ANALYSIS AND PERFORMANCE OF AN EFFICIENT ITERATIVE DETECTION STRATEGY FOR IDMA SYSTEMS

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Abstract IDMA is a multiple access scheme closely related to CDMA and of great interest for future mobile networks. In contrast to orthogonal schemes like TDMA or FDMA collisions are not avoided but the interference is treated by iterative detection exploiting channel coding. By tolerating a certain amount of interference a higher spectral efficiency is achieved. The number of supportable users can be further increased by an optimized power profile. In order to decode all users with reasonable complexity, efficient detection strategies should be considered. This paper investigates a complexity reduction for parallel interference cancellation (PIC) by means of decoding only promising users in the first iterations, which means a user- and iteration-wise switching strategy. The optimal strategy is found by variance transfer charts (VTC) and confirmed by bit error rate simulations. Furthermore, a scheduling strategy for successive interference cancellation (SIC) is considered and shown to be most efficient in terms of channel decoder evaluations.

1. Introduction

Iterative multiuser detection is widely used in CDMA systems and has been improved in the last years. IDMA can be regarded as a special case of CDMA where the spreading is done by an arbitrary low rate channel code equal for all users and the separation is done by user-specific interleavers as in Ping et al., 2006. Depending on the channel code additional coding gain can be introduced. IDMA has many advantages known from CDMA but some interesting differences. Interleaving is done on chip-level and therefore, the interleaver length is the spreading factor times higher than for CDMA which is advantageous for iterative detection. The channel decoder and the multi-layer detector

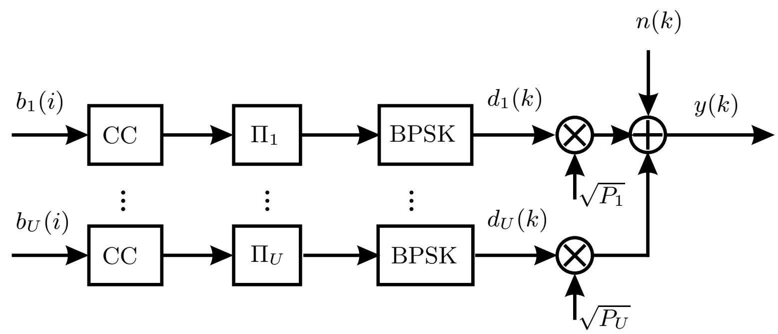

Figure 1. Transmitter of IDMA uplink

can be regarded as a serially concatenated system, so turbo-like detection is applied. Variance analysis of the parallel interference cancellation (PIC) in CDMA systems has been done e.g. in Schlegel and Shi, 2004 and can be easily applied to IDMA.

Although iterative detection has a complexity only linearly increasing e.g. with the number of users and iterations, it is desirable to further decrease detection complexity. In Kusume and Bauch, 2006, some simple complexity reduction techniques are investigated to be used in ad hoc networks. In this case not all users have to decode all layers of the other users. The channel code consists of a convolutional code followed by a repetition code. It is suggested to split up this concatenated channel code and only decode the repetition code for some users or some iterations to save complexity.

In this paper an uplink scenario is considered where the base station needs to decode all layers completely. For this case a user- and iteration-wise strategy is proposed and the choice of parameters is motivated by VTC analysis. This scheme does not effect the overall performance as long as the total number of iterations is sufficiently large. It will be shown that despite an increased number of iterations the overall complexity in terms of channel decoder evaluations will be significantly decreased. Furthermore, successive interference cancellation (SIC) will be considered as it is known to require less iterations than PIC. For this case a scheduling strategy for further complexity reduction will be derived. The paper is organized as follows: Section 2 introduces the system model of the considered IDMA uplink. In Section 3 the basics of analysis with variance transfer charts (VTC) are given and are used for complexity reduction of PIC and SIC in Section 4. Finally, Section 5 concludes this paper.

2. System Model

In this section the structure of a multiuser IDMA system is introduced. For simplicity a synchronous IDMA system over an AWGN channel with real val-

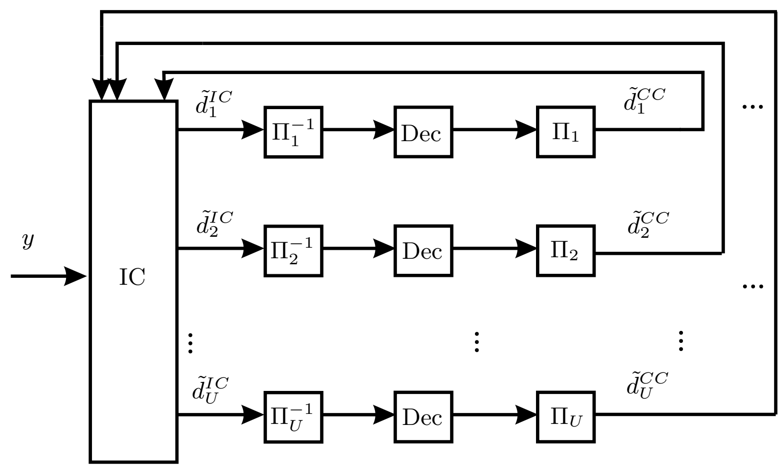

Figure 2. Iterative receiver for IDMA uplink

ued noise of variance σ_n^2 is assumed where each user transmits only one layer. The channel code consists of a serial concatenation of a $[5,7]_o$ outer convolutional code and an inner repetition code of rate $1/8$ and has the overall rate $R_c = 1/16$. The number of active users is denoted by U. The information bits $b_u(i)$ of user u are encoded, interleaved by a user-specific random interleaver Π_u and BPSK-modulated. The BPSK symbol of user u at a particular time instant k is denoted by $d_u(k)$. So the received signal can be written as

$$y(k) = \sum_{u=1}^{U} \sqrt{P_u} \cdot d_u(k) + n(k) \tag{1}$$

with P_u denoting the received power of user u and the total power $P_{tot} = \sum_u P_u$. Without loss of generality the users are assumed to be sorted according to decreasing powers P_u. Each user is interfered by noise and the signals of all other users. This multi-user interference (MUI) degrades performance significantly even for low system loads $\beta = U \cdot R_c$. At the receiver iterative soft interference cancellation is applied as in Kai et al., 2005, estimating the multi-user interference and canceling it before detection. The soft bit estimates after interference cancellation are denoted as $\tilde{d}_u^{IC}$. After soft output decoding the extrinsic soft bit estimates $\tilde{d}_u^{CC}$ are used as a-priori-information for the multi-user detector (MUD) in the next iteration. In this way, the reliability of the estimates can be improved in each iteration.

3. Analysis of MUD

Iterative detection schemes for serially concatenated systems can be analyzed by variance transfer charts (VTC) as done in Schlegel and Shi, 2004 for CDMA. The relation between input and output error variance of each component is called transfer function. For the channel decoder Monte Carlo simulations may be necessary, but the transfer function of the MUD can be easily calculated. The effective variance σ^2_{eff} of the u-th user after interference cancellation is given by

$$\sigma^2_{\text{eff},u} = \mathrm{E}\{|\sqrt{P_u} d_u - \tilde{d}_u^{IC}|^2\} = \sigma_n^2 + \sum_{v \neq u} P_v \; \sigma^2_{d,v} \tag{2}$$

and the error variance at the output of the channel decoder is defined as

$$\sigma^2_{d,u} = \mathrm{E}\{|d_u - \tilde{d}_u^{CC}|^2\} = f\left(\frac{\sigma^2_{\text{eff},u}}{P_u}\right) \tag{3}$$

which is a function of the SINR at the channel decoders input denoted as $f(\cdot)$. If all users have equal power $P_u = P$ the variances are the same for all users and (2) becomes

$$\sigma^2_{\text{eff}} = \sigma_n^2 + (U-1) \; P \; \sigma_d^2 \quad . \tag{4}$$

In this paper we won‘t restrict to equal powers for the users and therefore use average variances to describe a system with unequal powers in a similar way. The average error variance at the output of the interference canceler equals

$$\begin{aligned} \bar{\sigma}^2_{\text{eff}} &= \frac{1}{U} \sum_u \sigma^2_{\text{eff},u} = \sigma_n^2 + \frac{U-1}{U} \sum_u P_u \; \sigma^2_{d,u} \\ &= \sigma_n^2 + (U-1) \; \bar{P} \; \bar{\sigma}_d^2 \end{aligned} \tag{5}$$

with $\bar{P} = P_{\text{tot}}/U$ and

$$\bar{\sigma}_d^2 = \frac{1}{P_{\text{tot}}} \sum_u P_u \; \sigma^2_{d,u} \quad . \tag{6}$$

This is analog to the definition for equal powers in (4). The error variance σ_d^2 at the decoder output depends only on the SINR at the input as stated in (3)

$$\begin{aligned} \sigma^2_{d,u} &= f\left(\frac{1}{\mathrm{SINR}_u}\right) = f\left(\frac{\sigma^2_{\text{eff},u}}{P_u}\right) \\ &= f\left(\frac{\bar{\sigma}^2_{\text{eff}} + \bar{P} \; \bar{\sigma}_d^2 - P_u \; \sigma^2_{d,u}}{P_u}\right) \approx f\left(\frac{\bar{\sigma}^2_{\text{eff}}}{P_u}\right) \quad . \end{aligned} \tag{7}$$

Assuming that $\bar{\sigma}^2_{\text{eff}} \gg \bar{P}\ \bar{\sigma}^2_d - P_u\ \sigma^2_{d,u}$ for a large number of users, the approximation in (7) is tolerable. Taking (6) and (7), $\bar{\sigma}^2_d$ can be approximately expressed in terms of $\bar{\sigma}^2_{\text{eff}}$ by

$$\bar{\sigma}^2_d = \frac{1}{P_{\text{tot}}} \sum_u P_u\ \sigma^2_{d,u} \approx \frac{1}{P_{\text{tot}}} \sum_u P_u\ f\left(\frac{\bar{\sigma}^2_{\text{eff}}}{P_u}\right) \quad . \tag{8}$$

The VTC of a PIC reduces to a two-dimensional problem analog to the equal power case as shown in Figure 3.

4. Complexity Reduction

Complexity Reduction for PIC

Parallel interference cancellation in general means decoding all users at the same time in a parallel fashion.

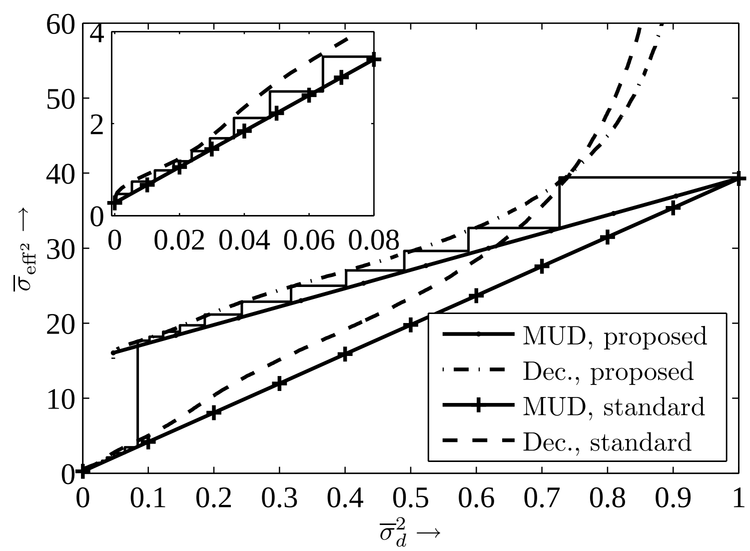

Figure 3. Transfer function and simulated trajectory for PIC of an IDMA system with 40 users

When considering unequal receive powers of the users, some may benefit more from decoding in a particular iteration and some user's benefit may be only marginal. In this case it is questionable, if it is worth computational effort to decode these users although their contribution to the overall convergence in a particular iteration is marginal. In Kusume and Bauch, 2006, a simple complexity reduction technique is considered suitable for at-hoc networks. It is suggested to split up the concatenated channel code and only decode the

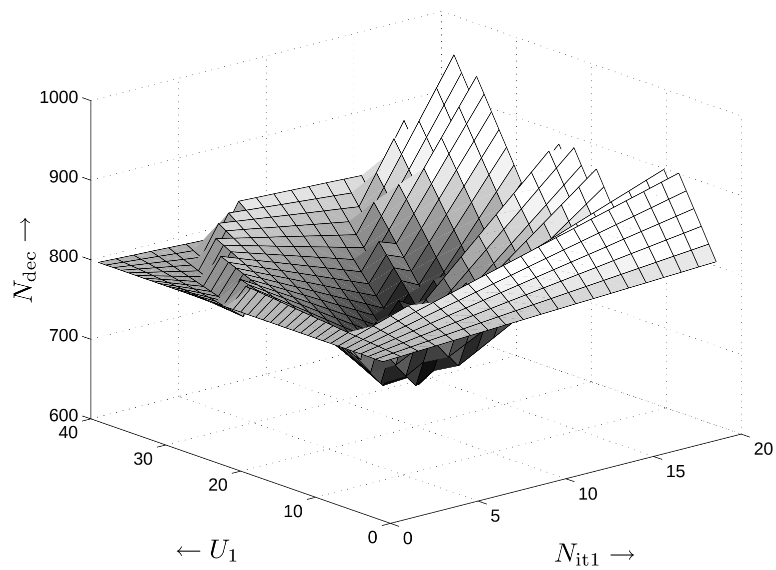

Figure 4. Number of channel decoder evaluations

repetition code for some users or some iterations to save complexity. Iteration-wise switching is analyzed by EXIT-Charts, but user-wise switching is only shown by simulations. A combination of both is not considered and the choice of parameters like number of layers not decoded completely is not motivated. In this paper a user- and iteration-wise switching strategy is proposed and the choice of parameters is motivated by VTC analysis. In the first N_{it1} iterations only the U_1 strongest users are considered. After a certain number of iterations the detector switches to the standard detection considering all layers.

In Figure 3 the resulting transfer functions for a system with 40 users, resulting in a load of $\beta = 2.5$ are depicted. In addition to the transfer functions of standard detection the resulting functions for the case of considering only U_1 users is shown.

Although the weaker users are not decoded during the first iterations they may be considered for interference cancellation. For theoretical considerations it makes no difference if the estimated interference is subtracted from the weaker users already in the first iterations or not until they are also decoded. If the weaker users are considered as noise during the first N_{it1} iterations, the calculations and transfer functions are much easier. Furthermore, a simulated trajectory is plotted to show the tightness of the prediction used.

The simulated trajectory matches the new detection in the first 11 iterations. Then the detection is switched and the trajectory follows the transfer function of the standard detection. Due to the tightness of the VTC analysis the number

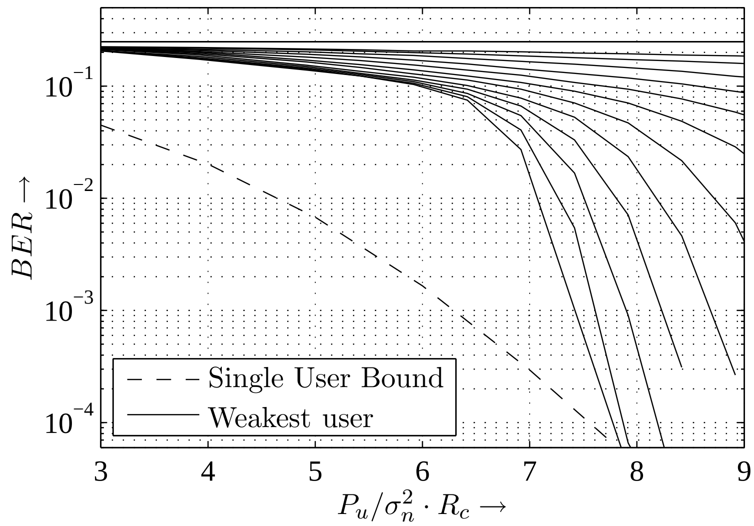

Figure 5. Bit error rate vs. E_b/N_0 for the weakest user

of channel decoding steps can be calculated by prediction of the trajectories without Monte Carlo simulations for every constellation of N_{it1} and U_1. Finally the case of minimum complexity can be predicted as shown in Figure 4. The minimum number of channel decoding steps is obtained at $N_{it1} = 11$ and $U_1 = 25$ and is equal to $N_{dec} = 675$. For this case BER simulation results for the weakest user are shown in Figure 5. Although the proposed strategy works for arbitrary power distributions in this paper only one special case is considered due to limited space. The power profile used in this paper was optimized as in Weitkemper et al., 2006 for a BER of 10^{-4} and 20 iterations considering standard detection.

Complexity Reduction for SIC

The analysis of successive interference cancellation schemes was investigated for the first time in Weitkemper et al., 2005, for CDMA and can also be applied to IDMA. Averaging over all users at a particular iteration is no longer justified for SIC. Already the second user in the first iteration sees an improved interference situation. The variance of the remaining MUI of the u-th user in iteration m can be calculated by

$$\sigma_{\mathrm{eff},u}^{2\,(m)} = \sigma_n^2 + \sum_{v=1}^{u-1} P_v\, \sigma_{d,v}^{2\,(m)} + \sum_{w=u+1}^{U} P_w\, \sigma_{d,w}^{2\,(m-1)} \tag{9}$$

where the superscript (m) denotes the iteration index. For the u-th user the improved estimation of the previous users of the current iteration is already used. Therefore, each user has different variances in each iteration and the behavior can not be predicted with the help of transfer functions displayed in a two dimension diagram as for PIC. Asymptotically SIC and PIC show the same performance if $m \to \infty$. In other words, the behavior of SIC only differs from PIC with respect to required number of iterations. It is well known that successive interference cancellation needs less iterations than PIC to reach the same performance. The reason for still considering PIC is the possibility of parallel processing, but if the constraint is not the overall time delay but the overall number of operations, SIC is superior to PIC. For that reason in this paper also the complexity of SIC is considered. Mostly the detection order is the natural ordering $1, 2, ..., U, 1, 2, .., U$. In this case the gain in convergence speed is only due to improved estimates within one iteration. Intuitively one would choose a descending, but fixed ordering. In this paper an optimized scheduling is derived. For simplicity, one channel decoding operation is called sub-iteration. In each sub-iteration the detector looks for and decodes that user which would gain most in terms of average error variance. Considering $\overline{\sigma}_d^2$ the improvement depending on the user w to be decoded next can be expressed as

$$\left.\overline{\sigma_d^2}\right|_w = \frac{1}{P_{\text{tot}}} \left(\sum_{u \neq w} P_u \sigma_{d,u}^2 + P_w f\left(\frac{\sigma_{\text{eff},w}}{P_w} \right) \right) . \tag{10}$$

So the performance difference depending on the user to be decoded next is simply the weighted improvement of σ_d^2. Finding the user delivering the best improvement concerning average error variance is given by

$$\max_u \; P_u \left(\sigma_{d,u}^2 - f\left(\frac{\sigma_{\text{eff},u}^2}{P_u} \right) \right) . \tag{11}$$

It can be calculated online because decisions are made for each iteration in time. The savings in terms of decoder steps of this scheme can be seen in Figure 6. The average error variance $\overline{\sigma}_{\text{eff}}^2$ is plotted over the number of channel decoder runs. For PIC the function looks like a staircase because the decoding step causes one improvement of the error variance after U simultaneous decoding steps. The scheme proposed in this paper improves slower in terms of iterations but faster in terms of channel decoder steps. For SIC with natural scheduling the improvement within one iteration (decoding user 1 up to user U) is obvious. Also the decreasing gain for the weaker users can be seen. The improved scheduling for SIC has a more heterogeneous slope and reaches the required SINR first. Even standard SIC with natural ordering requires much lower complexity than PIC to reach the same required SINR. For

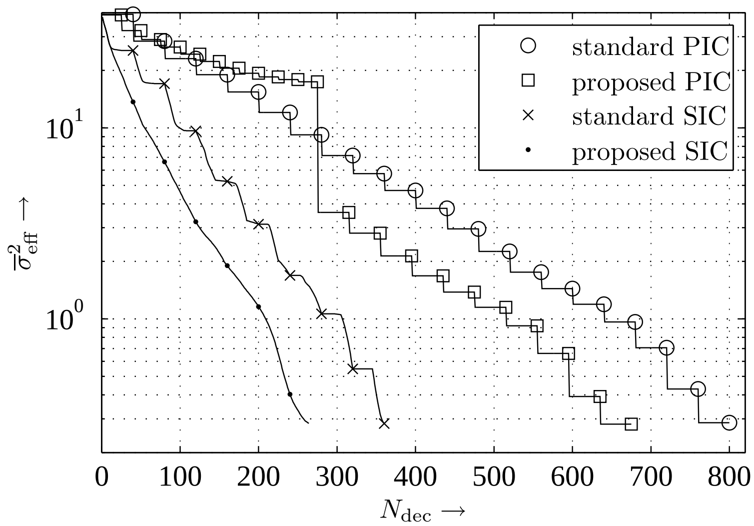

Figure 6. Comparison of complexity for SIC and PIC

the same system parameters standard SIC requires only 360 channel decoding steps whereas the two PIC schemes require 800 and 675, respectively. If the proposed scheduling is used for the SIC scheme, only 264 channel decoding steps are necessary which corresponds to a reduction of $\approx 27\%$ compared to standard SIC and even 67% compared to standard PIC.

5. Conclusion

In this paper, complexity reduction strategies for IDMA uplink detection are presented which are based on semi-analytical analysis with Variance Transfer Charts. A user- and iteration-wise detection strategy is proposed for parallel interference cancellation. The choice of parameters is based on VTC analysis. The overall complexity is reduced up to 16% without any performance degradation. Monte Carlo simulations verify the results by means of bit error rates. Furthermore, SIC is considered known to require less iterations than PIC achieving the same performance. In addition to the natural scheduling an improved scheduling is investigated for SIC. This improved SIC scheduling enables a complexity reduction of 67% compared to standard PIC without any performance degradation. Furthermore, the proposed scheduling for SIC can be calculated online during the detection process.

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