On the performance of fast feedback and link adaptation for MIMO eigenbeamforming in cellular systems

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Abstract— *Longterm eigenbeamforming techniques that combine beamforming gains with spatial multiplexing of data streams have proved to be a very strong candidate for link level processing. On system level, fast scheduling brings multi-user diversity which increases with the number of active users in the cell. We propose a system with user specific longterm eigenbeams to transmit spatially multiplexed data streams. For each data stream a feedback measurement regarding the link quality is performed and reported by each user for link adaptation and scheduling. Due to the scheduling the interference pattern usually changes at the moment of using the feedback measurement, leading to mismatches in the link adaptation and throughput loss compared with the ideal case. The aim of this paper is to investigate these new insights in the multi-user MIMO systems and propose advanced methods to decrease the mismatch in the feedback measurement. Simulation results are presented to evaluate the schemes taking as base the UMTS - HSDPA system extended for MIMO applications.*

I. Introduction

The purpose of this paper is to present a multi-user MIMO cellular system using long-term eigenbeamforming [1], [2] and link adaptation based on fast feedback [3], [4] and to highlight the problems that might appear in this combination. An inherent problem when combining eigenbeamforming, i.e. user specific beamforming weights, with fast feedback is that if the scheduler decision will change, the interference pattern will change and the feedback report will not be accurate anymore. The result will be throughput loss compared with the ideal scheme were perfect link adaptation is assumed. Note that this mismatch is independent of the velocity and no prediction is possible. Also, the effect is related to the link adaptation, where concrete MCS are defined and it is not visible for idealistic system assumptions and information theory investigation approaches [5], [6].

In a cellular system the interference is one of the major limiting factors of the link capacity. In the downlink the transmitter can be designed to minimize the interference between the served users (when it knows the channels to the users) [7], [8], but still the intercell interference can not be estimated. The quality of the link, including short term information about the channel and the interference, can be subject to feedback transmission from the receivers. This feedback is called fast feedback because it contains instantaneous (small scale fading) information about the environment the mobile is in. As with the channel state information, we can not assume the full information to be transmitted back from the receiver, but only a measure of the quality of the reception. Based on this feedback value, the transmitter will perform the scheduling of the users and adapt the Modulation and Coding Scheme (MCS).

II. System Model

We are proposing a cellular system using eigenbeamforming at the transmitter and Space-Time MMSE (ST-MMSE) equalization at the receiver [9], [10]. The transmitter (Tx) and a receiver (Rx) equipped with M_T, respective M_R antennas. We model a system using spatial multiplexing of data streams, the data to be transmitted being demultiplexed in N parallel streams. The Tx linearly maps the N streams on the M_T antennas, using the prefiltering matrix $\boldsymbol{V}$, Figure 1.a. The signal is then pulse shaped, passed through the channel and received with M_R antennas. At the receiver, the signal is filtered with the filter matched to the pulse shape and sampled before it enters the discrete time linear Space Time - MMSE (ST-MMSE) equalizer. We can describe an equivalent discrete time MIMO system, having N transmit antennas and M_R receive antennas, connected by an equivalent discrete time channel $h(k\Delta t)$, that is the result of the convolution of the transmit processing, the actual channel and the receiver front-end, Figure 1.b. The same link level model was used in [9] where the link to system level interface was investigated. The input-output relation of the equivalent MIMO frequency selective channel can be written in matrix form as:

$$\boldsymbol{y}(k) = \boldsymbol{\Gamma}\boldsymbol{x}(k) + \boldsymbol{n}(k), \tag{1}$$

where:

- $\boldsymbol{y}(k) = [y^0(k) \dots y^{M_\mathrm{R}-1}(k)]^\mathrm{T}$ is the received vector at moment k;

- $$\boldsymbol{\Gamma} = \begin{bmatrix} h^{00}(0) & \dots & h^{0,N-1}(0) & \dots & & & & \\ \vdots & \vdots & \vdots & \vdots & & & & \\ h^{M_\mathrm{R}-1,0}(0) & \dots & h^{M_\mathrm{R}-1,N-1}(0) & \dots & & & & \\ & & & \dots & h^{00}(L-1) & \dots & h^{0,N-1}(L-1) \\ & & & \vdots & \vdots & \vdots & \vdots \\ & & & \dots & h^{M_\mathrm{R}-1,0}(L-1) & \dots & h^{M_\mathrm{R}-1,N-1}(L-1) \end{bmatrix},$$

is the space-time channel matrix;

- $h^{rn}(l)$, $l = 0 \dots L-1$ is the channel impulse response

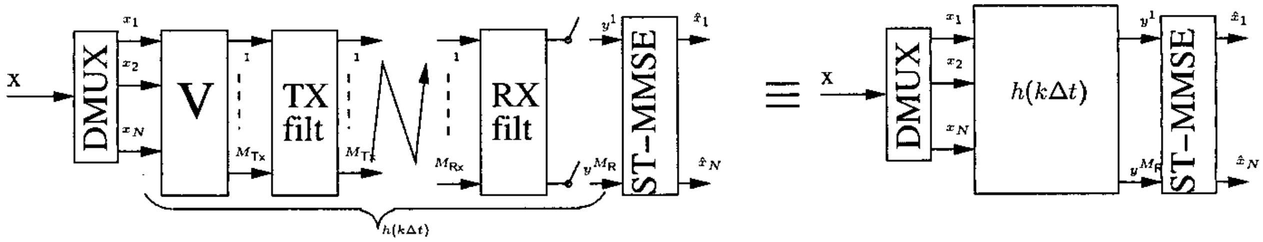

Fig. 1. a. Link level processing. b. Equivalent model.

from Tx antenna n to Rx antenna r, having length L symbol interval sampled.

- $x(k) = [x^0(k) \dots x^{N-1}(k) \dots x^0(k-L+1) \dots x^{N-1}(k-L+1)]^\mathsf{T}$ is the transmitted signal vector from antennas $0 \dots N-1$ that influences the received signal at moment k through the convolutive channel;
- $\boldsymbol{n}(k) = [n^0(k) \dots n^{M_\mathsf{R}-1}(k)]^\mathsf{T}$ is the noise realization vector;

The use of fast feedback in a mobile communication system makes sense only when the channel varies slowly enough, so that it is practically constant between the feedback measurement and the use of this information. We also make this assumption that the channel is constant, so we have dropped the index k for $\boldsymbol{\Gamma}$ in relation (1).

The prefiltering matrix $\boldsymbol{V}$ consists of the eigenvectors of the transmit spatial covariance matrix, restricted to the significant eigenmodes:

$$\begin{bmatrix} \boldsymbol{V} & \boldsymbol{V}_1 \end{bmatrix} \begin{bmatrix} \boldsymbol{\Lambda} & 0 \\ 0 & \boldsymbol{\Lambda}_1 \end{bmatrix} \begin{bmatrix} \boldsymbol{V} & \boldsymbol{V}_1 \end{bmatrix}^\mathsf{H} = \boldsymbol{R}_{\mathsf{Tx}}. \qquad (2)$$

Power and bit loading schemes based on the long term eigenvalues are well known to maximize the capacity [1], [2], [11]. The additional variation of the power on the eigenbeams will lead to an increased variation of the interference power, resulting in an increased mismatch of the feedback measurement. Also, many practical systems do not allow power loading schemes not to increase the signaling and the interference in the cell for the other users. Still using only bit loading as fast link adaptation partially compensates for the lack of power loading. In our application the total power of the transmitter is fixed being equally split among the eigenmodes. The number of eigenmodes N is so decided to maximize the link throughput.

For receive processing we have decided for Space-Time MMSE equalization, being the most flexible among the linear receivers [1], [10]. Compared with nonlinear receivers it provides a good equalization of the channel at a relatively low processing complexity. It is also considered as baseline for comparison of MIMO system level gains in standardization bodies such as 3GPP.

To perform FIR space time equalization over E chips we will have to rewrite equation (1) extending it for E received samples at the M_R receiver antennas.

$$\boldsymbol{y}_E(k) = \boldsymbol{\Gamma}_E \boldsymbol{x}_E(k) + \boldsymbol{n}_E(k), \qquad (3)$$

where now:[1]

- $\boldsymbol{y}_E(k) = [\boldsymbol{y}(k) \dots \boldsymbol{y}(k-E+1)]^\mathsf{T}$;
- $\boldsymbol{\Gamma}_E = \begin{bmatrix} \boldsymbol{\Gamma} & \boldsymbol{0}_{M_\mathsf{R}\times N} & \dots & \boldsymbol{0}_{M_\mathsf{R}\times N} \\ \boldsymbol{0}_{M_\mathsf{R}\times N} & \boldsymbol{\Gamma} & \dots & \boldsymbol{0}_{M_\mathsf{R}\times N} \\ \vdots & \vdots & \dots & \vdots \\ \boldsymbol{0}_{M_\mathsf{R}\times N} & \boldsymbol{0}_{M_\mathsf{R}\times N} & \dots & \boldsymbol{\Gamma} \end{bmatrix}$;
- $\boldsymbol{x}_E(k) = [x^0(k) \dots x^{N-1}(k) \dots x^0(k-E-L+2) \dots x^{N-1}(k-E-L+2)]^\mathsf{T}$;
- $\boldsymbol{n}_E(k) = [\boldsymbol{n}(k) \dots \boldsymbol{n}(k-E+1)]$.

Starting from $\boldsymbol{y}_E(k)$ we will derive the MMSE equalizer, which should recover the transmitted signal at antennas $1, \dots, N$, at some moment $k-d$. We are looking for a matrix $\boldsymbol{W}$ that by filtering $\boldsymbol{y}_E(k)$ will estimate the vector:

$$\boldsymbol{x}(k-d) = [x^0(k-d) \dots x^{N-1}(k-d)]^\mathsf{T}, \qquad (4)$$

minimizing the mean square error:

$$\boldsymbol{W} = \arg\min_{\boldsymbol{W}} \mathsf{E}\left\{ \|\boldsymbol{W}\boldsymbol{y}_E(k) - \boldsymbol{x}(k-d)\|^2 \right\}. \qquad (5)$$

The solution of this minimization problem is the Wiener filter [13], extended for the MIMO case [9]:

$$\boldsymbol{W} = \mathsf{E}\left\{\boldsymbol{x}(k-d)\boldsymbol{y}_E^\mathsf{H}(k)\right\} \left(\mathsf{E}\left\{\boldsymbol{y}_E(k)\boldsymbol{y}_E^\mathsf{H}(k)\right\}\right)^{-1}. \qquad (6)$$

Computing the two expectations and plugging them on the right side of relation (6) we get the space time equalizer matrix:

$$\boldsymbol{W} = \boldsymbol{R}_{\boldsymbol{x}\boldsymbol{x}_E} \boldsymbol{\Gamma}_E^\mathsf{H} \left(\boldsymbol{\Gamma}_E \boldsymbol{R}_{\boldsymbol{x}_E\boldsymbol{x}_E} \boldsymbol{\Gamma}_E^\mathsf{H} + \boldsymbol{R}_{nn} \right)^{-1}, \qquad (7)$$

where $\boldsymbol{R}_{\boldsymbol{x}\boldsymbol{x}_E} = \mathsf{E}\{\boldsymbol{x}(k-d)\boldsymbol{x}_E^\mathsf{H}(k)\}$, $\boldsymbol{R}_{\boldsymbol{x}_E\boldsymbol{x}_E} = \mathsf{E}\{\boldsymbol{x}_E(k)\boldsymbol{x}_E^\mathsf{H}(k)\}$ depend on the statistics of the input signals and $\boldsymbol{R}_{nn} = \mathsf{E}\{\boldsymbol{n}_E(k)\boldsymbol{n}_E^\mathsf{H}(k)\}$ depend on the statistics of the noise and the interference.

III. Link to System Level Interface

The link to system level interface must be a measure which can be used at system level to express as good as possible the link level performance, without simulating each link. In [9] we have shown that a good

[1] $\boldsymbol{0}_{M_\mathsf{R}\times N}$ denotes a matrix of size $M_\mathsf{R} \times N$ of zeros.

candidate for link to system level interface in MIMO systems with ST-MMSE equalization is the signal to noise and interference ratio (SINR) per stream at the output of the equalizer. This measure can be computed based only on the system level parameters (channel, intra/intercell interference) and can be easily mapped to link performance expressed by the frame error rate and throughput. The mapping is done assuming that the total interference and noise results in an additive Gaussian random variable, and using link level results for different modulation and coding schemes.

The SINR at the output of the equalizer can be computed writing the relation between the equalized signal and the transmitted signal:

$$\hat{\boldsymbol{x}}(k) = \boldsymbol{W}\boldsymbol{\Gamma}_E\boldsymbol{x}_E(k) + \boldsymbol{W}\boldsymbol{n}_E(k) \tag{8}$$

and expanding for each stream:

$$\begin{aligned}\hat{x}^n(k) = {} & \boldsymbol{w}_n^{\mathsf{T}}\gamma_{dN+n}x^n(k-d) + \\ & + \sum_{m=0;m\neq dN+n}^{N(E+L-1)-1} \boldsymbol{w}_n^{\mathsf{T}}\gamma_m x^{\lfloor \frac{m}{N} \rceil}\left(k - \left\lfloor \frac{m}{N} \right\rfloor\right) + \boldsymbol{w}_n^{\mathsf{T}}\boldsymbol{n}_E(k),\end{aligned} \tag{9}$$

where $\boldsymbol{w}_n^{\mathsf{T}}$ is the n^{th} row on matrix $\boldsymbol{W}$ and γ_m is the m^{th} column of the matrix $\boldsymbol{\Gamma}_E$. $\lfloor \frac{m}{N} \rfloor$ denotes the largest integer smaller than $\frac{m}{N}$ and represents the delay of the Tx signal; $\lfloor \frac{m}{N} \rceil$ denotes the remainder of the integer division of m to N and represents the index of the substream.

The first term on the right part of equation (9) represents the desired signal part in $\hat{x}^n(k)$, the second term represents the interference from the other streams and the remaining Intersymbol Interference (ISI) and the third part represents the noise component including the intra and intercell interference. Defining the average SINR as the ratio between the desired signal energy and the interference energy, the average SINR of the n^{th} stream will be given by:

$$SINR_n = \frac{|\boldsymbol{w}_n^{\mathsf{T}}\gamma_{dN+n}|^2\sigma_{x^n}^2}{\sum_{m=0;m\neq dN+n}^{N(E+L-1)-1}|\boldsymbol{w}_n^{\mathsf{T}}\gamma_m|^2\sigma^2_{x^{\lfloor \frac{m}{N} \rceil}} + \boldsymbol{w}_n^{\mathsf{T}}\boldsymbol{R}_{nn}\boldsymbol{w}_n^*}. \tag{10}$$

The next step is the mapping between SINR and throughput based on link level results. For example in [4] are presented link level results for HSDPA, for Modulation and Coding Schemes (MCS) listed in Table 1 and Chase Combining Hybrid Automatic Repeat Request (HARQ) scheme. Figure 2 shows these results that we will use also later on in our evaluations.

IV. System level model

We model the downlink of a cellular system. The serving base station (BS) is selected based on the average propagation attenuation (including pathloss, shadowing and antenna gains). We will model only the central BS, the rest of the BSs acting as intercell interference.

TABLE I

Reference MCS

MCS	Modulation	Code rate	Max rate per code [kbps]
5	16QAM	3/4	720
4	16QAM	1/2	480
3	QPSK	3/4	360
2	QPSK	1/2	240
1	QPSK	1/4	120

Each mobile station (MS) performs a feedback measurement of the link quality, based on which the BS will do the scheduling and the link adaptation (selection of the MCS).

The scheduling is a time division multiple access (TDMA) component, one user being scheduled at a time. We have investigated three classic scheduling strategies: Round Robin, maximum throughput and proportional fair scheduling.

V. Feedback measurement

We have already put in the introduction the problem of combining fast feedback with user specific beamforming vectors and scheduling. We will show in this section how the feedback measurement can be computed and what is the mismatch to the true value when the user is served. We will also show what are the effects of the mismatch and evaluate the associated loss.

The link to system level interface is the SINR per stream and we will use this measure also as feedback measurement being input to the scheduler decision and to selecting the modulation and coding scheme.

Let us first look at the signals in the system at the moment of feedback measurement. We can identify the following signals:

1. signals transmitted for the scheduled user(s);
2. other signals in the cell, like control channels, pilot channels;
3. signals coming from the surrounding BSs, that form the intercell interference.

More than this, each user will be able to estimate its own channel, based on the pilot channels. If we consider any user, let's call it user 1, its channel including the beamforming filtering will be denoted $\boldsymbol{\Gamma}_{E,1}$. It will receive all signals from the serving BS through the same physical channel, but prefiltered with the beamforming vectors corresponding to the scheduled users. The equivalent channels, including the beamforming vectors, will be denoted $\boldsymbol{\Gamma}_{E,m}$, $m \in \mathcal{U}_1$ being the indices of the scheduled users (user 1 can be or not among them). Further on, we denote the other channels in the cell, not bearing data, as $\boldsymbol{\Gamma}_{E,\text{oc}}$ and the channel through which the signal propagates to user 1 from the other cells with $\boldsymbol{\Gamma}_{E,inter}$, all including the corresponding beamforming vectors.

The equalizer matrix computed by user 1, will try to equalize its own channel and to minimize the interfer-

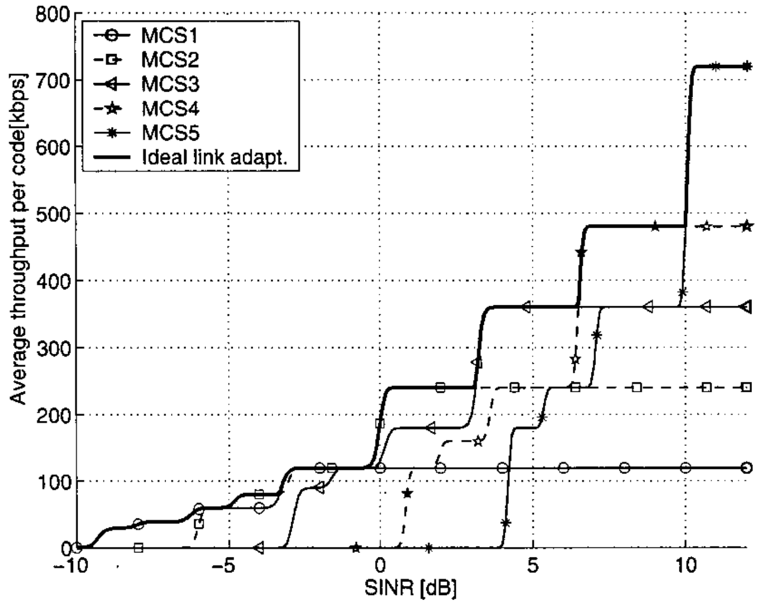

Fig. 2. Throughput curves for Chase Combining with different MCS

ence from the other signals (the superscript f denotes the moment of feedback measurement):

$$W^f = R_{xx_E,1}\Gamma_{E,1}^{\mathsf{H}}\left(\sum_{m\in\mathcal{U}_1} R_m + R_m + R_{nn}^t\right)^{-1}, \quad (11)$$

where $R_{nn}^t = \sum_{oc} R_{oc} + \sum_{inter} R_{inter} + R_{nn}$ is the total interference from non data channel, intercell interference and noise; $R_\alpha = \Gamma_{E,\alpha} R_{x_E x_E,\alpha} \Gamma_{E,\alpha}^{\mathsf{H}}$, $\alpha \in \{m, oc, inter\}$.

Next we compute the feedback SINR after equalization. It makes a difference if the user that we are looking at is itself scheduled or not. If user 1 is scheduled at the moment of feedback measurement, then the interference will come as self interference (intersymbol interference and interference from the other spatially multiplexed streams) denoted with index $self$, the interference from the other users scheduled (U), the other channels (oc) in the cell and the intercell interference ($inter$). Each is computed according to formula (10) with the equalizer matrix being W^f and the equivalent channel matrix defined above. The SINR expressed for each stream, $n = 1 \dots N$ is:

$$SINR_n^{f,1} = \frac{P_{S,n}^f}{P_{self,n}^f + P_{U,n}^f + P_{oc,n}^f + P_{inter,n}^f + P_{noise,n}^f}. \quad (12)$$

In the second case, if user 1 is not scheduled, then there is no data signal transmitted to him. Still it can compute from the equalizer matrix W^f and its estimated channel the power of the useful signal that it could receive if scheduled: $P_{S,n}^f$. The interference will come now from the data signals scheduled, the other non-data channels in cell and the intercell interference.

$$SINR_n^{f,2} = \frac{P_{S,n}^f}{P_{U,n}^f + P_{oc,n}^f + P_{inter,n}^f + P_{noise,n}^f}. \quad (13)$$

Starting from the feedback reports from all users, the scheduler will decide for a set of users $\mathcal{U}_2$ to be scheduled, that is likely to be different from the set that was transmitted to at the moment of feedback measurement. Due to the user specific eigenbeamforming, the interference pattern will change, the corresponding equalizer matrix must be computed and SINR will be different from the reported one.

Without loss of generality we can assume that user 1 is scheduled and we compute its equalizer matrix. To simplify the problem and to keep tractability we assume that the *physical channel* is slowly changing, so from the moment of feedback measurement until the moment of scheduling it is constant. We assume, also, that the non-data channels in the cell (voice channels, common channels, pilot channels) and the intercell interference remain constant in this time interval.

Then, the equalizer matrix of user 1 after scheduling (denoted by superscript s) will be:

$$W^s = R_{xx_E,1}\Gamma_{E,1}^{\mathsf{H}}\left(\sum_{m\in\mathcal{U}_2} R_m + R_{nn}^t\right)^{-1}. \quad (14)$$

We remark here that due to the fact that the physical channels are constant *the term* R_{nn}^t *is the same* between the feedback measurement and the scheduling. The equalizer matrix and the SINR are modified only due to the change in the beamforming vectors.

The SINR for each data stream to user 1 will be the ratio of power of the useful signal to interference, formed by self interference, intracell and intercell interference, and noise.

$$SINR_n^s = \frac{P_{S,n}^s}{P_{self,n}^s + P_{U,n}^s + P_{oc,n}^s + P_{inter,n}^s + P_{noise,n}^s}. \quad (15)$$

From equations (12), (13) and (15) we see that the reported $SINR^f$ is different from the $SINR^s$ the mobile will experience when scheduled. The effect of this mismatch is that the transmitter may decide to transmit on a *MCS that is not optimal*, resulting in throughput loss. We define the SINR mismatch as:

$$\Delta SIR_n = 10\log_{10}\left(\frac{SIR_n^s}{SIR_n^f}\right) \quad \text{[dB]}. \quad (16)$$

To estimate the actual mismatch in the link adaptation we have run several simulations with parameters of the HSDPA system [14] in a realistic frequency selective MIMO channel, described in [15]. We have allocated 50% of the power to scheduled users and 50% of the power to other channels (voice, pilot, common channels). 12 codes with spreading factor 16 are allocated to HSDPA. For scheduling we have implemented the standard single user scheduling techniques mentioned in section 2.4. Single user scheduling means that all the available resources are used for one user at a time, spatially multiplexing several streams. This leads to a simplification in the computation of the equalizer and the SINR, the sets $\mathcal{U}_1$ and $\mathcal{U}_2$ having only one element. The worst case scenario is when always a different user is served at the moment of feedback measurement than at the moment of scheduling (as it is the case in the Round Robin scheduling). For this case we present results in Table 2, for different antenna configurations and channel environments. As a figure of merit we have computed the mean mismatch, its standard deviation and the throughput loss compared with the ideal scheme where there is no mismatch in the link adaptation.

The conclusions that we can draw from this table is that for some scenarios the gain obtained by transmitting on the eigenbeamforming vectors of the users will be considerably diminished by the throughput loss due to mismatch in the link adaptation. This loss has to be taken into consideration when designing a scheme based on user specific beamforming vectors.

In the next section we propose methods to significantly decrease this loss, so that the benefits from MIMO eigenbeamforming can be fully exploited.

VI. Improved Feedback Measurement

In the previous section we have shown why there will be a link adaptation mismatch in MIMO eigenbeamforming and what are the effects of this mismatch. We will now investigate how the mismatch can be reduced, proposing modified schemes for computing the feedback SINR.

The difference in the SINR values comes from two reasons. First, the equalizer matrix is different at the two moments ($\boldsymbol{W}^f$, $\boldsymbol{W}^s$), due to the fact that the received signals that must be equalized have different components. This difference has an important influence on the useful signal power and the interference power, even if we assume that the physical channel is constant: the powers will be different, even if the same $\boldsymbol{\Gamma}_{E,1}$, $\boldsymbol{\Gamma}_{E,oc}$ and $\boldsymbol{\Gamma}_{E,inter}$ will enter the equations. Second, there are different signal components that enter the SINR formula after the scheduling (the sets $\mathcal{U}_1$ and $\mathcal{U}_2$ will have different elements).

To exemplify these issues we select one of the scenarios from Table 2 that show a large mismatch in the SINR: suburban macrocellular with 6 Tx and 4 Rx antennas. Assuming that user 1 is scheduled based on its feedback report, while at the moment of feedback measurement user 2 was scheduled, we compute:

$$\boldsymbol{W}^f = \boldsymbol{R}_{\boldsymbol{x}\boldsymbol{x}_E,1}\boldsymbol{\Gamma}_{E,1}^{\mathrm{H}}\left(\boldsymbol{\Gamma}_{E,2}\boldsymbol{R}_{\boldsymbol{x}\boldsymbol{x}_E,2}\boldsymbol{\Gamma}_{E,2}^{\mathrm{H}} + \boldsymbol{R}_{nn}^t\right)^{-1}, \quad (17)$$

$$SINR_n^f = \frac{P_{S,n}^f}{P_{2,n}^f + P_{oc,n}^f + P_{inter,n}^f + P_{noise,n}^f}, \quad (18)$$

$$\boldsymbol{W}^s = \boldsymbol{R}_{\boldsymbol{x}\boldsymbol{x}_E,1}\boldsymbol{\Gamma}_{E,1}^{\mathrm{H}}\left(\boldsymbol{\Gamma}_{E,1}\boldsymbol{R}_{\boldsymbol{x}\boldsymbol{x}_E,1}\boldsymbol{\Gamma}_{E,1}^{\mathrm{H}} + \boldsymbol{R}_{nn}^t\right)^{-1}, \quad (19)$$

$$SINR_n^s = \frac{P_{S,n}^s}{P_{self,n}^s + P_{oc,n}^s + P_{inter,n}^s + P_{noise,n}^s}. \quad (20)$$

Further on, we have designed two genie aided methods of measuring the feedback SINR. The first method assumes that user 1 knows beforehand the equalizer matrix $\boldsymbol{W}^s$ and uses it also for feedback measurement. This will lead to a perfect estimation of the useful signal power, interference power from non-data channels, intercell interference and noise power. We denote this as genie equalizer (GW). The second method subtracts ideally the interference from the user 2 and adds its own self interference in the SINR formula, but not in the computation of the equalizer; we call it genie interference (GI):

$$\boldsymbol{W}^{f,GW} = \boldsymbol{W}^s = \boldsymbol{R}_{\boldsymbol{x}\boldsymbol{x}_E,1}\boldsymbol{\Gamma}_{E,1}^{\mathrm{H}}\left(\boldsymbol{\Gamma}_{E,1}\boldsymbol{R}_{\boldsymbol{x}\boldsymbol{x}_E,1}\boldsymbol{\Gamma}_{E,1}^{\mathrm{H}} + \boldsymbol{R}_{nn}^t\right)^{-1} \quad (21)$$

$$SINR_n^{f,GW} = \frac{P_{S,n}^s}{P_{2,n}^{f,GW} + P_{oc,n}^s + P_{inter,n}^s + P_{noise,n}^s}, \quad (22)$$

$$\boldsymbol{W}^{f,GI} = \boldsymbol{W}^f = \boldsymbol{R}_{\boldsymbol{x}\boldsymbol{x}_E,1}\boldsymbol{\Gamma}_{E,1}^{\mathrm{H}}\left(\boldsymbol{\Gamma}_{E,2}\boldsymbol{R}_{\boldsymbol{x}\boldsymbol{x}_E,2}\boldsymbol{\Gamma}_{E,2}^{\mathrm{H}} + \boldsymbol{R}_{nn}^t\right)^{-1} \quad (23)$$

TABLE II

SINR MISMATCH RESULTS AND THROUGHPUT LOSS

	Micro cellular			Suburban macro		
Ant conf.	$\Delta SINR$[dB]	std{$\Delta SINR$}	T loss[%]	$\Delta SINR$[dB]	std{$\Delta SINR$}	T loss[%]
1x1	0	0	0	0	0	0
2x1	-0.24	0.60	4.6	0.05	0.4	4.7
2x2	-0.17	0.61	2.7	-0.53	1.47	9.3
4x1	-0.26	1.05	10.5	0.22	0.88	12.6
4x2	0.06	0.73	7.3	-0.39	1.58	13.3
4x4	-0.33	1.02	9.4	-1.38	1.52	9.89
6x1	-0.30	1.29	12.7	0.30	1.23	16.6
6x2	0.22	1.01	12.7	0.11	1.41	13.3
6x4	-0.05	0.88	8.99	-0.86	2.19	14.2

$$SINR_n^{f,GI} = \frac{P_{S,n}^f}{P_{self,n}^{f,GI} + P_{oc,n}^f + P_{inter,n}^f + P_{noise,n}^f}. \quad (24)$$

Of course, a third genie can be considered, that fixes both the W and the $SINR$ formula, which will lead to no mismatch at all.

A comparison of the three methods (the normal and the 2 genie methods) is presented in Figure 3. We can see how much the feedback SINR can be corrected by the ideal assumptions.

In order to derive realistic improved schemes for feedback measurement we will follow the directions of the genie methods: stabilize the equalizer matrix and compensate for the variation in the interference due to changes in the scheduled users.

It must be noted that the signals for the scheduled users can, in practice, not be distinguished from the other interference (non-data channels and intercell interference) to be extracted in the equalizer matrix computation or in the SINR formula. The only available information is the channel of the user that performs the measurement.

Method 1: addition of the own channel in the equalizer matrix.

$$\begin{aligned} \boldsymbol{W}^{f,1} = \boldsymbol{R}_{\boldsymbol{xx}_E,1}\boldsymbol{\Gamma}_{E,1}^{\mathsf{H}} \Big(&\boldsymbol{\Gamma}_{E,1}\boldsymbol{R}_{\boldsymbol{xx}_E,1}\boldsymbol{\Gamma}_{E,1}^{\mathsf{H}} + \\ &+\boldsymbol{\Gamma}_{E,2}\boldsymbol{R}_{\boldsymbol{xx}_E,2}\boldsymbol{\Gamma}_{E,2}^{\mathsf{H}} + \boldsymbol{R}_{nn}^t\Big)^{-1}. \end{aligned} \quad (25)$$

By this method it seems that we make a systematic error in the computation of the equalizer matrix, but it should not have a significant influence on the SINR because $\boldsymbol{W}^{f,1}$ appears both in the powers at the nominator and the denominator of the SINR:

$$SINR_n^{f,1} = \frac{P_{S,n}^{f,1}}{P_{2,n}^{f,1} + P_{oc,n}^{f,1} + P_{inter,n}^{f,1} + P_{noise,n}^{f,1}}. \quad (26)$$

The resulting SINR mismatch is plotted also in Figure 3. We see that the SINR mismatch is decreased leading to a lower throughput loss than the normal scheme. The performance of this method is limited to the genie equalizer performance.

Method 2: addition of the own channel and subtraction of an average interference of the other scheduled users in the equalizer matrix.

Not knowing the beamforming vectors of the scheduled users, user 1 can only assume that the power is uniformly radiated in the cell. This way it computes an average interference that can be subtracted in the computation of the equalizer matrix, besides adding its own channel.

$$\begin{aligned} \boldsymbol{W}^{f,2} = \boldsymbol{R}_{\boldsymbol{xx}_E,1}\boldsymbol{\Gamma}_{E,1}^{\mathsf{H}} \Big(&\boldsymbol{\Gamma}_{E,1}\boldsymbol{R}_{\boldsymbol{xx}_E,1}\boldsymbol{\Gamma}_{E,1}^{\mathsf{H}} + \boldsymbol{\Gamma}_{E,2}\cdot \\ &\cdot \boldsymbol{R}_{\boldsymbol{xx}_E,2}\boldsymbol{\Gamma}_{E,2}^{\mathsf{H}} - \overline{\boldsymbol{\Gamma}_{E,2}}\boldsymbol{R}_{\boldsymbol{xx}_E,2}\overline{\boldsymbol{\Gamma}_{E,2}}^{\mathsf{H}} + \boldsymbol{R}_{nn}^t\Big)^{-1}, \end{aligned} \quad (27)$$

$$SINR_n^{f,2} = \frac{P_{S,n}^{f,2}}{P_{2,n}^{f,2} + P_{oc,n}^{f,2} + P_{inter,n}^{f,2} + P_{noise,n}^{f,2}}. \quad (28)$$

The results, also plotted in Figure 3, are not as promising as with method 1. The explanation is that the equalizer do not adapt well anymore to the channel and interference, the feedback SINR not being accurate anymore.

Method 3: addition of self interference in the equalizer matrix and modification of the SINR formula to account for self interference and to subtract an average interference from the scheduled users.

We will use the equalizer matrix from method 1, which showed good performance and try to compensate for the differences in the formula of the SINR. We do this by adding the self interference term and subtracting an average interference of the scheduled users, again obtained by assuming uniformly radiated signal:

$$\begin{aligned} \boldsymbol{W}^{f,3} = \boldsymbol{W}^{f,1} = \boldsymbol{R}_{\boldsymbol{xx}_E,1}\boldsymbol{\Gamma}_{E,1}^{\mathsf{H}} \Big(&\boldsymbol{\Gamma}_{E,1}\boldsymbol{R}_{\boldsymbol{xx}_E,1}\boldsymbol{\Gamma}_{E,1}^{\mathsf{H}} + \\ &+\boldsymbol{\Gamma}_{E,2}\boldsymbol{R}_{\boldsymbol{xx}_E,2}\boldsymbol{\Gamma}_{E,2}^{\mathsf{H}} + \boldsymbol{R}_{nn}^t\Big)^{-1}, \end{aligned} \quad (29)$$

$$SINR_n^{f,3} = \frac{P_{S,n}^{f,3}}{P_{self,n}^{f,3} + P_{2,n}^{f,3} - \overline{P_{2,n}^{f,3}} + P_{oc,n}^{f,3} + P_{inter,n}^{f,3} + P_{noise,n}^{f,3}} \quad (30)$$

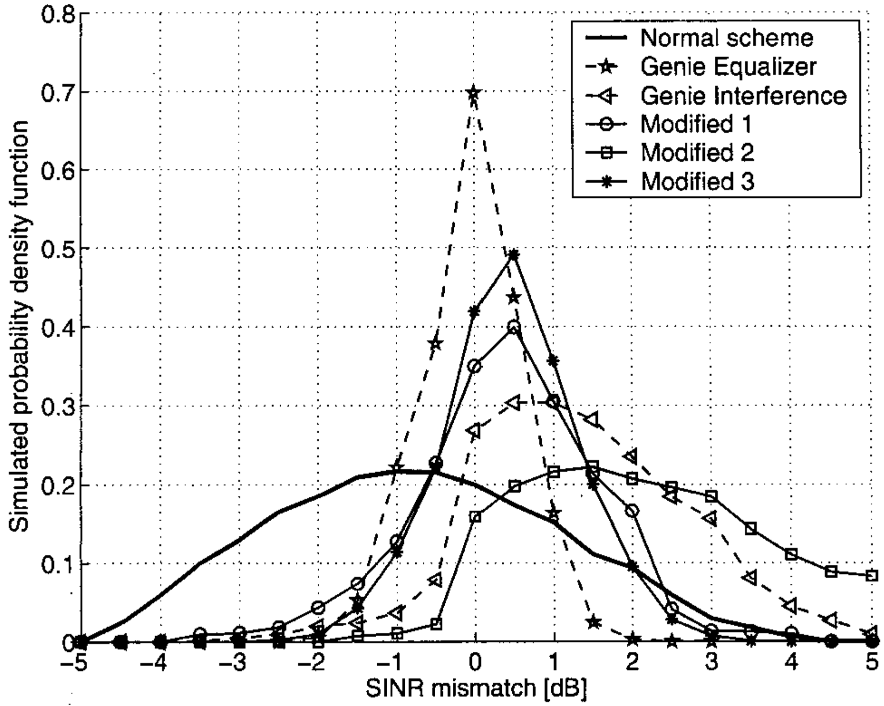

Fig. 3. Comparison of the SINR mismatch for the normal and the modified schemes.

This method that combines both effects have proven to be the most suitable.

scheme	mean [dB]	std [dB]	T loss [%]
normal	-0.86	2.19	14
genie W	0.08	0.62	2.3
genie I	0.97	1.55	9.1
modif.1	0.46	1.04	6.5
modif.2	1.71	2.15	16
modif.3	0.45	0.89	5.3

TABLE III
SINR MISMATCH RESULTS

Several simulations were performed for the other channel environments, antenna configurations and all the three scheduling strategies. We do not present all here due to lack of space. The improvements are similar. Still, to get a first insight about the gains from using several antennas at the transmitter and at the receiver and to see the improvement of the modified schemes over the normal scheme we present average cell throughput results of the data users for MIMO-HSDPA. We compare the normal scheme with the modified scheme 3, for 4, respectively 2 transmit antennas and increasing number of receiver antennas.

VII. Conclusions

We have presented a MIMO cellular system where users are served on the eigenmodes of the spatial channel covariance matrix. Each user measures the link quality, computing the SINR after ST-MMSE equalization and reports it to the BS for link adaptation and scheduling. The benefits of eigenbeamforming and fast link adaptation are well known in the open literature. We investigated here the problems that appear in the combination of these methods.

The reported SINR is dependent on the interference status at the moment of feedback measurement. After scheduling, the users served by the BS will probably change. Even if we assume that the physical channel remains the same (for low mobile velocity and fast scheduling), due to the directivity of the radiation with user specific beamforming the interference pattern will change and the SINR experienced by the scheduled users will be different from the one reported. This difference will lead to mismatches in the link adaptation and finally to throughput loss compared with the ideal scheme where there is no mismatch.

Taking as example the UMTS-HSDPA system extended for MIMO applications, we have simulated the throughput loss due to this effect. Further on we have shown what are the limits that can be achieved when genie information is available for computation of the feedback SINR. Following the same direction we have

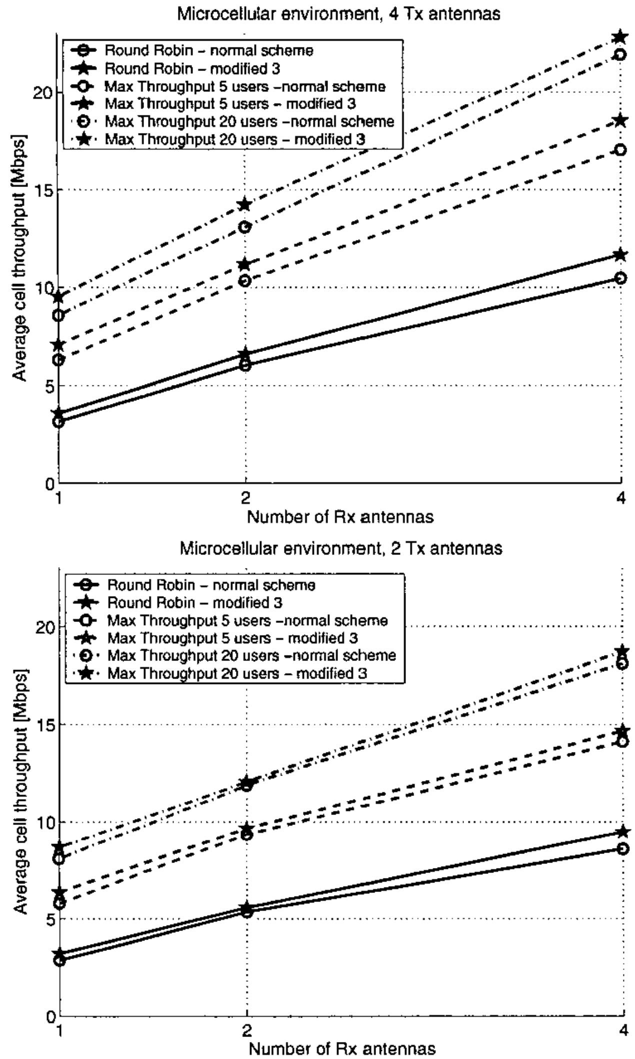

Fig. 4. Average throughput results for MIMO-HSDPA in microcellular environment

developed realistic schemes that improve the feedback measurement and have tested them with simulations.

In the formalism the problem is defined, the investigation can be easily extended to spatial parallel scheduled users, where more than 1 user is scheduled at a time.

These results are important steps towards a realistic estimation of the system level performance of MIMO systems.

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