel is modeled using the spatial channel model extended (SCME) [22]. Table 1 summarizes the configuration of the channel model. We use the high angle spread option in order to demonstrate the performance in a highly scattered environment.

We apply two different transmit codebooks. The first is the LTE codebook for transmission on four antenna ports [10]. The LTE-codebook has 16 elements which results in 4 bits per SB for the feedback of the CDI. Furthermore, it consists of four unitary groups which makes it applicable for PU2RC. The second codebook is the beamforming codebook proposed in [14]. It is designed such that the “beam distance method” (as explained in IV-A) can be used. For this second codebook we additionally apply tapering [23], i.e. codebook elements with different amplitudes per antenna port. In the simulations we use a windowing of \([0.6, 1, 1, 0.6]\), this results in reduced side lobes.

C. Feedback Codebook Generation

A feedback codebook generated by the LBG algorithm, as described in section III-D, is compared with a feedback codebook given by line of sight (LOS) channels with equidistant angles of departure (AoD). The \( n \)th component of \( \nu_i \in \mathcal{V}_{LOS} \) is defined as:

\[
(\nu_i)_n = \frac{1}{\sqrt{N}} e^{-j \frac{2\pi}{\lambda} n \delta_i \sin(\theta_i)}
\]

(15)

where \( \delta_i \) is the position of the \( n \)th antenna element, \( \lambda \) is the wavelength and the LOS AoD are chosen to be \( \theta = [-60^\circ, -43^\circ, -26^\circ, -8.5^\circ, 8.5^\circ, 26^\circ, 43^\circ, 60^\circ] \).

Figure 1 demonstrates the performance of the rate approximation with GUS for two different 3 bit feedback codebooks: The LBG–optimized feedback codebook and the LOS rate approximation; beam distance codebook [3 bit].

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TABLE I

<table>
<thead>
<tr>
<th>Configuration of Channel Model</th>
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<tbody>
<tr>
<td>Parameter</td>
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<tr>
<td>Channel Model</td>
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<tr>
<td>Scenario</td>
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<tr>
<td>Tx antennas</td>
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<tr>
<td>Rx antennas</td>
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<tr>
<td>Tx antenna spacing</td>
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<td>Sampling frequency</td>
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<td>System bandwidth</td>
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<td>Carrier frequency</td>
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<tr>
<td>Wavelength (λ)</td>
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<tr>
<td>Base station to user distance</td>
</tr>
</tbody>
</table>

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Fig. 1. Spectral efficiency vs. averaged SNR for the rate approximation approach with GUS. The LBG–optimized feedback codebook (blue) outperforms the LOS feedback codebook (blue dash) and the beam distance method (cyan).

The upper bound is given by the GUS with perfect CSI at the base station and fixed beamforming. Setup: \(|M| = 10, |S| \leq 4\), transmit codebook: beam distance codebook.
feedback codebook. The rate approximation with the LOS feedback codebook already outperforms the beam distance method, as shown later on. With the optimized feedback codebook the performance is even better. The upper bound is given by the GUS with perfect CSI at the base station.

D. SINR-Based Simulations

Based on the user selection $S$ and the selected beamforming matrix $W \in \mathcal{W}(|S|)$ we evaluate the achieved sum rate:

$$\sum_{m \in S} \bar{r}_m(S, W, H_m)$$

(16)

where $\bar{r}_m(S, W, H_m)$ is defined in (5). The quality of service weights are chosen as $\alpha_m = 1$ for all $m \in M$. Note that this implies perfect link adaption.

Fig. 2. Spectral efficiency vs. averaged SNR. "DPC" denotes the dirty paper coding limit for equal power allocation over the subcarriers (using the algorithm in [21]). Setup: $|M| = 8$, $|S| \leq 2$, transmit codebook: beam distance codebook [3 bits] (LTE codebook [4 bit] for PU2RC), feedback codebook: LOS codebook.

Fig. 3. CDF of the spectral efficiency at averaged SNR of 20 dB. Setup: $|M| = 8$, $|S| \leq 2$, transmit codebook: beam distance codebook [3 bits] (LTE codebook [4 bit] for PU2RC), feedback codebook: LOS codebook.

Fig. 4. Spectral efficiency vs. averaged SNR. Comparing the brute force user selection with the GUS. Setup: $|M| = 10$, $|S| \leq 4$, transmit codebook: beam distance codebook [3 bits] (LTE codebook [4 bit] for PU2RC), feedback codebook: LOS codebook.

Fig. 5. Cell throughput vs. averaged SNR. Comparing different feedback and user selection schemes, with $|M| = 8$ and $|S| \leq 2$. The lower bound is given by the round robin user selection. The upper bound is given by the DPC limit for equal power allocation over the subcarriers (using the algorithm in [21]). Since DPC in general selects all users $S = M$ for transmission, the figure additionally shows the DPC limit for the best subset $S$ with $|S| = 2$. The beam distance method which requires 3 bit for CDI feedback outperforms the PU2RC which requires 4 bit of CDI feedback. Both methods are outperformed by the rate approximation. Additionally, the performance of the rate approximation method can be scaled by increasing the size of the feedback codebook (3 bits and 4 bits shown in the figure). The upper bound is given by the case with perfect CSI at the base station. These observations are substantiated by Fig. 3 which shows the cumulative distribution function (CDF) of the spectral efficiency at 20dB for the same setup.
Fig. 4 compares the brute force user selection with GUS selection. In the case of perfect CSI at the base station the brute force selection outperforms the GUS. If we apply the rate approximation to obtain the CSI the performance of both user selection algorithms similar. The PU2RC and the beam distance method are both outperformed by the rate approximation with GUS.

E. Link Level Simulations

The link level is configured according to the present LTE configuration [10]. We use different modulation and coding schemes which are defined in Table II. We apply ideal channel estimation.

<table>
<thead>
<tr>
<th>Modulation</th>
<th>code rate</th>
<th>max. cell throughput</th>
</tr>
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<tbody>
<tr>
<td>QPSK</td>
<td>0.30</td>
<td>0.46 [Mbit/sec]</td>
</tr>
<tr>
<td>16QAM</td>
<td>0.58</td>
<td>1.69 [Mbit/sec]</td>
</tr>
<tr>
<td>64QAM</td>
<td>0.58</td>
<td>2.54 [Mbit/sec]</td>
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</tbody>
</table>

Fig. 5 shows the cell throughput that is achieved with the transmit codebook designed for the beam distance method [14]. The figure demonstrates that the performance of the rate approximation limited feedback scheme can be scaled by changing the size of the feedback codebook. With same amount of feedback (i.e. 3 bit) the proposed scheme outperforms the beam distance method.

V. CONCLUSION

We introduced a new limited feedback scheme for the downlink of multiuser MIMO OFDM communication systems. The method provides the base station with an accurate approximation of all multiuser rates that can be achieved by choosing the transmit beamforming vectors from a fixed transmit codebook. Making the interference situation available to the base station enables efficient scheduling even for the case of a small number users. In the simulations we demonstrated that the proposed method outperforms other methods that are discussed in the context of LTE. Moreover, our proposed method gives the possibility to design feedback codebooks for different environments. Furthermore, having estimates of all multiuser rates available at the base station can give additional gains if multiple base stations are cooperating.

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This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE "GLOBECOM" 2009 proceedings.