Adaptive MIMO Transmission in a Realistic Multicell Scenario

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***Abstract*— Cochannel interference in multicellular radio systems is a challenge when full area coverage needs to be ensured. On the physical layer there exist several concepts to combat the interference. However, their performance in an orthogonal frequency division multiple access (OFDMA) system has not been thoroughly investigated yet. One promising technique is the employment of multiple antennas at the terminal side for the purpose of interference rejection. To increase the cell capacity furher and under the assumption of a narrowband feedback channel, unitary beamforming can be used at the base station. We provide a performance evaluation of these techniques for an OFDMA system in the downlink and give quantitative results for the achievable capacity gains.**

***Index Terms*— OFDMA, cochannel interference, array signal processing, interference suppression, adaptive transmission**

I. INTRODUCTION

Both inter-site and intra-site interference, i.e. cochannel interference (CCI), are limiting factors for the performance of full-coverage multicellular radio systems. Consider the downlink transmission from the base station (BS) to the mobile terminal (MT). Recently, it has been proposed to use coordinated joint transmission (JT) for all base stations in a service area to reduce the CCI. In [1] the authors state that JT would completely remove the CCI. The ultimate capacity limit of cellular systems, given by the mean capacity of isolated cells, can be reached herewith [2].

In practice, however, it is difficult to obtain the precise downlink channel state information (CSI) required for JT at the base station. It is shown in [3] that requirements are much stricter than those for joint detection in the opposite uplink direction. The complexity is another issue. JT requires fast signaling links over the backbone to a central unit where the signals are jointly processed. Distributed approaches with reduced complexity are described in [4].

In the following, we consider the use of multiple antennas at the terminal side for the purpose of CCI rejection. In addition, we combine it with closed-loop unitary beamforming at the BS, which is known as grid of beams (GoB) concept. The idea is shown in Fig. 1. Single-antenna terminals are unprotected against CCI (a). On the other hand multi-antenna MTs, which are assumed as the baseline for enhanced cellular systems [5], may use sophisticated signal processing to combine received signals in order to improve the desired signals, and to reject interfering signals simultaneously (Fig. 1 b) [6]. This approach is known as interference rejection combining (IRC). Even in the case of multi-antenna BSs, forming a set of unitary beams, the IRC approach can be supported. Assuming a narrowband feedback channel, the terminal can select the most suitable beam, i.e. the beam which maximizes its own signal (Fig. 1 c). Note that in all neighboring cells the beams are selected independently.

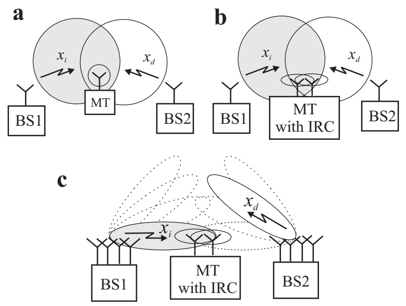

Fig. 1. a) Single-antenna terminals are unprotected against CCI. b) Multi-antenna terminals can use IRC to improve their performance. c) Within a multicell scenario including multi-antenna BS (adaptive GoB) the MT may benefit from IRC, too.

Two weak requirements must still be met: Local oscillators at the BSs must be synchronized, e.g. by coupling them to the global positioning system (GPS). Next, receivers must be able to estimate the interference or at least most of it. Future wireless systems like 3G Long Term Evolution (3G-LTE) and High Speed OFDM Packet Access (HSOPA) exhibit mechanisms for that purpose. Thus, the objective of this paper is to provide a thorough performance evaluation of IRC and unitary beamforming in a realistic multicell scenario and to provide quantitative results for the achievable capacity gains. Results may serve as a baseline for future work which includes partially and fully coordinated transmission.

The paper is organized as follows. In section III, we introduce linear receiver techniques to reduce the CCI at the terminal. In section IV, we describe the simulation environment and compare the results with measurements in the Universal Mobile Telecommunications System (UMTS) network. Finally, results are given in section V.

II. NOTATION

Vectors are indicated by bold face small letters, e.g. $\mathbf{h}$ is a column vector. Bold face capital letters are used to indicate matrices, e.g. channel matrix $\mathbf{H}$. The Hermitean transpose of a vector or matrix, i.e. the complex conjugate transpose, is given by $(\cdot)^H$.

Transmission over a frequency selective channel in the discrete time domain may be described

$$\widehat{\mathbf{y}}(k) = \sum_{l=0}^{L-1} \widehat{\mathbf{H}}(l)\mathbf{x}(k-l) + \mathbf{n}(k) \ , \tag{1}$$

where $\mathbf{H}(l)$ is the channel matrix of tap l, $\mathbf{x}(k)$ is the transmit symbol vector and $\mathbf{n}(k)$ is the additive white Gaussian noise vector. The frequency equivalent channel matrix for each subcarrier Ω in an orthogonal frequency division multiple access (OFDMA) system is given by

$$\mathbf{H}(\Omega) = \sum_{l=0}^{L-1} \widehat{\mathbf{H}}(l) \exp\left(-j2\pi\Omega\frac{l}{N}\right) \ , \tag{2}$$

where L and N are the maximum number of resolvable taps in the time domain and desired subcarriers, respectively. Consider the performance at the 0-th subcarrier, i.e. $\Omega = 0$ for independent channel realizations. This leads to

$$\mathbf{y} = \mathbf{H}(\Omega = 0)\mathbf{x} + \mathbf{n} \tag{3}$$

In the following, we consider the multicellular and single-input multiple-output (SIMO) channels in the downlink with $N_T = 1$ and $N_R = 2$, for simplicity. Thus, the transmission system may be rewritten as

$$\mathbf{y} = \mathbf{h}_i x_i + \underbrace{\sum_{\substack{\forall k\\ k\neq i}} \mathbf{h}_k x_k + \mathbf{n}}_{\mathbf{z}_i} \ , \tag{4}$$

where $\mathbf{h}_i$ and $\mathbf{h}_k$ are the channel vectors (SIMO) of the desired user i and all interfering BSs.

III. PARTIAL INTERFERENCE REDUCTION TECHNIQUES

Linear equalization is favorable since it is easy to implement at the MT. However, in contrast to the nonlinear equalization, it suffers from higher noise enhancement due to fading [7].

A. Maximum Ratio Combining (MRC)

The channel is equalized using the hermitean transpose of the desired user channel. Thus, the estimate $\hat{\mathbf{x}}$ is given

$$\hat{\mathbf{x}} = \mathbf{h}_i^H \left[\mathbf{h}_\mathbf{i} x_i + \mathbf{z}_i\right] \tag{5}$$

The signal to interference and noise ratio (SINR) of the desired channel i is given by

$$\text{SINR}_i = \mathrm{E}\left\{ \frac{\left|\mathbf{h}_i^H \mathbf{h}_i x_i\right|^2}{\left|\mathbf{h}_i^H \mathbf{z}_i\right|^2} \right\} \geq \frac{\mathrm{E}\left\{\left|\mathbf{h}_i^H \mathbf{h}_i x_i\right|^2\right\}}{\mathrm{E}\left\{\left|\mathbf{h}_i^H \mathbf{z}_i\right|^2\right\}} \tag{6}$$

Applying the Jensen's Inequality for convex functions leads to the lower bound of the instantaneous SINR. Simplifcation results in

$$\text{SINR}_i \geq \frac{\sigma_{x_i}^2 \mathbf{h}_i^H \mathbf{h}_i}{\sigma_n^2 + \sum\limits_{\substack{\forall k\\ k\neq i}} \sigma_{x_k}^2 \left(\mathbf{h}_i^H \mathbf{h}_i\right)^{-1} \mathbf{h}_i^H \mathbf{h}_k \mathbf{h}_k^H \mathbf{h}_i} \ , \tag{7}$$

where σ^2 indicates the power of the corresponding stochastic process. Observe that the interference is weighted by the inverse of the summed energy of the desired channel $\mathbf{h}_i$.

B. Maximum SINR Receiver

A suitable technique for interference reduction is the maxiumum SINR (maxSINR) receiver. By employing multiple receive antennas it is possible to enhance the desired signal while suppressing the interference. It determines the joint optimum for the receive beam pattern reducing the influence of all interferers. Thus, the SINR can be given as

$$\text{SINR}_i \geq \sigma_i \frac{\mathbf{w}_i^H \mathbf{h}_i \mathbf{h}_i^H \mathbf{w}_i}{\mathbf{w}_i^H \mathbf{Z}_i \mathbf{w}_i} \ , \tag{8}$$

where $\mathbf{Z}_i = \sigma_n^2 \mathbf{I} + \sum\limits_{\substack{\forall k\\ k\neq i}} \sigma_k \mathbf{h}_k \mathbf{h}_k^H$ and $k \in \mathcal{K}$.

(8) is individually maximized by using the normalized minimum mean square error (MMSE) solution [8]

$$\mathbf{w}_i^{\text{maxSINR}} = \alpha \mathbf{Z}_i^{-1} \mathbf{h}_i \ , \tag{9}$$

where $\mathbf{Z}_i^{-1}$ is the inverse of $\mathbf{Z}_i$ and α is constant[1].

Hence, the achievable SINR with full channel knowledge for all interfering BSs is given by [9]

$$\text{SINR}_i \geq \sigma_i \mathbf{h}_i^H \mathbf{Z}_i^{-1} \mathbf{h}_i \tag{10}$$

C. Maximum SINR Receiver with Limited Interference Knowledge

Since it is more realistic to assume that the MT cannot detect and estimate the channels of all interferers, we examine a reduced joint optimization approach for the IRC. Consider the terminal may detect a set, consisting of $(|\mathcal{N}| - 1)$ strongest interferers with $\mathcal{N} \subset \mathcal{K}$ including its own BS's signal.

$$\mathbf{w}_i^{\text{maxSINR}} = \alpha \widetilde{\mathbf{Z}}_i^{-1} \mathbf{h}_i \ , \tag{11}$$

where $\widetilde{\mathbf{Z}}_i = \sigma_n^2 \mathbf{I} + \sum\limits_{\substack{k\in\mathcal{N}\\ k\neq i}} \sigma_k \mathbf{h}_k \mathbf{h}_k^H$.

D. Estimation of Interference

One may think of a simple mechanisms to gain the interference knowledge which is necessary to support IRC at the MT. Under the assumption of quasi static channels, it is possible to estimate the covariance matrix of the received signal vector $\mathbf{y}$ over several independent identically distributed (i.i.d.) transmitted symbols. The results in Fig. 2 indicate that it may be sufficient to average $\mathbf{y}\mathbf{y}^H$ over 11 symbols to achieve a similar normalized mean square error (MSE) as in the case of including the three strongest, perfecly known interferers into the covariance matrix.

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[1] Since α does not affect the SINR we don't consider its value.

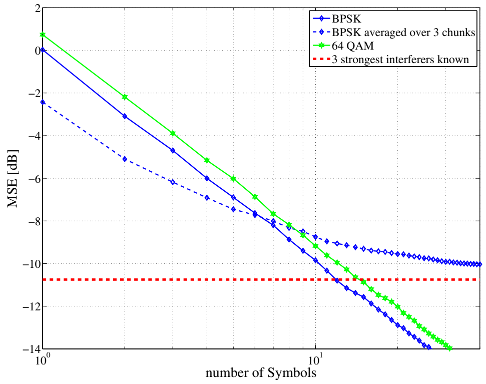

Fig. 2. MSE of the estimated autocorrelation matrix of the received signal by varying the number of transmitted symbols within a quasi static channel (1 chunk = 240 kHz).

E. Multiple-Antennas at the Base Stations (GoB)

Consider the BSs have multiple antennas. Thus the coverage area may be served by a set of unitary beams (GoB), formed at the BSs. Assuming a narrowband feedback channel, the MT in the desired sector selects the beam which maximizes the own signal. All other beams from the neighboring cells are selected randomly, for simplicity. The unitary beam vectors $\mathbf{b}$ are derived here from the DFT matrix. The effective channel to a specific BS results in a SIMO channel $\mathbf{h}_{\text{eff}}$ (12). Thus the techniques discussed above may be used in the same way.

$$\mathbf{y} = \underbrace{\mathbf{H}_i\mathbf{b}_i}_{\mathbf{h}_{\text{eff},i}} x_i + \sum_{\substack{\forall k \\ k \neq i}} \underbrace{\mathbf{H}_k\mathbf{b}_k}_{\mathbf{h}_{\text{eff},k}} x_k + \mathbf{n} \qquad (12)$$

IV. MULTICELL SIMULATION ENVIRONMENT

A. Simulation Assumptions

The simulation assumptions are given in Table I. Applied is the 3GPP SCME channel model, with some modifications, discussed below.

For the sectorization the simulation scenario is initialized cell-wise, i.e. independently for each BS. The large scale parameters are kept fixed for all 3 sectors belonging to the same BS while the small scale parameters are randomized as indicated in [10]. A so-called scenario-mix is introduced. The different BSs may experience different channel conditions, e.g. line of sight (LOS) or non line of sight (NLOS), which is more realistic than assuming same conditions for all channels. The state is changed within the simulation following a distance dependent stochastic process, based on experimental results [11]. This scenario mix models the interference statistics more realistically, and leads to higher average cell capacities.

TABLE I
SIMULATION ASSUMPTIONS.

parameter	value
channel model	3GPP SCME[2]
scenario	urban-macro
additional modifications	scenario-mix[3]
f_c	2 GHz
intersite distance	500m
number of BSs	19 having 3 sectors each
antenna elements ; spacing	1,2,4 ; 4λ
BS height	32m
antenna elements ; spacing	2 ; $\lambda/2$
MT height	2m

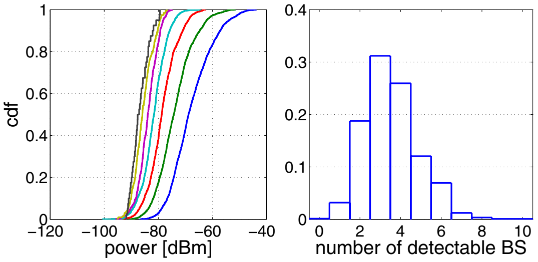

Fig. 3. Left: Measured Top-$|\mathcal{N}|$ power statistics of a specific operator. Right: Probability that a certain number of BSs can be identified at the MT.

B. Comparison with Measurements

For validation purposes we performed measurements in the commercial 3G network using the TSMU radio network analyzer from Rohde&Schwarz on a 10 km track through the western part of the city in Berlin, Germany. Results are based on the downlink common pilot channel (CPICH), which is always transmitted in each sector with 10% of power. It has a spreading factor of 256 and sector-selective scrambling. The CPICH of other sectors can be suppressed by at most $10\log_{10} 256 = 24$ dB in the absence of data, hence we cannot observe most of the dense weaker signals obvious in simulation results. In practise, there is always an upper limit of the number of interferers which can be identified by a MT.

In Fig. 3 (left), the measured Top-$|\mathcal{N}|$ power statistics are given for a network operator having a relatively dense deployment. It matches well with simulation results, hence our simulator describes a dense multicell scenario in urban environments realistically. The plot in Fig. 3 (right) shows the probability that a certain number of BSs can be identified at the terminal. On average, 3-4 detectable BS (2-3 interferers) can be identified in the scenario, but this number has a considerable variance. The impact of limited knowledge about interferers is included in the algorithm described in section III-C.

V. PERFORMANCE EVALUATION

For the performance evaluation, the statistics of the achievable capacity (13) are given for different techniques.

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[2] Spatial Channel Model Extended.

[3] i.e. each cell, consisting of 3 sectors, may have different channel conditions, e.g. LOS or NLOS [11].

TABLE II

ACHIEVABLE MEDIAN CAPACITY [BIT/S/HZ] FOR DIFFERENT CONFIGURATIONS. 10% VALUES ARE GIVEN IN BRACKETS.

	single-antenna MT	two-antenna MT
$N_T = 1$	1.6 (0.6)	3.5 (1.1)
$N_T = 2$ (GoB)	2.1 (0.8)	4.2 (1.3)
$N_T = 4$ (GoB)	3.0 (1.0)	4.9 (1.9)

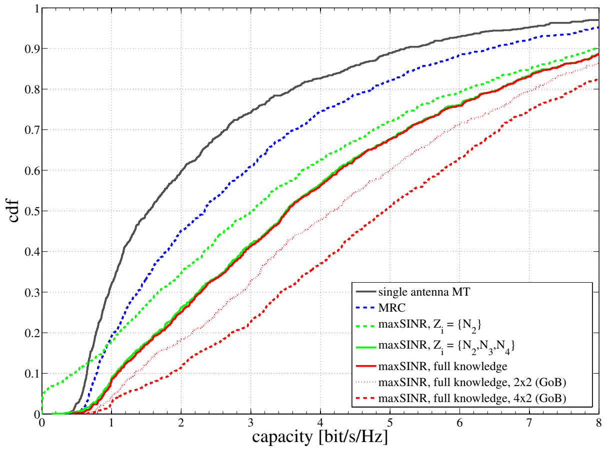

Fig. 4. Achievable capacities by using MRC or IRC in conjunction with unitary beamforming.

$$C_{\text{Shannon}} = \log_2(1 + \text{SINR}) \tag{13}$$

From the performance comparison given in Fig. 4 it is obvious that IRC is not suitable for all users. For different user scenarios, e.g. cell-edge and cell-centered users, different approaches should be used. Consider the case of a cell-edge user which cannot distinguish more than two BS, i.e. its own and one additional interfering one. In the low SINR regime the use of the maxSINR is inferior to the maximum ratio combining (MRC) approach and results in an outage probability ($C \leq 0.01$ bit/s/Hz) of 6%. In practise, an adaptive scheme for interference reduction and signal enhancement, considering both MRC and IRC is superior to a fixed approach. Based on the detectable number of interferers, the MT may decide which receiver technique should be used without requiring any signaling overhead. Note that the IRC outperforms the MRC considering more than two interfering BSs.

Fig. 4 presents the achievable performance gains when using both, multi-antenna terminals and BSs. In this case we consider BSs may have $N_T = \{1, 2, 4\}$ transmit antennas and use unitary beamforming for single stream service. Observe that the capacity of a user may be increased by a factor of three due to IRC at the MT and unitary beamforming at the BS, Tab. II. IRC with a single-antenna BSs is more efficient than unitary beamforming with two-antenna BSs and single-antenna terminal. This is due to the precise channel knowledge available at the MT, enabling optimal instead of unitary beamforming.

VI. CONCLUSION

In this paper we investigated two efficient techniques to reduce the interference in a multicell downlink scenario where multi-antenna BS and multi-antenna MT are used. These are interference rejection combining and unitary beamforming. In a realistic multicell scenario, the performance was evaluated for different numbers of BS antennas ($N_T = \{1, 2, 4\}$) and different receiver algorithms. It was shown that the MT significantly benefits from its precise channel knowledge. Thus, IRC at the terminal is the most efficient technique to reduce the interference without channel knowledge at the transmitter. Furthermore, it was pointed out, that an adaptive approach is favorable using different receiver techniques. It is based on the interference scenario experienced at the MT.

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