Volume:03 Issue:06 Pages:1438-1443 (2012) ISSN : 0975-0290.

Performance Enhancement of MC-CDMA Systems through MAP based Multiuser Detection

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ABSTRACT

The joint Multiuser Detection (MUD) and turbo coding are the two powerful techniques for enhancing the performance of the MC-CDMA systems. The Multiple Access Interference (MAI) is one of the factors that affect the Bit Error Rate (BER) performance of the MC-CDMA systems. Maximum a posteriori (MAP) criterion based multi user detector greatly improves the system performance and mitigates the effects of MAI. However its complexity increases exponentially with increase in number of users. In this paper a Logarithmic-MAP (LOG-MAP) based MUD is proposed for the MC-CDMA systems. It is shown that the proposed LOG-MAP based MUD scheme improves the BER of the system greatly and it also reduces the MAI and complexity of the system.

Keywords – Logarithmic Maximum A posteriori, Multiple Access Interference, Multicarrier Code Division Multiple Access, Multiuser Detection, Turbo codes.

Date of Submission: February 16, 2012 Date of Acceptance: April 25, 2012

I. INTRODUCTION

In wireless communications, the spectral limitation and distortion due to multipath channels are the main restricting problems [1], and the conventional code division multiple access (CDMA) is not practical when the data transmission rate is very high. To combat these difficulties and to improve the system performance to achieve multiple access properties for communication networks, multicarrier CDMA (MC-CDMA) systems based on the combination of CDMA and orthogonal frequency division multiple access (OFDM) are used [1, 2]. The MC-CDMA system uses frequency domain spreading [2], multicarrier direct sequence CDMA (MC-DS-CDMA) [2, 3], multi tone CDMA (MT-CDMA) including serial-to-parallel (S/P) MT-CDMA [1], replica MTCDMA [1] and S/P-replica MT-CDMA [1] systems which use time-domain spreading.

Any MC-CDMA system exploits frequency diversity resulting in good bit-error-rate (BER) performance, but due to the loss of orthogonality of the received spreading code sequence (SCS), and multiple access interference (MAI) [3] it brings the use of multiuser detection (MUD) algorithms for this system. Therefore, many techniques have been proposed to further improve the performance of MC-CDMA systems over fading channels, among them applying channel coding algorithms. (In particular convolutional codes [3, 4, 5] and turbo codes) The advent of turbo codes [5, 6, 7] has motivated a lot of research in MUD using iterative or turbo decoder techniques for MC-CDMA systems. For turbo MAP based MUD, the computational complexity increase exponentially with the number of users and the number of states in each user's encoder [1]. In this paper a low-complexity iterative MUD approach for MC-CDMA systems is proposed, this scheme can effectively alleviate the harmful effects of MAI. The proposed method is based upon the use of iterative or "turbo" processing techniques. For instance, a suboptimal iterative multiuser receiver structure [8], consisting of optimal maximum *a posteriori* (MAP)-based iterative MUD. The MAP algorithm is one of a soft input/soft output (SISO) channel decoder technique, which takes soft Input and produces the decoder output as soft decision. The receiver of MC-CDMA system could achieve near signal user. Performance conversely its computational complexity is still very high. The MAP decoder [10, 11] is operated in the log domain in order to reduce computational complexity of the MAP based MUD scheme [12, 13]. To enhance the system performance of MAP based MUD in terms of BER, this paper presents a low complexity iterative Log-MAP-based MUD scheme.

The paper is organized as follows. In Section I the introduction of the proposed method is described. The section II elaborates the MC-CDMA system model. The proposed iterative Log-MAP-based MUD algorithm is presented in Section III. Numerical results and conclusion are presented in section IV and V respectively.

II. SYSTEM MODEL

In this section a synchronous MC-CDMA system, with K users assuming perfect frame synchronization is shown in the Fig. 1.The information bits $b^{(k)}$ of the k^{th} user can be encoded using a convolutional coder. To avoid the burst errors due to occasional deep fades. The coded bit of the k^{th} user at the t^{th} time interval is then spread by a PN sequence and transmitted using MC-CDMA, where the total number of subcarriers is equal to the length of the signature sequence. Further assuming that channel responses of the subcarriers are independent, at the receiver, the signal of each user is de-spread and maximum ratio combining (MRC) in the frequency domain is performed.

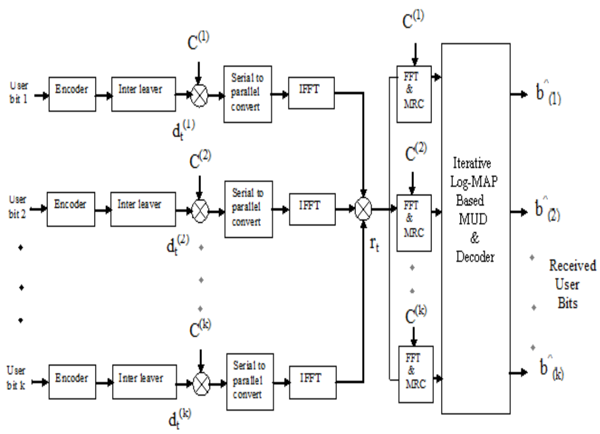

Fig. 1 Coded MC-CDMA system model

The received signal $\vec{r}_t$ at the t^{th} time interval is given by

$$:\vec{r}_t = IFFT\{A_t G_t \vec{d}_t\} + n_t \quad (1)$$

where A_t is a $L \times K$ matrix with the k^{th} column of A_t denoting a signal vector of the k^{th} user that includes the channel response and spreading codes in all carriers, and $\vec{d}_t$ is the transmitted coded bits vector of the K users. Likewise, G_t denotes the average power of all users.

$$:A_t = [\vec{s}_{t,}^{1} \vec{s}_{t,}^{2} ......, \vec{s}_{t}^{K}]$$

$$:\vec{s}_{t,}^{K} = [\vec{s}_{t,1}^{k}, \vec{s}_{t,2}^{k} ......, \vec{s}_{t,L}^{k}]^T \quad , \qquad k=1,\ldots\ldots,K$$

$$:\vec{s}_{t,l}^{k} = H_{t,l}^{k} \cdot c_l^{(k)}, \qquad l=1,\ldots\ldots..,L$$

Finally

$$:G_t = \text{Diag}\{\sqrt{p_t^1}, \sqrt{p_t^2}, ..., \sqrt{p_t^k}\}$$

where $H_{t,l}^{k}$ is the channel frequency response at the l^{th} subcarrier of the k^{th} user, and p_t^k is the received power of the k^{th} user at the t^{th} time interval. The matched filter (MF) output includes the de-spreading and MRC operations, can be written as

$$:\vec{y}_t = A_t^H .FFT\{IFFT\{A_t G_t \vec{d}_t\} + \vec{n}_t\}$$

$$:= R_t G_t \vec{d}_t + v_t \quad (2)$$

Where R_t is the cross correlation matrix as $R_t = A_t^H A_t$.

The equation (2) gives the received signal output $\vec{y}_t$.

III. PROPOSED ITERATIVE MUD ALGORITHM

3.1 Optimal MAP-Based MUD Algorithm

As in the case of a conventional serial turbo code, the detector consists of two main parts, a MAP-based MUD structure and K parallel single-user MAP based decoders [11]. It is shown that iterations between the two parts separated by de-interleavers (π^{-1}) and interleavers (π) are performed. In this case, two extrinsic information's λ_{1e}^k and λ_{2e}^k of the k^{th} user, from the MAP based MUD and single-user MAP based decoders, are exchanged respectively during the iterations. The MAP-based multiuser detector gives a *posteriori* log-likelihood ratio (LLR) of a transmitted "+1" or a transmitted " -1" for the code bit $\vec{d}_t$ of the k^{th} user at the t^{th} time interval. The LLR is given by

$$:\Lambda_1(d_t^{(k)}) \triangleq \log \frac{P(d_t^{(k)} = +1 \mid \overline{y_t})}{P(d_t^{(k)} = -1 \mid \overline{y_t})}$$

$$= \log \frac{p(\overline{y_t} | d_t^{(k)} = +1)}{p(\overline{y_t} | d_t^{(k)} = -1)} + \frac{P(d_t^{(k)} = +1 \mid \overline{y_t})}{P(d_t^{(k)} = -1 \mid \overline{y_t})}$$

$$k = 1,\ldots K \quad (3)$$

The first term in (3) is known as the *extrinsic* information, which is derived from the MAP-based MUD and is denoted by λ_{1e}^k . In order to calculate the *extrinsic* information of the k^{th} user, λ_{1e}^k the *a priori* information of all coded bits should be known which is denoted by λ_{10}^k for 1^{st} iteration. The calculations of the extrinsic information in MAP-MUD are conducted in an iterative fashion given the *a priori* information. The conditional likelihood probability distribution of $\vec{y}_t$ with Gaussian probability density function can be given by

$$:p(\overline{y_t} | d_t^{(k)} = d) = \frac{p(\overline{y_t} | d_t^{(k)} = d)}{p(d_t^{(k)} = d)}$$

Volume:03 Issue:06 Pages:1438-1443 (2012) ISSN : 0975-0290.

$$= \sum_{\vec{d_t}:d_t^{(K)}=d} P_r\{\vec{y_t} \mid \overline{d_t}\} \cdot \prod_{\substack{i \neq k \\ i=k}}^{K} P_r\{d_t(i)\} \quad (4)$$

Since there is no priori information available in the first iteration, it is assumed that the coded bits are equally likely.

In the following iterations, the *a priori* information of MAP based MUD is obtained from the *extrinsic* information delivered by the k[th] user's channel decoder in a previous iteration as

$$: \lambda_{10}^{k} = \lambda_{2e}^{k} \quad (5)$$

Finally, the channel decoder computes the *a posteriori* LLR of the information bits during the last iteration.

3.2 *Log-MAP based Multiuser Detector*

Log-MAP based MUD can be termed as *soft input soft output* (SISO) Decoder [13]. It is a decoding algorithm that accepts soft inputs from the demodulator called a-priori information and produces soft outputs called a-posteriori information. The reliability of a decoded bit is best represented by the *a posteriori probability* (APP). The original maximum a posteriori (MAP) algorithm [10, 11] is unsuitable for practical implementations because of the required multiplications and exponential operations. By formulating this algorithm in the logarithmic domain, the multiplications become addition and exponentials disappear. The additions, however, become the soft combining operation, so that the estimation user bits are much easier in Log-MAP based MUD.

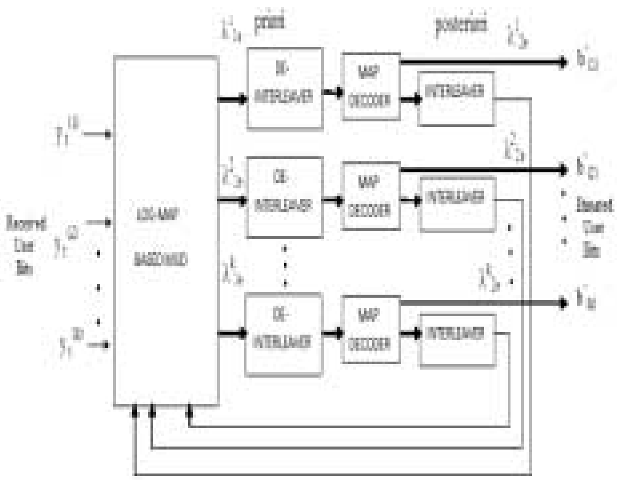

Fig. 2 Proposed Log-MAP Based MUD

Fig. 2 shows the proposed Log-MAP based MUD the received user bits are decoded using an iterative MUD process using Log-MAP algorithm [12, 13]. Since there is no priori information available in the first iteration, it is assumed that the coded bits are equally likely. In the following iterations, the *priori* information of MAP based MUD is obtained from the *extrinsic* information delivered by the k[th] user channel decoder in a previous iteration From the received bits $y_t^{(k)}$.The estimated *priori* λ_{1e}^{k} information goes through iterative decoding process. The priori information is decoded by the MAP decoder and interleaved using a random interleaver, the estimated *posteriori* λ_{2e}^{k} information is fed back to the Log-MAP section for further processing. The turbo MUD process is repeated for all K users. At the end of I iterations the required extrinsic information (LLR) for K users will be found using Log-MAP algorithm.

3.3 *Log-MAP Algorithm*

The main difference between the MAP and Log-MAP algorithm is, In MAP algorithm the LLR is the Multiplication of all the state metrics, $\alpha(s_t)$, $\beta(s_{t+1})$ and $\gamma(s_t \rightarrow s_{t+1})$ [13] . But in Log-MAP algorithm the Natural logarithm is taken to the LLR equation, therefore the multiplication of state metrics become addition. This feature of the proposed system reduces the complexity in calculation of the extrinsic information and also enhances the BER performance of the system.

The LLR equation for the MAP based MUD is

$$: \Lambda_1(d_t^{(k)}) \triangleq \log \frac{P(d_t^{(k)} = +1 \mid \overline{y_t})}{P(d_t^{(k)} = -1 \mid \overline{y_t})} \quad (6)$$

The MAP algorithm finds the probability of expected states from $P[s_t \rightarrow s_{t+1} \mid \overline{y_t}]$, where s_t represents the states of the trellis at time t, of each valid state transmission in the trellis diagram given the received vector $\overline{y_t}$. From the definition of conditional probability,

$$: P[s_t \rightarrow s_{t+1} \mid \vec{y_t}] = \frac{P[s_t \rightarrow s_{t+1} \mid \vec{y_t}]}{P[\vec{y_t}]} \quad (7)$$

Now using the Markov process,

$$: P[s_t \rightarrow s_{t+1} \mid \vec{y_t}] = \alpha(s_t)\beta(s_{t+1})\gamma(s_t \rightarrow s_{t+1}) \quad (8)$$

In the above equation the term $\alpha(s_t)$ represents the probability of the current state, $\beta(s_{t+1})$ represents the final states probability and $\gamma(s_t \rightarrow s_{t+1})$ represents the branch metric of the state transition.

$$: \alpha\,(s_t) = P[s_t\,,(y_0\,,y_1,...,y_{t-1})]$$
$$: \gamma(s_t \rightarrow s_{t+1}) = P[s_{t+1}\,,\,\vec{y}_t \mid s_t]$$
$$: \beta(s_{t+1}) = P(y_{t+1},....y_{L-1|} \mid s_{t+1})$$

The forward recursion and backward recursions are carried out to find the current and final state estimates. $\alpha(s_t)$ is found using forward recursion,

$$: \alpha(s_t) = \sum_{s_{t-1}\in A} \alpha(s_{t-1}).\gamma(s_{t-1} \rightarrow s_t) \quad (9)$$

$\beta(s_{t+1})$ is found using backward recursion

$$: \beta(s_t) = \sum_{s_{t-1}\in B} \beta(s_{t+1}).\gamma(s_t \rightarrow s_{t+1}) \quad (10)$$

Where A, B are the sets of states s_{t-1} and s_{t+1}, by applying the natural logarithm to the LLR equation

$$\begin{aligned} : \Lambda_t &= \ln\{\textstyle\sum_{s_1} \exp[\overline{\alpha}(s_t) + \overline{\gamma}(s_t \rightarrow s_{t+1}) + \overline{\beta}(s_{t+1})]\} \\ &\quad - \ln\{\textstyle\sum_{s_0} \exp[\overline{\alpha}(s_t) + \overline{\gamma}(s_t \rightarrow s_{t+1}) + \overline{\beta}(s_{t+1})]\} \\ &= \max\nolimits^*_{s_1} [\overline{\alpha}(s_t) + \overline{\gamma}(s_t \rightarrow s_{t+1}) + \overline{\beta}(s_{t+1})] \\ &\quad - \max\nolimits^*_{s_0} [\overline{\alpha}(s_t) + \overline{\gamma}(s_t \rightarrow s_{t+1}) + \overline{\beta}(s_{t+1})] \quad (11) \end{aligned}$$

Where the terms,

$$: \overline{\alpha}(s_t) = \ln(\alpha(s_t))$$
$$: \overline{\beta}(s_t) = \ln(\beta(s_t))$$
$$: \overline{\gamma}(s_t \rightarrow s_{t+1}) = \ln(\gamma(s_t \rightarrow s_{t+1}))$$

The final estimates or the required user information is found from equation (11) is given by,

$$: \mathrm{LLR} = \ln\ (e^a\ +\ e^b\ )\ \approx\ \max(a,\ b)\ +\ f_c \quad (12)$$

The term f_c is said to be correction factor of Log-MAP algorithm. Since the LLR value is less complex to calculate in Log-MAP algorithm, the proposed system obtains better solution to the complexity problem than existing MAP based MUD and this scheme improves the BER performance of MC-CDMA system effectively.

IV. NUMERICAL RESULTS

The simulation results and comparisons of the proposed system were executed and analyzed using MATLAB version 7.5.0. The BER performance of the proposed system applied over an AWGN channel is compared with the optimal MAP based MUD given in [11]. The code rates used are 1/2 and 1/3 with constraint length 3. The interleaver used is a punctured interleaver for the code rate 1/2 and un punctured for the code rate of 1/3.It is assumed that the receiver has perfect knowledge about the signal to noise Ratio (SNR) and the noise variance. The encoder used is a turbo encoder with code rate = 1/n and constraint length k.

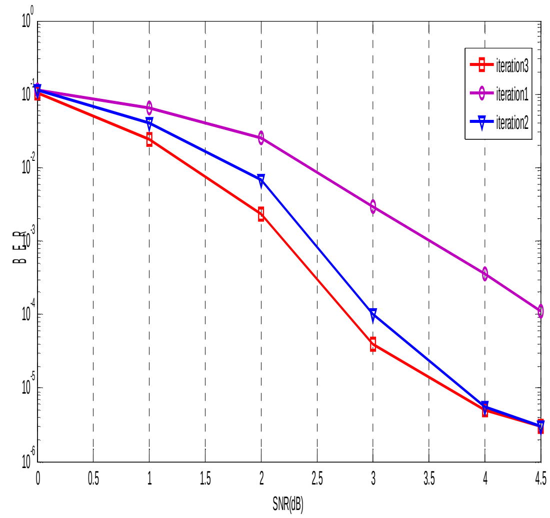

Fig. 3 BER Performance of turbo Log-MAP based MUD with code rate 1/2.

Fig. 3 shows the system performance as a function of BER and number of Iterations used. This figure lists the BER of the system with variations in SNR. The number of iterations used is I=3 and the code rate used is 1/2. As the number of iteration increases the decoder performance reaches near optimum. For the iteration 3 the system reaches the BER over 10^{-6}.

In Fig. 4 BER performance for the code the rate of 1/3 is plotted and results were analyzed with SNR=4.5 dB, number of iterations I=3. As the number iterations increases the BER also increases gradually and at the end of I=3 the MUD's performance reaches the BER of 8.1910^{-8}. Since the BER is reduced greatly the channel coding can be bandwidth efficient.

The comparison of the Log-MAP based MUD of code rate 1/3 with optimal MAP based MUD is performed and the results are shown in Fig. 5. Form the result analysis it is clear that Log-MAP based MUD outperforms the optimal MAP based MUD with the BER of 8.1910^{-8}, which is almost double the BER of the optimal MAP based MUD given in the reference [11]. Since the Log-MAP based MUD reduced the BER greatly by mitigating MAI, the bandwidth of the channel can be utilized fairly, to allocate more number of users.

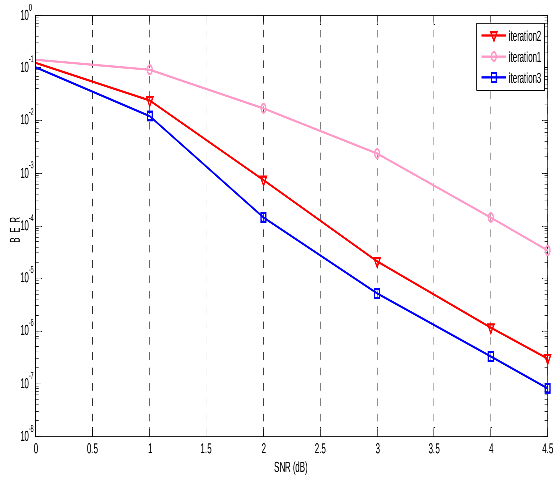

Fig. 4 BER Performance of turbo Log-MAP based MUD with code rate 1/3.

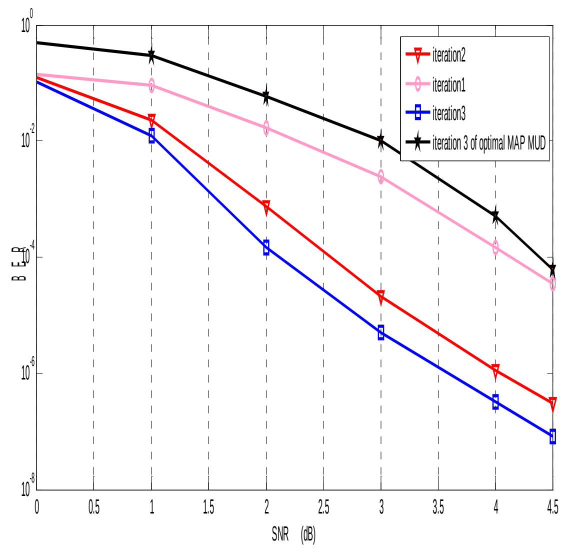

Fig. 5 comparison of proposed Log-MAP based MUD with optimal MAP based MUD.

V. CONCLUSION

In this paper, an iterative Log-MAP based MUD for coded MC-CDMA systems was presented. The proposed scheme is featured as an effective MAP-based MUD scheme that can reduce the MAI, computational complexity and greatly improves the BER performance compared with the conventional optimal MAP schemes. The numerical results have demonstrated that the BER performance of our proposed scheme approaches near optimum for the code rates of 1/2 and 1/3.

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