

A Joint Channel and Information Sequence Estimation Technique

BACKGROUND TO THE INVENTION

This invention relates to a joint channel and information sequence estimation technique and more particularly to a method for estimation of the unknown parameters critical for effective receiver operation in the uplink of a Code-Division-Multiple-Access (CDMA) system with an optional antenna array.

In CDMA based multiple access systems the interference, due to the presence of other users, is a limiting factor in the performance of conventional receivers, for example as described in [1] TIA/EIA IS-95A: Mobile Station-Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular System, March 1995. Only when this interference is removed completely can ideal performance be achieved. Ideal performance is defined herein to be the information bit error rate that would be achieved if only one user was transmitting in the system. Consideration is given to cross-user interference arising due to:

1. the lack of orthogonality between the spreading waveforms; and
2. the non-ideal nature of the beam pattern, e.g. the presence of side-lobes.

It should be noted that the present invention is not limited to wideband CDMA systems.

Recently, a receiver has been proposed that, given perfect knowledge of the directions of arrival (DOA) and multipath channels of each user over time, offers a new order of performance for complexity in CDMA systems with and without an antenna array (See [2] P.D. Alexander, A.J. Grant, and M.C. Reed, "Iterative detection in code-division multiple-access with error control coding" in European Transactions on Telecommunications Special Issue on CDMA Techniques for Wireless Communications

Systems, 1998 (to appear) and [3] P.D. Alexander and M.C. Reed, "*Iterative interference reduction in CDMA*" in Multiaccess, Mobility and Teletraffic: Advances in Wireless Networks, (Melbourne, Australia), pp. 29-35, Dec. 1997). This receiver draws together many ideas that had appeared previously. In particular, a receiver for the CDMA uplink is described in [4] T.R. Giallorenzi and S.G. Wilson, "*Suboptimum multiuser receivers for convolutionally coded asynchronous DS-CDMA systems*" IEEE Trans. Commun., vol. 44, pp. 1183-1196, Aug. 1996 which is very similar to the receiver described in [2] where an antenna array is integrated. The contribution in [2] may then be viewed as the realisation that CDMA and CDMA with an antenna array can be modelled according to a similar structure. This realisation allows the application of any receiver designed for CDMA to the SDMA problem, and to the CDMA with antenna array case. The realisation was made independently of [2] in [5] "*Blind equalisation in antenna array CDMA systems*", H. Liu and M.D. Zoltowski, IEEE Trans. Signal Processing, vol. 45, pp. 161-172, Jan. 1997 where only the simplest receivers were considered. The combination of the ideas presented by Giallorenzi *et al.* [4] and Liu *et al.* [5] constitute the idea proposed in [2].

The structure of the receiver proposed in [2] resembles that of a Turbo Decoder as described in [6] S. Benedetto and G. Montorsi, "*Iterative decoding of serially concatenated convolutional codes*" IEE Electron. Lett. Vol. 32, pp. 1186-1188, June 1996 and [7] US Patent 5,446,747. Turbo codes have revolutionised the error control coding field. Indeed Sergio Verdu, who is one of the world leaders in the area of multiuser communications, called it a "Turbo-revolution". Turbo codes are iterative in nature and many receivers for CDMA and related channels such as the ISI channel have been proposed in the last year. All offer unprecedented performance-for-complexity. In the case of the ISI channel all of the intersymbol interference can be removed even for what are traditionally "difficult" channels [8] C. Douillard, C.B. Michel Jezequel, A. Picart, P. Didier, and A. Glavieux, "*Iterative correction of intersymbol interference: Turbo-*

equalisation," European Transactions on Telecommunications, vol. 6, pp. 507-511, Sept. 1995. The same is true for CDMA see [3] and [9] M.L. Moher, "*Turbo-based multiuser detection*" in Proc. IEEE Int. Symp. on Information Theory, (Ulm, Germany), p. 195, June 1997 and as already mentioned CDMA with antenna arrays [2].

The performance of these systems is dependent on knowledge of the "channel". In traditional Turbo codes this means that the generator polynomials of each of the constituent codes must be known at the receiver. In the ISI and CDMA problems one of the two codes is in fact the channel itself. This requires a characterisation of the code or, in this case, the channel at the receiver, i.e. channel estimation must be performed. Furthermore, an inaccurate estimate of the channel would result in the receiver trying to decode a convolutional code according to the incorrect trellis: the channel estimation must, therefore, be accurate.

In all of the above mentioned systems, the channel, be it CDMA, ISI or any other, is assumed known at the receiver.

It should be noted at this point that the vast array of other types of receivers, proposed for the CDMA case, in particular as described in [10] A. Duel-Hallen, J. Holtzman, and Z. Zvonar, "*Multiuser detection for CDMA systems*", IEEE Personal Communications Magazine, pp. 46-58, April 1995, are not competitive with the receivers discussed above. Perhaps these receivers are a few times less complex but their performance is not of the same order as that provided by embodiments of the invention. For example, iterative receivers embodying the invention can provide five times as much capacity in CDMA for about a five times increase in complexity compared to conventional techniques. For the first time, the number of users can exceed the processing gain of spreading.

The channel, in the context of this invention, shall mean the beamforming and multipath coefficients pertaining to each user. Traditionally, these are treated separately at the receiver as described in [11] S. Tanaka, M. Sawahashi, and F. Adachi, "*Pilot symbol-assisted decision-directed coherent adaptive array diversity for DS-CDMA mobile radio reverse link*," IEICE Transactions, vol. E80-A, pp. 2445-2454, Dec. 1997. When training symbols are employed (as will certainly be the case in IMT-2000) adaptive techniques can be employed to remove the need to explicitly estimate the channel. As will be described later, such adaptive receivers are not competitive on a performance-for-complexity basis with the integrated receiver to be described.

The performance of other stand-alone channel estimators (such as: [12] S.E. Bensley and B. Aazhama, "Subspace-based channel estimation for code division multiple access communication systems," IEEE Trans. Commun., vol. 44, pp. 1009-1020, Aug. 1996; [13] P.D. Alexander and A.J. Grant, "Multipath channel estimation for asynchronous random-code-division multiple-access," in IEEE Trans. Commun., 1998 - under revision for IEEE Trans. Commun.; and [14] B. Steiner and P. Jung, "Optimum and suboptimum channel estimation for the uplink of CDMA mobile radio systems with joint detection," European Transactions on Telecommunications, vol. 5, pp. 39-50, Jan.-Feb. 1994) is inherently flawed due to either their blind nature or the quality of the fed-back decisions in decision-directed mode.

SUMMARY OF THE INVENTION

Thus, one aspect of the present invention provides a channel estimator for performing channel estimation on a plurality of channels, including: means for receiving a signal consisting of a superposition of signals from a plurality of channels; means for constructing, from the signal, an observation sequence estimate modelling the contributions to the signal from each channel; means for constructing, from the

observation sequence estimate an estimate modelling the behaviour of each channel, the estimate being dependent on a number of parameters; means for computing at least one contribution to the observation sequence estimate for each channel which is not dependent on at least one of the parameters, the contributions being functions of some or all of the estimates modelling the behaviour of the other channels; and means for removing the contribution, for each of the contributions, from the observation sequence estimate to form a new estimate modelling the behaviour of each channel.

BRIEF DESCRIPTION OF THE DRAWINGS

In order that the present invention may be more readily understood, embodiments of the invention will be described, by way of example, with reference to the accompanying drawings, in which:

FIGURE 1 is a graph showing the Mean Square Error (MSE) for four estimators used with embodiments of the invention against signal-to-noise ratio (SNR);

FIGURE 2 is a graph showing the Mean Square Error (MSE) for four estimators used with embodiments of the invention against quality of prior probability estimates;

FIGURE 3 is a system diagram of a channel estimator embodying the present invention;

FIGURE 4 is a graph showing a comparison between the channel estimate (solid lines) and the actual channel (dashed lines) over a number of iterations; and

FIGURE 5 is a graph showing the performance of two channel estimators used with embodiments of the present invention against single user performance (perfect).

DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

Using the present invention, the channel is estimated using an integrated approach with the only penalty being perhaps that an extra iteration of the algorithm need be executed to get ideal performance. In some sense, as described later, there is no performance degradation even though the channel is unknown. The present invention is decision directed, but the quality of the symbol estimates are iteratively improved along with the quality of the channel estimate. None of the known channel estimation procedures exploit the error control coding on the information bearing symbols. In the channel estimator proposed herein this error control coding is explicitly incorporated in the channel estimation algorithm.

One aspect of the present invention provides a method for receiving a code-division multiple-access (CDMA) signal at an antenna array, which method comprises the steps of:

1. converting the CDMA signal to baseband;
2. recognising symbol boundaries in every multipath for every user in the baseband signal;
3. initialising the symbol estimates for every user at the symbol rate;
4. generating an estimate of the channel of every user using the training symbols and the information bearing symbol estimates;
5. generating new symbol estimates of each users signal using said channel estimates and symbol estimates;
6. deinterleaving each user's sequence;
7. generating new symbol estimates of each user's signal by decoding each users sequence according to their corresponding error control code;
8. interleaving each users sequence; and

9. repeating steps 4 through 8 until a desired number of iterations have been executed.

A further aspect of the present invention provides a receiver for CDMA signals comprising:

- (a) means to convert a CDMA signal to a baseband signal
- (b) means to recognise symbol boundaries in every multipath for every user in the baseband signal
- (c) means to initialise the symbol estimates for every user at the symbol rate
- (d) means to generate an estimate of the channel of every user using the training symbols and the information bearing symbol estimates
- (e) means to generate new symbol estimates of each users signal using said channel estimates and symbol estimates
- (f) means to deinterleave each user's sequence
- (g) means to generate new symbol estimates of each users signal by decoding each user's sequence according to their corresponding error control code
- (h) means to interleave each user's sequence and
- (i) means to repeat steps (d) through (h) until a desired number of iterations have been executed.

An embodiment of the invention employs a model similar to that described in [13], [15] P.D. Alexander and A.J. Grant, *"Multipath channel estimation for asynchronous random-code-division multiple-access"* in 47th International Vehicular Technology Conference, (Phoenix, Arizona), pp. 1609-1613, May 1997 and [16] P.D. Alexander and M.C. Reed, "Performance analysis of an iterative receiver for CDMA incorporating an antenna array", submitted to Globecom '98 where it is assumed that K users each transmit L binary symbols $\{d_{k,t} \in \{-1,1\} : t = 1, \dots, L\}$ via BPSK modulation of the length N spreading codes $\{s_{k,t} \in \{-1/\sqrt{N}, 1/\sqrt{N}\}^N : t = 1, \dots, L\}$. This model permits the spreading

code to change from symbol interval to symbol interval. It is assumed that the multipath impulse response of the channels over which the users transmit to the base station are invariant during the L symbol intervals. This condition is enforced by low vehicle speeds, high signalling rate and short packet lengths L .

An important assumption is that the delay of the multipath taps is externally supplied. This would be normally be done via a sliding correlator with dither control. Tap m of M is therefore represented by an unknown complex amplitude $\alpha_{k,t,m}$, and a known delay $\tau_{k,t,m} \in (0, NS)$. The use of a B element antenna array is modelled at the receiver by defining for each user k , symbol t and multipath m , a set of B antenna element phases $\phi_{k,t,m,b}$. Note that multipath components are allowed to arrive from different directions.

Unlike the model of [15] chip-rate oversampling and chip waveform modelling are incorporated in the present model. Sampling the down-converted signal at each of the receiver antennae at S samples per chip interval and collecting all of the samples into one stream $\underline{e}$, we may now write:

$$\underline{e} = \underline{A}_S \underline{A}_A \underline{A}_M \underline{d} + \underline{n} \quad (1)$$

$$= \underline{A} \underline{d} + \underline{n} \quad (2)$$

where $\underline{A} = \underline{A}_S \underline{A}_A \underline{A}_M$. The constituent matrices are now described.

$\underline{A}_S$, $(L+1)NSB$ by $LBMK$. This contains information pertaining to the spreading codes and the multipath delays (all of which are assumed known at the receiver) and has column j

$$\begin{bmatrix} \underline{0}((t-1)NS\tau_{k,m})B + b \\ ((\underline{S}_{k,t} \otimes [1, \underline{0}_{S-1}]^* \underline{c}) \otimes [1, \underline{0}_{B-1}]) \\ \underline{0} \end{bmatrix} \in \Re^{(L+1)NSB, 1} \quad (3)$$

where j, k, t, m and b are uniquely related by

$$j = (((t-1)K + k - 1)M + m - 1)B + b \quad (4)$$

Each column of this matrix contains a spreading code and when applied via the inner product operation a spreading code correlation results. There are LBMK such correlators, one for each multipath and one for each antenna element.

A_A, LBMK by LMK. This matrix describes the phases of each user's multipath component at each antenna element over time. It has column j

$$\begin{bmatrix} 0_{(j-1)B} \\ e^{j\varphi_{k,t,m,1}} \\ \vdots \\ e^{j\varphi_{k,t,m,B}} \\ 0_{(LMK-j)B} \end{bmatrix} \in \mathbb{C}^{LBMK,1} \quad (5)$$

where j, k, t and m are uniquely related by

$$j = ((t-1)K + k - 1)M + m \quad (6)$$

Each column of this matrix is a set of phases which when applied via the inner product operator result in a beamforming operation. There are LKM such beam-formers. One for each path. Given an angle of arrival, θ , at an $\lambda/2$ spaced uniform linear array, the phases are determined according to $\phi_b = \pi(b-1) \cos(\theta)$.

A_M, LMK by LK. The received amplitude and phase of each of the LKM multipath

components as they would be measured on a single antenna are included in this matrix which has column j

$$\begin{bmatrix} 0_{(j-1)M} \\ \alpha_{k,t,1} \\ \vdots \\ \alpha_{k,t,M} \\ 0_{(LK-j)M} \end{bmatrix} \in \mathbb{C}^{LMK,1} \quad (7)$$

where j , k and t are uniquely related by

$$j = (t-1)K + k \quad (8)$$

Each column of this matrix contains the impulse response of the multipath channel. Its application via the inner product operation results in a RAKE combiner. There are LK such combiners, one for each symbol transmitted by each user.

It is assumed that $\underline{A}_S$ is known and $\underline{A}_A$ and $\underline{A}_M$ are unknown at the receiver. An estimator for the product $\underline{A}_{AM} = \underline{A}_A \underline{A}_M$ shall be proposed, since it is this matrix, along with $\underline{A}_S$ that form $\underline{A}$ according to Eqn. 2. Like many receivers proposed for third generation systems, the iterative receiver proposed in [2] requires knowledge of $\underline{A}$ for its operation.

It can be seen that there is one channel, or column of $\underline{A}_{AM}$, for each bit transmitted. The channel contains information regarding the DOA of each path and the multipath tap weights for each user. The non-zero part of column $j = (i-1)K + k$ of $\underline{A}_{AM}$ is defined as the BM element vector

$$\underline{h}_{k,t} = \begin{bmatrix} e^{h_{k,t,1}} \alpha_{k,t,1} \\ e^{h_{k,t,2}} \alpha_{k,t,2} \\ \vdots \\ e^{h_{k,t,M}} \alpha_{k,t,M} \end{bmatrix} \in \mathbb{C}^{BM} \quad (9)$$

which can be considered as the channel for user k since it is assumed invariant over the signalling interval.

The representation (1) is not just a factorisation of the full channel but divides the information into parameters assumed known and unknown at the receiver. Since $\underline{A}_s$ is known at the receiver, the following matched filtering operation may be performed:

$$\begin{aligned} \underline{y} &= \underline{A}^T \underline{s} \underline{e} \\ &= \underline{R}_s \underline{A}_s \underline{d} + \underline{z} \in \mathbb{C}^{LKMB,1} \end{aligned}$$

A conventional trained estimator is disclosed in [14]:

$$\hat{\underline{h}}_k = \frac{1}{L} \sum_{t=1}^L \underline{y}_{k,t} d_{k,t} \quad (10)$$

where an empirical expectation has been performed and $\underline{y}_{k,t}$ is the collection of samples from M matched filters for $\underline{s}_{k,t}$. This estimator is interference limited, or equivalently, suffers from the near-far problem. It is desirable to address the problem of long training sequences via the use of decision feedback "training" and the near far problem via interference cancellation. To this end it is necessary to consider first the problem of channel estimation when there is a non-trivial prior distribution on the "training" symbols. True trained estimation can be executed when one of $P(d_{k,t} = -1)$ and $P(d_{k,t} = 1)$ is one and the other is zero. Considering the general case where

$$\begin{aligned} P(d_{k,t} = 1) &= \rho_{k,t} \\ P(d_{k,t} = -1) &= 1 - \rho_{k,t} \end{aligned} \tag{11}$$

with moments

$$\begin{aligned} E\{d_{k,t}\} &= \rho_{k,t} - 1 \\ E\{d_{k,t}^2\} &= 1 \end{aligned}$$

with a view to decision direction estimation rather than pure trained estimation. This sort of information is available in the iterative receiver proposed in [13] where these priors are manipulated over iterations of the receiver. An estimate of the symbol may be formed using the expectation operator $\hat{d}_{k,t} = 2\rho_{k,t} - 1$. It is noted that if symbols were transmitted according to some distribution with $\rho \notin \{0, 0.5, 1\}$ then any particular symbol contains, in some sense, a known part and an unknown part and is therefore useful for training and information transport, simultaneously.

Since the conventional channel estimator is interference limited and there already exists an interference canceller in the iterative proposal in [13], it is proposed to perform the channel estimation after the interference cancellation operation. The issue here is that interference cancellation requires knowledge of the channels of all users. It is assumed that the existence of some channel estimate, although it may be poor, is good enough to allow the single user decoder stage to improve the quality of the $\rho_{k,t}$. This channel estimate is denoted as $\underline{A}^{\circ}_{AM}$. Such a channel estimate could be generated using Eqn. 10 and a very short training sequence of, for example, ten symbols. Indeed such a channel estimate can be modelled as a noisy version of the actual channel. The power of this noise can be used to determine if the error control coding is at a rate above capacity, where the capacity is reduced due to the presence of the noise in the channel estimate.

Furthermore the analytical technique employed in [2] can be used to determine the minimum number of training symbols that must be employed to ensure convergence.

Channel estimation is performed for each user by employing a statistic resulting from interference cancellation which uses an estimate of the channel.

$$\underline{y}^i = \underline{A}_s^T (\underline{e} - \underline{A}_s \underline{A}_{AM}^{i-1}) + \underline{A}_{AM}^{i-1} \hat{\underline{d}} \quad (12)$$

Under the ideal conditions of: 1) no noise; 2) perfect channel estimate; and 3) orthogonally received waveforms, $\underline{A}_s^T \underline{A}_s = \underline{I}$ we have

$$\underline{y}^i = \underline{A}_{AM} \underline{d}$$

Under non-ideal conditions we have

$$\underline{y}^i = \underline{A}_{AM} \underline{d} + \underline{z}$$

so

$$\underline{y}_{k,i}^i = \underline{h}_k \underline{d}_{k,i} + \underline{z}_{k,i} \quad (13)$$

The single user channel estimation problem for $\underline{h}_k$ can now be expressed. The iteration index i and the user index k are dropped for the purposes of clarity.

MMSE-based channel estimation using non-trivial priors:

Given the set of observations according to (13)

$$\{\underline{y}_t^i : t = 1, \dots, L\} \quad (14)$$

and a corresponding set of priors on the symbols

$$\{P(d_t^i): t=1, \dots, L\} \quad (15)$$

compute an estimate of the channel $\underline{h}$. The linear scalar MMSE criteria defined as follows are arbitrarily employed. A set of weights $\{\alpha_t \in \mathbb{R} : t=1, \dots, L\}$ are selected in order to minimise the average mean square error (MSE).

$$\underline{h} = \arg \min_{\underline{h}} E \left\{ \left\| \sum_t \alpha_t \underline{y}_t - \underline{h} \right\|_2^2 \right\} \quad (16)$$

Applying the expectation, one obtains

$$E \left\{ \left\| \sum_t \alpha_t \underline{y}_t - \underline{h} \right\|_2^2 \right\} = \sum_t \alpha_t^2 (w E\{d_t^2\} + \sigma_z^2) + \sum_t \sum_{t' \neq t} \alpha_t \alpha_{t'} w E\{d_t d_{t'}\} - 2 \sum_t \alpha_t w E\{d_t\} + w$$

Let us define

$$\mu_t = E\{d_t\} = 2\rho_t - 1 \quad (17)$$

Using the statistical independence of d_t in t and the second moment of d_t we get

$$E \left\{ \left\| \sum_t \alpha_t \underline{y}_t - \underline{h} \right\|_2^2 \right\} = \sum_t \alpha_t^2 (w + \sigma_z^2) + \sum_t \sum_{t' \neq t} \alpha_t \alpha_{t'} w \mu_t \mu_{t'} - 2 \sum_t \alpha_t w \mu_t + w$$

We now take each of the derivatives with respect to the MMSE filter $\underline{\alpha}$

$$\frac{\partial \mathcal{E} \left\{ \left\| \sum_i \alpha_i y_i - h \right\|_2^2 \right\}}{\partial \alpha} = 2\alpha_i (\omega + \sigma_i^2) + 2 \sum_{i \neq i} \alpha_i \mu_i \mu_i \omega - 2\omega \mu_i \quad (18)$$

the vector form of the equation can be constructed by placing the μ_i into a vector $\underline{\mu}$

$$\frac{\partial \mathcal{E} \left\{ \left\| \sum_i \alpha_i y_i - h \right\|_2^2 \right\}}{\partial \alpha} = (\underline{M}\omega + (\omega + \sigma_i^2)\underline{I})\underline{\alpha} - \omega \underline{\mu} \quad (19)$$

where

$$\underline{M} = \underline{\mu} \underline{\mu}^T - \text{diag} (\underline{\mu} \underline{\mu}^T)$$

Since we are interested in setting this derivative to zero we may divide through by w (let $\gamma = w/\sigma_z^2$) to get

$$(\underline{M} + (1 + \gamma^{-1})\underline{I})\underline{\alpha} = \underline{\mu} \quad (20)$$

The weights $\underline{\alpha}$ which solve (20) will be a minimum of the cost function since it is quadratic. The solution is

$$\underline{\alpha}_{MMSE} = (\underline{M} + (1 + \gamma^{-1})\underline{I})^{-1} \underline{\mu} \quad (21)$$

which is not practical to compute since $\underline{M}$ is $L \times L$. Driven by the need for less complex estimator derivation, there is now proposed three alternative and approximate estimators:

Estimator 1 ($\underline{\alpha}_1$):

The first estimator is yielded by assuming

$$E\{d_i\}^2 = 1 \quad (22)$$

In this case (20) becomes

$$(\underline{\mu}\underline{\mu}^T + \gamma^{-1}I)\underline{\alpha} = \underline{\mu} \quad (23)$$

which has the solution

$$\underline{\alpha} = \frac{1}{\gamma^{-1} + \|\underline{\mu}\|_2^2} \underline{\mu} \quad (24)$$

Estimator 2 (α_2):

In the second assumption we assume

$$E\{d_t\}^2 = 1 - \nu \forall t \quad (25)$$

In this case (20) becomes

$$(\underline{\mu}\underline{\mu}^T + (\nu + \gamma^{-1})I)\underline{\alpha} = \underline{\mu} \quad (26)$$

which has the solution

$$\underline{\alpha} = \frac{1}{\nu + \gamma^{-1} + \|\underline{\mu}\|_2^2} \underline{\mu} \quad (27)$$

We now apply as second minimisation of the MSE, now over ν . Substituting for $\underline{\alpha}$ in (18) we get

$$E\left\{\left\|\sum_t \alpha_t \underline{y}_t - \underline{h}\right\|_2^2\right\} = \frac{1}{C(\nu)^2} \sum_t \mu_t^2 (w + \sigma_z^2) + \frac{1}{C(\nu)^2} \sum_t \sum_{r \neq t} \mu_t \mu_r w - \frac{2}{C(\nu)} \sum_t w \mu_t^2 + w$$

where

$$C(\nu) = \nu + \gamma^{-1} + \|\underline{\mu}\|_2^2 \quad (28)$$

Simplifying we get

$$E\left\{\left\|\sum_i \alpha_i \underline{y}_i - \underline{h}\right\|^2\right\} = \frac{\omega \|\underline{\mu}\|_2^2 (1 + \gamma^{-1} + \|\underline{\mu}\|_2^2) - \omega \|\underline{\mu}\|_4^4}{C(\nu)^2} - \frac{2\omega \|\underline{\mu}\|_2^2}{C(\nu)} + \omega \quad (29)$$

Taking the derivative with respect to ν and setting to zero we get

$$\nu = 1 - \frac{\|\underline{\mu}\|_4^4}{\|\underline{\mu}\|_2^2} \quad (30)$$

which yields

$$\underline{\alpha} = \frac{1}{\gamma^{-1} + \|\underline{\mu}\|_2^2 + 1 - \frac{\|\underline{\mu}\|_4^4}{\|\underline{\mu}\|_2^2}} \underline{\mu}$$

Estimator 3 ($\underline{\alpha}_3$):

There is now discussed a third proposal that has a less strict development but interesting performance characteristics. From the form of the two previously described estimators, the inventor forms:

$$\underline{x}_i = \underline{y}_i \mu_i \quad (31)$$

It follows that

$$E\{\underline{x}\} = \underline{h} E\{d\mu\} \quad (32)$$

The channel estimate should therefore be formed from the empirical expectations

$$\hat{\underline{h}} = \frac{\sum_i \underline{x}_i}{\sum_i d_i \mu_i} \quad (33)$$

However since d_i is not known, $\text{sign}(\mu_i)$ is employed as an estimate of d_i i.e.,

$$\begin{aligned}\sum_i d_i \mu_i &= \sum_i d_i |\mu_i| \text{sign}(\mu_i) \\ &\approx \sum_i |\mu_i|\end{aligned}$$

The third estimator is therefore

$$\underline{\alpha} = \frac{1}{\|\underline{\mu}\|_1} \underline{\mu}$$

In summary three suboptimal MMSE-based filters $(\underline{\alpha}_1, \underline{\alpha}_2, \underline{\alpha}_3)$ for the estimation of $\underline{h}_k$ have been formulated. All are co-linear with $\underline{\mu}$.

$$\underline{\alpha}_1 = \frac{1}{\gamma^{-1} + \|\underline{\mu}\|_2^2} \underline{\mu}$$

$$\underline{\alpha}_2 = \frac{1}{\gamma^{-1} + \|\underline{\mu}\|_2^2 + 1 - \frac{\|\underline{\mu}\|_4^4}{\|\underline{\mu}\|_2^2}} \underline{\mu}$$

$$\underline{\alpha}_3 = \frac{1}{\|\underline{\mu}\|_1} \underline{\mu}$$

It should be observed that the second estimator is equivalent to the first if $\|\underline{\mu}\|_4^4 = \|\underline{\mu}\|_2^2$ which occurs when $\|\underline{\mu}\|$ approaches unity. For sufficiently large L and non-zero means $\underline{\mu}$ we can see that $\|\underline{\mu}\|_2^2 \gg \gamma^{-1}$. Since the signal-to-noise ratio (SNR) may be difficult to

estimate this assumption provides the benefit of dropping the SNR terms from the bottom line of the filters.

Since $|x_i| \leq 1 \forall i$ we have

$$\|\underline{x}\|_1 \geq \|\underline{x}\|_2^2 \geq \|\underline{x}\|_4^4$$

which implies that

$$\|\underline{\alpha}_3\| \leq \|\underline{\alpha}_2\| \leq \|\underline{\alpha}_1\|$$

according to any natural norm. Loosely speaking, $\underline{\alpha}_3$ constructs "conservative" short channel estimates while $\underline{\alpha}_3$ is more "bold". As shall be seen, this "attitude" is important when the estimators are misled by incorrect priors as occurs in practice.

Note that when $|\mu_i| = 1 \forall i$ all of the estimators are equivalent to the MMSE if the SNR term is ignored.

The following description verifies the effectiveness of the proposed approximate MMSE channel estimators for the case where the priors on the symbols are not uniform and also when the receiver is given only estimates of these prior distributions.

Figure 1 shows the MSE performance of all four proposals. As expected the true MMSE estimator is better than the others. The simplest estimator (α_3) has the worst MSE performance of all. The theoretical performance is also shown in Figure 1 and good agreement with simulation is observed. Note that if hard priors were employed (i.e. $p(d)$ is an impulse at either -1 or +1) then all but α_3 provide MMSE performance. The L

priors were chosen by first taking L realisation of a uniform random variable on the real line $(0.8, 1)$. These values were then randomly assigned to either $p(d = -1)$ or $p(d = 1)$ with equal likelihood. The complementary probability was then set according to $p(d = -1) + p(d = 1) = 1$.

Considering the case where the true priors are hard (i.e. $p(d)$ is an impulse at either -1 or $+1$) but only estimates of these priors are available at tile receiver, attempts are made to model the scenario of a channel estimator that uses decision feedback. In order to model the errors in the priors estimated at the receiver one simply adds a random quantity drawn from a Gaussian distribution with variance D and mean zero to each of the true probabilities describing tile prior distribution. If the result probability is negative, then a new random quantity is selected. The two probabilities are then jointly scaled to fix $p(d = -1) + p(d = +1) = 1$. Consequently all four estimator are derived according to the incorrect priors. Using this error scenario, the behaviour of the four estimators is shown in Figure 2.

There are several interesting aspects in this result. Firstly, the MMSE estimator which like the other three estimators, was designed according to the incorrect priors does not have the best performance. Furthermore, the simplest estimator provides the best MSE performance for moderate inaccuracies in the priors. This observation is of significant practical importance.

It is stressed that the way in which errors are introduced in this example is arbitrary and may not reflect well the situation in practice.

A final observation is that the MSE performance of the MMSE, the α_1 and the α_2 estimators can be seen to improve with increasing inaccuracy in the priors. This can only explain this by the following scenario. As the noise added to the priors used to construct

the estimators becomes larger the Euclidean length of the estimator becomes shorter. The shorter the estimator, the lower the worst possible performance of the estimator, e.g. the all zero estimator can make no greater MSE than w , the energy in the actual channel. Following this unusual behaviour, the performance of the simplest channel estimator α_3 was studied as applied to the CDMA case.

Some of the previously discussed channel estimation procedures are now employed in a practical example, indeed the example used to derive the problem in the first place.

According to Equation 12 we must perform an interference cancellation before applying the estimators. Once this cancellation is performed a channel estimation is formed for each user independently. These individual channel estimates can then be used to form $\underline{A}_{AM}$. The previously described α_1 and α_2 estimators were studied. The priors used to construct the channel estimators are provided by the previous iterations of the receiver. The key aspects of this integrated channel estimation process are:

1. It is iterative with $\underline{A}_{AM}$ being changed with iteration;
2. Multiple access interference is removed before processing; and
3. A short training sequence is required to get an initial estimate.

A system diagram of the integrated channel estimator is shown in Figure 3. For details of the other blocks shown in Figure 3, reference should be made to [2]. Using results from [2] a performance analysis may be possible.

Using the channel estimation routine shown in Figure 3, it is hoped that over iterations both the data and channel estimate accuracy will improve. An example of this behaviour is shown in Figure 4 for user 1 with

- $K = 15$ users
- $N = 10$ spreading code length (BPSK modulation)

- $B = 3$ antenna elements
- $M = 2$ multipath components
- rate $1/2$, $G = 5, 7$ convolution code
- $E_b/N_0 = 2$ dB

The channel estimate is shown in Figure 4 along with the actual channel with dashed lines for real parts of the channel. Three iterations of the receiver are executed. The value of the channel estimate at iteration 0 is based on only channel observations since the decoders have not been employed yet. These initial channel estimates are very inaccurate compared to the final estimate, e.g., the real parts of taps 1 and 2. 10 training symbols with 190 information carrying symbols were used. Note that the tap convergence is not monotonic.

Figure 5 shows the performance of the receiver shown in Figure 3 with three channel estimators. In particular, α_1 and α_2 estimators are compared to the case where the channel is known exactly. The conditions of the simulation are the same as for Figure 4. It can be seen that there is little difference between the two MMSE-based channel estimators. There is a significant difference between the performance of the perfect case and the estimated case for a particular iteration. However, by the third iteration the system with channel estimation (of either kind) has very nearly achieved the ideal of single user performance. Thus, the imperfect channel knowledge has been traded for an extra iteration.



CLAIMS:

1. A method of channel estimation comprising the steps of: receiving a signal consisting of a superposition of signals from a plurality of channels; from the signal constructing an observation sequence estimate which models the contributions to the signal from each channel; constructing from the observation sequence estimate an estimate modelling the behaviour of each channel, the estimate being dependent on a number of parameters; computing at least one contribution to the observation sequence estimate for each channel which is not dependent on at least one of the parameters, the contributions being functions of some or all of the estimates modelling the behaviour of the other channels; and for each of the contributions removing the contribution from the observation sequence estimate to form a new estimate modelling the behaviour of each channel.
2. A method according to Claim 1, wherein the channels are CDMA channels.
3. A method according to Claim 1 or 2, wherein the process is repeated iteratively, the estimates computed for some or all of the channels from one observation sequence estimate being utilised in the formulation of estimates from the next or subsequent observation sequence estimates.



4. A method according to any preceding claim, wherein the estimates are computed using a linear function.

5. A method according to any preceding claim, wherein the at least one contribution to the observation sequence estimate which is not dependent on at least one of the parameters is removed from the observation sequence estimate by subtraction.

6. A method according to any preceding Claim, wherein the observation sequence estimate is

$$e[n] = \sum_{j,k,l} \alpha_{n,j,k,l} h_{k,j}[i] d_k[i],$$

where: the transmitted data sequences are $d_k[i]$; the effect of the channel is characterised by channel coefficient sequences $h_{k,j}[i]$; n , i , j and k are integers, n being the observation sample number; i being an index of the transmitted data sequence, j being an index of the diversity path of the transmitted data sequence and k indexing the users; and $\alpha_{n,j,k,l}$ provides for the timeliness of the transmitted data sequences appearance in the observation sequence estimate and provides facility for deterministic gain in the contribution of the modified data sequences to the observation sequence estimate.

7. A method according to Claim 6, wherein the method of constructing the new estimate modelling the behaviour of each channel includes two stages, the first of these



stages consisting of the removal of interference due to other channels from the observation sequence estimate, and the second of the stages consisting of the application of the constraints, whether linear or non-linear, to which the channel sequence must adhere.

8. A method according to Claim 7, wherein the equations for performing the first stage of calculating new estimates modelling the behaviour of a channel include:

$$x_k^d[n] = e[n] - \sum_j \sum_{k' \neq k} \sum_i \alpha_{n,j,k',i} \hat{h}_{k',j}[i] \hat{d}_k[i]; \text{ and}$$

$$x_{k,j}^h[n] = e[n] - \sum_{j' \neq j} \sum_{k' \neq k} \sum_i \alpha_{n,j',k',i} \hat{h}_{k',j'}[i] \hat{d}_k[i].$$

9. A method according to Claim 8, wherein the first stage of calculating new estimates modelling the behaviour of a channel is performed by first computing $z[n]$, where

$$z[n] = e[n] - \sum_{j,k,i} \alpha_{n,j,k,i} \hat{h}_{j,k}[i] \hat{d}_k[i],$$

and then obtaining $x_k^d[n]$ and $x_{k,j}^h[n]$ using the equations

$$x_k^d[n] = z[n] + \sum_j \sum_i \alpha_{n,j,k,i} \hat{h}_{k,j}[i] \hat{d}_k[i]$$

and



$$x_{k,j}^h[n] = z[n] + \sum_i \alpha_{n,j,k,j} \hat{h}_{k,j}[i] \hat{d}_k[i].$$

10. A channel estimator for performing channel estimation on a plurality of channels, including: means for receiving a signal consisting of a superposition of signals from a plurality of channels; means for constructing, from the signal, an observation sequence estimate modelling the contributions to the signal from each channel; means for constructing, from the observation sequence estimate an estimate modelling the behaviour of each channel, the estimate being dependent on a number of parameters; means for computing at least one contribution to the observation sequence estimate for each channel which is not dependent on at least one of the parameters, the contributions being functions of some or all of the estimates modelling the behaviour of the other channels; and means for removing the contribution, for each of the contributions, from the observation sequence estimate to form a new estimate modelling the behaviour of each channel.