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MMSE equalizer and chip level inter-antenna interference canceler for HSDPA MIMO systems

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Abstract— **In MIMO systems the interference from the same cell transmit (TX) antennas causes severe interference. Moreover, if the channel is frequency selective, also inter-chip interference is present. Canceling both inter-antenna and inter-chip interference is a challenging task, especially when the same codes are reused across the TX antennas. In this paper we propose a hybrid receiver combining minimum mean square error (MMSE) equalizer and chip level inter-antenna interference canceler. The performance is studied via simulations carried out in High Speed Downlink Packet Access (HSDPA) system with ITU channel.**

I. INTRODUCTION

Demand for higher data rate wireless communication is increasing. 3rd generation systems such as Wideband CDMA (WCDMA) can provide high data rates, see for example 3GPP specification on High Speed Downlink Packet Access (HSDPA) [1], [2]. With increased data rates higher spectral efficiency is needed. It is well known that the spectral efficiency can be improved by using multiple transmit and receive antennas (MIMO systems), see e.g. [3]. When multiple transmit antennas are used and the channel is frequency selective, the receiver design is challenging due to multiple sources of interferences. In HSDPA MIMO systems the receiver needs to mitigate inter-antenna interference, multi-user interference, inter-symbol interference and interference from neighbouring base stations. Additionally, gains offered by the multipath diversity and multiple receive antennas should be taken into account in the receiver design. The inter-antenna interference is strong in HSDPA systems due to the code reuse across the transmit antennas. In this paper we propose a joint MMSE equalizer and inter-antenna interference canceller for HSDPA MIMO systems. A MIMO system with layered BLAST technique, [4], where no information of the channel is available at the transmitter, is considered.

In MIMO systems interference can be canceled in a successive manner, see [5], [6]. If the same codes are reused across the transmit antennas, interference cancellation is typically performed after despreading, at symbol level. When the channel is flat fading the orthogonality of the codes used in WCDMA system is preserved and no multi-user interference is present. However, in multipath fading the inter-chip interference deteriorates the performance of a symbol level inter-antenna interference canceler, [7]. MMSE equalizer in WCDMA MIMO systems has been studied e.g. in [8], [9], [10]. The equalizer treats the inter-antenna interference as noise. Therefore it's ability to suppress inter-antenna interference is limited. In [9], [10] the performance of an MMSE equalizer is further improved by a adding a multiuser detector, such as parallel interference canceler (PIC), after equalization. In this paper we propose an alternative approach for combining MMSE equalization and interference cancellation.

In CDMA systems, the inter-antenna interference can be alternatively canceled at chip level. In order to benefit from the chip level cancellation, the receiver must know multiple codes, or single known code must have dominant power compared to other codes. Typically in HSDPA systems the receiver knows multiple codes. Therefore the MMSE equalization and inter-antenna interference cancellation can be done in a successive manner for each layer. This combination of an MMSE equalizer with ordered serial inter-antenna interference cancellation (OSIC) is denoted as MMSE-OSIC. A multistage extension of this receiver is called MMSE-MOSIC.

This paper is organized as follows. First in section II the HSDPA system model and conventional MMSE equalizer for MIMO systems are presented. In section III the MMSE-OSIC receiver is proposed. The multistage extension is presented in section IV. In section V simulation results are shown and some discussion of further work is given in section VI. Finally section VII concludes this paper.

II. SYSTEM MODEL AND MMSE EQUALIZER

The system model considered in this paper is based on the 3rd generation wideband CDMA model for high data rates, see [2]. The received signal is sampled at chip rate and stacked to a vector $\mathbf{y}$. At the receiver the signal transmitted from one base station with Q TX antennas may be written as:

$$\mathbf{y}(n) = \sum_{k=1}^{K}\sum_{q=1}^{Q} \mathcal{C}^{(k)}(n) A_q^{(k)} \mathbf{h}_q s_q^{(k)}(n) + \mathrm{ISI} + \mathbf{v}, \quad (1)$$

where K is the total number of codes, $\mathcal{C}^{(k)}(n)$ is the symbol dependent code convolution matrix, A is the symbol amplitude and $\mathbf{h}_q$ is the channel impulse response from qth antenna. With M receive antennas, the combined multipath multiple receive antenna channel impulse response is defined as a $LM \times 1$ vector $\mathbf{h}_q = [\mathbf{h}_{q1}^T \quad \dots \quad \mathbf{h}_{qm}^T]^T$, where the complex channel coefficients at the mth receive antenna

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are $\mathbf{h}_{qm}^T = [h_{qm}(1) \quad \ldots \quad h_{qm}(L)]^T$ and L denotes the channel length. We are assuming that the channel is constant during the observation period. ISI denotes the inter symbol interference from both the previous and following symbols. $\mathbf{v}(n)$ is the noise term which includes both the interference from other base stations and thermal noise. The transmitted symbols $s^{(k)}(n)$ are assumed to be independent and identically distributed such that $E\{s^{(k)}(n)s^{(p)}(a)^*\} = \delta(k-p)\delta(n-a)$.

The space-time MMSE equalizer $\mathbf{f}_q$ with multiple transmit antennas can be found as solution to the Wiener-Hopf equation considering the signals from interfering TX antenna as noise:

$$\mathbf{R}\mathbf{f}_q = \mathbf{r}_{yd_q}, \tag{2}$$

where $\mathbf{r}_{yd_q}$ is the cross-correlation between the received signal and transmitted signal from the qth TX antenna. The correlation matrix can be written in the multiple TX antenna case as

$$\mathbf{R} = E[\mathbf{y}\mathbf{y}^H] = \sum_q \sigma_{d_q}^2 \mathbf{H}_q \mathbf{H}_q^H + \mathbf{R}_v \tag{3}$$

where $\mathbf{R}_v$ is the noise correlation matrix, $\sigma_{d_q}^2$ is the transmitted power from the qth TX antenna, and $\mathbf{H}_q$ is the channel convolution matrix. The MMSE equalizer for the qth antenna is:

$$\mathbf{f}_q = \mathbf{R}^{-1}\sigma_{d_q}^2 \mathbf{h}_q, \tag{4}$$

In this paper we have used a block based approach to estimate the correlation matrix $\mathbf{R}$ and channel $\mathbf{h}$.

Let N denote the number of symbols in each block. The vector $\mathbf{y}$ without symbol index (n) is used to denoted received signal over one block. With one receive antenna we may estimate the correlation matrix as:

$$\hat{\mathbf{R}}_{m_1,m_1} = \mathcal{T}([a_{11}(0), a_{11}(1), \ldots, a_{11}(L-1), 0, \ldots]) \tag{5}$$

where $\mathcal{T}$ is an operator for construction of Toeplitz matrices [1] and and $a_{11}(l)$ is the auto-correlation of the signal $\mathbf{y}$ received at antenna $m = 1$ with lag l. For multiple receive antennas the correlation matrix has a block Toeplitz structure:

$$\hat{\mathbf{R}} = \begin{bmatrix} \hat{\mathbf{R}}_{m_1,m_1} & \hat{\mathbf{R}}_{m_1,m_2} & \cdots \\ \hat{\mathbf{R}}_{m_2,m_1} & \hat{\mathbf{R}}_{m_2,m_2} & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix}, \tag{6}$$

where, the correlation matrices, $\hat{\mathbf{R}}_{m_i,m_j}$, for each antenna pair m_i and m_j are estimated similarly as $\hat{\mathbf{R}}_{m_1,m_1}$ in equation (5). A conventional pilot based channel estimation averaged over the block is used to obtain channel estimates for each transmitting antenna.

III. MMSE - OSIC RECEIVER

The basic idea of MMSE-OSIC is straightforward interference cancellation. It is applied to the layers in descending order in channel strength, i.e. for $|\mathbf{h}_1|^2 > |\mathbf{h}_2|^2 > \cdots > |\mathbf{h}_q|^2$. After the channel and correlation matrix are estimated, the equalizer is calculated using (4) and MMSE equalization and symbol decisions are performed for the strongest layer. Assuming that P codes are known at the receiver, a part of the chip-level signal transmitted from the first antenna can be estimated as

$$\hat{\mathbf{y}}_1(n) \approx \sum_{p=1}^{P} \mathcal{C}^{(p)}(n) A_1^{(p)} \hat{\mathbf{h}}_1 \hat{s}_1^{(p)}(n).$$

where $\hat{s}$ are the estimated symbols. Let $\mathbf{y}_2 = \mathbf{y} - \hat{\mathbf{y}}_1$ denote the inter-antenna interference free signal for the second layer. Channel, correlation matrix and equalizer for the second antenna can be estimated from this $\mathbf{y}_2$.

The ability of the MMSE-OSIC to cancel inter antenna interference depends on the power allocated to known codes versus the total transmitted power. To illuminate this, let us write the correlation matrix for the second antenna after the interference from the first antenna has been canceled:

$$\mathbf{R}_2 = (\sigma_{d1}^2 - \sigma_{\tilde{d}1}^2)\mathbf{H}_1\mathbf{H}_1^H + \sum_{q=2}^{Q} \sigma_{dq}^2 \mathbf{H}_q \mathbf{H}_q^H + \mathbf{R}_v, \tag{7}$$

where σ_{d1}^2 and $\sigma_{\tilde{d}1}^2$ are total transmitted power from TX 1 and the power used to transmit known codes. In equation (7) it is assumed that all the symbol decisions are correct. Since in practise, the symbols need to be estimated MMSE-OSIC will be beneficial only in systems where $(\sigma_{d1}^2 - \sigma_{\tilde{d}1}^2) << \sigma_{d1}^2$. For example in HSDPA systems, where multiple codes are known, the interference from interfering antenna can be estimated to the level that the MMSE-OSIC will provide performance improvements over MMSE equalizer.

The MMSE-OSIC algorithm for Q transmit antennas is written in Table I. The equalizer delay τ is set to $\tau = \lfloor (F + L - 1)/2 \rfloor$, see [11], where F denotes the equalizer length. The symbol decision is denoted with Ψ and the channel estimation with Φ. We have used here hard decisions in symbol estimation and conventional pilot based averaging as channel estimator.

The signal covariance matrix can be formed in two alternative ways: using the sample covariance matrix, i.e. equations (5) and (6) or the estimated channels and signal power estimates, see equation (7). In this paper we have used equations (5) and (6).

Similarly to other interference cancellation schemes, the performance of MMSE-OSIC is also sensitive to errors in the interference estimate used in the cancellation. The quality of the initial stage estimates, i.e. quality of symbol and channel estimates after MMSE-equalization, have significant impact on the receiver performance. The influence of symbol estimation error will be illustrated via simulation, by comparing to results with assumption of perfect symbol knowledge. It is well known that the performance of MMSE-equalizer can be improved with longer filters and with more accurate channel estimates. These will be also emphasized with simulations.

In the next section we'll consider multistage interference cancellation and improvement in channel estimation obtained

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[1] As defined in Matlab :toeplitz($[a_{11}(0), a_{11}(1), \ldots, a_{11}(L-1), 0, \ldots]$)

TABLE I

THE MMSE-OSIC FOR Q TX ANTENNAS

```
$\hat{\mathbf{R}}_1 = \hat{\mathbf{R}}, \mathbf{y}_1 = \mathbf{y}, \hat{\mathbf{h}}_1 = \hat{\mathbf{H}}_1(:,\tau)$
for $q = 1, \dots, Q$
    $\mathbf{f}_q = \hat{\mathbf{R}}_q^{-1} \sigma_{d_q} \hat{\mathbf{h}}_q,$
    for $n = 1, \dots, N$
        $\hat{\mathbf{z}}_q(n) = \mathbf{f}_q^H \mathbf{y}(n)$
        $\hat{s}_q^{(p)}(n) = \Psi(\mathbf{c}^{(p)H} \hat{\mathbf{z}}_q(n)), \ \forall p \in 1, \dots, P$
        $\mathbf{y}_{q+1}(n) = \mathbf{y}_q(n) - \sum_p \mathcal{C}^{(p)} A_q^{(p)} \hat{\mathbf{h}}_q \hat{s}_q^{(p)}(n)$
    end
    $\hat{\mathbf{R}}_{q+1}$ using equations (5) and (6) or (7)
    $\hat{\mathbf{h}}_{q+1} = \Phi(\mathbf{y}_{q+1})$
end
```

by this multistage approach. Other potential improvements will be discussed later in section VI.

IV. MMSE - MOSIC RECEIVER

It's well known that increasing the number of stages improves the performance in an interference canceller. This holds also to MMSE-OSIC receiver and especially when the channels have equal magnitudes, i.e. $|\mathbf{h}_1|^2 \approx |\mathbf{h}_2|^2$. The improvement of MMSE-OSIC over MMSE equalizer depends on the detection order of layers and it is not always straight forward to decide which layers should be detected first. Therefore we propose a MMSE-OSIC that operates in multistage (iterative) manner and call this receiver as MMSE-MOSIC. This means that after estimating the signals from all the TX antennas with the algorithm given in Table I, the signal form first antenna can be re-estimated after canceling the interference from all other antennas. This can be repeated for all antennas. A general description of the MMSE-MOSIC algorithm, using multiple cancellation stages for each Q TX antennas is given in Table II.

Similarly to other multistage IC receivers, the improvement of additional stages saturates gradually as the number of stages increases. In Figure 1, we have plotted the variation of raw bit error rates (BER) over 250 different channel realizations for a 2×2 MIMO system. It shows clearly that the second stage interference cancellation for each antenna will provide in average only a minor gain compared to one stage canceler. Yet, the gain obtained by performing one IC stage at each antenna is clear. Since the complexity of the receiver increases rapidly with multiple stages, we would like to use as few stages as possible.

In the simulations we use two stage MMSE-MOSIC algorithm for a 2×2 MIMO. This algorithm is implemented as given in Table II with $W = 1$ and $Q = 1$, i.e. omitting the two first **for**-loops. The results are further averaged over the two different orders of TX antennas used in the reception.

The performance improvement of the MMSE-MOSIC method over MMSE equalizer and MMSE-OSIC is not only due to inter-antenna interference cancellation, but also due to improved channel estimates after this cancellation. Since also the pilot signal is spread with same code (all ones) in

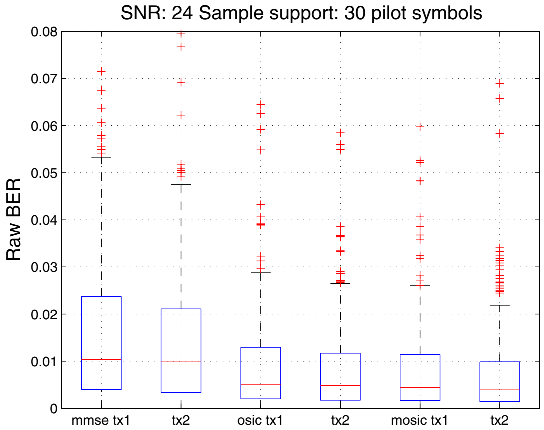

Fig. 1. *Variation of raw BER of MMSE equalizer and proposed MMSE-MOSIC with one and two stages for each antenna.* $P = 8$ *known codes and* $P_I = 24$ *interfering codes. ITU Vehicular A channel and one interfering BS with* 5*dB weaker power. In the boxplot, box defines the quantile range (from 25% percentile to 75% percentile). The line inside the box is the median. The 'whiskers' are lines extending from each end of the box to show the extent of the rest of the estimates. The length of a whisker is defined as 1.5 times the length of the quintile range. The possible outliers, outside the whiskers area, are marked by crosses.*

TABLE II

THE MMSE-MOSIC FOR Q TX ANTENNAS

```
Apply MMSE-OSIC given in Table I
for $w = 1, \dots, W$
    for $q = 1, \dots, Q$
        for $n = 1, \dots, N$
            $\mathbf{y}_q(n) = \mathbf{y}(n) - \sum_{j \neq q} \sum_p \mathcal{C}^{(p)} A_j^{(p)} \hat{\mathbf{h}}_j \hat{s}_j^{(p)}(n)$
        end
        $\hat{\mathbf{R}}_q$ using equations (5) and (6)
        $\hat{\mathbf{h}}_q = \Phi(\mathbf{y}_q)$
        $\mathbf{f}_q = \hat{\mathbf{R}}_q^{-1} \sigma_{d_q} \hat{\mathbf{h}}_q$
        for $n = 1, \dots, N$
            $\hat{\mathbf{z}}_q(n) = \mathbf{f}_q^H \mathbf{y}(n)$
            $\hat{s}_q^{(p)}(n) = \Psi(\mathbf{c}^{(p)H} \hat{\mathbf{z}}_q(n)), \ \forall p \in 1, \dots, P$
        end
    end
end
```

all transmit antennas, the chip level inter-antenna interference cancellation clearly improves the conventional pilot based estimation. Consequently MMSE-MOSIC will yield superior performance over pure MMSE equalization and single stage MMSE-OSIC receiver. MMSE-MOSIC will also improve the performance in case more advanced channel estimation methods are used. This is shown via simulations with perfect channel knowledge.

V. SIMULATION EXAMPLES

In this section, simulations are carried out to study the performance of the proposed MMSE-MOSIC receiver in 2×2 MIMO systems. One and two stage receivers are denoted as MMSE-OSIC and MMSE-MOSIC respectively. Raw bit error rate (BER) is used as a performance measure. For comparison, results for conventional MMSE equalizer are shown also.

The channel coefficients are generated using the METRA channel model software based on Vehicular A and Pedestrian A specifications, see [12], [13]. For the vehicular channel the delay spread is about 11 chips and the average power of the channel taps are: $[0\ \ -1\ \ -9\ \ -10\ \ -15\ \ -20]$ dB. For pedestrian case the averaged powers are $[0\ \ -9\ \ -19\ \ -23]$ dB and delay spread is about 2 chips. We have combined the channel with transmit and receive filters, i.e. two root raised cosine filters with roll off factor 0.22. After filtering the sampling is performed once per chip and 11 and 5 chip long channels are used. The equalizer length for each antenna was set to either $F = 2L$ or $F = 3L$. Two antennas are employed both at the receiver and at the transmitter. Antenna spacings for the vehicular channels were $d = \lambda/2$ and $d = 2\lambda$ and for the pedestrian case $d = \lambda$ and $d = 10\lambda$, where λ is the wavelength. All the shown results are averaged over 200 random channel realizations. An asynchronous interfering base station with single transmit antenna is simulated with 120 speech users and one pilot signal. Same channel profile, but independent realization is used.

The spreading code is a combination of orthogonal variable spreading factor (OVSF) codes and long Gold codes (complex). The spreading factor of 16 is used for the HSDPA codes. The pilot signal is simulated with 256 and 10% of the total transmitted power, [1], [2]. Interfering users are modelled as speech users with spreading factor 128. Number of HSDPA signals is denoted by P and number of speech users by P_I. QPSK modulation is used.

In Figure 2, BER results are shown for MMSE equalizer, one stage MMSE-OSIC and two stage MMSE-MOSIC with both known and estimated channels. Additionally, the influence of symbol estimation errors is emphasized with BER-curve assuming known symbols. If all the transmitted symbols from interfering TX were known, the inter-antenna interference could be canceled entirely. This performance bound for MMSE-MOSIC is also a single TX antenna (SIMO) curve. It is plotted in figure a) with known channel. The improvement obtained with MMSE-MOSIC over MMSE equalization is clearly seen with both known and estimated channels, see figures 2 a) and b) respectively. The estimation of the symbols for MMSE-MOSIC curves is done with simple hard decision. The difference in performance between estimated and known symbols indicates that advanced symbol detection could improve the performance further.

The increase in filter length will provide improved performance of both MMSE equalization and MMSE-MOSIC receiver. Yet, by increasing the length beyond $F = 2L$ does not necessary provide significant gains. This is emphasized in Figure 3 where two filter lengths, $F = 2L$ and $F = 3L$, are shown. Both increasing the filter length and usage of MMSE-MOSIC increase the complexity of the receiver. When the power allocated to known HSDPA codes is large (in this figure 55% of the total transmitted power), the MMSE-MOSIC receiver with $F = 2L$ will have superior performance over the MMSE equalizer with longer length.

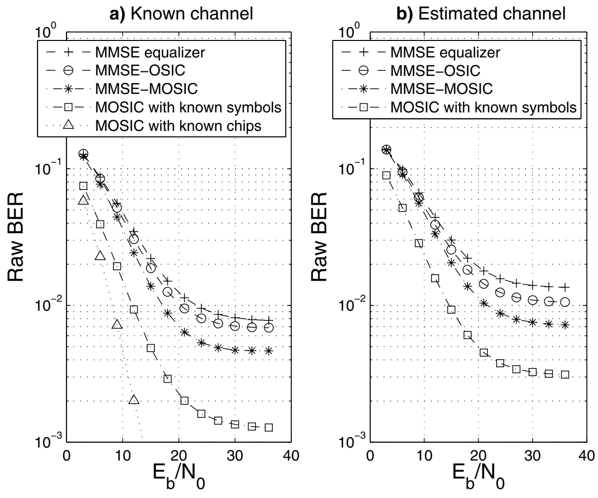

Fig. 2. *Performance of MMSE equalizer and proposed MMSE-OSIC and two stage MMSE-MOSIC receivers.* 2×2 *MIMO model with ITU Veh A channel model* ($L = 11$) *averaged over 200 random realizations.* $|\mathbf{h}_1|^2 = |\mathbf{h}_2|^2$ *and* $F = 2L$. *In figure a) perfect channel knowledge assumed and in b) the signal statistics are estimated by averaging over 3 slots (1 TTI). An interfering BS is causing interference with* 5*dB lower power.* $P = 8$ *HSDPA codes with 65 % of the total transmitted powers and the pilot signal were assumed known.* $P_I = 24$ *interfering speech users are present.*

Finally in Figure 4 we have studied Pedestrian A channel case where only one strong path is present on average. Consequently inter-path interference is not as dominant as inter-antenna interference. In this case the improvement obtained with the MMSE-MOSIC receiver is not as significant as seen in earlier figures. However, in the majority of the cases improvements are seen. In Figure 4 are shown BER-curves where 25% of the worst cases are neglected. For comparison, also MMSE equalizer results are shown for all channel realizations. This reference curve is similar to both known and estimated channels indicating the channel estimate is quite accurate. Also MMSE-MOSIC with estimated symbols has nearly identical performance with MMSE when averaged over all the channel realizations.

VI. DISCUSSION

A major drawback of MMSE-MOSIC is increased computational complexity. For example, with the 2×2 MIMO system using the two stage MMSE-MOSIC, the equalization needs to be done three times. Also the cancelation of the inter-antenna interference increases complexity.

The simulation results show that by improving symbol estimation further gain can be achieved. In the shown examples, the gain assuming perfect knowledge of the symbols was over 5 dB at BER 10^{-2} compared to hard symbol decision. The gain is quite similar with both known and estimated channels. Therefore, further studies should be carried out in coded systems.

Alternatively, the influence of erroneous interference estimate could be reduced via partial (soft) interference cancellation:

$$\mathbf{y}_{q+1} = \mathbf{y}_q - \rho\hat{\mathbf{y}}_q,$$

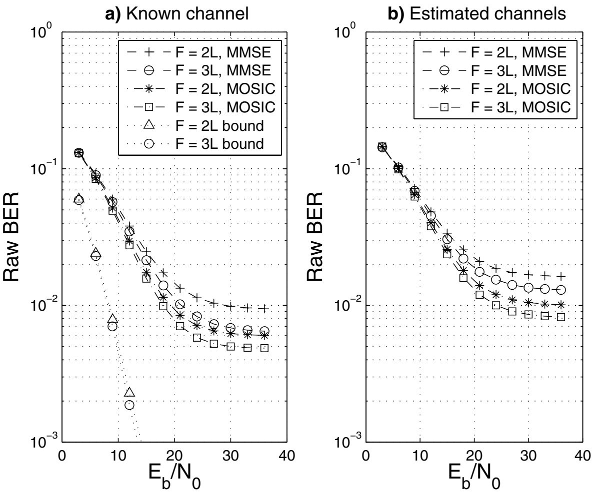

Fig. 3. *Performance of MMSE equalizer and proposed two stage MMSE-MOSIC receivers with two different filter lengths, $F = 2L$ and $F = 3L$. 2×2 MIMO model with ITU Veh A channel model ($L = 11$) averaged over 200 random realizations. $|\mathbf{h}_1|^2 = |\mathbf{h}_2|^2$. In figure a) perfect channel knowledge assumed and in b) the signal statistics are estimated by averaging over 3 slots (1 TTI). An interfering BS is causing interference with* 6*dB lower power.* $P = 8$ *HSDPA codes with 55 % of the total transmitted powers and the pilot signal were assumed known.* $P_I = 40$ *interfering speech users are present.*

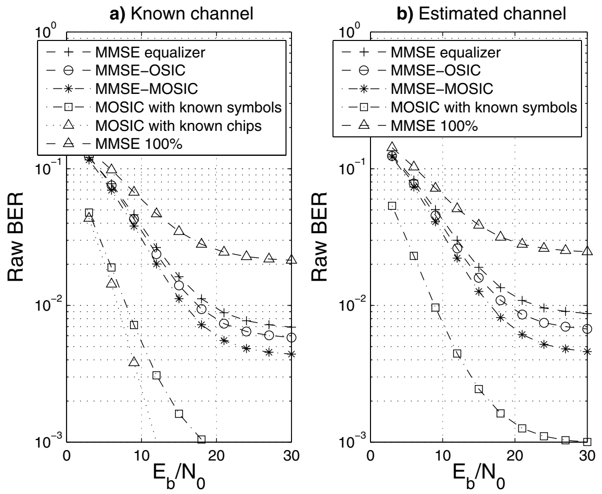

Fig. 4. *Performance of MMSE equalizer and two stage MMSE-MOSIC receivers with $F = 2L$. 2×2 MIMO model with ITU Ped A channel profile ($L = 5$) averaged over* 75% *of the 200 random realizations. $|\mathbf{h}_1|^2 = |\mathbf{h}_2|^2$. In figure a) perfect channel knowledge assumed and in b) the signal statistics are estimated by averaging over 3 slots (1 TTI). An other cell is causing interference with* 3*dB lower power.* $P = 8$ *HSDPA codes with 65 % of the total transmitted powers and the pilot signal were assumed known.* $P_I = 24$ *interfering speech users are present.*

where $\rho < 1$ is a soft cancellation parameter. However, since defining a good value for ρ is not trivial this improvement is left for further study.

VII. CONCLUSIONS

In this paper we have proposed a hybrid receiver which combines MMSE equalizer with a chip level multistage ordered inter-antenna interference canceler, MMSE-MOSIC. The method is designed for HSDPA systems where the receiver knows multiple transmitted codes and the proportion of the transmitted power allocated to know codes can be large. Consequently, the performance of a conventional MMSE equalizer can be improved by cancelling estimated inter-antenna interference prior to equalization. Performance improvements are seen especially when the interference cancellation stage is performed at least once for each layer. Simulation examples performed in MIMO HSDPA system show significant gains over MMSE equalizer in frequency selective channels. They also show that MMSE-MOSIC is more sensitive to symbol estimation errors than channel estimation errors. In conclusion we can say that the proposed receiver structure improves the performance in HSDPA MIMO systems, at the cost of increased computational the complexity.

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