Two Low Complexity Multiuser Detectors for Uplink MC-CDMA Systems

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Abstract — In this paper, we introduce two novel low complexity detectors derived from the MAP-DFE detector for MC-CDMA uplink system. By simulation, we show small performance loss while reducing excessively the complexity.

Keywords - multiuser detector; low complexity; MC-CDMA; high dimension MIMO; MAP-DFE; BDFE.

I. INTRODUCTION

The multi-carrier code division multiple access (MC-CDMA), initially proposed by [1] is one of the most promising access techniques for 4G mobile communication systems. MC-CDMA uplink spreads the incoming data symbol stream onto different sub-carriers by using a specified spreading code. However, the frequency selectivity of wireless channels and the independent channel fading of each user still cause spreading codes of different users to lose orthogonality and generate multiple access interference (MAI). To mitigate the MAI, we have proposed an enhanced maximum a posteriori decision feedback equalization (E-MAP-DFE) multiuser detector [3], which provides very high performance improvement as compared to the classic detectors: block linear equalization (BLE) and the classic block decision feedback equalization (BDFE) and even to the original MAP-DFE [4].

The original MAP-DFE uses the local iterative detection technique. In each iteration, the detector performs the BLE detection, the MAP operation corresponding to calculate the a posteriori error probabilities of symbol \( P_{\text{es}} \) on the outputs of BLE, the threshold selection for assigning the output symbols and the interference cancellation (IC). In the enhanced version, E-MAP-DFE, we have introduced two improvement techniques: the in phase and quadrature (IQ) processing and the \( P_{\text{es}} \) optimization. This paper addresses the complexity issue. We present two novel detectors: MAP-BDFE and MAP-DFE with low complexity (MAP-DFE-LC). The first one is non iterative and the second one is able to control the maximum number of iterations and so the complexity of the iterative detector.

The rest of the paper is organized as follow. In Section II, we introduce the basic uplink MC-CDMA system. Then we describe the known symbol detection techniques in Section III. In Section IV, we introduce the MAP-BDFE technique and the MAP-DFE-LC technique. Finally, we present simulation results in Section V and our conclusions in Section VI.

II. SYSTEM DESCRIPTION

The block diagram of the MC-CDMA synchronized uplink system is shown in Fig.1. Each symbol is spread into \( S_F \) chips. The spread chips are then distributed to different sub-carriers, as far as possible, within the \( N_C \) available sub-carriers of an OFDM block. Each OFDM block holds \( N_C / S_F \) symbols. We use the Walsh-Hadamard codes and have \( K \) active users. The guard interval is considered in IFFT block and the guard interval remove is done in FFT block. The received signal vector within the same group of \( S_F \) spread chips can be written as:

\[
\mathbf{r} = \mathbf{A} \mathbf{d} + \mathbf{z}
\]

where \( \mathbf{d} = (d_1, d_2, \ldots, d_K)^T \) consists of the transmit complex symbols of all \( K \) users by omitting the symbol index \( j \).

\[
\mathbf{A} = \begin{bmatrix}
H_1(l)c_1(l) & \cdots & H_K(l)c_K(l) \\
\vdots & \ddots & \vdots \\
H_1(S_F)c_1(S_F) & \cdots & H_K(S_F)c_K(S_F)
\end{bmatrix}
\]

is a \( S_F \times K \) matrix determined by spreading codes, \( c_k(l) \), and channel frequency coefficients, \( H_k(l) \), and has it's \((l,k)\)-th element equal to \( H_k(l)c_k(l) \). \( \mathbf{z} \) is the noise vector with all the elements being independent complex Gaussian variables with zero mean and variance \( \sigma_0^2 \). The detectors estimate the \( K \times 1 \) data vector from the \( S_F \times 1 \) received signal vector by supposing a perfect estimation on the \( K S_F \) channel frequency coefficients.
III. KNOWN DETECTION TECHNIQUES

We will recall here two well known multiuser detectors [2]: BLE and BDFE. For the BLE detector, the data vector is estimated by

$$\hat{d}_{\text{BLE}} = (A^H A + \sigma^2 I)^{-1} A^H r = B^{-1} A^H r$$

(1)

with $B = (A^H A + \sigma^2 I)$ and $\sigma^2 = \sigma_0^2 S_F$.

One of the methods to solve equation (1) consists in applying the Cholesky decomposition on the matrix $B$. When this decomposition is considered, we can also perform an inner hard decision feedback, which is called BDFE. To minimize the error propagation within BDFE, the ordering approach is systematically applied to reorganize the order of detection according to the power of every symbol.

Now we recall the MAP-DFE [4]. As shown in Fig. 2, the key idea is to use the threshold selection on the $\text{Pes}$ of the symbols $\hat{d}^{(i)}_{\text{BLE}}$ to determine the symbols to be output from MAP-DEF detector at each iteration $i$ with $i=1,2,...$. If no symbol has its $\text{Pes}$ lower than the specified threshold, the symbol with the lowest $\text{Pes}$ will be output. The contributions of the output symbols on $\hat{A}^{(i)}$, $\hat{B}^{(i)}$ and $\hat{r}^{(i)}$ will be cancelled by supposing that the hard decisions on the output symbols are correct. The algorithm repeats iteratively until detecting all the remaining symbols. The detector can have at maximum $K$ iterations. The calculation of the $\text{Pes}$ of the symbol of user $k$ having power $E_k$ uses the following variance and mean:

$$\sigma_k^2 = \sigma^2 / E_k$$

and

$$E(\hat{d}_{\text{BLE},k}) = d_k.$$
The $P_{es}$ ordered BDFE uses the estimated $P_{es}$ on $\hat{d}_{BLE}$ to determine the order of its inner decision feedback, while a classic ordered BDFE uses the symbol powers. The operation diagram of MAP-BDFE is included in the higher part of Fig. 3, with the switches connected to 2. The $\hat{d}_{MAP-BDFE}$ corresponds to the output of MAP-BDFE. Note that when the enhanced version with the IQ processing and the $P_{es}$ optimization is applied, we call this as E-MAP-BDFE.

### B. MAP-DFE-LC

For the basic MAP-DFE, the average complexity can be reduced by increasing conveniently the threshold [4]. But higher the threshold, higher symbol error rate (SER) can be produced. Nevertheless, the complexity of an MAP-DFE detector remains important with the maximum number of iterations, $I_{MAX}$, equal to $M$, which reflects the peak complexity of this type of detector. The new MAP-DFE-LC detector with the operation diagram given in Fig. 3 aims to decrease $I_{MAX}$ by choosing its value between $[1, M]$ while preserving good performance. Hence, firstly, we set the $P_{es}$ threshold equal to the system performance target, for example SER equal to $10^{-5}$, and then we limit the number of selected symbols at each iteration to $M_X$ with

$$M_0 \leq M_X \leq \min(2 \times M_0, M)$$

for $M_0 = \left\lfloor \frac{M}{I_{MAX}} \right\rfloor$.

By setting the $P_{es}$ threshold at SER target, the detector has a good performance at SER higher than the threshold. Moreover, by introducing $M_X$, the limitation on the number of selected symbols with the lowest $P_{es}$, the detector can assume a good performance at SER lower than the threshold. This is due to the increase of the number of iterations, thus the number of IC processes. However, the $M_X$ value should not be set very low because this yields to a larger number of symbols to be detected at the last iteration, which can degrade performance. Secondly, we use the MAP-BDFE described above at the possible $I_{MAX}$-th iteration. Note that all symbols can be detected before $I_{MAX}$-th iteration. In this case the MAP-BDFE is not needed. If $I_{MAX} = 1$, only MAP-BDFE will be used. Note that when the enhanced version with the IQ processing and the $P_{es}$ optimization is applied, we call this as E-MAP-DFE-LC.

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![Fig.3. Operation diagram of MAP-DFE-LC](https://example.com/fig3.png)
V. SIMULATION RESULTS

Tab. 1 lists the parameters used in our simulation. For 4-QAM and with IQ processing, SER corresponds to bit-error-rate (BER). In Fig. 4, we illustrate the BER versus Eb/N0 curves of a full load system by considering the detectors: true E-MAP-DFE-LC with $I_{\text{MAX}} = 4$, $M_x = 10$ and the $P_{\text{es}}$ threshold $= 10^{-3}$, E-MAP-BDFE and different variants of E-MAP-DFE-LC. The first variant (V1) do not consider $M_x$. The second one (V2) uses only the BLE at the $I_{\text{MAX}}$-th iteration. The third one (V3) sets $M_x = 1$. As expected, all the variants are worse than the true one. In Fig. 5, we compare the different detectors and the single user matched filter bound. To show the performance limit of E-MAP-DFE, the threshold for the E-MAP-DFE detector is set to zero, which means the symbol having the lowest $P_{\text{es}}$ is output at each iteration. At full load case, E-MAP-DFE-LC takes $P_{\text{es}}$ threshold $= 10^{-3}$ and for $\{I_{\text{MAX}}, M_x\} = \{8, 5\}$, $\{4, 10\}$ and $\{2, 18\}$, the loss with respect to (w.r.t.) E-MAP-DFE at BER $= 10^{-3}$ are only 0.15, 0.4 and 0.9 dB, respectively. Recall that E-MAP-DFE has $I_{\text{MAX}} = 32$. Moreover, E-MAP-DFE-LC with $I_{\text{MAX}} = 8$ is 0.65 and 0.25 dB from the single user matched filter bound at BER $= 10^{-3}$ and $10^{-4}$, respectively. In the full load case, the non iterative E-MAP-BDFE has only a loss of 1.7 dB w.r.t. E-MAP-DFE and a loss of 0.8 dB w.r.t. MAP-DFE at BER $= 10^{-3}$; and at BER $= 10^{-4}$, the first loss becomes 1.9 dB; the second 0.4 dB. Moreover, at BER $= 10^{-3}$ and for a full load system, E-MAP-BDFE provides a gain of 3.7 dB over BDFE; and for a half load system E-MAP-BDFE is only 0.25 dB from the single user matched filter bound.

Tab. 1. Parameters of the simulated MC-CDMA system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation</td>
<td>4-QAM</td>
</tr>
<tr>
<td>RF bandwidth</td>
<td>57.6 MHz</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>5 GHz</td>
</tr>
<tr>
<td>Number of FFT points</td>
<td>1024</td>
</tr>
<tr>
<td>Available subcarriers $N_c$</td>
<td>736</td>
</tr>
<tr>
<td>Guard interval</td>
<td>216</td>
</tr>
<tr>
<td>Spreading factor</td>
<td>16</td>
</tr>
<tr>
<td>Channel, mobile speed v</td>
<td>BRAN-E [5], 50 km/h</td>
</tr>
</tbody>
</table>

VI. CONCLUSION

Two novel low complexity detectors, MAP-DFE-LC and MAP-BDFE are introduced for guiding the detector design to make a good performance and complexity trade-off. MAP-DFE-LC decreases the complexity with a very small performance loss as counterpart. MAP-BDFE corresponds to the particular case of MAP-DFE-LC with one iteration. The enhanced versions E-MAP-DFE-LC and E-MAP-BDFE of the previous detectors can be obtained by applying the IQ processing and the $P_{\text{es}}$ optimization described in [3]. The E-MAP-BDFE detector is only 0.25 dB from the single user matched filter bound for a half load system and at BER $= 10^{-3}$. The E-MAP-DFE-LC detector with the maximum number of iterations $I_{\text{MAX}} = 8$ has a loss of 0.15 dB compared to the E-MAP-DFE detector having a $I_{\text{MAX}} = 32$ and is 0.65 dB from the single user matched filter bound for a full load system and at BER $= 10^{-3}$.

We should note here that although in this paper these two low complexity detectors are applied to the MC-CDMA receiver, they can also be used very efficiently as a spatial symbol detector for a high dimension MIMO system, where the maximum likelihood (ML) detector or the ML like sphere decoder [6] becomes prohibitively expensive.

REFERENCES

Fig. 4. Different variants of the E-MAP-DFE-LC detector for a full load system.

Fig. 5. Comparison of different detection technique.