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CENTRALIZED ADAPTIVE MMSE DETECTORS FOR MULTIRATE DS-CDMA IN MULTIPATH FADING CHANNELS

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Abstract:

Future mobile systems will support services with different data rates. In this paper, we propose centralized feed-forward feedback architectures for adaptive Minimum Mean Square Error (MMSE) detectors for asynchronous multirate Direct Sequence Code Division Multiple Access (DS-CDMA) systems. A multipath Rayleigh fading channel is assumed. The MMSE detector is implemented using the Recursive Least Squares (RLS) algorithm. We compare between the different proposed architectures and the results are verified using simulations.

1. Introduction:

With the rapid growth of cellular networks, portable computing, and high speed fixed networks as the Internet, there has been a great demand to integrate fixed wired networks with wireless mobile networks. Future third generation Direct Sequence Code Division Multiple Access (DS-CDMA) systems are required to support a variety of multimedia applications including voice, data, facsimiles, and video. To communicate multiple data rates using the same modulation scheme, different access schemes have been developed for multirate DS-CDMA.

The popular schemes are the Multi-Code (MC), the Variable Spreading Length (VSL), and the Variable Chip Rate (VCR) access schemes. In the MC scheme, a user is assigned a number of spreading codes proportional to its data rate. In the VSL scheme, the code spreading gains are inversely proportional to the data rates. In the VCR scheme, the chip rates are proportional to the data rates. An MC CDMA access scheme results in a single rate system with a signaling rate equal to that of the lowest data rate but this scheme has a poor performance and suffers from the delays due to multiplexing the high rate data and transmitting it in parallel [1][2].

We consider centralized adaptive Minimum Mean Square Error (MMSE) receivers for multirate DS-CDMA systems employing the VCR or the VSL access schemes over an asynchronous multipath Rayleigh fading channel. The detector is centralized in the sense that different users with different data rates are detected. We propose different Feed-Forward Feed-Back (FF-FB) architectures for the implementation of the adaptive MMSE receiver in a multirate system.

2. Multirate System Model:

For simplicity, we consider a dual data rate, asynchronous DS-CDMA system. The ratio between the High Rate (HR) and the Low Rate (LR) is M such that $T_s^{(l)} = MT_s^{(h)}$, $T_s^{(.)}$ is the symbol duration, and the superscripts *(l)* and *(h)* refer to the LR and HR users respectively. The received baseband signal model can be written as

$$r(t) = \sum_{n=-\infty}^{\infty}\left(\sum_{k=1}^{K^{(l)}} r_k^{(l)}(n) + \sum_{k=1}^{K^{(h)}} r_k^{(h)}(n)\right) + z(t), \tag{1}$$

where $K^{(l)}$ and $K^{(h)}$ are the number of the LR and HR users respectively and $z(t)$ is an Additive White Gaussian Noise (AWGN) with zero mean and variance $\sigma_z^{\,2} = N_o/2$. The received signal due to user k sampled at a multiple U of the chip rate is $r_k^{(.)}(n) = \sum_{m=-\infty}^{\infty} A_k^{(.)} d_k^{(.)}(m) h_k^{(.)}(n - mN^{(.)}U)$, where $A_k^{(.)}$ is the received amplitude of user k, $d_k^{(.)}(n) = a_k^{(.)}(n) + jb_k^{(.)}(n)$ is the n_{th} QPSK symbol of the k_{th} user with variance $\left(\sigma_d^{(.)}\right)^2$ and is uncorrelated within and among users. $N^{(.)}$ is the spreading gain. The signature of user k is

$$h_k^{(.)}(n) = \sum_{m=-\infty}^{\infty} g_k^{(.)}(m) s_k^{(.)}(n - mU - \Delta_k U) \tag{2}$$

such that the k_{th} user's normalized spreading sequence is $s_k^{(.)} = [s_k^{(.)}(0),....,s_k^{(.)}(N^{(.)}-1)]^T \in [0, T_s^{(.)})$, ${s_k^{(.)}}^T s_k^{(.)} = 1$, $N^{(.)} = T_s^{(.)} / T_c^{(.)}$ where $T_c^{(.)}$ is the chip duration , $\tau_k^{(.)} = \Delta_k T_c^{(.)} \in [0, T_s^{(.)})$ is the delay of the k_{th} user, and $g_k^{(.)}(n) = g_k(t)\Big|_{t=n(T_c^{(.)}/U)}$ is the sampled vector of the multipath channel impulse response of unity gain and maximum order $q^{(.)}$ such that $\|h_k\| = 1$ and $q^{(.)} = \left\lceil T_m / T_c^{(.)} \right\rceil$, where $\lceil \; \rceil$ denotes upper integer and T_m is the delay spread. The multipath channel impulse response is $g_k(t) = \sum_{p=1}^{P} \alpha_{k,p} \delta(t - \tau_{k,p})$ where $\tau_{k,p} \in [0, T_m)$ and $\alpha_{k,p}$ are the delay and complex gain of the p_{th} path of the k_{th} user respectively.

For linear detection, the soft output of the filter having tap weight vector, $w_k^{(.)}$, is

$$\hat{d}_k^{(.)}(n) = \left(\hat{a}_k^{(.)}(n) + j\hat{b}_k^{(.)}(n)\right) = {w_k^{(.)}}^H(n) r^{(.)}(n), \tag{3}$$

where $(.)^H$ is the Hermitian transpose, and the hard output is

$$\tilde{d}_k^{(.)}(n) = \tilde{a}_k^{(.)}(n) + j\tilde{b}_k^{(.)}(n)\,,\ \tilde{a}_k^{(.)}(n) = \mathrm{sgn}(\hat{a}_k^{(.)}(n))\,, \text{ and } \tilde{b}_k^{(.)}(n) = \mathrm{sgn}(\hat{b}_k^{(.)}(n))\,, \tag{4}$$

where $r^{(.)}(n)$ is the received signal vector for the n_{th} symbol interval and is of length $\tilde{N}^{(h)}U$ and $\tilde{N}^{(l)}U$ for the high rate users and low rate users respectively, such that $\tilde{N}^{(.)}$ is the length of the user's observation window in terms of its chip duration.

3. MMSE Detection of Multirate Data

Centralized detectors with FF taps as well as FB taps are considered. In a Fully Connected (FC) receiver, all users having the same data rate share the same filter contents. We denote the contents of the FF filter acquired for the detection of the n_{th} symbol of user $k^{(.)}$ by $F^{(.)}(n)$ ($F^{(l)}$ and $F^{(h)}$ for the LR and HR users respectively). The FF tap-weight vector of the $k^{(.)}{}_{th}$ user is represented by $x_k^{(.)}$. The decision FB filter contains previous hard symbol decisions and its contents are denoted by the vector $\tilde{\tilde{d}}^{(.)}(n)$. The vector of the FB filter tap weights for user $k^{(.)}$ is in its turn denoted by $y_k^{(.)}$. The vector $w_k^{(.)} = \left[{x_k^{(.)}}^T, {y_k^{(.)}}^T\right]^T$ is the vector of aggregated FF and FB tap weights for user $k^{(.)}$ and the aggregated vector of the filter contents for the HR or the LR users is $v^{(.)}(n) = \left[\left(F^{(.)}(n)\right)^T, \left(\tilde{\tilde{d}}^{(.)}(n)\right)^T\right]^T$, such that $w_k^{(.)}$ and $v^{(.)}(n)$ are of size $\left(\tilde{N}_t^{(.)} \times 1\right)$ where $\tilde{N}_t^{(.)}$ is the total length of the filter. The MMSE filter applies the following detection rule,

$$\hat{d}_k^{(.)}(n) = {w_k^{(.)}}^H v^{(.)}(n) \text{ or } \hat{d}^{(.)}(n) = {W^{(.)}}^H v^{(.)}(n)\,, \tag{5}$$

where $\hat{d}_k^{(.)}(n)$ is the soft estimate of the n_{th} transmitted symbol, $d_k^{(.)}(n)$, of user $k^{(.)}$. The hard symbol decisions are given by Eq.(4). The vector of aggregated tap weight vectors for users with the same data rate is $W^{(.)} = [w_1^{(.)}, w_2^{(.)}, ..., w_K^{(.)}]$ and is of size $\left(\tilde{N}_t^{(.)} \times K^{(.)}\right)$, where $\hat{d}^{(.)}(n) = \left[\hat{d}_1^{(.)}(n), \hat{d}_2^{(.)}(n), ..., \hat{d}_K^{(.)}(n)\right]^T$. Denoting $(.)^+$ as the pseudo-inverse, the optimum weight vector achieving the MMSE solution is equal to [3]

$$w_k^{(.)} = \left(R^{(.)}\right)^+ J_k^{(.)}, \ \ W^{(.)} = \left(R^{(.)}\right)^+ J^{(.)} , \qquad (6)$$

where $J_k^{(.)} = E\left\{v^{(.)}(n)\left(d_k^{(.)}(n)\right)^*\right\}$ is the cross correlation between the desired response and the filter contents, $R^{(.)} = E\left\{v^{(.)}(n)\left(v^{(.)}(n)\right)^H\right\}$ with size $\left(\tilde{N}_t^{(.)} \times \tilde{N}_t^{(.)}\right)$ is the correlation matrix of the filter contents, $v^{(.)}(n)$. $J^{(.)} = E\left\{v^{(.)}(n)\left(d^{(.)}(n)\right)^H\right\} = [J_1^{(.)}, J_2^{(.)}, ..., J_K^{(.)}]$, where $d^{(.)}(n) = \left[d_1^{(.)}(n), d_2^{(.)}(n), ..., d_K^{(.)}(n)\right]^T$. $(.)^*$ is the complex conjugate. The MMSE filter can be implemented using the adaptive RLS algorithm [3] where $d_k^{(.)}(n)$ is used during the training mode and is replaced by $\tilde{d}_k^{(.)}(n)$ during the decision directed mode.

4. Feed-Forward MMSE Filters

We propose a Rate Connected (RC) FF filter where all users transmitting at the same data rate share the same FF filter contents. The FF filter contents are acquired by sampling the received signal at a multiple, *U*, of the chip rate which is equivalent to *U* Chip Matched Filters (CMF) acquiring chip rate samples at relative delays $T_c^{(.)}/U$. The number of samples acquired by each CMF is equal to $N_f^{(.)}$, where $N_f^{(.)} \geq N^{(.)} + T_m / T_c^{(.)}$ for synchronous CDMA and $N_f^{(.)} \geq 2N^{(.)} + T_m / T_c^{(.)}$ for asynchronous CDMA, to ensure that the FF filter spans all the desired users' signatures for the specified symbol interval [4][5]. The RC-FF filter has a total of $\tilde{N}_f^{(.)} = UN_f^{(.)}$ coefficients. The oversampling ratio, *U,* is to be as large as the complexity allows taking into consideration the convergence times of the adaptive algorithms. The total contents of the RC-FF filter are acquired at a rate of $1/T_s^{(.)}$ and are given by the vector,

$$F^{(.)} = \left[f(1), f(2), ..., f(\tilde{N}_f^{(.)})\right]^T . \qquad (7)$$

When employing the RC-FF filter architecture, we have two sets of FF filter contents, one for the HR users and the other for the LR users. Each filter spans all the desired signal energies corresponding to the symbols to be detected. Letting the users share their FF filter contents in that manner has the advantage of reducing the computational complexity and avoiding the receiver to synchronize to each user independently.

5. Rate Connected Feedback Filters

A Rate Connected (RC) FB filter is proposed. In a RC-FB filter, all users with the same data rate share the same FB filter contents. The FB filter for users transmitting at a data rate $1/T_s^{(.)}$ contains the previous $N_b^{(.)}$ detected symbols from all users having the same data rate. The RC-FB filter contains a total of $N_b^{(.)}K^{(.)}$ symbols sampled at a rate of $1/T_s^{(.)}$. The RC-FB filter has the advantage of suppressing the Inter-Symbol Interference (ISI) from the desired user, as well as subtracting the Multiple Access Interference (MAI) due to other users transmitting at the same data rate. A disadvantage of the RC-FB filter is that it ignores the MAI due to other users transmitting at a different data rate. Defining $\tilde{d}_k^{(.)} = \left[\tilde{d}_k^{(.)}(n-1), \tilde{d}_k^{(.)}(n-2), ..., \tilde{d}_k^{(.)}(n-N_b^{(.)})\right]^T$, the RC-FB filter contents are represented by,

$$\tilde{\tilde{d}}^{(.)}(n) = \left[\tilde{d}_1^{(.)T}, \tilde{d}_2^{(.)T}, ...\tilde{d}_{K^{(.)}}^{(.)\,T}\right]^T . \qquad (8)$$

6. Fully Connected Feedback Filters

A Fully Connected (FC) FB filter is also proposed where all users have access to previously detected symbols from all other users. Block diagrams for the RC-FF / FC-FB filter for the LR users at symbol index n^l, and HR users at symbol index n^h, are shown in Fig.(2) and Fig.(3) respectively.

Considering a dual rate system, we have the following transmitted pattern for a synchronous system:

$T_s^{(l)}$

$d_k^{(l)}(1)$			$d_k^{(l)}(2)$			....	$d_k^{(l)}(n)$		
$d_i^{(h)}(1)$	....	$d_i^{(h)}(M)$	$d_i^{(h)}(M+1)$	....	$d_i^{(h)}(2M)$	....	$d_i^{(h)}((n-1)M+1)$	....	$d_i^{(h)}(nM)$

$T_s^{(h)}$

Fig.(1) Pattern of transmitted symbols.for the LR user, *k*, and the HR user, *i.*

A similar pattern can be generated for an asynchronous multipath system by extending the observation window used for the detection of one symbol to span the transmitted symbol as well as its multipath components as described for the FF filter contents.

The FC-FB filter has two categories, the HR-FC-FB filter and the LR-FC-FB filter. The HR-FC-FB filter is the one designed for the HR users, where as the LR-FC-FB filter is the one designed for the LR users.

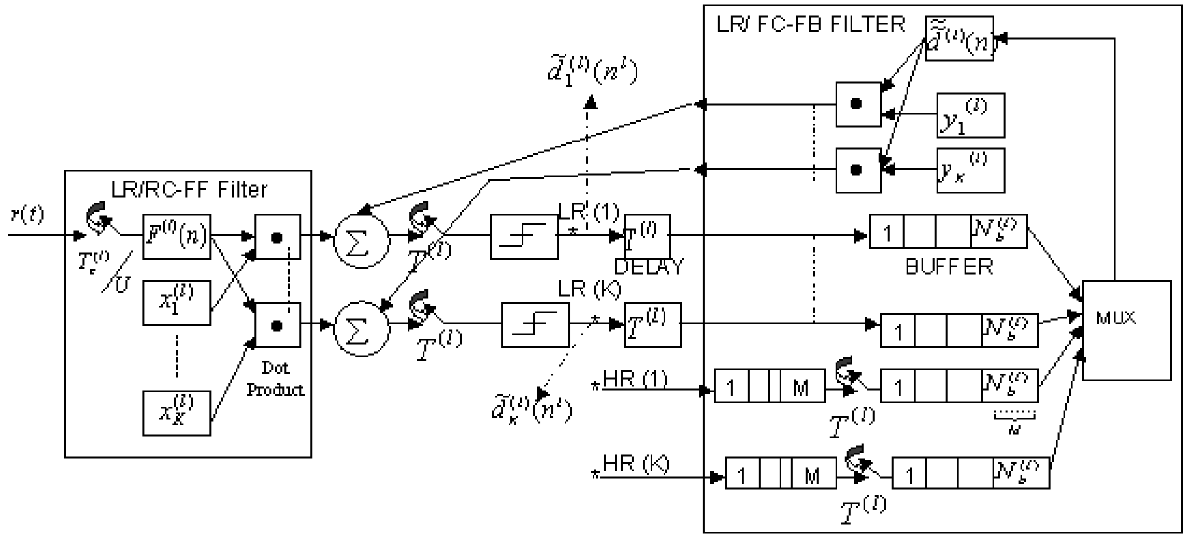

Fig.(2) LR RC-FF / FC-FB Filter for the low rate users

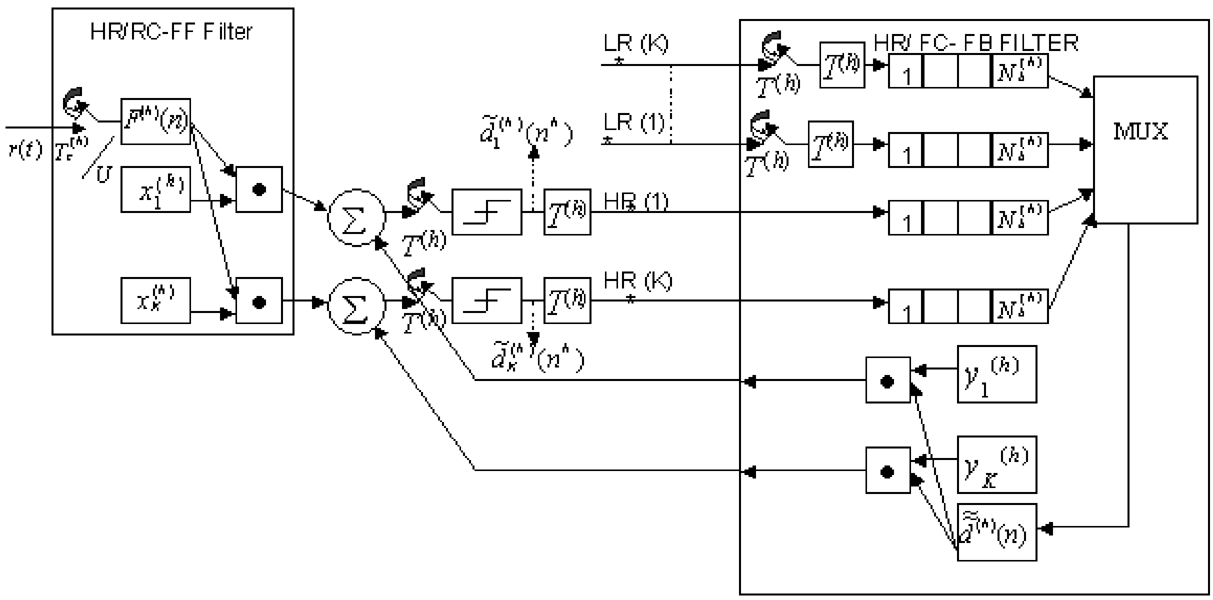

Fig.(3) HR RC-FF/ FC-FB for the high rate users

6.1 HR-FC-FB Filter

The HR-FC-FB filter has feedback taps from both the high rate users and the low rate users. The low rate detected symbols are sampled at the high data rate. The vector spanning the last *m* hard output symbols from the k_{th} low data rate user's filter starting at the n_{th} low rate detected symbol is defined as follows,

$$d'^{(l)}_{k,n}(m) = \left[\tilde{d}^{(l)}_k(n),............, \tilde{d}^{(l)}_k(n-m+2), \tilde{d}^{(l)}_k(n-m+1)\right]^T_{m\times 1} \quad (9)$$

Sampling the vector, $d'^{(l)}_{k,j}(m)$, at the high data rate, $1/T^{(h)}_s$, we obtain the vector

$$d'^{(l,h)}_{k,Mj}(mM) = \Bigg[\overbrace{\tilde{d}^{(l,h)}_k(Mj),......, \tilde{d}^{(l,h)}_k(M(j-1)+1)}^{\tilde{d}^{(l)}_k(j)},......$$

$$...,\tilde{d}^{(l,h)}_k(M(j-m+1)),.......,\tilde{d}^{(l,h)}_k(M(j-m)+1)\Big]^T_{mM\times 1};\ j=1,2,3,...\ , \quad (10)$$

where $d'^{(l,h)}_{k,Mj}(mM)$ is the vector of decisions of the k_{th} LR user sampled at the data rate of the HR user. The vector spans *mM* samples starting with the sample overlapping with the high rate symbol of index *Mj,* such that;

$$\forall k = 1,2,...M\ , \qquad \tilde{d}^{(l,h)}_k(Mn+k) = \begin{cases} \tilde{d}^{(l)}_k(n+1)..;...t \in \left[(Mn+k-1)T^{(h)}_s, (Mn+k)T^{(h)}_s\right) \\ 0...............;...otherwise \end{cases}, \quad (11)$$

and is equivalent to over-sampling the LR symbols with a ratio *M,* as $\tilde{d}^{(l)}_k(n+1) = \sum_{k=1}^{M} \tilde{d}^{(l,h)}_k(Mn+k)$.

The HR-FC-FB filter contents, sampled at the high data rate, for the detection of the n_{th} high rate symbol are as follows,

$$\tilde{\tilde{d}}^{(h)}(n) = \left[\tilde{d}^{(h)T}_1, \tilde{d}^{(h)T}_2, ...\tilde{d}^{(h)\,T}_{K^{(h)}}, \tilde{d}^{(l,h)T}_1, \tilde{d}^{(l,h)T}_2, ..., \tilde{d}^{(l,h)T}_{K^{(l)}}\right]^T, \quad (12)$$

$\tilde{d}^{(h)}_k = \left[\tilde{d}^{(h)}_k(n-1), \tilde{d}^{(h)}_k(n-2).....\tilde{d}^{(h)}_k(n-N^{(h)}_b)\right]^T$, $\tilde{d}^{(l,h)}_k = d'^{(l,h)}_{k,(n-M)}(N^{(h)}_b)$, where $N^{(h)}_b$ is the number of HR symbols spanned by the filter. The sample index of the oversampled LR symbols starts from *(n-M)* due to the relative delay encountered in the detection of the LR symbols. In other words, *M* HR symbols are detected before only one LR symbol is detected.

6.2 LR-FC-FB Filter

Similarly, the LR-FC-FB filter should contain previously detected symbols from all the users. A low rate symbol spans *M* high rate symbols, so a low rate user could view a HR user as *M virtual* LR users. The signature of the virtual LR user is of duration equal to that of the low rate user's signature. It matches the signature of its corresponding high rate symbol during the symbol interval and is zero elsewhere.

We define the feedback vector spanning the last $N^{(l)}_b$ symbols of the k_{th} LR user as follows

$$\tilde{d}^{(l)}_k = \left[\tilde{d}^{(l)}_k(n-1), \tilde{d}^{(l)}_k(n-2).....\tilde{d}^{(l)}_k(n-N^{(l)}_b)\right]^T \quad (13)$$

The vector containing the last *M* detected symbols of the k_{th} HR user, (equivalent to *M* virtual low rate users), before the detection of the n_{th} LR symbol is defined as (see Fig.(1))

$$\tilde{d}^{(h,l)}_k(n) = \left[\tilde{d}^{(h)}_k(nM-1), \tilde{d}^{(h)}_k(nM-2),......., \tilde{d}^{(h)}_k((n-1)M)\right]^T. \quad (14)$$

For the detection of the n_{th} data symbol of the LR users, the LR-FC-FB filter, containing the last $N^{(l)}_b$ LR detected symbols of each LR user and the last $MN^{(l)}_b$ HR detected symbols of each HR user, is defined as follows

$$\tilde{\tilde{d}}^{(l)}(n)=\left[\tilde{d}_1^{(l)T},\tilde{d}_2^{(l)T},........,\tilde{d}_{K^{(l)}}^{(l)\;T},\tilde{d}_1^{(h,l)T},\tilde{d}_2^{(h,l)T},..........,\tilde{d}_{K^{(h)}}^{(h,l)T}\right]^T, \qquad (15)$$

where $\tilde{d}_k^{(h,l)}=\left[\left(\tilde{d}_k^{(h,l)}(n)\right)^T,\left(\tilde{d}_k^{(h,l)}(n-1)\right)^T,...........,\left(\tilde{d}_k^{(h,l)}(n-N_b^{(l)}+1)\right)^T\right]^T$.

7. Performance of the FF FB Architectures

7.1 Interference Suppression using Decision Feedback Filters

It was shown in [4][5] that for a single rate CDMA system, the FB taps of an FC architecture have the effect of subtracting out the postcursor ISI and MAI. Thus, the FB tap weights have the effect of removing the MAI from the desired detected symbol due to all the users' symbols sharing the FB filter's contents. It is, thus, evident that in case of the proposed RC-FF/RC-FB filter, the MAI interference is subtracted due to users transmitting at the same data rate only. On the contrary, the FB taps in the RC-FF/FC-FB filter suppress the MAI interference due to the users having the same data rate as well as those transmitting at other data rates.

7.2 Probability of Error

The Signal to Interference and Noise Ratio (SINR) is the ratio between the desired signal power and the sum of the powers due to noise and interference at the output of the filter. The SINR could be used to approximate the Bit Error Rate (BER) of the k_{th} user's MMSE detector, P_e^k, as follows [6], where the superscript (.) was dropped for ease of notation,

$$P_e^k=Q\left(\sqrt{SINR}_k\right)\cong Q\left(\sqrt{\frac{J_k^H R^+ J_k}{\sigma_d^2-J_k^H R^+ J_k}}\right)\le Q\left(\sqrt{\frac{2E_b^k}{N_o}}\right), \qquad (16)$$

such that $Q(a)=(2\pi)^{-1/2}\int_a^\infty e^{-t^2/2}dt$ is the unit Gaussian tail probability, and the last term on the right hand side represents the single user bound for the BER of QPSK or BPSK transmission over a channel with no MAI or ISI [7]. E_b^k is the signal energy per bit and $N_o/2$ is Power Spectral Density (PSD) of the AWGN. The BER calculation assumes that the residual interference at the output of the filter could be modeled as an AWGN and ignores the effect of error propagation due to FB taps [4][5].

8. Comparisons and Simulations

Simulations for the proposed FF-FB architectures for MMSE filters for Multirate CDMA are presented in this section. The adaptive filters are implemented using the RLS algorithm. We assume a dual rate system using the VCR access scheme. Walsh codes of order 3 are used for spreading. The spreading gain is thus 8. The system proposed has 4 LR users and 4 HR users transmitting QPSK symbols over a multipath Rayleigh fading channel. A synchronous system is assumed to avoid averaging over the relative delays of the users. The ratio M between the high data rate and the low data rate is 2. The bit rate for the HR users is 2 Mbps and that for the LR users is 1 Mbps. The RC-FF filter should span all the multipath components of the users. Assuming that the maximum delay spread is equal to one high rate symbol, we take $N_f^{(h)}=2*N^{(h)}=16$ and $N_f^{(l)}=12$ chip rate samples to span the same duration of multipath components. We take $U=2$ in our simulations. As for the FB filters, we take $N_b^{(.)}=2$. In the following simulations, we assume a multipath Rayleigh fading channel with three paths with relative delays of [0, 2, 7] HR chips and with relative gains of [0, –3, –3] dB respectively. The maximum Doppler spread is set to be 100 Hz. The RLS adaptive filter is trained for 100 symbols for both the HR and the LR filters. The simulation is done for 1000 LR symbols (2000 bits) or 2000 HR symbols. The BER is calculated during the decision directed mode only. The BER is averaged over all users having the same data rate except when simulating the NF resistance when the interfering users are discarded. We denote the amplitude gains of the LR and HR users by A_L and A_H respectively. Assuming a RC-FF filter for all users, comparisons are made between the FF filter with no FB (FF), the FF-FB filter using RC-FB (FF RC FB), and that using FC-FB (FF FC FB), for the LR and HR users.

Case (a): The MAI due to the LR users is emphasized by making A_L = 20 dB. The average BER of the HR users is plotted in Fig.(4). The FF-FC-FB filter has superior performance over the other two filters.

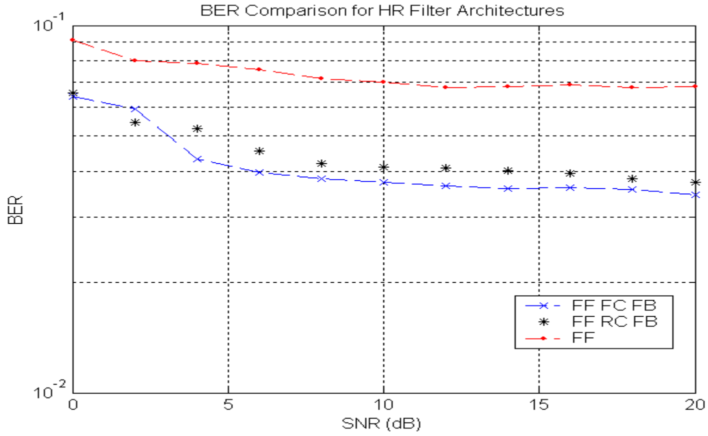

Fig.(4) BER vs SNR of HR when LR users are 20 dB higher

Case (b): The LR users are at unity gain and the HR users are 20 dB higher. The average BER of the LR users is plotted in Fig.(5). In this case, the RC-FF filter is the worst due to error propagation of the FB taps as a result of not suppressing the increased interference from the HR users. The FF-FC-FB filter on the other hand suppresses the MAI due to the increased gain of the HR users.

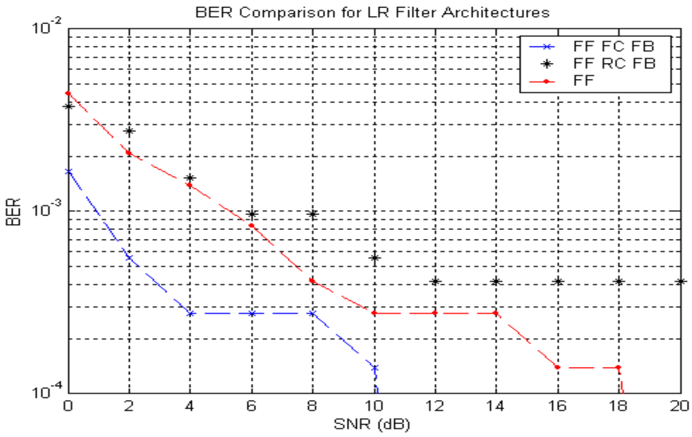

Fig.(5) BER vs SNR of LR when HR users are 20 dB higher

Case(c): A NF scenario, where the amplitude gains of one HR user and one LR user are varied from –5 dB to 40 dB, is simulated. The average BER of the other HR and LR users are plotted in Fig(6) and Fig.(7) respectively. The adaptive filter is sensitive to NF situations, but filters with FB taps, however, show better performance gains. The LR filters have lower BERs as due to the relatively lower delay spread and thus better multipath combining.

9. Conclusions

We proposed different architectures for centralized feed-forward feedback detectors designed for asynchronous multirate DS-CDMA systems. All users transmitting at the same data rate share the same FF filter contents using the RC-FF filter architecture. This avoids synchronization problems as well as significantly reduces the computational complexity required for adaptive implementation. In a RC-FF/RC-FB filter architecture, each user's filter acquires decision FB symbols from users transmitting at the same data rate only. In a RC-FF/FC-FB filter architecture, all users acquire decision FB symbols from all the users transmitting at different data rates.

The RC-FF/FC-FB filter has superior performance over other types due to suppression of the MAI from both the LR and HR users. The FB filter has also the effect of suppressing the post-cursor ISI.

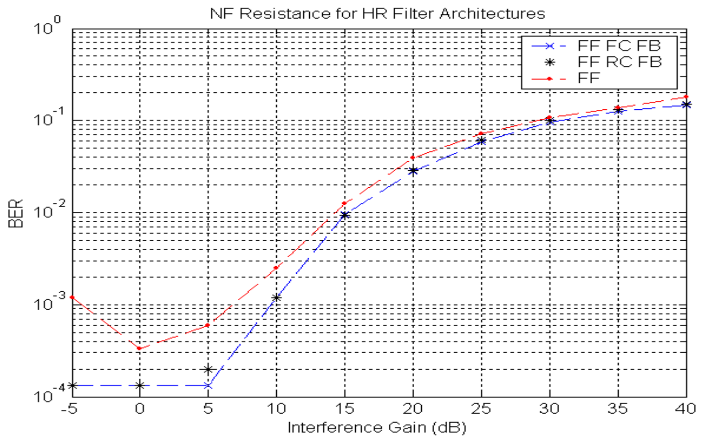

Fig.(6) NF Resistance of HR-FF-FB filters

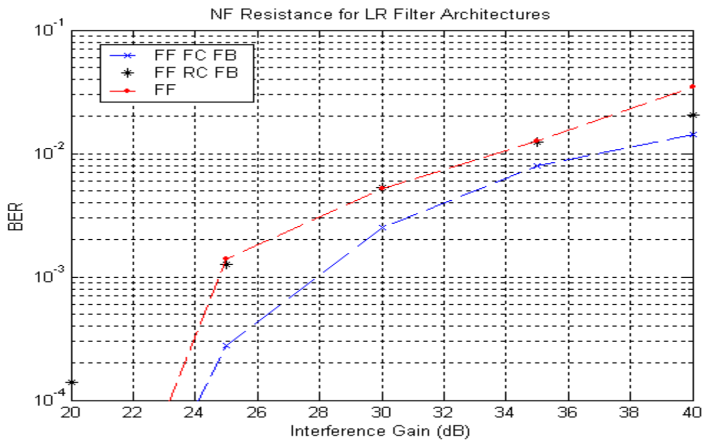

Fig.(7) NF Resistance of LR-FF-FB filters

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