Multi-User MIMO-OFDM Cell Throughput under Real-World Propagation Conditions

Norbert Geng
Information and Communication Mobile – Mobile Phones
Siemens AG
D-81667 Munich, Germany
Norbert.Geng@siemens.com

Ingo Viering and Mario Kiessling
Information and Communication Mobile – Networks
Siemens AG
D-89077 Ulm, Germany
Ingo.Viering@... and Mario.Kiessling@icn.siemens.de

***Abstract* — In recent years, an innumerable number of papers has been published on MIMO (multiple input multiple output) systems. The original and most of the current work deals with a single link between a multi-element antenna (MEA) transmitter and a MEA receiver. However, link-level capacity gain does not necessarily translate into a similar system-level gain. Therefore, several researchers have investigated the performance of MIMO systems on cell or even system level, including intracell and/or intercell interference. While these multi-user MIMO investigations are very helpful, presented (simulation) results have been mostly limited to simple propagation scenarios (e.g., flat fading and/or i.i.d. Rayleigh fading). Here we present results for the uplink sum capacity of multiple MIMO users in a single cell (i.e., intercell interference is not explicitly accounted for) based on a channel model which accounts for partial MIMO correlations, large-scale fading effects, variable delay spread, non-vanishing Ricean factor, and random user orientation. We concentrate on the cell capacity. However, estimation of the maximum uplink cell throughput for real-world AMC (adaptive modulation and coding) is similarly possible via the SNR gap approximation and power/bit loading. According to the simulation results, beamforming is the capacity-achieving strategy for a large number of users within the cell. This is consistent with theoretical results derived recently by other researchers. However, the simulated results here cover the entire range from optimum single-user performance (i.e., transmission on spatial eigenmodes plus water filling) to the capacity when the number of users greatly exceeds the number of base station antennas (i.e., with beamforming being the best strategy).**

Keywords — MIMO; spatial multiplexing; cell capacity; uplink; system-level simulations; water filling; power and bit loading

I. INTRODUCTION

Various publications exist on the information-theoretical derivation of the bandwidth efficiency (or normalized link capacity) in bps/Hz of MIMO systems [1,2]. Based on this pioneering MIMO work, researchers extensively investigated link throughput as well as TX and RX processing for MIMO transmission on link level [1-6], initially starting with uncorrelated flat-fading channels and successively taking into account more and more real-world effects (e.g., MIMO subchannel correlations [4,5] or frequency selectivity [2,6]).

However, since the ultimate goal is the improvement of the spectrum efficiency (in bps/Hz/cell), researchers have recently started investigations on cell-optimum MIMO accounting for intracell interference or even MIMO on system level accounting for intercell interference as well [7-20]. These references also include closely related work on optimum uplink/downlink beamforming (i.e., SIMO or MISO). Unfortunately, the interesting proposals on cell-optimum MIMO processing in [12,17] have not been tested for real-world propagation scenarios and channels. Similarly, published system-level results [7–11] are limited to i.i.d. Rayleigh-fading MIMO subchannels which is far from reality in many cases.

As a first step towards more realistic simulation results, we investigate cell-optimum multi-user MIMO for the uplink (i.e., vector multiple access channel), where we counteract frequency selectivity via application of OFDM (i.e., MIMO-OFDM). The formulation and algorithm used here is very similar to the iterative water filling proposed in [17]. Since the focus is on a single cell, intracell interference is explicitly included in the optimization step. However, intercell interference is treated as additive noise (i.e., increasing the effective noise variance and possibly altering the noise covariance matrix). For simplicity, most of the discussion in this paper is for flat fading, with the extension to the frequency-selective case being fairly straightforward when using MIMO-OFDM. We compute the cell sum capacity (i.e., the maximum aggregate throughput) under real-world propagation conditions, including for example non-zero MIMO correlations, random user orientation, arbitrary array geometry, log-normal fading, and small-scale Ricean fading. Similar to the discussion in [2,4,6,12,17,18], we assume ideal short-term channel state information (CSI) at both transmitter and receiver. Hence, instantaneous water filling across spatial modes and OFDM subcarriers is possible. Of course, for real-world systems, water filling has to be replaced by some power and bit loading algorithm [6,21].

The paper is organized as follows. Section II summarizes the multi-user MIMO system model for downlink and uplink. The corresponding rate-sum maximization tasks are discussed in section III. Subsequently, we focus on the multiple access channel (i.e., uplink) and summarize the iterative water-filling algorithm proposed in [17] in section IV, extended to MIMO-OFDM. The scatterer-based MIMO channel model utilized in the simulations is briefly discussed in section V before section VI presents simulation results for different sets of parameters (e.g., number of users, number of TX and RX antennas).

II. MULTI-USER MIMO SYSTEM MODEL

As noted before, the formulation here will be limited to the flat-fading case for simplicity, although extension to frequency-selective channels is straightforward when applying OFDM to counteract intersymbol interference (ISI) (see section IV).

A. Multi-User MIMO Downlink System Model

Consider the downlink to K users represented by subscript k=1,...,K with in general multiple antennas at transmitter (base station BS) and receiver (user terminal). The received vector signal of user k can be written as

$$\begin{aligned} \mathbf{y}_k &= \mathbf{H}_k \left(\mathbf{x}_k + \sum\nolimits_{\mu=1,\mu\neq k}^{K} \mathbf{x}_\mu \right) + \mathbf{n}_k \\ &= \mathbf{H}_k \, \mathbf{x}_k + \left(\sum\nolimits_{\mu=1,\mu\neq k}^{K} \mathbf{H}_k \, \mathbf{x}_\mu + \mathbf{n}_k \right) \\ &= \mathbf{H}_k \, \mathbf{x}_k + \mathbf{z}_k \quad \text{for} \quad k = 1,2,...,K \end{aligned} \tag{1}$$

with the $M_k \times M_{BS}$ matrix channel between the M_{BS} base-station array elements and the M_k array elements of user k represented by $\mathbf{H}_k$. The received additive noise plus intercell interference is characterized by the covariance matrix $\mathbf{R}_{n_k n_k}=E\{\mathbf{n}_k \mathbf{n}_k^{\mathsf{H}}\}$. The received vector $\mathbf{y}_k$ at antenna array k can be written as a superposition of the desired signal $\mathbf{H}_k\mathbf{x}_k$ and noise plus intercell plus intracell interference $\mathbf{z}_k$. Note that (in general) $\mathbf{z}_k$ will be non-Gaussian (e.g., for a small number of intercell and/or intracell interferers). However, in [22] it has been shown that the capacity may still be closely approximated by the Shannon formula $\log_2(1+SINR)$, if the noise plus interference $\mathbf{z}_k$ is zero-mean, additive, and statistically independent from user signal $\mathbf{x}_k$.

B. Multi-User MIMO Uplink System Model

In contrast to the multi-user MIMO downlink, where each received vector signal only depends on a single MIMO matrix, the received signal in the uplink is influenced by a total of K MIMO channels $\mathbf{H}_k$ of dimension $M_{BS} \times M_k$ from each user to the receiving base station. For simplicity, we use the matrix $\mathbf{H}_k$ for uplink and downlink, although both are at the best related by $\mathbf{H}_{UL,k}=\mathbf{H}_{DL,k}^{\mathsf{T}}$ (UL: uplink, DL: downlink) in case of TDD and at low terminal speed. For FDD, only the large-scale properties (e.g., power delay profile, power angular spectrum) are similar, but the instantaneous channel realizations are not.

Keeping this simplification in mind, the received signals at the base station can be written as

$$\begin{aligned} \mathbf{y} &= \sum\nolimits_{k=1}^{K} \mathbf{H}_k \, \mathbf{x}_k + \mathbf{n} = \mathbf{H}\,\mathbf{x} + \mathbf{n} \\ &= \begin{bmatrix} \mathbf{H}_1 & \mathbf{H}_2 & \ldots & \mathbf{H}_K \end{bmatrix} \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \ldots \\ \mathbf{x}_K \end{bmatrix} + \mathbf{n} \end{aligned} \tag{2}$$

with the $M_{BS} \times 1$ vector $\mathbf{n}$ including again noise and intercell interference. The multi-user MIMO uplink may be viewed as a large MIMO system represented by the MIMO channel matrix $\mathbf{H}$ of dimension $M_{BS} \times \Sigma M_k$. However, although fast feedback from the base station to each user terminal enables joint optimization of the antenna weight vectors, powers, and modulation and coding (MCS) schemes for all parallel data streams of all users (at least for low terminal speed and hence quasi-static channels), we cannot assume any correlation between user data. Therefore, the joint signal covariance matrix $\mathbf{R}_{xx}=E\{\mathbf{x}\mathbf{x}^{\mathsf{H}}\}$ is blockdiagonal, i.e.,

$$\mathbf{R}_{xx} = \mathrm{blockdiag}(\mathbf{R}_{x_1 x_1}, \mathbf{R}_{x_2 x_2}, ..., \mathbf{R}_{x_K x_K}) \ . \tag{3}$$

III. Multi-User MIMO Sum Capacity Problem

After having defined the multi-user MIMO formulation in the previous section, we can now set up the joint optimization problems. Here we exclusively focus on the sum-rate maximization problem for limited transmit power (i.e., transmit power constraint) which has been recently discussed by Cioffi et al in [13,16–18]. We do not consider more advanced optimization strategies involving individual quality-of-service or SINR constraints for all users as discussed for beamforming in [19,20].

A. Multi-User MIMO Downlink Sum Capacity Problem

Similar to the uplink we could also define a large effective $\Sigma M_k \times M_{BS}$ MIMO system in the downlink. Unfortunately, joint processing of the receive vector $\mathbf{y}=[\mathbf{y}_1^{\mathsf{T}},\mathbf{y}_2^{\mathsf{T}},..,\mathbf{y}_K^{\mathsf{T}}]^{\mathsf{T}}$ is not feasible in general. Each MEA user terminal only has access to its own received signal samples. In addition, we assume that the user terminals are not aware of the (instantaneous) downlink MIMO channels of the other users (via e.g. fast feedforward from the BS). Thus, the users treat the intracell interference as additive noise term.

Under these assumptions the optimization task for the base station is (C denotes the normalized capacity in bps/Hz/cell)

$$C = \max_{\mathbf{R}_{x_k x_k}, \forall k} \sum_{k=1}^{K} \log_2 \frac{\det(\mathbf{R}_{z_k z_k} + \mathbf{H}_k \, \mathbf{R}_{x_k x_k} \mathbf{H}_k^{\mathsf{H}})}{\det(\mathbf{R}_{z_k z_k})} \tag{4a}$$

$$\text{subject to} \quad \sum\nolimits_{k=1}^{K} \mathrm{trace}\,(\mathbf{R}_{x_k x_k}) \leq P_{BS\,\max} \tag{4b}$$

with the maximum BS TX power $P_{BS\max}$ and the definition

$$\mathbf{R}_{z_k z_k} = \mathbf{R}_{n_k n_k} + \sum\nolimits_{\mu=1,\mu\neq k}^{K} \mathbf{H}_k \, \mathbf{R}_{x_\mu x_\mu} \, \mathbf{H}_k^{\mathsf{H}} \ . \tag{4c}$$

The derivation is straightforward when using (1) and the well-known results in [2–4]. The solution of (4) implicitly includes a minimization of the detrimental effect of intracell multi-user interference included in the covariance matrices $\mathbf{R}_{z_k z_k}$ for noise plus intercell interference ($\mathbf{n}_k$) plus intracell interference.

While for future, most likely downlink-limited, high-speed mobile radio systems the downlink is more interesting than the uplink (discussed next), we nevertheless restrict the remainder of this paper to the MIMO uplink. The more complicated joint downlink optimization will be subject to future research.

B. Multi-User MIMO Uplink Sum Capacity Problem

When representing the multi-user MIMO uplink as a single large MIMO system of dimension $M_{BS} \times \Sigma M_k$ as in (2) the capacity can be immediately written in the form [2–4]

$$C = \max_{\mathbf{R}_{xx}} \ \log_2 \frac{\det(\mathbf{R}_{nn} + \mathbf{H}\,\mathbf{R}_{xx}\,\mathbf{H}^{\mathsf{H}})}{\det(\mathbf{R}_{nn})} \ . \tag{5}$$

However, according to (3) we must assume the data from individual users to be uncorrelated. Keeping this restriction in mind and applying the definitions in (2), the multi-user MIMO sum-rate maximization problem can be written as [13,16–18]

$$C = \max_{\mathbf{R}_{x_k x_k}, \forall k} \log_2 \frac{\det\left(\mathbf{R}_{nn} + \sum_{k=1}^{K} \mathbf{H}_k \, \mathbf{R}_{x_k x_k} \, \mathbf{H}_k^{\mathsf{H}}\right)}{\det(\mathbf{R}_{nn})} \qquad \text{(6a)}$$

$$\text{subject to} \quad \operatorname{trace}(\mathbf{R}_{x_k x_k}) \le P_{k\,\max} \quad \forall k = 1,2,...,K \qquad \text{(6b)}$$

with $P_{k\max}$ representing the maximum transmit power for the kth user (which in general are different for different users).

IV. Solution for the Multi-User MIMO Uplink

An iterative water-filling solution to the rate-sum maximization problem (6) has recently been proposed in [17] and will be summarized next (and finally extended to MIMO-OFDM).

Note that unlike the sum capacity (4) for the downlink, the multi-user uplink cell capacity (6) is not written as a sum over K individual single-user capacities (although these are coupled even for the downlink). However, for an application of the optimum single-user MIMO transmission scheme [4] which uses water filling onto the spatial eigenmodes, such a sum over individual (though coupled) single-user capacities for the uplink is advantageous and derived next.

Based on elementary algebra we can write the uplink rate-sum maximization problem (6) in the form

$$C = \max_{\mathbf{R}_{x_k x_k}, \forall k} \sum_{k=1}^{K} \log_2 \frac{\det(\widetilde{\mathbf{R}}_{z_k z_k} + \mathbf{H}_k \, \mathbf{R}_{x_k x_k} \, \mathbf{H}_k^{\mathsf{H}})}{\det(\widetilde{\mathbf{R}}_{z_k z_k})} \qquad \text{(7a)}$$

$$\text{subject to} \quad \operatorname{trace}(\mathbf{R}_{x_k x_k}) \le P_{k\,\max} \quad \forall k = 1,2,...,K \qquad \text{(7b)}$$

$$\widetilde{\mathbf{R}}_{z_k z_k} = \mathbf{R}_{nn} + \sum\nolimits_{\mu=k+1}^{K} \mathbf{H}_\mu \, \mathbf{R}_{x_\mu x_\mu} \, \mathbf{H}_\mu^{\mathsf{H}}, \qquad \text{(7c)}$$

where (7c) characterizes noise plus intercell interference $\mathbf{n}$ and the remaining intracell interference for the kth user after ideal subtraction of the multiple access interference due to the users 1 to k–1. This corresponds to error-free successive interference cancellation (SIC) at the receiver, starting with user 1 (having to deal with all intracell interference) up to user K (which sees the single-user MIMO channel without intracell interference).

Since here we are only interested in the uplink cell capacity, we can similarly use any ordering of the K users. Note that the new formulation in (7) can be written for any permutation of the K users and thus for any corresponding SIC ordering at the receiver. The specific order does not change the sum capacity since it is known for the optimization of the transmit strategy. Of course, in a real system the order is chosen according to user priorities, starting with the user of lowest priority. But since here we are only interested in the sum capacity, the order k=1,2,...,K is used throughout the remainder of this paper.

Now the iterative water filling solution proposed in [17] is obvious. While the discussion before has been limited to flat fading for simplicity, we briefly summarize the final algorithm [17] extended to the frequency-selective case through application of multi-carrier transmission (OFDM with N subcarriers).

$$
\begin{array}{l}
\text{initialize } \mathbf{R}^{\nu}_{x_k x_k} \quad \forall k = 1,2,....,K \text{ and } \forall \nu = 1,2,...,N \\
\text{repeat} \\
\quad \text{for } k = 1,2,...,K \\
\quad \widetilde{\mathbf{R}}^{\nu}_{z_k z_k} = \mathbf{R}^{\nu}_{nn} + \sum_{\mu=k+1}^{K} \mathbf{H}^{\nu}_{\mu} \mathbf{R}^{\nu}_{x_\mu x_\mu} \mathbf{H}^{\nu\,\mathsf{H}}_{\mu} \quad \forall \nu = 1,2,...,N \\
\quad \mathbf{R}^{\nu}_{x_k x_k} = \arg \max_{\mathbf{R}^{\nu}_{x_k x_k}} \sum_{\nu=1}^{N} \log_2 \dfrac{\det(\widetilde{\mathbf{R}}^{\nu}_{z_k z_k} + \mathbf{H}^{\nu}_k \mathbf{R}^{\nu}_{x_k x_k} \mathbf{H}^{\nu\,\mathsf{H}}_k)}{\det(\widetilde{\mathbf{R}}^{\nu}_{z_k z_k})} \\
\qquad\qquad \text{subject to } \sum\nolimits_{\nu=1}^{N} \operatorname{trace}(\mathbf{R}^{\nu}_{x_k x_k}) \le P_{k\,\max} \\
\quad \text{end} \\
\text{until desired accuracy reached}
\end{array} \qquad (8)
$$

Here the superscript ν=1,...,N represents the OFDM subcarrier index. In each iteration we have to solve a single-user MIMO-OFDM water-filling problem, the solution being similar to the well-known spatial water-filling solution in [4]. After the SVD eigenmode decomposition of the MIMO channel on each subcarrier, we perform water filling across both the spatial modes and the OFDM subcarriers. Note that even for fairly complicated cases (e.g., K=32 users, M_{BS}=8 antennas at the BS, M_k=4 antennas at each mobile terminal, and N=32 subcarriers), the algorithm (8) typically converges in less than 8 iterations to an accuracy of 0.01bps/Hz for the sum capacity.

In a real-world system with a finite set of modulation and coding schemes (MCS), MIMO-OFDM power and bit loading could be employed in a final run for k=K to k=1 (i.e., opposite order) without changing the antenna weights. Although this is in general not the maximum-throughput solution, it should be close to optimum, if we first solve (8) for a well selected SNR gap $\Gamma \ge 1$ to characterize the MCS set in use (where before we applied Γ=0dB for simplicity) [7]. An efficient MIMO-OFDM loading algorithm can for example be based on a combination of [6] and [21]. However, here we exclusively present capacity results without this final loading step.

V. Scatterer-Based MIMO Channel Model

For meaningful performance evaluations of MIMO systems, it is essential to include real-world effects like MIMO subchannel correlations or the influence of any array geometry at base station (BS) and mobile terminal (MS). While this is in principle possible via covariance-matrix based MIMO channel modeling, it is far more flexible and intuitive to apply a ray-based solution [23,24]. Hence, we implemented a COST259-like model for pico-cellular environments which is well in line with large-scale averaged power delay profiles (e.g., exponential on average for picocells) and power angular spectra (e.g., Laplacian shape on average).

To achieve this, scatterers are randomly positioned within a set of elliptical rings surrounding TX and RX [24]. Each ring represents a certain excess delay bin. The long-term average powers of the multipath signals are selected such that on large-scale average (e.g., averaged over a large set of users at different locations relative to the BS) the power delay profile (PDP) is exponential. Due to multiple scatterers in each delay bin and the simulation of small-scale fading through an explicit movement of the mobile, small-scale fading on the taps resembles a Rayleigh distribution. An optional line-of-sight (LOS) component can be added, leading to overall Ricean fading with preselected Rice factor. Due to the scatterer distribution within elliptical rings the power azimuth spectrum (PAS) resembles the well-known Laplacian shape when averaged over many large-scale snapshots. Example PDPs and PASs (here at TX, similar for RX) are shown in Fig. 1 for the parameters given.

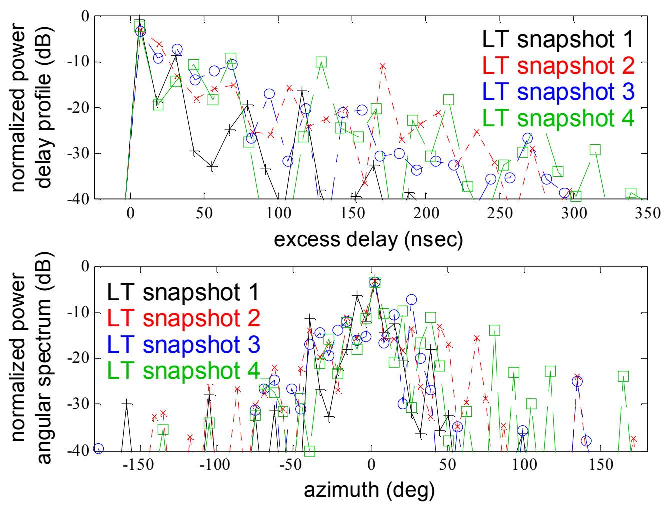

Figure 1. Large-scale (LT: long-term) spatio-temporal properties of simulated MIMO channels in pico-cellular environment. Rice factor, RMS delay spread, and the number of scatterers are varied according to log-normal distributions of mean 0.5 (Rice factor), 60nsec (delay spread), and 100 (# of scatterers).

For scatterer (or wave) based channel modeling, multipath angles at TX and RX are directly available. Thus, any antenna pattern and arbitrary array geometries are easily incorporated. This makes the comparison of different antenna configurations (leading e.g. to different MIMO correlations) an easy task.

For multiple users within a cell, the parameters for such a MIMO channel are created for each user, including in addition the large-scale path loss (according to a log-distance path loss model) and log-normal shadowing. Correlations between user parameters are included for users close to each other.

VI. Simulation Results for Multi-User MIMO Uplink

Although we presented an algorithm for computing the uplink sum capacity of multiple MIMO-OFDM users in (8), the results here are limited to the flat-fading (or single subcarrier) case. These results separate the gain due to frequency diversity from the gain due to MIMO or multiple users (i.e., multi-user diversity). However, with a sufficiently large number of users within the cell and/or sufficiently uncorrelated antenna signals increasing the overall diversity order further (e.g., via OFDM in frequency-selective channels) does not improve the capacity significantly. This has been shown by simulations for MIMO-OFDM (with the results not given here due to space limits).

Figs. 2 and 3 show the cumulative distribution function for the uplink sum capacity in a 120°-sectorized picocell for 4 and 8 antenna array elements at the BS, respectively.

The simulations have been performed for a carrier frequency f_0=5GHz. The available transmit power for each user terminal is P_{kmax}=50mW. The cell radius is R_{cell}=150m. Large-scale fading is computed applying a path-loss exponent of γ=3.5 and log-normal standard deviation of σ=8dB for the random shadowing. The RMS delay spread, the Rice factor, and the number of scatterers are selected according to individual log-normal distributions. Mean delay spread, Rice factor, and number of scatterers are 80nsec, 0.5, and 35, respectively. The random user parameters are correlated for users close to each other.

The user location and (in case of multiple antennas at the user terminal) orientation are randomly selected. While the BS employs a uniform linear array (ULA) with inter-element spacing of 2λ, the mobile terminals utilize uniform circular arrays (UCA) with inter-element spacing of λ/2 (see the insets in the figures). However, for M_k=2, the UCA reduces to a 2-element ULA for each mobile and for M_k=1, no MEA is used at all.

All figures clearly show multi-user diversity gain since the probability of having to deal exclusively with a large path loss and/or bad multipath behavior decreases with the number of users (i.e., there will always be some good users). In addition, capacity increases with the number of users due to the possibility of simultaneously serving users through SDMA (space division multiple access), if the number of BS antennas is large enough to separate users and the spatial signatures are distinct.

While for a single user in the cell, we can see MIMO gains typical for link level (through optimum spatial multiplexing on eigenmodes plus water filling), general MIMO (i.e., each user is in principle allowed to transmit several data streams in parallel) does not improve capacity relative to beamforming (i.e., each user is only allowed to transmit a single data stream) for a large number of users. The fact that beamforming is the capacity-achieving MIMO strategy for the multi-user uplink, has also recently been published in [18]. However, our results are not due to an asymptotic analysis, but based on simulations for real-world MIMO channels. The results show that the gain by employing multiple antennas at each mobile terminal is not as large as often postulated (i.e., multi-user uplink capacity does not increase linearly with the number of MS antennas as on link level for i.i.d. Rayleigh fading and high SNR). While the spatial-multiplexing gain is quite large for a small number of simultaneously active users (relative to the number of BS antennas), beamforming (i.e., no spatial multiplexing for individual user) is optimum for a large number of users. Nevertheless, employing multiple antennas at each mobile terminal still gives a significant gain (although not quite as large as on link level) due to spatial diversity and/or beamforming gain.

VII. Conclusions

We presented (real-world) simulation results for the multi-user MIMO uplink cell capacity. We validated that beamforming is the capacity-achieving multi-user MIMO strategy for a large number of users within a cell. This theoretical result has been published previously by other research groups. However, utilizing our simulations we may decide on the maximum gain achievable for the cell throughput when applying MEAs at the mobile terminal for any set of parameters (i.e., not limited to a large number of users). The relative gain due to spatial multiplexing (which significantly increases the complexity relative to beamforming) strongly depends on the number of simultaneously active users. Therefore, the decision on whether to use or not to use spatial multiplexing in future mobile radio standards must include traffic considerations and user scenarios.

Future work will be on the multi-user MIMO downlink. In addition, a solution of the rate-sum maximization problem (for up- and downlink) should be found in case of only partial (i.e., long-term) channel knowledge in the optimization step. While the discussion here was limited to a single cell, simulations of MIMO on system level (e.g., explicitly accounting for spatially-colored intercell interference) must be the final goal.

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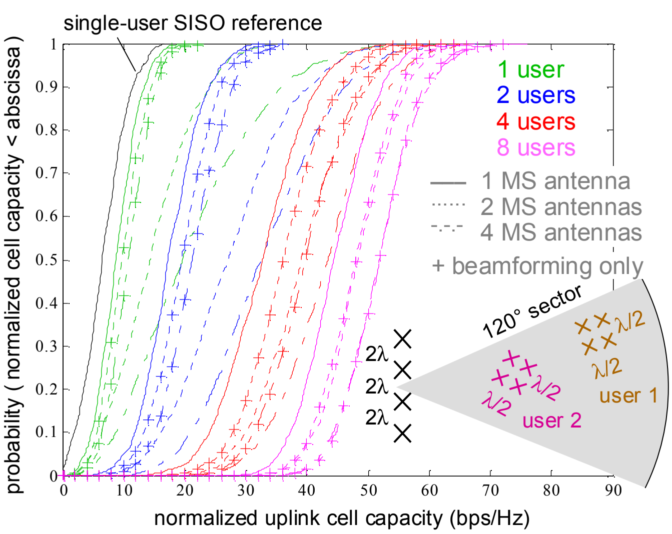

Figure 2. Distribution for the normalized uplink cell capacity (in bps/Hz/cell) of a 120°-sectorized picocell and 4-element uniform linear array (ULA) at the BS. The number of users and number of antennas at each mobile (here equal for all users) varies. The remaining parameters are as summarized in the text.

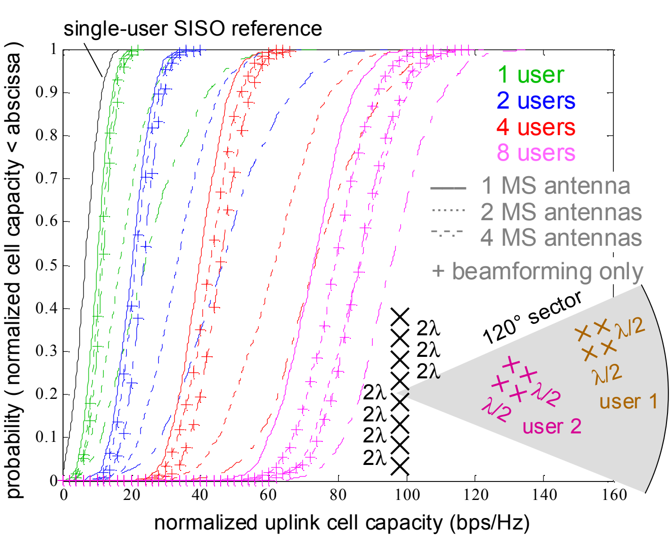

Figure 3. As in Fig. 2, but for 8-element uniform linear array (ULA) at the BS.

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