Multistage Interference Cancellation with Decision Directed Channel Estimation in Multirate DS/CDMA on a Mobile Radio Channel

Ann-Louise Johansson and Arne Svensson

Chalmers University of Technology
Department of Information Theory
S-412 96 Gothenburg, Sweden
e-mail: anne.johansson@it.chalmers.se, arne.svensson@it.chalmers.se

Abstract—A combination of a hybrid interference cancellation (IC) scheme and decision directed channel estimation is proposed for the uplink of multirate direct-sequence code division multiple access (DS/CDMA) systems communicating over mobile radio channels. The hybrid IC scheme includes both non-decision directed and decision directed IC, joined together with a modified RAKE combiner for utilization of the diversity. The channel estimator is a decision directed minimum mean square error estimator that utilizes the fading correlation. The performance is evaluated via computer simulations for a multiple data rate scheme, parallel channels, in a multipath environment.

I. Introduction

A possible multiple access technique for digital cellular mobile communication systems is direct-sequence code division multiple access (DS/CDMA). It is a flexible multiple access method, suitable for transmission of variable data rates [1], which makes it a good prospect for next generation systems.

Two of the most important factors that limit the capacity of a multiuser DS/CDMA system are signal interference between users and possibly large variations in the power of the base station's received signal from different users. The former is referred to as multiple access interference (MAI) and the latter as the near-far effect. The power variations that causes the near-far effect is due to the difference in distance between the users and the base station, as well as fading and shadowing. One way to combat this is to use stringent power control [2]. Another approach would be to use more sophisticated receivers which are near-far resistant [3]. Because of MAI's contribution to the near-far problem and its limiting of total system capacity, a lot of attention has recently been given to the subject of multiuser detectors that have the prospect of both mitigating the near-far problem and cancelling the MAI [3]-[10].

The multiuser detectors in [3]-[10] are all designed for single rate systems. In [11], however, a dual rate scheme based on multi-processing gains is considered for the decorrelating detector. In this paper we consider another method, parallel channels, for handling multiple data rates in DS/CDMA systems. It was analysed together with interference cancellation (IC) in [12], [13]. Employing this multirate scheme, a user transmits information simultaneously over as many channels as required for a specific data rate. Each user employs several spreading sequences and the information is transmitted synchronously.

A multistage non-decision directed interference cancellation (NDDIC) scheme for M-ary QAM in a single path environment was analysed in [12]. A hybrid IC scheme consisting of both NDDIC (no knowledge of the channel parameters) and decision directed IC (DDIC) (known or estimated channel parameters) together with a modified RAKE was considered in [13] for a multipath environment. Channel estimation was performed using pilot symbols. This, however, increases the information bit rate of each user and therefore also the full load in the system. In the end, the system capacity is decreased. This is circumvented by using a decision directed approach also for channel estimation [14], [15]. In this paper we propose that decision directed minimum mean squared error estimation (DDMSEE) is applied for multirate DS/CDMA systems with hybrid IC on mobile radio channels. DDMSEE was proposed in [14] for DQPSK and in [15] for DQAM on single path Rayleigh fading channels. The NDDIC considers each received path of each user as a separate signal, which means that after the NDDIC stages the DDMSEE may be applied to each path. Note that since the channel estimation is decision directed the modulation needs to be differentially encoded in contrast to the pilot symbol scheme in [10] and [13].

The structure of the paper is as follows. In Section II we present the model for a parallel channel system with QAM and transmission on Rayleigh fading multipath channels. The multistage hybrid IC scheme is described in Section III and the channel estimator is presented in Section IV. In Section V the simulations are discussed and the numerical results are presented in Section VI. The paper ends with discussions in Section VII. In Section IV scalars are lower case, vectors are bold lower case, and matrices are bold upper case. The symbols $(.)'$ and $(.)^*$ are the transposition and complex conjugate.

II. System Model

We consider a model for a system with square lattice DQAM signalling over slow, frequency-selective Rayleigh fading channels. The received signal is the sum of the reflections of all the signals embedded in AWGN with a two-sided power spectral density of

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$N_0/2$. Assuming that there are K users and P multipaths, the received composite signal is

$$r(t) = \sum_{k=1}^{K}\sum_{p=1}^{P} \alpha_{k,p}\sqrt{\frac{2E_0}{T}} d_k^I(t-\tau_{k,p})\, c_k^I(t-\tau_{k,p}) \cos(\omega_c t + \phi_{k,p}) + \alpha_{k,p}\sqrt{\frac{2E_0}{T}} d_k^Q(t-\tau_{k,p})\, c_k^Q(t-\tau_{k,p}) \sin(\omega_c t + \phi_{k,p}) + n(t) \quad (1)$$

The information-bearing signal, $d_k^{I/Q}(t)$, is an infinite sequence of rectangular pulses of duration T with $A_{k,j}^{I/Q}$ amplitude. The amplitudes of the quadrature carriers for the k^{th} user's j^{th} symbol element, $A_{k,j}^I$ and $A_{k,j}^Q$, generate together M equiprobable and independent symbols. The amplitudes are then affected by the channel gain of each path, $\alpha_{k,p}$, which are assumed to be i.i.d. random Rayleigh variables. Each user k has two signature sequences, c_k^I and c_k^Q, which are used for spreading the signal in the in-phase (I) and the quadrature (Q) branch, respectively. They consist of sequences of antipodal, unit amplitude, rectangular pulses of duration T_c. The period of all the users' signature sequences is $N = T/T_c$, so there is one period per data symbol. N is also referred to as the processing gain. The variable $\tau_{k,p}$ is the time delay and $\phi_{k,p}$ is the phase of the k^{th} user's p^{th} path. These are, in the asynchronous case i.i.d. uniform random variables over $[0, T)$ and $[0, 2\pi)$, respectively. Initially, the only parameters which are assumed to be known are the time delays, $\tau_{k,p}$, of the various users.

The general model for a multipath, asynchronous DS/CDMA system with DQAM is given above. When parallel channels are employed, $r(t)$ is modified to include an extra sum over L. This sum represents the signals transmitted by each user. The L signals are transmitted synchronously, thus the time delay, phase, and channel gain are equal for the different signals.

III. Multistage Interference Cancellation in a Multipath Environment

A multistage hybrid IC [13] employs a combination of NDDIC and DDIC together with a modified RAKE. This is illustrated in Fig. 1. In a multipath environment we have to employ a RAKE receiver to take advantage of the diversity of the channel. The RAKE receiver demands knowledge of the channel parameters and for the channel estimation we apply DDMSEE. The combination of NDDIC and DDIC is used to reduce the complexity of the scheme. The channel parameters are not needed in the NDDIC scheme, so estimation of the channel parameters is performed only in combination with the RAKE and DDIC.

The proposed RAKE receiver with a hybrid IC scheme in Fig. 1 works as follows. r_0^1 is the received composite baseband signal, which is the input to the NDDIC stages [12]. All paths of the K user's L parallel channels are treated as separate users. They are ordered independently and cancelled one by one according to their received signal power. Estimates of the different signals are obtained from the output of the matched filters or, equivalently, the projection of the received signal in the direction of the different spreading sequences. The estimates are in turn subtracted from the composite signal. In this way we attempt to cancel the interference in the system. After i stages of NDDIC, the MAI and the intersymbol interference (ISI) between the paths are reduced. Out from the NDDIC stages we get the residual baseband signal, r_{KPL}^i, and KPL signal estimates, where $d_{k,l,p}^i$ is the k^{th} user's baseband signal of the l^{th} parallel channel's p^{th} path. The signals belonging to each user are grouped together and fed to the DDIC units. A vector with the signal estimates of the paths of the k^{th} user's parallel channels are denoted $\boldsymbol{d}_k'$. The output from the DDIC unit is $\boldsymbol{b}_k$, a vector containing the symbols transmitted over the k^{th} user's parallel channels. This is shown in the left part of Fig. 1 and a block diagram of a DDIC unit for the k^{th} user is illustrated in Fig. 2. The estimation of the channel parameters of the P paths is shown in Fig. 3. The estimation is discussed in detail in Section IV.

In the last stage of the hybrid IC a RAKE is combined with DDIC to benefit from both removal of the Gaussian noise and the diversity. The resulting baseband signal before the DDIC unit is

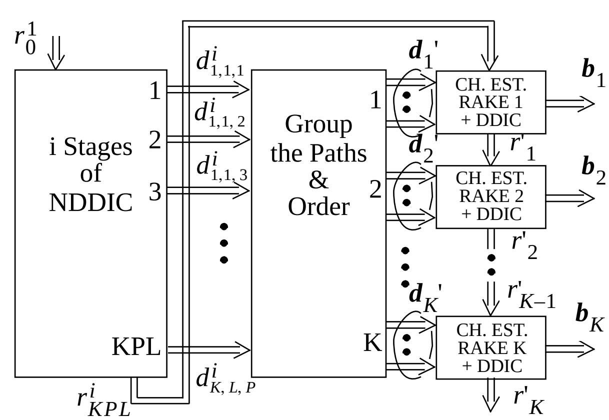

Fig. 1. Hybrid interference cancellation scheme.

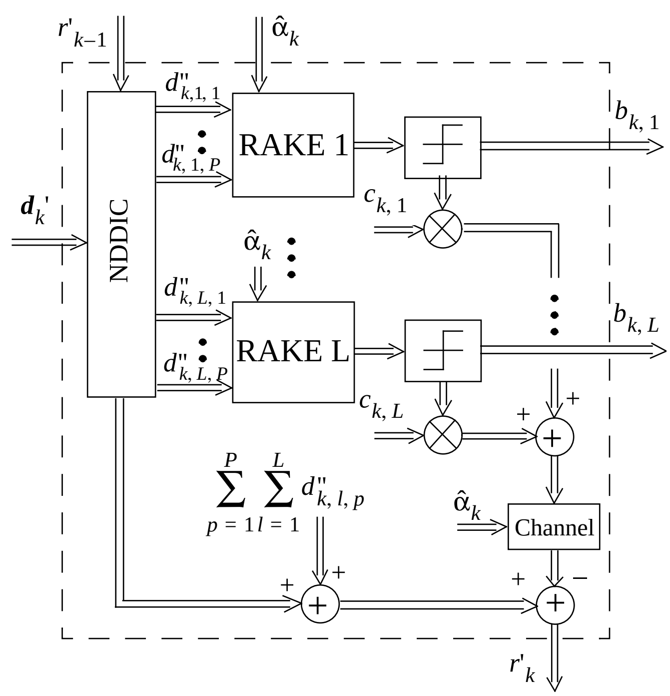

Fig. 2. Decision directed interference cancellation in combination with a modified RAKE.

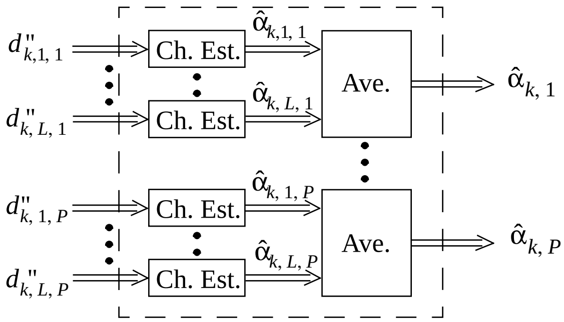

Fig. 3. Estimation of channel parameters.

r'_{k-1}. First new estimates of the baseband signals corresponding to the user's paths are obtained using NDDIC. This is done successively, because if the received multipath signal is regenerated and a conventional RAKE [16] is employed, the ISI, which is partly removed in the NDDIC stages, would be introduced again. Hence, in the modified RAKE the signals are fed separately to the combiner together with the channel estimates, $\hat{\alpha}_k$, from the DDMSEE. $\hat{\alpha}_k$ is an vector with estimates of the channel gains of the P paths, which are equal for all the L parallel channels. After the symbols have been detected, the estimated channel parameters are used to regenerate the signals corresponding to the user's all paths, which are then cancelled from the composite baseband signal. This is done simultaneously for all parallel channels. The scheme is repeated successively for all the users. If more than one stage of RAKE and DDIC is implemented, the regenerated signals, corresponding to the various paths, are fed to the subsequent stage in the same manner as to the first stage.

IV. Decision Directed Channel Estimation

A decision directed channel estimation scheme is proposed in [14] and [15] for DQPSK and DQAM, respectively. In this paper we consider only DQPSK. After the NDDIC stages most of the interference, on each received path, from other paths and other users is cancelled. Assuming that all the interference is removed, the received sample for each symbol of each path is modelled as the product of the transmitted symbol and the complex channel gain (fading) plus additive white Gaussian noise. That is,

$$s_j = \alpha_j b_j + n_j , \tag{2}$$

where j is an index specifying the symbol. Any subscript specifying the user, parallel channel and path is dropped. If previous decisions are assumed to be correct, the optimum minimum means square error estimate of the channel gain is equal to a linear combination of the last F received samples on that path [17]. Hence, this predictor minimises the expectation

$$E\{|\hat{\alpha}_j - \alpha_j|\} , \tag{3}$$

where the estimate is given by

$$\hat{\alpha}_j = \boldsymbol{h}'\boldsymbol{y}_j . \tag{4}$$

$\boldsymbol{y}_j$ is a vector containing the F previously received samples scaled, to avoid a time-varying filter, with the transmitted symbols, i.e.,

$$y_i = s_i / d_i . \tag{5}$$

In our case we use the past decision, $\hat{d}_i$, since we do not know the transmitted symbol. For the first decision at least one known symbol is demanded or, if a F tap filter is going to be used directly, F known symbols are needed. The F weighting coefficients in the vector $\boldsymbol{h}$ are obtained by solving a linear equation system given by

$$\boldsymbol{h} = \Phi^{-1}\varphi , \tag{6}$$

where

$$\Phi = E\{\boldsymbol{y}^*_j \boldsymbol{y}'_j\} = \begin{bmatrix} \rho_0 + \frac{2\sigma^2}{A^2} & \rho_1 & \cdots & \rho_{F-1} \\ \rho_1 & \rho_0 + \frac{2\sigma^2}{A^2} & \cdots & \rho_{F-2} \\ & & & \\ \rho_{F-1} & \rho_{F-2} & \cdots & \rho_0 + \frac{2\sigma^2}{A^2} \end{bmatrix} \tag{7}$$

and

$$\varphi = E\{\alpha_j \boldsymbol{y}^*_j\} = \begin{bmatrix} \rho_1 & \rho_2 & \cdots & \rho_F \end{bmatrix}' \tag{8}$$

The variance of the noise is $2\sigma^2$ and A is the amplitude of the symbols. The noise variance and the transmitted power is assumed to be known. ρ_f is the correlation of the fading given by

$$\rho_f = E\{\alpha_j \alpha^*_{j-f}\} . \tag{9}$$

In this paper where we consider a system with parallel channels, the channel estimates can be improved through averaging, which is illustrated in Fig. 3. When there is a channel estimator connected to each path, L of the obtained estimates are estimates of the same parameter, since the parallel channels are synchronous. The output from the group of estimators is then an average of the L estimates. We get P estimates out of the DDMMSE estimator and they are used for the RAKE combining of the paths and DDIC for the user's parallel channels.

More details of this DDMSEE is found in [14] and [15].

V. Simulations

We have considered asynchronous systems and frequency-selective Rayleigh fading with two equally strong, independently fading paths per user. In all the simulations the different IC schemes operates block-wise on the data where two guard symbols have been employed in the beginning and the end of each block to avoid edge effects. In this paper we have studied the case when the channel does not change over the time of transmission of a block, which corresponds to slow vehicular speed. For this assumption the correlation of the fading between two samples, ρ_f, is 1 and, without error propagation, the filter would simply perform an averaging of the weighted samples. In the NDDIC part of the hybrid IC, all paths are ranked separately using the outputs of the matched filters. A new ranking according to the users' total received power is done before the stage with RAKE and DDIC. This ranking is also obtained using the outputs of the matched filters, since the estimation of the channel parameters is integrated with the IC scheme. The aim is to reduce the interference before the channel parameters are estimated. That improves the estimates and, consequently, also the interference cancellation. The parameter settings used in the simulations are given in Table 1.

All the simulated systems are chip-rate sampled, which limits the possible time-lags between users to be multiples of chip-times. This is a restriction that should be modified for simulations of more realistic scenarios. It should also be noted that for high values of E_b/N_0 the results are less accurate, due to limited simulation runs.

VI. Numerical Results

The simulation results from a parallel channel system with 15 QPSK users and two parallel channels per user are shown in Fig. 4. The channel is a Rayleigh fading channel with two paths and the detector is a hybrid IC with two NDDIC stages and one stage with RAKE and DDIC. Orthogonal Gold sequences of length 128 are used. The results are from a system with known channel parameters and two systems where the channel is estimated. The estimation is performed using a FIR filter of length 5 and 11. The graph depicts that the loss caused by estimation with a filter of length 5 is only about 1 dB compared to the results when using known channel parameters. The bit error probability with estimated channel parameters decreases a little if a longer filter, 11 taps, is employed. Small performance gains is also obtained when a hybrid IC with an additional RAKE and DDIC stage is used.

Table 1. Parameter settings for the simulations.

Simulation parameters	
Multirate Scheme	Parallel Channels
Channel	Rayleigh Fading, 2 Paths
Detection	Coherent
Modulation	DQPSK
Channel Estimation	DDMSEE
Ranking	MF Outputs
Signature Sequences	Orth. Gold Seq.
Time Delays	Perfect Estimates
Processing Gain	128
Block Length	28
Filter Length	5 or 11 Taps
Error Propagation	Yes

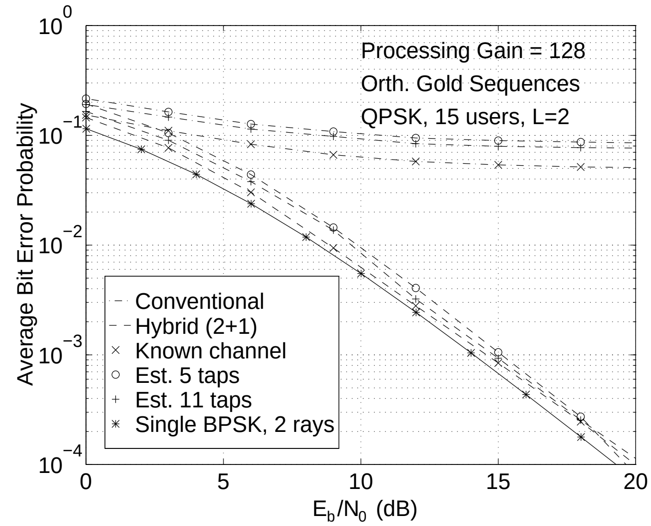

Fig. 4. Simulations of systems with 15 QPSK users, 2 parallel channels per user, and 2 paths per user. The performance of the conventional detector and the hybrid IC for known and estimated channel parameters is shown. Estimation filters with 5 and 11 taps.

Fig. 5 shows the performance of two parallel channel systems. One system has 15 QPSK users and the other has 30 QPSK users. The users in both systems have two parallel channels each and the estimation is performed using a FIR filter of length 5. Orthogonal Gold sequences of length 128 are used. Note the high load of the system with 30 users. It corresponds to the same throughput as 120 BPSK users. For E_b/N_0 values up to 12 dB, the performance of the large system is only 2 dB from the single user bound using a hybrid IC with 2+2 stages. It can be seen that an extra RAKE and DDIC stage improves the performance of the large system significantly, while for the system with less load the improvement is only marginal.

The results in Fig. 6 are from a system with 15 QPSK users and four parallel channels per user. A hybrid IC with two NDDIC

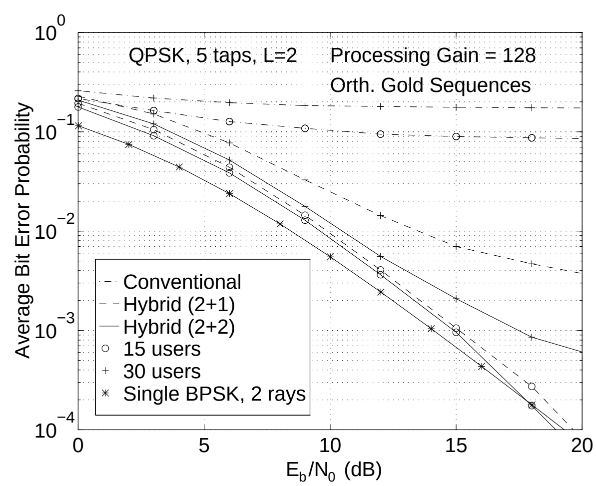

Fig. 5. Simulations of asynchronous systems with 15 and 30 QPSK users, 2 parallel channels per user, and 2 paths per channel. The performance of the conventional detector and the hybrid IC for estimated channel parameters is shown.

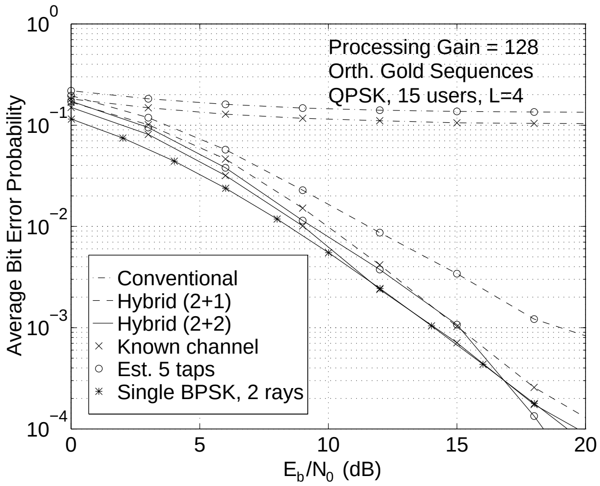

Fig. 6. Simulations of asynchronous systems with 15 QPSK users, 4 parallel channels per user, and 2 paths per channel. The performance of the conventional detector and the hybrid IC, for known and estimated channel parameters, is shown.

stages and one or two RAKE and DDIC stages is employed. Orthogonal Gold sequences of length 128 are used and the length of the FIR filter is 5. The throughput is the same as for the system with 30 users in Fig. 5 but the bit error probability for this system is lower. This can be explained by the improved estimates, which are achieved through averaging of the L estimates. In Fig. 6 the average is taken from four estimates and in the systems in Fig. 5 the average is taken from two estimates. The crossing of the single user bound in the high E_b/N_0 region is caused by inaccuracy in the simulation results.

VII. Discussion & Conclusions

This paper presents a novel combination of a multistage hybrid IC scheme for multipath environments and a decision directed minimum mean square error channel estimator, which is evaluated together with a multiple data rate scheme denoted parallel channels. The hybrid IC includes a combination of non-decision directed and decision directed IC combined with a modified RAKE receiver. The decision directed minimum mean square error estimator is implemented by an F tap FIR filter on each received path, whose input is the last received samples on that particular path. The coefficients in the filter is chosen to minimize the mean square error between the true and estimated channel gain. Fading correlation between paths of a user's parallel channels is used to improve the performance.

The results show that good performance, within 1-2 dB of the single user bound, can be obtained for systems employing the hybrid IC system together with decision directed minimum mean square error channel estimation for estimation of the channel parameters.

In this paper we have for simplicity evaluated the estimation scheme for slow, frequency-selective Rayleigh fading. Hence, for this channel it is not meaningful to compare the results to those obtained using estimation with pilot symbols, since the comparison depends on the size of the data blocks. The DDMMSE scheme is actually designed for a time varying channel and we will evaluate it for channels according to Jakes model [14]. For this type of channel, pilot symbols have to be sent at a rate proportional to the fading rate and the advantage of our estimation scheme, when considering the total load of a system, is evident.

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