ADAPTIVE BLIND CHIP-LEVEL MULTIUSER DETECTION IN MULTI-RATE SYNCHRONOUS DS-CDMA SYSTEM WITH PARTIAL LOADING

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ABSTRACT

This paper addresses an adaptive blind multiuser detection strategy for a multi-rate direct sequence CDMA downlink channel. Specifically, two chip-level equalisation schemes, using either variable spreading length (VSL) or multi-code (MCD) multi-rate access modes, are proposed and tested. Both equalisers can be updated by minimising a hybrid CM/MSE cost function based on the constant modulus (CM) criterion for active users and a mean square error (MSE) criterion for inactive users in a partially loaded system. The BER performance and the convergence of the proposed algorithms are analysed and compared through various simulations in both partially or fully loaded systems. Essentially, our results show that the VSL algorithm exhibits faster convergence than the MCD scheme while similar BER performance over different multi-path channels is achieved.

1. INTRODUCTION

Next generation wireless systems are required to provide high-speed access and support various multi-rate services such as voice, video, data etc. Two approaches namely, multi-code (MCD) and variable spreading length (VSL) also called multiple processing gain (MPG) or variable processing gain (VPG) access schemes, have been proposed to support such multi-rate services [4, 5]. Since both schemes are based on direct sequence (DS) CDMA techniques, the system's performance over a dispersive channel is limited mainly due to multiple access interference (MAI) and inter-symbol interference (ISI). Significant efforts have focused on developing multiuser detection techniques to suppress MAI and ISI. Specifically, blind detection strategies can offer better spectrum efficiency by not requiring pilot signals or training sequences [1, 7, 8, 6].

A popular blind approach to suppress MAI and ISI is the minimum output energy (MOE) algorithm, cancelling MAI and ISI terms but passing the desired user by constraints [2]. Other blind schemes have been performed using the CM criterion [7, 3], whereby additional mutual deccorelation of the recovered user sequence is required. Alternatively, In [8] a blind scheme, so called FIRMER-CMA, similar to [7, 3] but neither constraint nor mutual deccorelation are required, has been developed. Since the FIRMER-CMA algorithm is only suitable for fully loaded systems, a hybrid CM/MSE algorithm, suitable for partial loading scenario, is derived in [9]. However in both algorithms [8, 9] multi-rate services have not been considered.

In response to this scenario, we propose in this paper two blind chip-level equalisers similar in structure to [9] which can support either VSL or MCD multi-rate access modes. Based on a brief definition of the VSL and MCD signal models in Sec. 2, a hybrid CM/MSE cost function is derived for each model in Sec. 3. The performance of the proposed equalisers is compared and analysed in Sec. 4, and conclusions are drawn in Sec. 5.

2. SIGNAL MODEL

We consider the DS-CDMA downlink model in Fig. 1 with a maximum of M symbol-synchronous active users, $l = 0(1)M-1$, which can support multi-rate signals with different processing gains N_l, $l = 0(1)M-1$, by using either VSL or MCD access modes. Let N denote the basic processing gain (lowest rate), therfore $N = \max(N_l)$, and the ratio $N/N_l = d_l$ where d_l is an integer. In the case of a partially loaded system with $K \leq M$, we assume the first K users with signals $u_l[n_l]$, $l = 0(1)K-1$, to be active, while for the remaining $K - M$ user signals $u_l[n_l] = 0$, $\forall n_l, l = K(1)M-1$. Note that n_l is the l^th user's symbols index.

In the VSL scheme, the chip rate is constant, and the signals $u_l[n_l]$ are code multiplexed using Walsh sequences of different lengths N_l. In MCD systems, the signals streams $u_l[n_l]$ are split into d_l sub-streams. These sub-streams can be considered as virtual user signals with the same processing gain N at the same basic rate, which are code multiplexed using Walsh sequences extracted from an $N \times N$ Hadamard matrix. As shown in Fig. 1, in both modes the resulting chip rate signal is further scrambled by $c[m]$ prior to transmission over a dispersive channel with impulse response $g[m]$ and corruption by additive white Gaussian

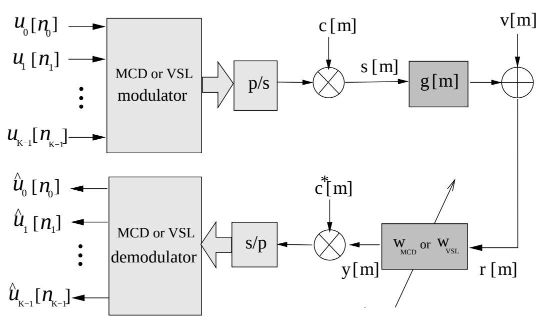

Fig. 1. Multi-rate DS-CDMA downlink signal model.

noise $v[m]$, which is assumed to be independent of the transmitted signal $s[m]$.

In the system model given on Fig. 1, the dispersive channel $g[m]$ destroys the orthogonality of the Walsh codes, such that direct decoding of the received signal $r[m]$ with descrambling by $c^*[m]$ and code-matched filtering will lead to MAI and ISI corruption of the decoded user signals. In order to re-establish orthogonality of the codes, a chip rate equaliser can be utilised. In the following, we are concerned with the blind updating of the equaliser coefficients $w_{\mathrm{VSL}}[m]$ and $w_{\mathrm{MCD}}[m]$ in both VSL and MCD modes. Before we present the proposed equalisation criteria adopted, we first derive the detected user signals $u_l[n_l]$ as a function of the chip-rate equaliser, in both modes. To avoid cumbersome notation, we use the same signals notations for the two systems (the difference being clear from the context).

2.1. VSL Systems

For the decoding, Walsh sequences are used as matched filters. In the VSL system, the sequence for decoding the lth user, contained in a vector $\mathbf{h}_l^{N_l}$, can be taken from an $N_l \times N_l$ Hadamard matrix. The lth user is thus decoded as

$$\hat{u}_l[n_l] = (\mathbf{h}_l^{N_l})^{\mathrm{T}} \cdot \begin{bmatrix} c^*[n_lN_l] & & \mathbf{0} \\ & c^*[n_lN_l-1] & \\ & & \ddots \\ \mathbf{0} & & c^*[n_lN_l-N_l+1] \end{bmatrix} \cdot \begin{bmatrix} y[n_lN_l] \\ y[n_lN_l-1] \\ \vdots \\ y[n_lN_l-N_l+1] \end{bmatrix}$$

$$= (\tilde{\mathbf{h}}_l^{N_l}[n_lN_l])^{\mathrm{T}} \cdot \begin{bmatrix} \mathbf{w}_{\mathrm{VSL}}^{\mathrm{H}} & & \mathbf{0} \\ & \mathbf{w}_{\mathrm{VSL}}^{\mathrm{H}} & \\ & & \ddots \\ \mathbf{0} & & \mathbf{w}_{\mathrm{VSL}}^{\mathrm{H}} \end{bmatrix} \cdot \begin{bmatrix} r[n_lN_l] \\ r[n_lN_l-1] \\ \vdots \\ r[n_lN_l-L-N_l+2] \end{bmatrix}$$

The operator $(\cdot)^*$ is the complex conjugate of $(\cdot)$, and the superscripts $(\cdot)^{\mathrm{T}}$ and $(\cdot)^{\mathrm{H}}$ denote the transpose and the Hermitian operators respectively, and $y[m]$ is the equaliser output signal. The descrambling code $c^*[m]$ has been absorbed into a modified and time-varying code vector $\tilde{\mathbf{h}}_l^{N_l}[n_lN_l]$, and $\mathbf{w}_{\mathrm{VSL}} \in \mathbb{C}^L$ contains the equaliser's L chip-spaced complex conjugate weights. Rearranging $\mathbf{w}_{\mathrm{VSL}}$ and and $\tilde{\mathbf{h}}_l^{N_l}[n_lN_l]$ yields

$$\hat{u}_l[n_l] = \mathbf{w}_{\mathrm{VSL}}^{\mathrm{H}} \cdot \begin{bmatrix} (\tilde{\mathbf{h}}_l^{N_l}[n_lN_l])^{\mathrm{T}} & & \mathbf{0} \\ & (\tilde{\mathbf{h}}_l^{N_l}[n_lN_l])^{\mathrm{T}} & \\ & & \ddots \\ \mathbf{0} & & (\tilde{\mathbf{h}}_l^{N_l}[n_lN_l])^{\mathrm{T}} \end{bmatrix} \cdot \begin{bmatrix} r[n_lN_l] \\ r[n_lN_l-1] \\ \vdots \\ r[n_lN_l-L-N_l+2] \end{bmatrix}$$

$$= \mathbf{w}_{\mathrm{VSL}}^{\mathrm{H}} \, \mathbf{H}_l^{N_l}[n_lN_l] \, \mathbf{r}_{n_lN_l}, \qquad (1)$$

with $\mathbf{H}_l^{N_l}[n_lN_l] \in \mathbb{C}^{L\times(N_l+L-1)}$ being a convolutional matrix comprising of the lth user's modified code vector $\tilde{\mathbf{h}}^{N_l}[n_lN_l]$ and $\mathbf{r}_{n_lN_l} \in \mathbb{C}^{N_l+L-1}$.

2.2. MCD Systems

In MCD systems, the signal streams $u_l[n_l]$ are split into d_l sub-streams $u_{l,p}[n]$, $p = 0(1)d_l - 1$, where p denotes the sub-stream number. The pth sub-stream of the lth user signal $u_{l,p}[n]$ can be derived, as shown in Fig. 2, from the original signal stream as follows

$$u_{l,p}[n] \quad = \quad u_l[nd_l + p]. \qquad (2)$$

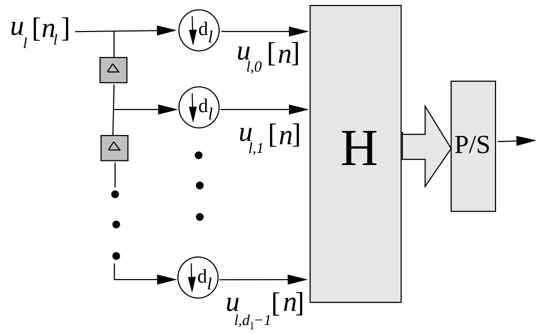

Fig. 2. Multi-code (MCD) transmission scheme, whereby a high rate user is demultiplexed into d_l low rate signals.

These sub-streams can be considered as virtual users signals, which are code multiplexed using Walsh sequences $\mathbf{h}_{l,p}$ extracted from an $N \times N$ Hadamard matrix. Similar to the analysis in Sec. 2.1, the pth virtual user of the lth user signal is decoded as :

$$\hat{u}_{l,p}[n] = \mathbf{w}_{\mathrm{MCD}}^{\mathrm{H}} \cdot \begin{bmatrix} \tilde{\mathbf{h}}_{l,p}^{\mathrm{T}}[nN] & & \mathbf{0} \\ & \tilde{\mathbf{h}}_{l,p}^{\mathrm{T}}[nN] & \\ & & \ddots \\ \mathbf{0} & & \tilde{\mathbf{h}}_{l,p}^{\mathrm{T}}[nN] \end{bmatrix} \cdot \begin{bmatrix} r[nN] \\ r[nN-1] \\ \vdots \\ r[nN-L-N+2] \end{bmatrix}$$

$$= \mathbf{w}_{\mathrm{MCD}}^{\mathrm{H}} \, \mathbf{H}_{l,p}[nN] \, \mathbf{r}_{nN}, \qquad (3)$$

with $\mathbf{H}_{l,p}[nN] \in \mathbb{C}^{L\times(N+L-1)}$ being a convolutional matrix comprising of the pth virtual user's modified code vector $\tilde{\mathbf{h}}_{l,p}[nN]$.

3. PROPOSED EQUALISATION CRITERIA

Let us assume that the K active user signals $u_l[n_l]$ consist of symbols with a constant modulus γ, such as BPSK, QPSK, or 8-PSK. Therefore, the idea is to blindly adapt the equaliser and track any channel variations by forcing all received active user symbols onto a constant modulus while minimising decoded inactive user symbols to zero in the mean square error (MSE) sense. Accordingly two hybrid cost functions for VSL and MCD modes arise.

3.1. Cost Functions

For the VSL scheme we define

$$\xi_{\mathrm{VSL}} = \sum_{l=0}^{K-1} \mathcal{E}\{(\gamma^2 - |\hat{u}_l[n_l]|^2)^2)\} + \sum_{l=K}^{M-1} \mathcal{E}\left\{(|\hat{u}_l[n_l]|)^2\right\}, \quad (4)$$

while for MCD we have

$$\xi_{\mathrm{MCD}} = \mathcal{E}\left\{\sum_{l=0}^{K-1}\sum_{p=0}^{d_l-1}(\gamma^2 - |\hat{u}_{l,p}[n]|^2)^2\right\} + \mathcal{E}\left\{\sum_{l=K}^{M-1}\sum_{p=0}^{d_l-1}(\hat{u}_{l,p}[n])^2\right\}, \quad (5)$$

where γ is the modulus of active user symbols, and $\mathcal{E}\{\cdot\}$ is the expectation operator. The equaliser coefficients in both VSL and MCD systems can be determined such the proposed cost functions are minimised. A Simple recursive rule, called stochastic gradient descent technique is presented in the next section.

3.2. Stochastic Gradient Adaptation

Both cost functions are minimised in order to update equaliser coefficients $\mathbf{w}_n$, by using a simple stochastic gradient descent algorithm

$$\mathbf{w}_{n+1} = \mathbf{w}_n - \mu \nabla \hat{\xi} \tag{6}$$
$$\text{with } \hat{\xi} \in \left\{ \hat{\xi}_{\mathrm{MCD}}, \hat{\xi}_{\mathrm{VSL}} \right\}, \text{ and } \mathbf{w} \in \{\mathbf{w}_{\mathrm{MCD}}, \mathbf{w}_{\mathrm{VSL}}\}$$

where μ is the algorithm step size, and ∇ the gradient operator applied to instantaneous cost functions $\hat{\xi}_{\mathrm{MCD}}$ and $\hat{\xi}_{\mathrm{VLS}}$, i.e omitting expectation operators in (4) and (5). By applying complex vector calculus and using (1) and (3), the gradient term, in both systems, can be obtained.

VSL System. For the VSL systems the gradient of the instantaneous cost function $\hat{\xi}_{\mathrm{VLS}}$ can be derived as:

$$\frac{\partial \hat{\xi}_{\mathrm{VSL}}}{\partial \mathbf{w}^*_{\mathrm{VSL}}} = -2 \sum_{l=0}^{K-1} \left\{ (\gamma^2 - |\hat{u}_l[n_l]|^2) \mathbf{H}_l^{\mathrm{N}_1}[n_l N_l] \mathbf{r}_{n_l N_l} \; \hat{u}_l^*[n_l] \right\} + + \sum_{l=K}^{M-1} \left\{ \mathbf{H}_l^{\mathrm{N}_1}[n_l N_l] \mathbf{r}_{n_l N_l} \; \hat{u}_l^*[n_l] \right\} \tag{7}$$

MCD System. Similarly the gradient of the instantaneous cost function $\hat{\xi}_{\mathrm{MCD}}$ can be writen as

$$\frac{\partial \hat{\xi}_{\mathrm{MCD}}}{\partial \mathbf{w}^*_{\mathrm{MCD}}} = -2 \sum_{l=0}^{K-1} \sum_{p=0}^{d_l-1} \{ (\gamma^2 - |\hat{u}_{l,p}[n]|^2) \mathbf{H}_{l,p}[nN] \mathbf{r}_{nN} \; \hat{u}^*_{l,p}[n] \} + + \sum_{l=K}^{M-1} \sum_{p=0}^{d_l-1} \{ \mathbf{H}_{l,p}[nN] \mathbf{r}_{nN} \; \hat{u}^*_{l,p}[n] \} \tag{8}$$

The algorithms described by (6) with its component, either in (7) for VSL mode or (8) for MCD scheme, differs from the standard CM algorithm [10] or its extension in [3] in the inclusion of a code filtered term $\mathbf{H}_l^{\mathrm{N}_1}[n_l N_l] \mathbf{r}_{n_l N_l}$ or $\mathbf{H}_{l,p}[nN] \mathbf{r}_{nN}$ rather than just the equaliser input $r[n]$.

4. SIMULATION RESULTS

We analyse and compare the performance of the two MCD and VSL equalisers in a multirate DS-CDMA downlink system with a basic processing gain $N = 256$ for mainly two different transmission scenarios. In the first scenario, we assume a fully loaded system with 9 users, 2 low rate users with spreading factor of 256, and the seven remaining users with a set of spreading factors of $\{2, 4, 8, 16, 32, 64, 128\}$. In the second scenario, we assume a partially loaded system, whereby one of the precedent users is removed. We first demonstrate and compare the convergence behaviour in Sec. 4.1 and later the bit error performance in Sec. 4.2.

4.1. Convergence

We utilise the two proposed algorithms to update two chip-level equalisers with $L = 10$ coefficients over a three path dispersive channel. The adaptation is initialised with the second coefficient in the weight vector set to unity. With the step size selected such as to obtain the half of the maximum convergence speed without incuring divergence. The evolution of the filter coefficients' real part of the two algorithms, in a fully loading scenario are shown in Fig. 3, and the convergence behaviour of the learning curves of both algorithms for two partially loading schemes, whereby either the user with spreading gain $N_8 = 256$ or $N_7 = 128$ have been removed, is demonstrated in Fig. 4. Obviously, the VSL-CDMA system exhibits faster convergence than the MCD-CDMA system for both fully and partially loading scenarios.

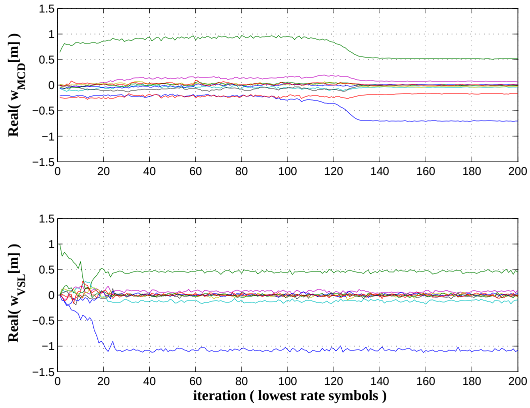

Fig. 3. Convergence behaviour of the fully loaded system with $N = 256$ over a dispersive channel with $\mathrm{SNR} = 20$dB, (top) MCD-CDMA mode, and (bottom) VSL-CDMA scheme.

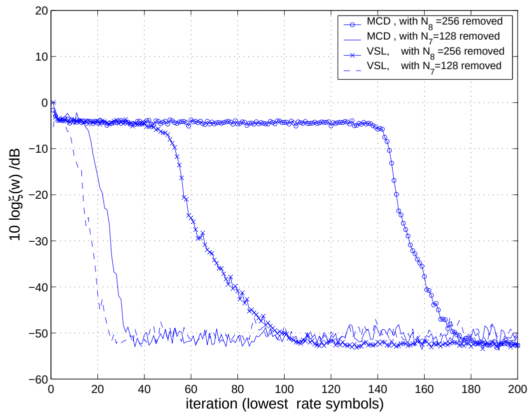

Fig. 4. Learning curves of the partially loaded system, of both MCD-CDMA and VSL-CDMA modes.

It can be noted from Figs. 3 and 4 that the algorithms succeed to minimise their cost functions, whereby a remaining error floor is due to model truncation. Moreover, inactivating user (here with $N_7 = 128$) can be seen to improve the convergence of both systems considerably compare to systems with stronger loading.

4.2. Bit Error Performance

In order to assess the BER performance, the algorithms have been adapted for various SNRs, and the CMA's phase ambiguity has been recovered. Fig. 5 shows the BER of both MCD and VSL modes in three cases, fully loaded system with 9 active users which have the following spreading gains 2,4,8,16,32,64,128,256,and 256 respectively; in the second case, the user with spreading gain of 128 was removed, and finaly the user with spreading gain 4 is inactive. The BER performance is compared to the optimal QPSK performance in a dispersion-free AWGN channel. Note that the

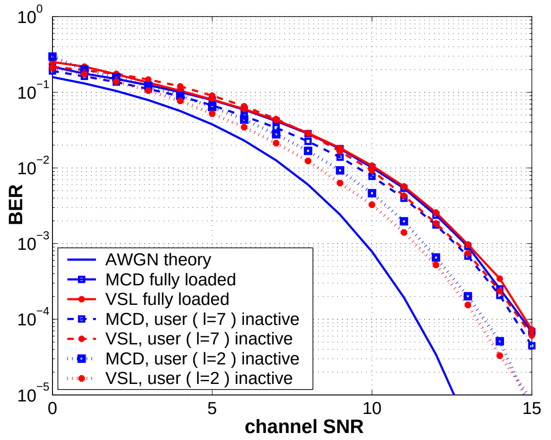

Fig. 5. BER performance proposed algorithm of both VSL and MCD modes in three cases, fully loaded system, partially loading with one inactive user with $N_7 = 128$, partially loading with one removed user with $N_2 = 4$, compared to the BER in an AWGN channel.

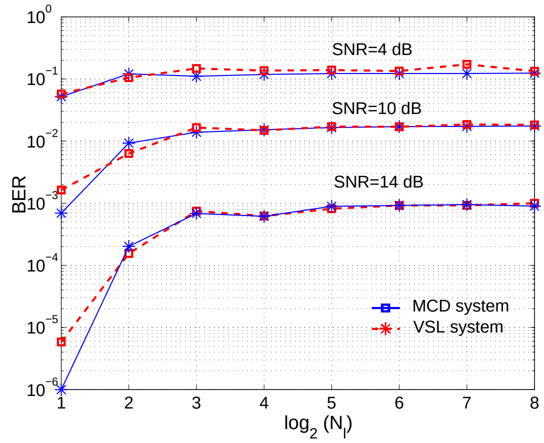

Fig. 6. BER performance of both modes in dependence of the spreading gain of the removed user for different channel SNR values.

two proposed algorithms show similar bit error performance in both fully loaded system and the partially loading case when the inactive user is close to the basic rate ; however the BER curves of both modes exhibit better performonce when the inactive user has a higher rate $N_2 = 4$ than the two other cases. In Fig. 6 represents the effect of the rate of the inactive user on the BER performance of both modes. Note that both modes MCD and VSL show similar BER performance when the removed user has low rate, close to the basic one. It is clear that within the hybrid cost function, the MSE term for inactive users generally can, if present, enhance the system performance significantly.

5. CONCLUSIONS

Two blind chip-level equalisation approaches using either VSL or MCD access modes for a DS-CDMA downlink scenario with partial loading have been presented, which differ from previously blind algorithms by code-prefiltering of its input and require no additional constraints. Two hybrid CM/MSE blind equalisation algorithms are derived to be minimised, in order to enforce CM conditions on various active user signals and MSE criteria on the remaining inactive users. The VSL algorithm shows faster convergence and outperforms the MCD equaliser in both fully and partially loaded systems. Similar BER performance in fully loaded system and partially loading has been noticed when the inactive user has low rate.

6. REFERENCES

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