A Novel Multiuser Detector for LDPC-Coded DS-UWB Space Formation Flying

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Abstract. Space formation flying has attracted a lot of attention recently. In this paper, we using direct-sequence ultra-wideband (DS-UWB) as the physical layer of inter-spacecraft communications. The traditional multiuser detection method like soft-input soft-output (SISO) cost too much computation. The proposed multiuser detector no longer uses interleaving, and the computational complexity has a linear relationship with the number of users. The bit error ratio (BER) simulation result shows that the proposed method approaches the single-user system with increasing signal-to-noise ratios (SNRs).

Keywords: Space formation flying; Multiuser detection; DS-UWB; SISO.

1. Introduction

With the development of space technology, space formation flying has attracted considerable research interest due to its high efficiency, flexibility, and affordability [1]. Spacecraft flying in formation requires efficient and reliable inter-spacecraft communications. Ultra-wideband (UWB) technology can be a suitable way for the physical layer of inter-spacecraft communications in space formation flying systems [2]. The advantages of UWB are high data transmission rate, low power density, high interference resistance, and strong multipath resolution. Direct sequence ultra-wideband (DS-UWB) is one of the mainstays for UWB multiple accesses scheme [3]. Using code division multiple access (CDMA), the DS-UWB system can support several users simultaneously communicate on a common carrier frequency to transfer data. However, the limited transmission power constrains the quality of communication of spacecrafts. As well as the presence of multiple access interference and inter-symbol interference will seriously deteriorate the reliability of multiuser system. As a result, multiuser detection and error control coding are necessary to guarantee reliable communication between spacecrafts.

The soft-input soft-output (SISO) multiuser detectors are often considered as optimum or suboptimum [4-6]. It requires lot of a priori information about the multiuser system and has an exponential computational complexity with the number of users. Many efforts have been made to optimize performance and computational complexity [7-10]. In this paper, we proposed a novel multiuser detector for LDPC-Coded DS-UWB space formation flying. By using our HISO multiuser detector, the detector can achieve near single-user system BER performance at the cost of linear complexity.

The rest of this paper is organized as follows. Section II gives the system model; the proposed multiuser detector is given in Section III. Then in section IV, simulation results are demonstrated. At last, conclusions are given in section V.
2. System Model of Iterative Multiuser Detector

2.1. Signal Model for DS-UWB MA Service

For optimal soft-input soft-output (SISO) multiuser detectors, the framework of DS-CDMA UWB system is shown in Fig.1, the received signal \( r(t) \) for SISO multiuser detector can be written as

\[
r(t) = \sum_{k=1}^{K} \sum_{i=1}^{M} b_{ij} A_k c_i (t - (i - 1)T_s) p_i (t - (i - 1)T_c - jT_c - \tau_i) + n(t)
\]  

The BPSK symbols are spread with the specific pseudorandom (PN) codes \( c_i(k) \). The BPSK symbol is then modulated with the chip pulses \( p_i(t) \) which often adopts the second derivative of a Gaussian pulse with a duration of a nanosecond; \( A_k \) is the amplitude of received signal; The BPSK symbol duration is written as \( T_c \), each symbol is divided into chips with duration \( T_c \) and the random delay of different transmitter is noted as \( \tau_i \). \( M \) denotes the length of bits per packet; \( n(t) \) is the white Gaussian noise. The received signal for all \( K \)-user spacecraft at \( i \)th bit can be written as the following \( K \)-dimension vector

\[
y_i = RA \hat{b}_i + n_i.
\]  

\( R \) denotes the normalized cross-correlation matrix of different user’s transmission waveform whose element is \( r_{ik} \) \( (i, k = 1, 2, \ldots, K) \). \( r_{ik} \) is the cross-correlation coefficient between the user \( i \) and user \( k \).

\[
b_{\text{optimal}} = \arg \max_b \{2b^T A \hat{y} - b^T A R A b\}
\]

2.2. Iterative Multiuser Detector Structure

\[
\text{Figure 2. A coded CDMA system with SISO iterative multiuser receiver.}
\]
In order to ensure the statistical independence between different spacecraft, interleaved coding is used between the above two parts. The output of SISO multiuser detector can be written as

$$\Lambda_{d}[b_{k,a}] = \log \frac{p(b_{k,a} = +1 | y_{k,a})}{p(b_{k,a} = -1 | y_{k,a})}$$

$$= \log \frac{p(y_{k,a} | b_{k,a} = +1)}{p(y_{k,a} | b_{k,a} = -1)} + \log \frac{p(b_{k,a} = +1)}{p(b_{k,a} = -1)},$$

$$1 \leq k \leq K, 1 \leq n \leq M$$

(4)

3. The Proposed Iterative Multiuser Detector

From previous section, the message delivered by the a full-complexity SISO multiuser detector can be expressed as

$$\lambda_{d}[b_{k,a}] = \log \frac{\sum_{b_{k,a} \in \{\pm 1\}^K} \Omega(b)}{\sum_{b_{k,a} \in \{\pm 1\}^K} \Omega(b)}$$

(5)

where

$$\Omega(b) = \exp \left\{ \left( y_j - RAb \right)^{-1} R^{-1} \left( y_j - RAb \right) \right\}^{K} p(b_{j})$$

$$= \exp \left\{ \frac{2b^{T}A_{j} - b^{T}ARAb}{2\sigma^2} \right\}^{K} p(b_{j})$$

(6)

And $\Delta 2$ is the probability that the other K-1 users’ candidate vectors are equal to the transmitted symbol vector.

$$\Delta 3[b_{j,a}] = \prod_{j=1}^{K} p(b_{j}) = \prod_{j=1}^{K} \left( 1 + b_{j} \tanh \left( \frac{1}{2} \lambda_{d}[b_{j,a}] \right) \right)$$

(7)

In order to get the result of the multiuser detector from (5), we need to calculate (6) and (7) 2K-1 times which is rather complicated and costly. In practical usage, we need to ensure the signal processing speed and avoid complicate calculation. For simplicity, we set $\Delta 2$ equals to 1 for any other code vector, and $\Delta 2$ equals to 0 when the iteration reaches convergence. The output of optimal multiuser gets the maximum value of $\Delta 1$. Then, output of HISO multiuser detector can be derived from the output of SISO multiuser detector which is written in (4). Thus, we can get

$$\lambda_{d}[b_{j,a}] \approx \log \frac{\exp \left\{ \frac{2b^{T}A_{j} - \hat{b}^{T}ARAb}{2\sigma^2} \right\}}{\exp \left\{ \frac{2b^{T}A_{j} - \hat{b}^{T}ARAb}{2\sigma^2} \right\}}$$

$$= \frac{2(e^{b^{T}A_{j} - \hat{b}^{T}ARAb})}{\sigma^2} - \frac{2(e^{b^{T}A_{j} - \hat{b}^{T}ARAb})}{2\sigma^2}$$

where $\hat{b} = [ b_1, b_2, ..., b_{k-1}, +1, b_{k+1}, ..., b_K ]$; $\hat{b} = [ b_1, b_2, ..., b_{k-1}, -1, b_{k+1}, ..., b_K ]$. Further simplification, we can get
\[ \alpha[b_{k,j}] = (b_i^* - b_j^*) A y_i = 2 A_y y_{k,i} \]  
(9)

\[ \hat{b} A R A b = \sum_{i=1}^{K} \sum_{j=1}^{K} A_i A_j \rho_{y_i} b_j b_j \]
\[ = \sum_{i=1}^{K} \sum_{j=1}^{K} A_i A_j \rho_{y_i} b_j b_j + \sum_{i=1}^{K} A_i A_j \rho_{y_i} b_j b_j + 2 \sum_{j=1}^{K} A_i A_j \rho_{y_i} b_j b_j \] 
(10)

Only the third term in (10) has the variable \( b_i \). So, we can get
\[ \alpha 2[b_{k,j}] = \hat{b}_A R A b - \hat{b}_A R A b \]
(11)

From (9) and (11) we can see that the HISO multiuser output is
\[ \hat{\lambda}[b_{k,i}] = \frac{2 \alpha[b_{k,i}] - \alpha 2[b_{k,i}]}{2 \sigma^2} \]
\[ = \frac{2 A_y y_{k,i} - \sum_{j=1}^{K} A_j \rho_{y_j} b_j}{\sigma^2} \]
(12)

In (12), we can see that the multiuser detector has a linear computational complexity to number of users \( K \). For a \( K \)-user coded DS-CDMA system with code length \( M \), the linear complexity HISO multiuser detector can be expressed by
\[ \lambda_i = \frac{2 A (Y - R A B) + \rho A B}{\sigma^2} \]  
(13)

where \( \lambda_i \), \( Y \) and \( B \) are \( K \times M \) matrix and the \( k \)th row \( i \)th column element of these variables can be expressed as \( \lambda_i[b_{k,i}], y_{k,i} \), and \( b_{k,i} \) respectively. And \( \rho \) is the diagonal element of \( R \).

4. Numerical Results and Discussions

We use (8160, 7136) LDPC code proposed in the Consultative Committee for Space Data System (CCSDS) 131.0-B-2 bluebook for simulation. The SIC-MMSE and the Maximum a posteriori (MAP) based multiuser detectors are used for comparison.

In figure 3, the performance of the proposed HISO multiuser detector with output of matched filters as initial values are presented. From figure 3 we can see that the HISO multiuser detector has a close BER performance with single user after 3 iterations when SNR is above 4dB. In practical usage, the communication system usually working in a high SNR condition. So, it is reasonable to say that the proposed HISO multiuser detector can achieve similar performance compared with MAP and SIC-MMSE based multiuser detector. It is worth noting that the computation complication of MAP and SIC-MMSE based multiuser detector are \( O(2) \) and \( O(K^2) \) respectively while our HISO multiuser detector is \( O(K) \).
The initial value of multiuser detectors influences the calculation error of (14). We use the MMSE hard decision result as the initial value of multiuser detectors and the performance is shown in Figure 4. Compare the two way of generating initial values, we can see that the performance of multiuser detectors is improved when using MMSE hard decision as the initial value. The HISO multiuser detector use less iteration to achieve a close single user performance. And the descent pace of BER has increased during 3-4 dB SNR. The result shows that the performance of proposed multiuser detector can have close performance with MAP and SIC-MMSE based multiuser detector even under low SNR condition when we have a good initial value. Form above analyse we can say that by choosing a better hard decision as initial value of multiuser detectors we can improve convergence speed and reduce iterations to get the same performance.

5. Conclusion

In this paper, a low complexity HISO iterative multiuser detector for LDPC-coded DS-CDMA based
UWB system is proposed. The proposed multiuser detector is basically an interference cancellation method. So, its computational complexity has a linear relationship with the number of user spacecraft. The simulation results show that the proposed algorithm can achieve the bit error rate performance close to single user condition at the cost of low computational complexity. The initial value of the iterative multiuser detectors can seriously impact the performance result. There is still some work for choosing the best initial value for the multiuser detectors. A proper initial value strategy can further improve the proposed HISO multiuser detectors.

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