A FPGA implementation of GMM MUD algorithm for space formation aircraft communication system

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Abstract. Space formation aircraft communication system needs to meet strong anti-interference ability, low power consumption and high transmission rate performance. Ultra-wideband (UWB) has high data transfer rate, low device complexity, high interference resistance and confidentiality. Therefore, UWB technology is used in space formation aircraft communication system, which is direct sequence ultra-wideband (DS-UWB) space formation aircraft communication system. This paper, we put forward a multi-user detection (MUD) algorithm based on Gaussian Mixture Model (GMM) in DS-UWB communication system and its field-programmable gate array (FPGA) implementation. We adopt a way which based on MATLAB and FPGA platform, and results show that MUD algorithm based on GMM has better bit error rate (BER) performance compared to classical multi-user detection algorithm.

1 Introduction

The key of space formation aircraft to achieve the interconnection between the various aircraft in the formation is establishing inter-satellite links (ISL) [1]. As a multi-user system, the space formation aircraft communication system focus on the multiple-access communication technology [2]. The direct-sequence ultra-wideband system (DS-UWB) [3,4,5] has aroused widely concern as a UWB multiple-access communication system that is currently being studied. However, the multiple-access interference (MAI) problem which limited the system capacity and performance [6]. Hence, multi-user detection (MUD) [7] is proposed to suppress the impact of MAI and improve the performance in DS-CDMA system. There are many MUD algorithms with excellent performance, such as matched filter detector (MF), optimum multi-user detector (OMD) [8], decorrelation multi-user detector (DEC) [9], minimum mean square error multi-user detector (MMSE) [10] and artificial intelligence algorithms.

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In this paper, we present a field-programmable gate array (FPGA) implementation of the MUD detector based on Gaussian Mixture Model (GMM). In terms of the bit error rate (BER), it's significantly better than MF, slightly better than MMSE and DEC, and approximates OMD. In addition, system has lower computational complexity and larger capacity.

The remainder of the paper is organized as follows: Section II describes the signal model, the channel model and the receiver model of DS-UWB communication system. Section III introduces the FPGA Implementation of GMM MUD algorithm. Section IV presents the implementation results. Finally, Section V concludes our paper.

2 DS-UWB system model

2.1 DS-UWB signal model

DS-UWB system transmitter model block diagram is shown in Fig.1. Initially, encode the source data into binary baseband information bits. The pseudo-random code is then used to encode the baseband bits to distinguish different users in the system. Each encoded baseband information bit will be represented as a series of repetitive pseudo-random code sequences. Finally, the pulse former generates ultra-wideband pulses.

Fig. 1. DS-UWB system transmitter model block diagram.

The k th user's transmit signal of the DS-UWB system can be written as [11]:

$$s^{(k)}(t) = \sum_{j=-\infty}^{\infty} \sum_{i=0}^{N_s-1} d_j^{(k)} c_i^{(k)} p(t - iT_c - jT_f) \quad (1)$$

We assume there is a DS-UWB system with K active users, employing binary phase-shift key (BPSK) modulation. Where $d_j^{(k)} \in \{-1, +1\}$ denotes the baseband information bit of the k th user, $c_i^{(k)} \in \{-1, +1\}$ denotes the symbol corresponding to the i th chip in the coded pseudo-random sequence of user k , $\{c_i^{(k)}\}_{i=0,1,\dots,N_s-1}$ denotes the address code of user k , T_c denotes the pulse repetition period, T_f denotes the chip period. We consider that each BPSK symbol can be divided into N_s chips.

2.2 DS-UWB channel model

Considering the environment of space formation aircraft in outer space, the effects of multipath can be omitted. Furthermore, the main noise interference is approximately additive white Gaussian noise. Therefore, the channel model is an Additive White Gaussian Noise (AWGN) channel.

The electromagnetic wave propagation loss model can be defined as:

$$S_R(f) = S_T(f)G_tG_r\left(\frac{c}{4\pi df}\right)^2 \quad (2)$$

where $S_R(f)$ denotes received signal power spectral density, $S_T(f)$ denotes transmit signal power spectral density, G_t denotes the gain of the transmitter antenna and G_r denotes the gain of the receiver antenna, c denotes the speed of light, d denotes the distance between the receiver antenna and the transmitter antenna.

It can be known that the signal-to-noise ratio (SNR) of the receiver can be expressed as:

$$SNR_R(f) = \frac{S_R(f)}{N_0} = \frac{1}{N_0} S_T(f)G_tG_r\left(\frac{c}{4\pi df}\right)^2 \quad (3)$$

where $N_0=k_B T$ denotes power spectral density of noise in free space AWGN channels in outer space, T denotes absolute temperature, k_B denotes boltzmann constant ($1.38 \times 10^{-23} \text{J/K}$).

It is assumed that the power spectral density of the transmitted signal is constant regardless of S_T and frequency, we can obtain:

$$\begin{cases} SNR_R(f) = \frac{a^2}{f^2} \\ a^2 = \frac{1}{N_0} S_T G_t G_r \left(\frac{c}{4\pi d}\right)^2 \end{cases} \quad (4)$$

where f_h denotes UWB signal upper cutoff frequency, f_l denotes UWB signal lower cutoff frequency.

2.2 DS-UWB receiver model

DS-UWB receiver model block diagram is shown in Fig.2.

Fig. 2. DS-UWB receiver model block diagram.

We assume that the system has K users and the signal received by the receiver can be expressed as:

$$r(t) = \sum_{k=1}^K \alpha_k \sqrt{P_k} d_i^{(k)} \sum_{j=0}^{N_c-1} c_j^{(k)} p(t - iT_f - jT_c - \tau_k) + n(t), t \in [iT_f, (i+1)T_f] \quad (5)$$

where α_k denotes the signal gain of the k th user, P_k denotes the signal power of user k , τ_k denotes the random delay of the user k 's signal reaching the receiver. The matched filter template signal of user p ($p=1, 2, \dots, K$) in the matched filter of the receiver can be written

as:

$$m_p(t) = \sum_{j=0}^{N_s-1} c_j^{(p)} p(t - iT_f - jT_c - \tau_p) \quad (6)$$

The output of the signal matching filter correlator of user p can be expressed as:

$$\begin{aligned} y_i^{(p)} &= \int_{iT_f + \tau_p}^{(i+1)T_f + \tau_p} r(t) m_p(t) dt \\ &= \alpha_p \sqrt{P_p} E N_s d_i^{(p)} + \sum_{\substack{k=1 \\ k \neq p}}^K \alpha_k \sqrt{P_k} d_i^{(k)} \sum_{j=0}^{N_s-1} c_j^{(p)} c_j^{(k)} \int_{-\infty}^{\infty} p(t - jT_c - \tau_p) p(t - jT_c - \tau_k) dt + n_p \end{aligned} \quad (6)$$

where $\int_{iT_f + \tau_p}^{(i+1)T_f + \tau_p} r(t) m_p(t) dt$ denotes the matched filter output of the baseband information bits of user p. $\alpha_p \sqrt{P_p} E N_s d_i^{(p)}$ denotes the MAI to user p. Another item denotes the Gaussian white noise value after the matched filter.

3 FPGA implementation of the GMM MUD algorithm

The overview of the FPGA-based GMM MUD system block diagram is shown in Fig.3.

Fig. 3. Overview of the FPGA-based GMM MUD.

The FPGA hardware platform of multi-user detection algorithm based on Gaussian mixture model selects DE3 development board from Altera. The design chooses FPGA/Matlab joint debugging method based on serial interface. Using Matlab to generate signal $r(t)$ and receive data d . Hence, FPGA data transmission and reception are realized through RS232.

The FPGA block diagram for the GMM MUD algorithm as shown in Fig.4.

Fig. 4. FPGA block diagram for the GMM MUD algorithm.

3.1 GMM-based multi-user detector

The GMM is a model formed by clustering several Gaussian probability density functions. GMM MUD structure block diagram is shown in Fig.5.

Fig. 5. GMM MUD structure block diagram.

The Gaussian mixture model can be defined as:

$$p(x) = \sum_{i=1}^K w_i p(x | \mu_i, \sigma_i^2) \quad (7)$$

where K denotes the number of models, w_i denotes the weight of the i th Gaussian model, and $\sum_{i=1}^K w_i = 1$. μ_i denotes the mean of the i th Gaussian model, and σ_i^2 denotes the variance of the i th Gaussian model.

For a given number of models K , the GMM uses parameter estimation method to obtain the weight w_i , mean μ_i , and variance σ_i^2 of each mixture component. The function can be written as:

$$L = \prod_{j=1}^m \log\left(\sum_{i=1}^K w_i p(x | \mu_i, \sigma_i^2)\right) \quad (8)$$

However, it is generally used to solve by the expectation maximization (EM) algorithm. Solving process can be expressed as:

- According to the given K value, initialize the weight w_i , mean μ_i and variance σ_i^2 .
- Expectation-step. Calculate the i th sample x_i , which is the posterior probability generated by the k th model.
- Maximization-step. Update the mean and variance by the posterior probability obtained in E-step.
- Repeat E-step and M-step until the likelihood function increment is less than the convergence threshold.

3.2 Control state machine

The key task of Control State Machine is drive the other sub-modules, in this way to control the system work orderly. The state-transition diagram is shown in Fig.6.

Fig. 6. State-transition diagram.

- $S0$: System initial state.
- $C1$: Received data valid.
- $S1$: FIFO1 receive data .
- $C2$: FIFO1 is full.
- $S2$: Read and process data from FIFO1.
- $C3$: FIFO1 is empty.
- $S3$: Write the processed data to FIFO2.
- $C4$: FIFO2 is full .
- $S4$: Send the data in FIFO2 .
- $C5$: FIFO2 is empty.
- $S5$: Clear all.
- $C6$: Receive data valid signal enable.

3. Implementation results and analysis

In this section, we set the number of users in the communication system to 10, the SNR ranging from 0dB to 10dB spaced 1dB, the serial port baud rate is 230400, and send 500000 modulation code elements. The BER performance of the GMM-based multi-user detector is shown in Fig.7.

Fig.7. The result of BER performance.

We present result to show the detection performance of the GMM-based multi-user detector. In Fig.7, it can be seen that the performance of FPGA measured bit error rate based on Gaussian Mixture Model multi-user detection is lower than the theoretical bit error rate. When the SNR is low, the BER performance of the GMM-based multi-user detector is close to DEC multi-user detection and MMSE multi-user detection. When the SNR is high, the BER performance of the GMM-based multi-user detector is better than DEC multi-user detection and MMSE multi-user detection.

4 Summary

The FPGA implementation of GMM MUD algorithm have been proposed in this paper. The processing speed of the design is faster than the theoretical algorithm. While ensuring the capability, the algorithm has lower complexity, faster speed and real-time performance. Furthermore, the system is more implementable.

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