A Reduced Complexity Algorithm for Multi User Detection in DS UWB Systems

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Abstract

UWB is the latest technology to cause huge advances in wireless communication, networking, and radar and positioning systems. Many novel algorithms for the multiuser detection have been proposed for a DS-UWB multiuser communication system. In this paper we have proposed a reduced complexity Multi User detector based on minimum mean square error (MMSE). The algorithm exploit the inherent multipath diversity and also mitigate the effects of both inter symbol interference(ISI) and multiuser interference (MUI) with the reduced complexity. Simulation results show that the algorithm perform better than the other known detectors with the same complexity in literature.

Keywords: UWB, Multi User Detection, Matching Pursuit Algorithm;

1. Introduction

Ultra-Wideband (UWB) is a technology for transmitting message expanded over a very large bandwidth. UWB is one of the latest technologies calling for major advances in radar and positioning systems wireless communication and networking. UWB technology has some very attractive features such as low power density, huge multi-path diversity, very low complexity signal processing, multiple access capability, synchronization

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precision etc and because of this has captured wide attention. On the flip side the strict timing requirement need highly competent synchronization algorithms and the highly frequency selective nature of the UWB channels makes the receiver design very complex. Moreover, as the UWB is also used in multiuser systems many researchers are pursuing their research in multi-user detection.
2. **Background**

Very narrow pulse width characteristics of UWB enhance its ability to resolve multipath. The multipath diversity can be effectively exploited using a Rake receiver. The frequency selective nature of the channel make the UWB system suffer from severe intersymbol interference (ISI) when transmitted with high data rate. To overcome the effect of ISI, Rake receiver must be followed by an equalizer. Many methods combining the RAKE and equalization were proposed for direct sequence UWB (DS-UWB) systems.

Wireless transmission of UWB signals is severely affected by multipath fading, intersymbol interference (ISI), Multi User Interference and other interferences. Hence the transmitted waveform is severely distorted when it arrives at a receiver. The reflections, refractions and scattering happening in the wireless propagation cause multipath fading and ISI. Despite huge ISI and multipath fading UWB systems have to accommodate multiple users and they should be interoperable with other systems too. Hence MUI and other interferences cause huge problems for UWB systems. In literature most of the times these problems have been dealt separately and most of the receiver architecture deal with the problems in a one-by-one manner. Because of this approach the complexity of the receiver and size increases drastically.

RAKE and equalization methods perform very bad in multi user environment when Multi User Interference is high. The Rake receiver, with maximum ratio combining (MRC), is effective only when the signal is affected only by additive white Gaussian noise (AWGN). The BER performance of Rake combiner will depend heavily on the signal-to-interference-plus-noise ratio (SINR) when multi user interference is dominating.

When old methods of matched filter and RAKE receivers can exploit the processing gain of the spread spectrum system and reduce interference to some extent, the MMSE multiuser detection (MUD) offers very good interference rejection. MUD is the most effective method in rejecting wideband interferers, or CDMA users in a network where many users simultaneously access the same channel using different spreading codes. But Conventional multi-user detection (MUD) algorithms require huge complexity. In some killer applications such as sensor networks, these requirements cannot be afforded and simple interference resistant schemes expected.

3. **System Model**

A DS - CDMA based UWB multi-user-system having $N_u$ active users is considered. At the transmitter of the $u$th user, BPSK symbols $a_k^u \in \{1, -1\}$ are spread using hadamard code and modulated with chip pulses $g_c(t)$,

$$g^u(t) = \sum_{i=0}^{N_C-1} c_i^u g_c(t - iT_c)$$  \hspace{1cm} (1)

where $\{c_i^u\} \in \{1, -1\}$ denotes the spreading sequence of code length $N_C$ and chip duration $T_C$. Let the UWB channel impulse response be written as

$$h^u(t) = \sum_{i=1}^{J} a_i \delta(t - \tau_i)$$  \hspace{1cm} (2)

The transmitted signal after passing through the channel received at the receiver can be written as,

$$r^u(t) = \sum_{k=-\infty}^{\infty} a_k^u g^u(t-kT_g) * h^u(t) = \sum_{k=-\infty}^{\infty} a_k^u P^u(t-kT_g)$$  \hspace{1cm} (3)
$T_g$ denotes the symbol duration. The signal at the receiver after synchronization can be given as

$$r^u(t) = \sum_{k=-\infty}^{\infty} a_k^u p^u(t - kT_g) + n(t)$$  \hspace{1cm} (4) 

1. **Transmitted UWB pulse**

2. **Received UWB pulse**

4. **Linear Multi User Detector**

The linear receiver can be designed as a MMSE linear equalizer (Weiner Filter) which optimally weights and combines the received samples in symbol duration such that the mean square error is minimum. The block diagram of a linear detector based receiver can be given by FIG.1. The coefficients of the filter are optimized by applying MMSE criteria.
3. Linear MMSE MUD

The received waveform can be written in discrete domain as

$$r_1 = \sum_{u=1}^{N_u} \sum_{k=-\infty}^{\infty} a_k^u p^u (l-kN_s) + n_l$$

(5)

Where $N_s$ is the ratio of the sampling frequencies

$$\frac{f_s}{f_r} = N_s > 1$$

The received signal for a single user, user 1 can be written as

$$r_1 = \sum_{k=-\infty}^{\infty} a_k^1 p^1 (l-kN_s) + \sum_{u \neq 1} \sum_{k=-\infty}^{\infty} a_k^u p^u (l-kN_s) + n_l$$

(6)

In the above equation second term represents the multiuser interference (MUI) from users other than 1. Therefore it can be written as

$$r_1 = \sum_{k=-\infty}^{\infty} a_k^1 p^1 (l-kN_s) + m_1 + n_l$$

(7)

Where $m_1$ is the MUI.

Let $r_k = [r_{kN_s+1}, r_{kN_s+2}, \ldots, r_{k(N_s+1)}]$ be a single frame which represents the samples of a single received symbol in symbol duration $N_s$ and $r_k$ the samples of the received signal when $a_k$ is transmitted. Our aim is to choose the linear filter coefficients $w = [w_1, \ldots, w_{N_s}]$ such that the mean square error $E||a_k-wr_k||^2$ is minimum.

The above mentioned MMSE problem can be solved by the Weiner-Hopf equation $w = \gamma_r \Gamma_r^{-1}$ where $\Gamma_r = E[\eta_k \eta_k^H]$ represents the received vector autocorrelation matrix and $\gamma_r = E[a_k \eta_k^H]$ is a vector representing the cross correlation between the transmitted symbol and the corresponding received samples.

The estimate of the transmitted symbol at the receiver can be calculated as

$$a_k = \text{sign}(w_r)$$
But the optimum MMSE based MUD is highly complex as it involves a huge matrix inverse in the filter coefficient estimation.

5. **Proposed Low Complexity Linear Multi User Detector**

In the proposed low complexity Linear Multi User Detector, the complexity reduction is achieved by reducing the size of the matrices, \( \Gamma_{RR} \) and \( \gamma_{ar} \). This is accomplished by reducing the size of \( r_k \) by selecting the optimal channel path. Thus only the optimal received samples and not all the samples will be used for finding \( \Gamma_{RR} \), \( \gamma_{ar} \) and \( w \). For optimal selection of \( N \) out of \( N_s \) taps an exhaustive search is needed. The algorithms like greedy algorithm are computationally complex and not feasible in real time. The Matching Pursuit algorithm seems to be a best suit for this.

Consider \( A = [a_1, a_2, ..., a_{N_{tr}}] \) as the input training symbol sequence where \( N_s \) is the number of training symbols and \( R \) as received training symbol sequence where,

\[
R = \begin{pmatrix}
   r_1^1 & r_1^2 & r_1^3 & \cdots & r_{N_s}^1 \\
   r_1^2 & r_2^2 & r_2^3 & \cdots & r_{N_s}^2 \\
   r_1^3 & r_2^3 & r_3^3 & \cdots & r_{N_s}^3 \\
   \vdots & \vdots & \vdots & \ddots & \vdots \\
   r_1^{N_{tr}} & r_2^{N_{tr}} & r_3^{N_{tr}} & \cdots & r_{N_s}^{N_{tr}}
\end{pmatrix}
\]

Where \( r_j^k = r_{kN_s+j} \)

The process of tap selection can be considered as forming an observation matrix \( R_s \) by selecting a subset of columns from \( R \) such that LS estimation error \( E = A^T A - A^T P_S A \) is minimum or Projection power \( \| P_S A \|^2 = A^T P_S A \) where projection matrix \( P_S = R(R^T R)^{-1} R^T \) and \( P_S^T P_S = P_S P_S^T \). Matching Pursuit Algorithm which selects a subset of taps which satisfy this criterion is as follows:

Initialize by setting \( n = 0 \) and \( A_{res}(0) = A \)

2) Set \( n = n+1 \). Select a new column \( R_s \) by \( s = \arg\max_k (A_{res}^{(n-1)})^T P_{R_k} A_{res}^{(n-1)} \) where \( k \) denotes the column index for \( R \), the projection matrix for column vector \( R_k \) is defined as \( P_{R_k} = \frac{R_k R_k^T}{\|R_k\|^2} \) and the projection power of the signal \((A_{res}^{(n-1)})^T P_{R_k} A_{res}^{(n-1)}\) is given as \((A_{res}^{(n-1)})^T P_{R_k} A_{res}^{(n-1)} = \frac{|R_k^T A_{res}^{(n-1)}|^2}{\|R_k\|^2}\)

3) Update the residue \( A_{res}^{(n)} = A_{res}^{(n-1)} - P_{R_s} A_{res}^{(n-1)} \) and continue the iteration loop for tap selection until \( n = N \)
The receiver structure for proposed reduced complexity MUD as follows:

4. Proposed Reduced Complexity Linear MMSE MUD

6. Order of Computational Complexity Reduction

The computational complexity of MMSE – MUD filter coefficient calculation is \(O(N_s \times N_s \times N_s) + O(N_{tr} \times N_s \times N_s) + O(N_s))\). But the computational complexity of proposed reduced complexity MUD is the addition of computational complexity of MP tap selection and computational complexity of proposed reduced complexity MUD filter coefficient calculation. The computational complexity of MP tap selection is \(O(N \times N_{tr} \times N_s)\). The computational complexity of proposed reduced complexity MUD filter coefficient calculation is \((O(N \times N \times N) + O(N_{tr} \times N \times N) + O(N))\). Hence the computational complexity of proposed reduced complexity MUD filter coefficient calculation is \(O(N_{tr} \times N \times N_s) + (O(N \times N \times N) + O(N_{tr} \times N \times N) + O(N))\). In our simulation we when \(N_{tr} = 50\), \(N_s = 80\) and \(N = 20\), the computational complexity of MMSE – MUD filter coefficient is \(O(512000 + 320000 + 80 = 832080)\) and the the computational complexity of proposed reduced complexity MUD filter coefficient calculation is \(O(80000 + 8000 + 20000 + 20 = 108020)\).

7. Simulation results and Discussions

The BER performance of the proposed low complexity multi user detector for a DS-UWB system is presented in this section. Performance of Low complexity MUD is compared with the other detectors. A multiuser DS-UWB system with BPSK modulation was considered for the simulation. Hadamard code of length 8 is used for spreading. Hence the processing gain of DS sequence is 8.

5. BER Performance of the proposed algorithm for varying SNR
The sampling rate at the receiver is selected to be twice the chip rate. The CM2 channel model of IEEE 802.15.3 is used for simulating the channel. RAKE-MMSE-Linear equalizer, Linear MUD and Reduced complexity Linear MUD are compared and the BER vs Average SNR plots of the three detectors are given below.

6. BER Performance of the proposed algorithm for varying Number of Users

It is clear from the figure FIG 3 that the proposed scheme performs significantly better than RAKE-MMSE-Linear equalizer but not better than Linear MUD. The BER performance with varying number of users for a fixed SNR is shown in FIG 4. It shows that illustrates that reduced complexity Linear MUD gives a significant gain when compared to the Rake MMSE as the number of users increases and again not better than Linear MUD.

8. Conclusion

As the number of users increases, MUI increases significantly. The RAKE receiver with MRC is effective only in single user environment with the interference is Gaussian where as the Linear MUD can reduce the effects of the multiuser interference to a great extent. Reduced complexity Linear MUD’s performance is better than RAKE-MMSE-Linear equalizer but not Linear MUD. Channel parameters, spreading sequence and pulse shape of the transmitter need not be known to the receiver. Thus Reduced Complexity MUD offers a scheme with a much reduced complexity compared to Linear MUD but with a performance closer to that of the Linear MUD

References