Intra-cell Interference Aware Equalization for TxAA HSDPA

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***Abstract*—In TxAA HSDPA downlink a basestation is capable of serving several users simultaneously. The users are distinguished by different spreading sequences and their data chip streams are weighted by individual precoding coefficients. In this contribution we derive an MMSE equalizer for TxAA HSDPA downlink that takes the interference of the other users into account. Compared to the straightforward receiver that neglects the interference of other users, a performance gain of up to 4 dB can be achieved.**

I. Introduction

Already back in 1999, the UMTS standard specified a so-called closed loop mode with transmit diversity (TxAA) [1]. In TxAA, the data of one user is weighted by precoding coefficients and transmitted at two antennas. The precoding coefficients are continuously reported to the basestation by the user equipment, thus the name "closed loop". A few years ago, 3GPP standardized the so-called High Speed Downlink Packet Access (HSDPA) mode as an extension of UMTS [2]. HSDPA increases the available downlink data rate by employing Adaptive Modulation and Coding (AMC), by allowing several spreading codes to be assigned to one user, and by numerous other features. Since the wireless multipath channel destroys the orthogonality of the spreading codes, HSDPA receivers are usually based on MMSE equalization [3, 4]. Further improvements of the downlink data rate are expected to be achieved by the recent introduction of MIMO techniques into the UMTS standard. As MIMO scheme for the Frequency Division Duplex (FDD) system, the 3GPP has chosen the dual-stream transmit diversity mode (D-TxAA) [5] because of its backward compatibility to TxAA. In D-TxAA a second data stream is transmitted via spatial multiplexing when the user experiences a large signal to interference ratio. At low signal to interference ratios, D-TxAA is the same as TxAA whereas at the user equipment D-TxAA requires a second receive antenna for detecting both data streams.

In this work, we develop the system model and MMSE equalizer for TxAA. The important difference to the SISO HSDPA equalizer is that in TxAA, the equalizer has to consider the precoding coefficients of all users currently receiving data (this can be easily seen in the system model presented in the next section). Fading simulations utilizing a link measurement model already showed potential performance increases for such an equalizer that considers the precoding coefficients of all users [6]. In contrast to TxAA, in the dual stream mode of D-TxAA only one user can receive data at the same time[1], therefore the receiver does not have to deal with interference from other user's data streams.

The paper is organized as follows. In Section II, we present the TxAA system model. The corresponding MMSE equalizer is derived in Section III. In Section IV we elaborate on the complexity of our equalizer structure and the required signalling effort. Simulation results obtained with a standard compliant physical layer HSDPA simulator are shown in Section V. Finally, Section VI concludes the paper.

II. TxAA System Model

In TxAA, multiple users can be served in the downlink simultaneously. Every user is assigned a specific number of orthogonal spreading sequences of length 16. At a maximum, 15 spreading sequences can be assigned to all users, the 16-th orthogonal spreading sequence is required for transmitting the pilot channel, the synchronization channel, and the control channels.

We define the spread and scrambled chip stream of user k at time instant i as

$$\mathbf{s}_i^{(k)} = \left[s^{(k)}[i], \ldots, s^{(k)}[i - L_\mathrm{h} - L_\mathrm{f} + 2]\right]^\mathrm{T}, \qquad (1)$$

where L_h and L_f are the length of the channel impulse response and the equalizer length, respectively. Thus, the vector $\mathbf{s}_i^{(k)}$ contains the $(L_\mathrm{h}+L_\mathrm{f}-1)$ recent chips. We assume that the energy of the chip stream $\mathbf{s}_i^{(k)}$ of each user k is normalized to one. By multiplying the chip stream $\mathbf{s}_i^{(k)}$ with the factor $\alpha^{(k)}$ (Figure 1), the base station can allocate a certain amount of transmit power to each user that is served in parallel. After power allocation, the chip streams are weighted by the complex precoding coefficients $w_1^{(k)}$ and $w_2^{(k)}$ at the first and

[1]When the dual stream mode of D-TxAA is enabled, 15 spreading codes of length 16 are assigned to a single user. The remaining codes of length >16 in the codetree are required for pilot and control channels.

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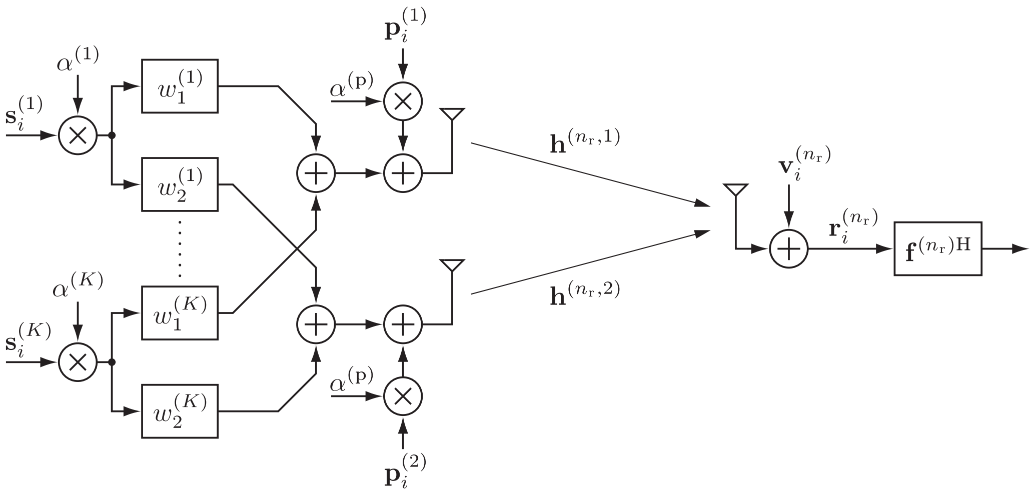

Fig. 1. TxAA transmission system with precoding (shown for the n_r-th receive antenna).

the second transmit antenna, respectively[2]. The weighted chip streams of all users are then added to the sequences $\alpha^{(\mathrm{p})}\mathbf{p}_i^{(1)}$ and $\alpha^{(\mathrm{p})}\mathbf{p}_i^{(2)}$, representing the sum of all channels that are transmitted without precoding, i.e. the common pilot channel, the synchronization channel, and the control channels.

The frequency selective channel between the n_t-th transmit and the n_r-th receive antenna is modeled by the $L_\mathrm{f}\times(L_\mathrm{h}+L_\mathrm{f}-1)$ dimensional band matrix

$$\mathbf{H}^{(n_\mathrm{r},n_\mathrm{t})} = \begin{bmatrix} h_0^{(n_\mathrm{r},n_\mathrm{t})} & \dots & h_{L_\mathrm{h}-1}^{(n_\mathrm{r},n_\mathrm{t})} & 0 \\ \ddots & & \ddots & \\ 0 & h_0^{(n_\mathrm{r},n_\mathrm{t})} & \dots & h_{L_\mathrm{h}-1}^{(n_\mathrm{r},n_\mathrm{t})} \end{bmatrix}, \quad (2)$$

where the $h_i^{(n_\mathrm{r},n_\mathrm{t})}$ represent the channel impulse response of the n_t-th transmit antenna to the n_r-th receive antenna. The full frequency selective MIMO channel is modeled by a block matrix $\mathbf{H}$ consisting of $N_\mathrm{R}\times N_\mathrm{T}$ ($N_\mathrm{T}=2$ for TxAA) band matrices defined in (2).

$$\mathbf{H} = \begin{bmatrix} \mathbf{H}^{(1,1)} & \mathbf{H}^{(1,2)} \\ \vdots & \vdots \\ \mathbf{H}^{(N_\mathrm{R},1)} & \mathbf{H}^{(N_\mathrm{R},2)} \end{bmatrix} \quad (3)$$

By stacking the received signal vectors of all N_R receive antennas

$$\mathbf{r}_i = \left[\left(\mathbf{r}_i^{(1)}\right)^\mathrm{T},\dots,\left(\mathbf{r}_i^{(N_\mathrm{R})}\right)^\mathrm{T}\right]^\mathrm{T} \quad (4)$$

and by stacking the transmitted signal vectors of the K users and the vectors $\mathbf{p}_i^{(1)}$ and $\mathbf{p}_i^{(2)}$

$$\mathbf{s}_i = \left[\left(\mathbf{s}_i^{(1)}\right)^\mathrm{T},\dots,\left(\mathbf{s}_i^{(K)}\right)^\mathrm{T},\left(\mathbf{p}_i^{(1)}\right)^\mathrm{T},\left(\mathbf{p}_i^{(2)}\right)^\mathrm{T}\right]^\mathrm{T} \quad (5)$$

we obtain the compact system description

$$\mathbf{r}_i = \mathbf{H}\left(\mathbf{W}\otimes\mathbf{I}_{L_\mathrm{h}+L_\mathrm{f}-1}\right)\mathbf{s}_i + \mathbf{v}_i = \mathbf{H}_w\mathbf{s}_i + \mathbf{v}_i. \quad (6)$$

Here, $\otimes$ denotes the Kronecker product, and $\mathbf{v}_i$ is an additive noise vector[3]. The $2\times(K+2)$ dimensional matrix $\mathbf{W}$ contains the precoding coefficients w of all users as well as the power normalization factors α and is defined as

$$\mathbf{W} = \begin{bmatrix} \alpha^{(1)}w_1^{(1)} & \dots & \alpha^{(K)}w_1^{(K)} & \alpha^{(p)} & 0 \\ \alpha^{(1)}w_2^{(1)} & \dots & \alpha^{(K)}w_2^{(K)} & 0 & \alpha^{(p)} \end{bmatrix}. \quad (7)$$

The two columns on the right side are specified by a single parameter $\alpha^{(p)}$ and control the pilot power, as indicated in Figure 1.

III. MMSE Equalizer

At the receiver, the transmitted chip sequence of a particular user is reconstructed using an MMSE equalizer. We assume in the following, without loss of generality that the sequence of user one is reconstructed.

The MMSE equalizer coefficients can be calculated by minimizing the quadratic cost function

$$J(\mathbf{f}) = \mathrm{E}\left\{|\mathbf{f}^\mathrm{H}\mathbf{r}_i - s_{i-\tau}^{(1)}|^2\right\}. \quad (8)$$

This cost function minimizes the distance between the equalized chip stream and the transmitted chip stream. In Equation (8)

$$\mathbf{f} = \left[\left(\mathbf{f}^{(1)}\right)^\mathrm{T},\dots,\left(\mathbf{f}^{(N_\mathrm{R})}\right)^\mathrm{T}\right]^\mathrm{T} \quad (9)$$

defines N_R equalization filters. Each filter

$$\mathbf{f}^{(n_\mathrm{r})} = \left[f_0^{(n_\mathrm{r})},\dots,f_{L_\mathrm{f}-1}^{(n_\mathrm{r})}\right]^\mathrm{T} \quad (10)$$

has a length of L_f. Note that because of the definition of $\mathbf{f}$ and $\mathbf{r}_i$, the inner product $\mathbf{f}^\mathrm{H}\mathbf{r}_i$ can be implemented by summing

[2]In the following derivation of Section III, we consider the general case with arbitrary precoding coefficients. In TxAA these coefficients are strongly quantized. Therefore, the standard compliant quantization is applied in the simulations presented in Section V.

[3]The noise vector here models the thermal noise at the receiver as well as the received interference from other basestations (inter cell interference).

the outputs of the N_{R} equalization filters $\left(\mathbf{f}^{(n_{\mathrm{r}})}\right)^{\mathrm{H}}$. This sum yields the MMSE estimate of the transmitted chip sequence.

The minimization of the cost function is performed by deriving (8) with respect to $\mathbf{f}^*$:

$$\frac{\partial J}{\partial \mathbf{f}^*} = \\ = \left(\mathbf{H}_w \mathbf{R}_{ss} \mathbf{H}_w^{\mathrm{H}} + \mathbf{R}_{vv}\right) \mathbf{f} - \sigma_s^2 \mathbf{H}_w \mathbf{e}_{\tau,(K+2)(L_{\mathrm{h}}+L_{\mathrm{f}}-1)} = 0. \quad (11)$$

The matrices $\mathbf{R}_{ss}$ and $\mathbf{R}_{vv}$ are the signal and the noise correlation matrices, respectively. The vector $\mathbf{e}_{\tau,(K+2)(L_{\mathrm{h}}+L_{\mathrm{f}}-1)}$ is a zero vector of length $(K+2)(L_h+L_{\mathrm{f}}-1)$ with a single "one" at position τ. The variable τ specifies the delay of the equalized signal and has to fulfill $\tau \geq L_h$ due to causality. The equalizer coefficients for the data stream of the first user are therefore given by

$$\mathbf{f} = \sigma_s^2 \left(\mathbf{H}_w \mathbf{R}_{ss} \mathbf{H}_w^{\mathrm{H}} + \mathbf{R}_{vv}\right)^{-1} \mathbf{H}_w \mathbf{e}_{\tau,(K+2)(L_{\mathrm{h}}+L_{\mathrm{f}}-1)}. \quad (12)$$

Equation (12) can be further simplified using the following assumptions.

- If the transmitted data signals of the users are uncorrelated and consume as already stated a chip energy of one, we obtain $\sigma_s^2 = 1$ and $\mathbf{R}_{ss} = \mathbf{I}$.
- We assume that the noise vector $\mathbf{v}_i$ is white with variance σ_v^2, thus $\mathbf{R}_{vv} = \sigma_v^2 \mathbf{I}$. The variance σ_v^2 is given by the thermal noise power and the interference power received from other base stations. Note that if the receiver shall be aware of the inter-cell interference in terms of its covariance properties, effort has to be put into the accurate estimation of the covariance matrix $\mathbf{R}_{vv}$.

Using the above assumptions, the equalizer can be represented as

$$\mathbf{f} = \left(\mathbf{H}_w \mathbf{H}_w^{\mathrm{H}} + \sigma_v^2 \mathbf{I}\right)^{-1} \mathbf{H}_w \mathbf{e}_{\tau,(K+2)(L_{\mathrm{h}}+L_{\mathrm{f}}-1)} = \\ = \left(\mathbf{H}\left(\mathbf{W}\mathbf{W}^{\mathrm{H}} \otimes \mathbf{I}_{L_{\mathrm{h}}+L_{\mathrm{f}}-1}\right)\mathbf{H}^{\mathrm{H}} + \sigma_v^2 \mathbf{I}\right)^{-1} \cdot \\ \cdot \mathbf{H} \begin{bmatrix} w_1^{(1)} \mathbf{e}_{\tau,(L_{\mathrm{h}}+L_{\mathrm{f}}-1)} \\ w_2^{(1)} \mathbf{e}_{\tau,(L_{\mathrm{h}}+L_{\mathrm{f}}-1)} \end{bmatrix}. \quad (13)$$

Since such an equalizer considers the interference of all users in the same cell (due to the full knowledge of the matrix $\mathbf{W}$), we will call it intra-cell interference aware equalizer. Alternatively to this equalizer one could build a straightforward MMSE equalizer. This standard equalizer is a special case of (13) and neglects the interference from other users. Therefore, we will call this equalizer the single user (SU) equalizer in the following. It can be calculated from (13) by using the slightly different matrix

$$\mathbf{W}^{(\mathrm{SU})} = \begin{bmatrix} \alpha^{(1)} w_1^{(1)} \\ \alpha^{(1)} w_2^{(1)} \end{bmatrix} \mathbf{e}_{1,K+2}^{\mathrm{T}}. \quad (14)$$

Note that if only a single user in the cell is receiving data, both equalizers are very similar. The only difference is that the intra-cell interference aware equalizer also considers the interference generated by the pilot, synchronization, and control channels.

TABLE I
SIMULATION PARAMETERS FOR CONSTANT $I_{\mathrm{OR}}/I_{\mathrm{OC}}$.

Parameter	**Value**
Number of active users	4
Desired user CQI	13
Interfering HS-PDSCH E_c/I_{or}	$[-6, -8, -10]$ dB
Interfering user CQIs	$[16, 11, 8]$
Precoding coefficients of interf. users	$[1, -j], [1, j], [1, -1]$
CPICH E_c/I_{or}	-10 dB
SCH/PCCPCH E_c/I_{or}	-12 dB
User equipment capability	6
Channel model	ITU Pedestrian A/B
UE speed	3 km/h

IV. COMPLEXITY

The complexity of calculating the intra-cell interference aware equalizer coefficients in Equation (13) is approximately the same as calculating the equalizer coefficients for the single user MMSE equalizer (since they differ only in the product $\mathbf{W}\mathbf{W}^{\mathrm{H}}$ of the rather small matrices $\mathbf{W}$). However, for calculating the interference aware equalizer, all precoding coefficients of all users currently receiving data have to be known. Since TxAA specifies only four different precoding coefficient vectors, there is a high probability that some users share the same precoding vector. By using the four precoding vectors defined for TxAA

$$\left\{ \begin{bmatrix} 1 \\ -\mathrm{j} \end{bmatrix}, \begin{bmatrix} 1 \\ \mathrm{j} \end{bmatrix}, \begin{bmatrix} 1 \\ -1 \end{bmatrix}, \begin{bmatrix} 1 \\ 1 \end{bmatrix} \right\}, \quad (15)$$

the precoding matrix $\mathbf{W}$ can be written as

$$\mathbf{W} = \begin{bmatrix} \tilde{\alpha}^{(1)} & \tilde{\alpha}^{(2)} & \tilde{\alpha}^{(3)} & \tilde{\alpha}^{(4)} & \alpha^{(p)} & 0 \\ -\mathrm{j}\tilde{\alpha}^{(1)} & \mathrm{j}\tilde{\alpha}^{(2)} & -\tilde{\alpha}^{(3)} & \tilde{\alpha}^{(4)} & 0 & \alpha^{(p)} \end{bmatrix}. \quad (16)$$

Here, the values $\left\{\tilde{\alpha}^{(1)}, \tilde{\alpha}^{(2)}, \tilde{\alpha}^{(3)}, \tilde{\alpha}^{(4)}\right\}$ denote the power of the data streams transmitted using the corresponding four precoding coefficient vectors. The factor $\alpha^{(p)}$ corresponds to the power of the pilots. Thus, only the four power values have to be signalled to the user equipments. If, for example, a quantization of four bits is used for the $\tilde{\alpha}$, a total signalling effort of 16 bits per HSDPA subframe is required in the downlink. Alternatively to the signalling in the downlink, the four power coefficients could also be estimated by the user equipment. In the simulations presented in the following, we will assume that the users have perfect knowledge of the power coefficients $\tilde{\alpha}$.

V. SIMULATION RESULTS

The results presented in this section were obtained using a standard compliant HSDPA simulator [7]. The simulation assumptions summarized in Table I correspond to a cell, in which four users are receiving data simultaneously. User 1 is moving through the cell and, hence, the precoding coefficients are adjusted adaptively as defined in the standard. The three interfering users are assumed to be stationary, thus their precoding coefficients and transmit power do not change. In our

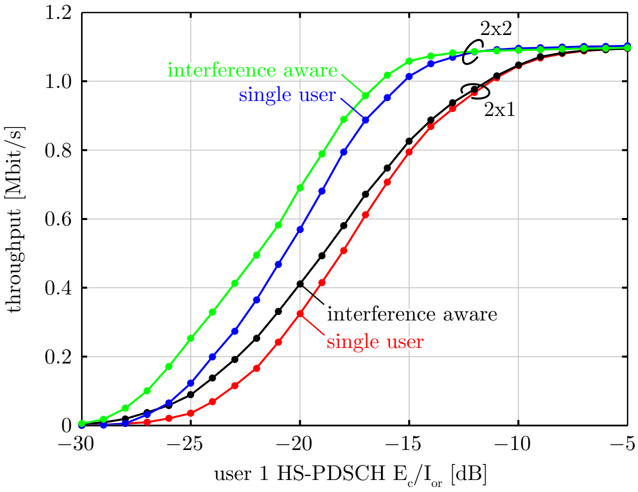

Fig. 2. Throughput of User 1 in a spatially uncorrelated ITU Pedestrian A channel.

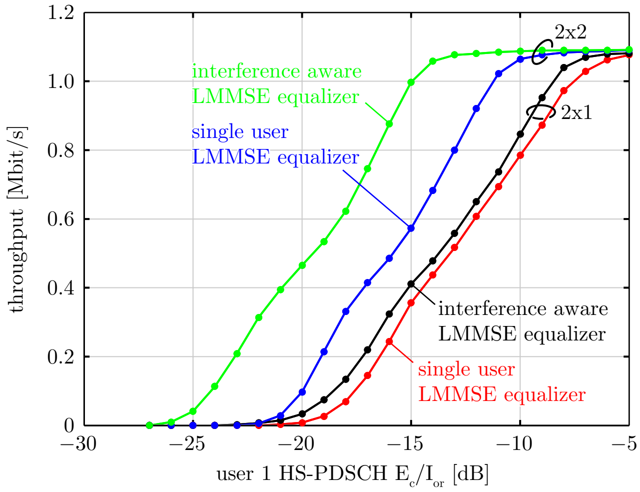

Fig. 3. Throughput of User 1 in a spatially uncorrelated ITU Pedestrian B channel.

simulations we assume that all users are always scheduled the same CQI value, i.e. no link adaptation besides the precoding. This simplification is necessary to avoid effects of the Node B scheduler on the throughput curves.

The achieved data throughput of User 1 in a Pedestrian A and a Pedestrian B [8] environment is plotted in Figure 2 and Figure 3, respectively. In both scenarios, the interference aware equalizer significantly outperforms the single user equalizer. We notice that the gain in the Pedestrian B channel is much larger than the gain in the Pedestrian A channel which has a much shorter maximum delay spread. This is caused by the larger loss of orthogonality in the Pedestrian B environment and the subsequently larger post equalization interference.

For larger numbers of receive antennas the simulation results show larger performance gains. Thus, the interference aware equalizer can indeed utilize the spatial information (in form of the precoding coefficients of the other users) to suppress interfering signals. The largest performance increase of the interference aware equalizer was found for the 2×2 Pedestrian B environment with 4 dB.

VI. Conclusions

We presented a system model for TxAA HSDPA that takes all users of one cell into account. The consideration of all users in the derivation of the MMSE equalizer leads to the intra-cell interference aware equalizer which has only slightly increased complexity compared to the single user MMSE equalizer. The calculation of the interference aware equalizer requires only the power distribution of the four different precoding vectors which can be signalled simultaneously to all users using only very few bits in a control channel. The performance gain of the intra-cell interference aware MMSE equalizer over the single user MMSE equalizer increases with the frequency selectivity and the number of receive antennas and reaches about 4 dB in a 2×2 Pedestrian B environment.

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