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A Hybrid Multiuser Detection Algorithm for Outer Space DS-UWB Ad-hoc Network with Strong Narrowband Interference

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Abstract

Formation flying is an important technology that enables high cost-effective organization of outer space aircrafts. The ad-hoc wireless network based on direct-sequence ultra-wideband (DS-UWB) techniques is seen as an effective means of establishing wireless communication links between aircrafts. In this paper, based on the theory of matched filter and error bits correction, a hybrid detection algorithm is proposed for realizing multiuser detection (MUD) when the DS-UWB technique is used in the ad-hoc wireless network. The matched filter is used to generate a candidate code set which may contain several error bits. The error bits are then recognized and corrected by an novel error-bit corrector, which consists of two steps: code mapping and clustering. In the former step, based on the modified optimum MUD decision function, a novel mapping function is presented that maps the output candidate codes into a feature space for differentiating the right and wrong codes. In the latter step, the codes are clustered into the right and wrong sets by using the *K*-means clustering approach. Additionally, in order to prevent some right codes being wrongly classified, a sign judgment method is proposed that reduces the bit error rate (BER) of the system. Compared with the traditional detection approaches, e.g., matched filter, minimum mean square error (MMSE) and decorrelation receiver (DEC), the proposed algorithm can considerably improve the BER performance of the system because of its high probability of recognizing wrong codes. Simulation results show that the proposed algorithm can almost achieve the BER performance of the optimum MUD (OMD). Furthermore, compared with OMD, the proposed algorithm has lower computational complexity, and its BER performance is less sensitive to the number of users.

Keywords: DS-UWB, multiuser detection, narrowband interference, error-bit corrector, code mapping, *K*-means clustering

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1. Introduction

1.1 DS-UWB ad-hoc network

In recent years, with the rapid development of space technology, the concept of outer space formation flying has attracted much interest because of its low cost, good performance, short development cycle and favorable flexibility [1]. One of the key enabling technologies in the formation flying is establishing the inter-aircraft wireless communication link. The ad-hoc wireless network based on direct-sequence ultra-wideband (DS-UWB) is an appropriate means for constructing communication links between the formation flying aircrafts.

The ad-hoc wireless network is a mobile self-organized network that can set up the network without special infrastructure facilities. In an ad-hoc network, each user can be seen as a node or router that constructs and maintains the network [2][3]. One of the superiorities of ad-hoc wireless network is its low hardware resource consumption, which makes it more suitable for the formation flying of outer space aircrafts while considering the payload limit.

In this paper, we mainly focus on the physical layer research of ad-hoc network. According to the concrete environment of outer space formation flying, it would be a wise choice to use DS-UWB techniques for establishing wireless communication links between the aircrafts. Since 1990s, much attention has been drawn to ultra-wideband (UWB) in both theoretical research and industrial applications, because of its attractive features, e.g., high data transmission rate, low power density, high interference resistance, strong multi-path resolution [4][5]. Recent years, National Aeronautics and Space Administration (NASA) has done some research work on the application of UWB in outer space aircrafts formation flying. Additionally, the UWB transmission based mini-AERCam system has been successfully developed that can automatically take pictures of aircrafts for the purpose of diagnosing and repairing faults [6].

The UWB ad-hoc wireless network is a multiple access system which contains several independent users, and it is necessary to select a suitable multi-access scheme when the UWB ad-hoc wireless network is applied to the outer space formation flying [7]. In the UWB communication system, the multiple access scheme includes two types: time hopping UWB (TH-UWB) and direct-sequence UWB (DS-UWB). In the former case, different users are separated by using different time chips and relative delays [8], while in the latter case they are separated by using orthogonal pseudo noise (PN) codes. In this paper, we discuss the DS-UWB multiple access scheme that combines both direct sequence code division multiple access (DS-CDMA) and UWB techniques [9]. As the DS-UWB communication system is an active-disturbance system, there exists multiple access interference (MAI). A traditional single-user receiver will suffer from the so-called near-far problem that the near-by signal source blocks the signal from far-away user. To solve the near-far problem, multiuser detection (MUD) technique should be adopted for mitigating MAI [10]. In addition, due to the wide bandwidth of UWB signal that spreads over more than several GHz, it is inevitable that the frequency spectrum of UWB signal will overlap with the spectrum of some ‘narrowband’ communication systems, e.g., GPS and TV broadcasting. These narrowband signals may act as strong narrowband interferences (NBI) to the UWB communication system [11]. For this reason, the strong NBI should be carefully considered in the performance analysis of MUD.

1.2 Related Work Of Mud Algorithms

Many methods of MUD have been proposed to solve the problem of MAI. In 1986, Verdu first proposed the algorithm of the optimum multiuser detection (OMD) based on maximum likelihood sequence detection (MLSD) [12]. The OMD has the optimal BER performance and the perfect NFE resistant ability, but it has difficulty in practical application because it will cause extremely high computational complexity [13]. In the DS-UWB system, minimum mean square error (MMSE) MUD algorithm is widely used, [14] proposed a MMSE implentation for DS-UWB. Moreover, [15] studied MMSE's capability of gathering multipath energy and suppressing intersymbol interference (ISI) that is caused by multipath . In addition, Rake receiver proposed in [16] can combine the multipath energy together and suppress additional noise and narrowband interference by utilizing the processing gain of the direct sequence spread spectrum (DS-SS) system. However, the MMSE MUD and Rake receiver must utilize a training sequence to estimate the channel. This approach can decrease the computational complexity, however, at the expense of worse BER performance when compared with OMD.

Recent years, many sub-optimal MUD algorithms have been proposed in literatures. A population declining mutated ant colony optimization (PDMACO) multiuser detector is proposed in [13], it can improve the BER and NFE performance by enlarging the searching range, but the implementation of PDMACO may also cause a computational complexity cost. In [17], a multiuser frequency-domain (FD) turbo detector which combines FD turbo equalization schemes with soft interference cancelation was studied, but its BER performance is unsatisfactory. A blind multiuser detector based on support vector machine (SVM) on a chaos-based code CDMA systems was proposed in [18], which does not require the knowledge of spreading codes of other users at the cost of training procedure. However, the tradeoff problem between computational complexity and BER performance still exists.

1.3 Contribution Of Our Work

In this paper, we propose a hybrid multiuser detector that combines theory of matched filter and error bits correction for an outer space DS-UWB based ad-hoc network. The matched filter exploits the correlations between received signal and the template signal. The error-bit corrector is then used to identify the wrong codes in the candidate codes set that is outputted from the matched filter. Specifically, the error-bit corrector is composed of code mapping algorithm and clustering algorithm. The proposed hybrid detector can pick out and correct the bit error without the aid of training sequences. It can obtain the BER performance similar to the OMD method in either additive white Gaussian noise (AWGN) or strong narrow-band interference (NBI) environment. Further, it is worthwhile to emphasized that the proposed hybrid MUD algorithm has a lower computational complexity, and its BER performance is more robust against the increase of the number of users, when compared with the OMD method.

The remainder of this paper is organized as follows. Section 2 describes the signal model of the DS-UWB communication system, including signal description, channel model and matched filter receiver structure. Section 3 presents the principle of the proposed multiuser detector. The simulation results are shown in Section 4. Finally, some remarkable conclusions of this paper are given in Section 5.

2. DS-UWB System Model

2.1 DS-UWB Signal Model

We consider a DS-CDMA based UWB system with K active users, where each transmitter employs binary phase-shift key (BPSK) modulation. At the transmitter k (k=1,2,…,K), BPSK symbols $b_k(i) \in \{-1,1\}_{i=1}^{M}$ are spread with the specific pseudorandom (PN) codes $c_k(t)$, which are the binary bit stream with the value of either -1 or 1. The BPSK symbol is then modulated with the chip pulses $p(t)$ which often adopts the second derivative of a Gaussian pulse with a duration of a nanosecond. M denotes the length of bits per packet. The symbol duration is denoted by T_s. We consider that each BPSK symbol can be divided into N_c chips each with duration T_c, where N_c equals to T_s/T_c. In each chip, a monocycle $p(t)$ is transmitted with the duration of T_p, where T_p represents the sign of a chip. Practically, the duration of a chip is much longer than the duration of an UWB pulse, i.e., T_c>> T_p. The kth user's transmit signal can be written as [11]:

$$x_k(t) = \sum_{i=1}^{M} \sum_{j=0}^{N_c-1} b_k(i) c_k(t-(i-1)T_s) p(t-(i-1)T_s - jT_c - \tau_k) \tag{1}$$

where τ_k represents the random delay of the kth transmitter's monocycle, where $0 \leqslant \tau_k < T_c$.

2.2 DS-UWB Channel Model

We assume that the UWB transmission channel suffers effects of multipath and is quasi-stationary within a transmission slot. Let $h(t)$ represent the impulse response of the transmission channel. In addition, we suppose that UWB signals reach the receiving antenna by L different paths. The channel impulse response can be written as [19]

$$h(t) = \sum_{l=1}^{L} \alpha_l \delta(t - \tau_l) \tag{2}$$

The received signal that is transmitted from the kth user is given by

$$v_k(t) = x_k(t) * h(t) \tag{3}$$

where * denotes a convolution operator. However, considering the particular environment of the outer space where the signal reflection seldomly exists, we can omit the effects of multipath. Hence, the number of path L is assumed to be 1 in (2). Due to the noise and narrowband interference, the received signal can be written as

$$r(t) = v(t) + n(t) + I(t) = \sum_{k=1}^{K} x_k(t) * h(t) + n(t) + I(t) \tag{4}$$

where $n(t)$ is zero-mean AWGN, and $I(t)$ represents the narrowband interference with an average power P_I, center frequency f_0 and signal bandwidth B. The form of the narrowband interference may vary due to different modulation schemes and baseband signal waveforms. Without loss of generality, the NBI is assumed to be a narrowband random signal, which can be written as

$$I(t) = \sqrt{2P_I}\, a(t) \cos(2\pi f_0 t + \theta_0)$$

where a(t) is a random process with the bandwidth of B, and θ_0 represents a random phase with an uniform distribution between 0 and 2π.

2.3 Matched Filter Receiver

In the receiver, the traditional receiver of a DS-UWB system consists of a pulse demodulator and a bank of matched filters corresponding to each user. We regard signal $r(t)$ as the input of the group of matched filters. Furthermore, the impact of ISI to the receiving performance is often very weak. So the ISI can be not taken into account when the base-band signal transmission rate is much lower than the UWB pulse rate [20].

We assume that the outer space DS-UWB ad-hoc network system is synchronized by the use of reference signals from the positioning system, and the number of transmitters is K. So the result of demodulating the ith information symbol of all K users can be expressed as a vector $\mathbf{y}$ with K elements. The kth element (k=1,2,…,K) of $\mathbf{y}$ is the output of matched filter corresponding to the transmitter k. It is the output of the filter matched to $x_k(t)$ in the ith information symbol interval and can be expressed as

$$y_k(i) = \int_{iT_s}^{(i+1)T_s} x_k(t) r(t) dt \tag{5}$$

To make the illustration clear and general, we can ignore the symbol interval i and assume that all the information symbol intervals are the same to the matched filter receiver. Thus, the element y_k can take place every element of time sequence $y_k(i)$. Substitute equation (4) to (5), we obtain

$$y_k = \int_0^{T_s} x_k(t) r(t) dt = A_k b_k + \sum_{\substack{i=1 \\ i\neq k}}^{K} A_i b_i r_{ik} + n_k + I_k \tag{6}$$

where the first part $A_k b_k$ is the ideal detection target of the kth matched filter and embraces the baseband information of user k, the second part $\sum_{\substack{i=1 \\ i\neq k}}^{K} A_i b_i r_{ik}$ denotes the MAI to the kth user where $r_{ik} = \int_0^{T_s} x_i(t) x_k(t) dt$ is the cross-correlation coefficient between the user i and user k, the third part $n_k = \int_0^{T_s} n(t) x_k(t) dt$ is the AWGN interference to the user k where the variance of random series n_k is σ^2, and the last part $I_k = \int_0^{T_s} I(t) x_k(t) dt$ is the narrowband interference to the user k.

Consequently, the K-dimensional vector $\mathbf{y}$ can be rewritten as:

$$\mathbf{y} = \mathbf{RAb} + \mathbf{n} + \mathbf{I} \tag{7}$$

where $\mathbf{R}$ denotes the cross-correlation matrix whose element is r_{ik} (i, k=1, 2, …, K), and matrix $\mathbf{A}$=diag$\{A_1, A_2, \dots, A_K\}$,vector $\mathbf{b} = [b_1, b_2, \dots, b_K]^T$, vector $\mathbf{y}=[y_1, y_2, \dots, y_K]^T$, vector $\mathbf{n}=[n_1, n_2, \dots, n_K]^T$ and vector $\mathbf{I}=[I_1, I_2, \dots, I_K]^T$.

After being processed by these matched filters, the output signal $\mathbf{y}$ should be judged by the sign detector as follows:

$$\mathbf{b} = \mathrm{sgn}(\mathbf{y}) \tag{8}$$

3. Hybrid MUD Algorithm

The main purpose of the proposed method is to pick out and correct the wrong codes among the received signals outputted by the matched filter. There is an ordinary way to pick out the error bits. Firstly, we map the received bits into a feature space to make the wrong codes and the right ones become different in some properties which can be easily distinguished. Secondly, we classify and pick out the wrong codes by using some approaches in the feature space. The proposed method in this paper can be called as error-bit corrector, which includes three stages, the first stage is corresponding to the code mapping, the second stage is code clustering, and the third stage, sign judgment. The block diagram of the algorithm is shown in **Fig.1**. The vector $\hat{\mathbf{b}} = [\hat{b}_1, \hat{b}_2, ..., \hat{b}_K]^T$ denotes the final output of the receiver.

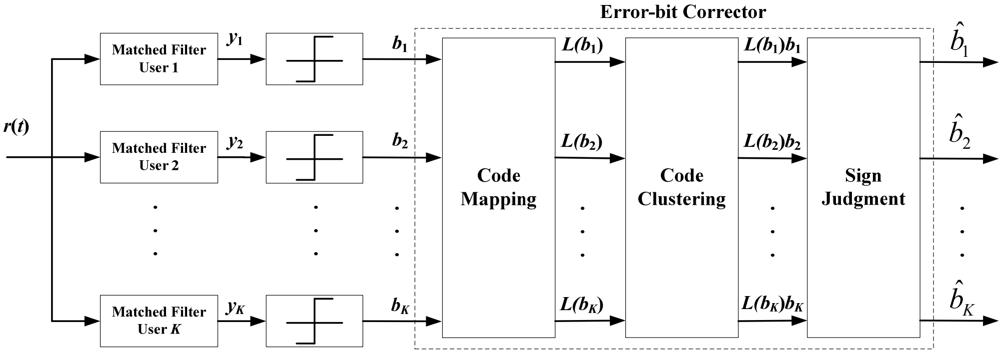


Fig. 1. Block Diagram of Hybrid algorithm with Matched Filter and Error-bit Corrector

3.1 Cod6cpping

Here, we construct a mapping function to map the candidate codes set to a one-dimensional feature space. The code mapping theory was firstly proposed in [21]. In [21], the code mapping theory is mainly applied into the design of q-Level complex m sequence in DS-CDMA systems. The code mapping method proposed here is quite different from [21]. In order to distinguish the right codes and wrong codes, we propose a detailed mapping function which is based on the optimal multi-user detection theory.

According to the theory of OMD [12], the optimum detection result satisfies the following expression

$$\hat{\mathbf{b}}_{\mathrm{OMD}} = \arg\{\max_{b\in\{-1,1\}} (2\mathbf{b}^{\mathrm{T}}\mathbf{Ay} - \mathbf{b}^{\mathrm{T}}\mathbf{Hb})\} \tag{9}$$

where $\mathbf{A}=\mathrm{diag}(A_1, A_2,\ldots, A_K)$ and the diagonal element A_k ($k\in[1,K]$, $k\in\mathrm{N}$) represents the signal amplitude of the kth user. $\mathbf{H}=\mathbf{ARA}$ and $\mathbf{R}=(r_{ij})_{K\times K}$ denotes the cross-correlation matrix which is diagonal element dominant, that is

$$r_{ii} >> | r_{ij} | \ (i,j=1,2,\ldots,K,\ i\neq j). \tag{10}$$

Let

$$F(\mathbf{b}) = \frac{1}{2}\mathbf{b}^{\mathrm{T}}\mathbf{Hb} - \mathbf{b}^{\mathrm{T}}\mathbf{Ay} \tag{11}$$

where $\mathbf{b}= [b_1, b_2,\ldots, b_K]^{\mathrm{T}}$ denotes the output of the sign detector based on formula (8) and is called the candidate codes set. According to (9), we can see that if the elements in $\mathbf{b}$ are all correct, the value of function $F(\mathbf{b})$ will achieve the minimum. By expanding (11), we get

$$F(\mathbf{b}) = F(b_1, b_2, ..., b_K) = \frac{1}{2}\sum_{i=1}^{K}\sum_{j=1}^{K} A_i A_j r_{ij} b_i b_j - \sum_{i=1}^{K} b_i A_i y_i \tag{12}$$

From (11) and (12), it is clear that function $F(\mathbf{b})$ is a quadratic form about vector **b**. Formula (12) is a second-order nonlinear equation, and it is not easy to solve the minimum of $F(\mathbf{b})$ and the corresponding value of **b**. In addition, the function $F(\mathbf{b})$ embraces cross-component $b_i b_j$ (i,j=1,2,…,K, $i \neq j$), and we can't judge a code independently by $F(\mathbf{b})$. Hence, it is not appropriate for function $F(\mathbf{b})$ to be the mapping function. In this case, it is better to calculate the derivative of function $F(\mathbf{b})$ to decrease the order of mapping function. By calculating the partial derivation of (11), we get

$$\frac{\partial F}{\partial \mathrm{b}} = \mathrm{Hb} - \mathrm{Ay} \tag{13}$$

By expanding (13), we get a Kth-order linear equations given as follows:

$$\begin{cases} \dfrac{\partial F}{\partial b_1} = \sum_{j=1}^{K} A_1 A_j r_{1j} b_j - A_1 y_1 \\ \dfrac{\partial F}{\partial b_2} = \sum_{j=1}^{K} A_2 A_j r_{2j} b_j - A_2 y_2 \\ \quad \cdots \\ \dfrac{\partial F}{\partial b_K} = \sum_{j=1}^{K} A_K A_j r_{Kj} b_j - A_K y_K \end{cases} \tag{14}$$

Now, we take into account that the MAI is the main interference source which largely affects the performance of the system. Let $L(b_i) = \sum_{j=1}^{K} A_i A_j r_{ij} b_j - A_i y_i$, i=1,2,…,K. Substitute the candidate codes set **b** into (9), there are two situations illustrated as follows:

1). No wrong code in **b**

Based on the theory of extreme value, if MAI is the only interference source (No AWGN and NBI exists in the channel), the results of equation (14) are strictly equal to **0**. In the case of both AWGN and NBI, we can see that $L(b_k)$=-$A_k(n_k+I_k)$ (k=1,2,…,K) when there is no error bit in the candidate codes set **b**.

2).Wrong codes exist in **b**

Suppose b_i ($i \in [1, K]$, $i \in$ N) be the wrong code (in other words, -b_i is the correct code), the other codes are correct. Substituting it to the ith equation of (11), and according to (6), we get

$$L(b_i) = \sum_{\substack{j=1 \\ j\neq i}}^{K} A_i A_j r_{ij} b_j - A_i y_i + A_i^2 r_{ii} b_i = \sum_{\substack{j=1 \\ j\neq i}}^{K} A_i A_j r_{ij} b_j - A_i y_i + A_i^2 r_{ii}(-b_i) + 2A_i^2 r_{ii} b_i = 2A_i^2 r_{ii} b_i - A_i(n_i + I_i)$$

As for k which does not equal to i, we get

$$L(b_k) = 2A_i A_k r_{ik} b_i - A_i(n_i + I_i), \quad k=1,2,\ldots,K,\ k \neq i$$

According to (14), we can see when the ith user's bit is wrong, then we get $|L(b_i)| >> |L(b_k)|$, k=1,2,…,K, $k \neq i$. Therefore, the function $L(\mathbf{b})$ can obviously differentiate the wrong codes and the right codes through the absolute value of it. In addition, $L(\mathbf{b})$ is a Kth-order linear equations which can get the result of $L(\mathbf{b})$ without complex computations. In conclusion, it is appropriate to set $|L(\mathbf{b})|$ as the mapping function in the hybrid MUD algorithm.

It is accessible to map **b** into a one-dimension feature space $|L(\mathbf{b})|$ to identify the wrong codes in the candidate set. Fig. 2 shows an example of the feature space mapping in the scenario of 10 users, with 6dB signal-to-noise ratio (SNR) and without ISI.

In **Fig. 2**, it is clear that the wrong codes and the right ones have a significant difference in the feature space mapped by |*L*(b)|. Almost all the values of |*L*(b)| corresponding to the wrong codes are greater than 260, in contrast the values of the right ones are smaller than 260. Hence, a threshold, as depicted in **Fig. 2**, can be set to make the judgment.

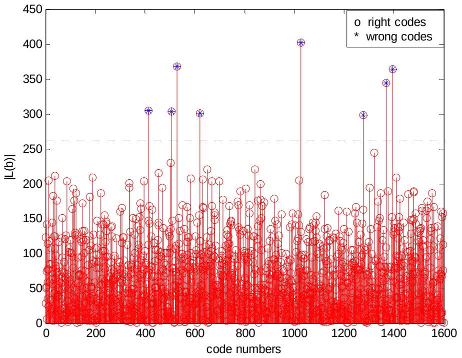


Fig. 2. Relationship between code numbers and mapping function |*L*(b)|.

3.2 Code Clustering

We use *K*-means clustering approach [22] to classify the candidate codes into right bits and wrong ones. The *K*-means clustering is a popular unsupervised clustering algorithm based on the partition of data, which can finish the classification without training samples. In this paper, the sample set in the feature space $|L(b_k)|$ (k=1,2,…,K) is classified into two categories as follows:

cat. 1: $|L(b_k)|$ which denotes the wrong code b_k;
cat. 2: $|L(b_k)|$ which denotes the correct code b_k.

Sometimes, all of the codes in the candidate set are correct and sorted into cat.2 along with the set of cat.1 is empty. In this situation, some specific measures should be taken into account in order to make the *K*-means clustering available.

Let m_1 and m_2 be the mean value of cat.1 and cat. 2. The mean squared error J_k can be considered as the criterion of the clustering. In the one-dimensional feature space, the parameter m_1, m_2 and J_k can be defined as follows:

$$m_1 = \frac{1}{N_1}\sum_{i=1}^{N_1}\left|L(b_i^{(1)})\right| \tag{15}$$

$$m_2 = \frac{1}{N_2}\sum_{i=1}^{N_2}\left|L(b_i^{(2)})\right| \tag{16}$$

$$J_k = \sum_{i=1}^{2}\sum_{L(b)\in cat_i}\left|\,|L(b^{(i)})| - m_i\right|^2 \tag{17}$$

where N_1 and N_2 denote the number of elements in cat.1 and cat. 2, and $L(b^{(1)})$ and $L(b^{(2)})$ represent the element attributed to cat.1 and cat.2, respectively.

The procedure of bit-error recognition using *K*-means clustering is presented by the following steps:

STEP 1: Set the initial value of m_1 and m_2. Generally, the initial value of m_2 can be set as 0, and that of m_1 can be set as a considerably large number according to the concrete situation.

STEP 2: For each sample $|L(b_k)|$ (k=1,2,…,K) in the feature space, calculate its distance to both mean values of the two categories.

$$\rho_j(k) = \big||L(b_k)| - m_j\big| \qquad j=1,2 \tag{18}$$

STEP 3: If $\rho_1(k) \leqslant \rho_2(k)$, b_k will be classified into cat.1 and regarded as a wrong code; on the contrary, b_k will be classified into cat.2 and regarded as a right one.

STEP 4: Update the value of m_2 by (16). Check the number of N_1, if N_1=0, maintain the initial value of m_1; else, update the value of m_1 by (15).

STEP 5: Update the error sum squares J_k by (17).

STEP 6: If the value of J_k does not change after two continuous iterations, stop the algorithm; or else, return to STEP 2.

3.3 Sign Judgment

As illustrated above, we recognize the wrong codes only by the absolute value of $L(\mathbf{b})$, which sometimes may regard some correct codes as the wrong codes. This may decrease the bit-error performance of the system because of the strong interference of AWGN and NBI. To make sure that the right codes are not classified to be wrong ones, the sign information of code should be utilized.

Assume b_k ($k \in \{1,2,\dots,K\}$) is the wrong code classified into cat.1 by K-means clustering, the other codes b_j ($j \in \{1,2,\dots,K\}$, $j \neq k$) are correct, and b_k equals to -1. Thus, the correct code $-b_k$=1, in this condition, we get

$$\begin{aligned} L(b_k) &= \sum_{\substack{j=1\\ j\neq k}}^{K} A_k A_j r_{kj} b_j - A_k y_k + A_k^2 r_{kk} b_k = \sum_{\substack{j=1\\ j\neq k}}^{K} A_k A_j r_{kj} b_j - A_k y_k + A_k^2 r_{kk}(-b_k) + 2A_k^2 r_{kk} b_k = \\ & 0 + 2A_k^2 r_{kk} b_k = -2A_k^2 r_{kk} < 0 \end{aligned} \tag{19}$$

We can see the mapping function $L(b_k)$ and the corresponding code b_k are the same sign. Similarly, when the wrong code b_k is positive, the same conclusion can be conducted. Therefore, the sign judgment of wrong codes can be given as follows:

$$L(b_k)b_k > 0 \tag{20}$$

On the contrary, if $L(b_k)b_k < 0$, code b_k must not be the wrong code that is caused by MAI. It is classified into cat.1 because the influence of AWGN or NBI. So the proposed MAI suppression algorithm may regard b_k as the right code and will not correct it. Therefore, we can use formula (20) to decrease the probability that the right codes are wrongly classified as the wrong ones, which guarantees that the performance of the hybrid MUD algorithm is better than that of the traditional detector. Finally the wrong codes will be corrected by the sign inversion.

To sum up, the proposed approach can make the multiuser detection with 4 steps. First, the candidate codes set $\mathbf{b}$ is mapped into a one-dimensional feature space by mapping function $|L(\mathbf{b})|$. Second, the wrong codes among the candidate codes set are picked out by using K-means clustering. Third, the sign judgment is used to eliminate the right one among the potential wrong codes picked out from the second step. Lastly, the wrong codes are corrected to obtain a better BER performance.

4. Simulation Results And Analysis

In this section, simulation results are presented in order to show the superiority of the hybrid multiuser detector that is based on matched filter and error-bit corrector with respect to both system performance improvement and computational complexity reduction. We present simulation results for the performance of the DS-UWB system with two types of multiuser receivers: the matched filter receiver and the proposed hybrid multiuser receiver in two different channel environments: the AWGN channel and the AWGN channel with strong NBI[23][24]. We set the chip transmission rate as 2.55Gcps with the UWB transmission bandwidth range 1~8GHz, and adopt the Kasami spreading codes with length of 255 in the transmitter. We assume that the signal is transmitted in an AWGN channel without ISI, and we regard global positioning system (GPS) and unified S-band (USB) signals as the strong NBI signals whose center frequencies are 1.8GHz and 2.4GHz, respectively. Our main destination is to examine a receiver's bit error rate (BER) which apparently implies the performance of the receiver on the condition of different SNR environments (AWGN channel environment) and the signal to interference ratio (SIR) situations. In addition, we can check the recognition rate of *K*-means clustering in this scenario.

4.1 BER Performance

First, we consider the AWGN channel environement. There are four kinds of detectors: matched filter receiver, decorrelation receiver (DEC), MMSE receiver, OMD receiver and the hybrid MUD receiver (EBR) as demonstrated in Section 3. The number of transmitters is set to 10 and the range of the received SNR at the receiver is 0dB~14dB. Here, we define SNR as the ratio of average energy per bit E_b over the power spectrum density of AWGN N_0. The curves of BER performance versus SNR are depicted in **Fig. 3**.

As shown in **Fig. 3**, the BER performance of the hybrid MUD receiver is superior to that of matched filter receiver and MMSE. Especially in the condition of high SNR circumstances (greater than 8dB), the detective performance of the hybrid MUD receiver is much better than that of the matched filter receiver (approximately 2~3 orders of magnitude higher). What's more important is that the BER performance of the hybrid MUD is very close to that of OMD receiver. In theory, the OMD receiver can completely eliminate the MAI and can arrive at the lower limit of BER in the condition of multiple users. This means that the hybrid MUD can correct almost all the wrong codes caused by MAI.

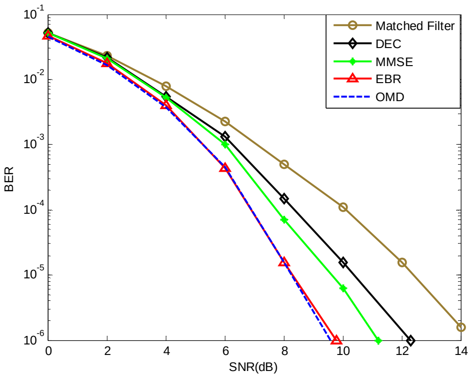


Fig. 3. BER performance versus SNR in 10-user condition

OMD can obtain the best BER performance at the expense of large computational complexity which rises up exponentially with the increase of the number of users. However, the computational complexity of hybrid MUD is much less than that of the OMD. In a *K*-user DS-UWB system, to detect the *K*-user vector b, the computational complexity of the OMD is 2^K times iterations to satisfy equation (9) [13].

The computational complexity of the proposed hybrid MUD includes three parts. The first part is the computational complexity of the code mapping. According to section 3.1, the mapping method is just a calculation of L(b), so the computational complexity of the first part can be neglected. The second part is the complexity of the K-means clustering. Due to section 3.2, the complexity of the code clustering is K times iterations. The third part is the complexity of the sign judgment. Similar to the code mapping, the complexity of the sign judgment is just the calculation of equation (20), so its complexity can be ignored too. Thus the computational complexity of the proposed hybrid MUD method approximately equals to K times iterations and is much less than that of OMD.

Let the normalized operation time per bit using matched filter detector equals to 1 in the condition of 10 users. **Table. 1** lists the relative operation time per bit using OMD, hybrid MUD and matched filter in the conditions of 10 and 20 users.

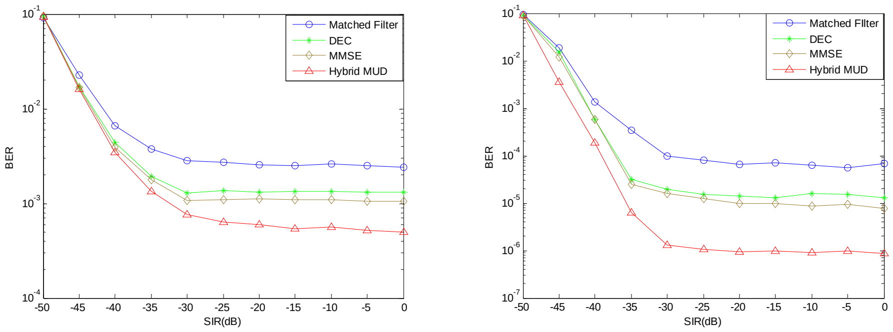
Table. 1 The comparison of computational complexity using different MUD algorithm

Number of Users	OMD	DEC	MMSE	Hybrid MUD	Matched Filter
10	34.92	1.10	1.18	1.06	1
20	35762.24	26.47	28.14	2.15	1.02

From **Table. 1**, we can see that the computational complexity of the hybrid MUD increases linearly with the increase of the number of users, and is in the same order of magnitude to the matched filter. This is because the main time consumption of hybrid MUD is for K-means clustering. We use K-means clustering in a one-dimentional feature space and the candidate codes are classified at most two classifications. So, the iteration of K-means clustering will be converged very soon and costs little quantity of computation. Hence, we can get a conclusion that the hybrid MUD can get good BER performance with low computational complexity.

Second, we add the strong NBI signal into the interference sources, that is, the total received signal can be expressed as formula (4). Here, we still simulate the BER performance of using matched filter receiver and the hybrid MUD algorithm to make comparison. We define SIR as the ratio of average energy per bit E_b over the average power of the narrowband interference signal (GPS or USB). The number of transmitter is also set to 10 and the range of SIR is set to be between -50dB to 0dB.

If the strong NBI signal is the GPS narrowband signal (center frequency at 1.8GHz), the curves of BER performance versus SIR are depicted in Fig. 4.



(a) (b)

Fig. 4. BER performance versus SIR with the GPS narrowband interference
(a) SNR=6dB; (b) SNR=10dB

If the strong NBI signal is the USB narrowband signal (center frequency at 2.4GHz), the curves of BER performance versus SIR are depicted in **Fig. 5**.

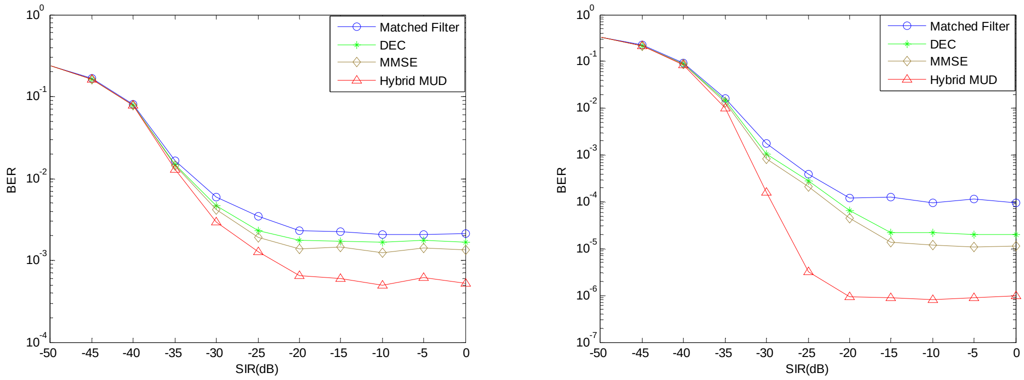


Fig. 5. BER performance versus SIR with the USB narrowband interference

(a) SNR=6dB; (b) SNR=10dB

As shown in **Fig. 4** and **Fig. 5**, the BER performance of Hybrid MUD receiver is superior to that of the matched filter receiver when considering strong NBI. In **Fig. 4**, the GPS signal is regarded as the NBI whose center frequency is 1.8GHz and its bandwidth is set to be 2.046 MHz. When the SIR varies from -50dB to -30dB, the BER obtained by both matched filter and hybrid MUD algorithm sharply decreases, and the reduction rate of hybrid MUD is greater than that of matched filter. When the SIR is greater than -30dB, with the increase of SIR, the BER of both hybrid MUD and matched filter converges to a constant value and nearly remain unchanged. Therefore, we can obtain the conclusion that when the SIR is less than -30dB, the BER performance is mainly influenced by the strong NBI, and when the SIR is greater than -30dB, the BER performance is mainly influenced by the AWGN and the impact of narrowband interference can be ignored. The SIR value of -30dB seems to be a threshold, which can make the NBI have little impact on the BER performance of the receiver. Further, the convergence value of BER equals to that of without NBI in the corresponding SNR condition which is depicted in **Fig. 3**. We can have similar conclusion by analyzing **Fig. 5**, except that the interference threshold of SIR turn out to be -25dB. **Table. 2** lists a series of the interference threshold values of SIR in the different SNR conditions.

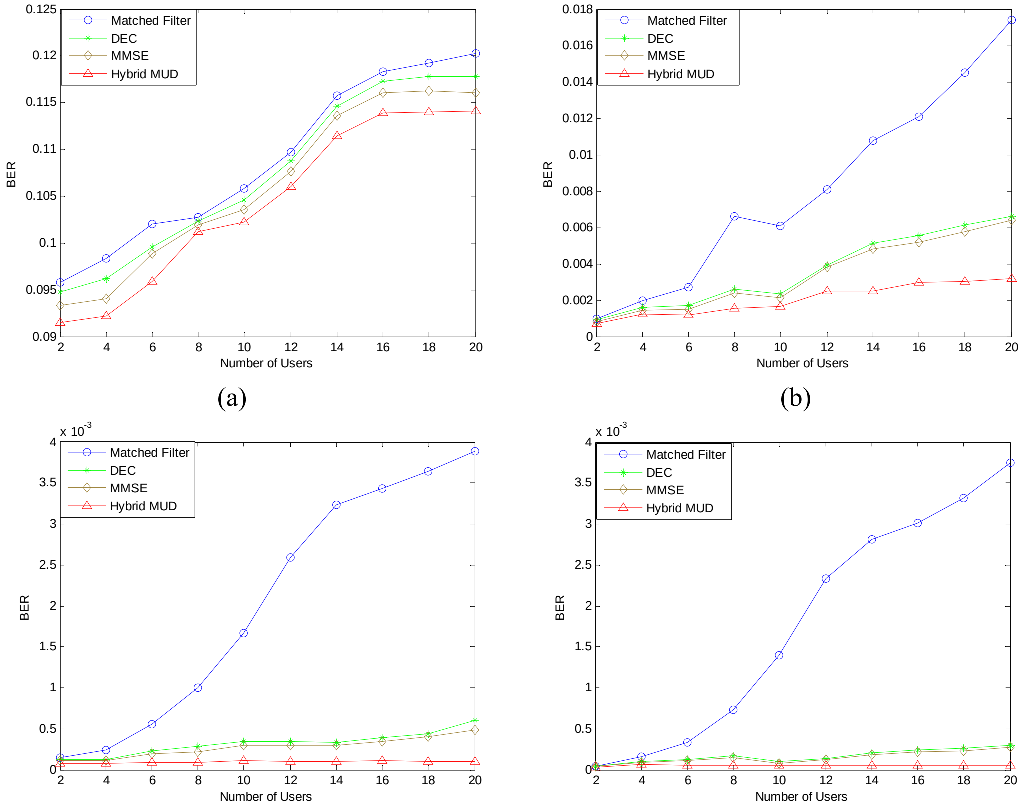
Table. 2 The Relationship between SNR and the interference threshold of SIR

SNR(dB)	**Threshold value of SIR (dB)**	
	USB	**GPS**
0	-32	-42
2	-21	-36
4	-20	-34
6	-19	-32
8	-18	-29
10	-15	-28
12	-14	-26

From **Table. 2**, we can see that with different narrowband interference signals, the threshold value of SIR becomes greater as the increase of SNR. However, in the same SNR condition, there are some differences between the thresholds of USB and GPS. That's because the center frequencies of USB and GPS are different. Compared to GPS, the center frequency of

USB signal is more close to that of the UWB signal. In other words, the energy entered to the UWB receiver is larger than that of the GPS signal. Hence, the USB signal can have more impact on the receiving performance than that of the GPS signal with the same power of NBI.

Furthermore, we consider another situation with different number of transmitters under the same SIR and SNR condition. To make the comparison apparent, the algorithms of matched filter receiver and hybrid MUD detector are simulated. The simulation results are shown in **Fig. 6** with the SIR of -40dB, -30dB, -20dB and -10dB and with the SNR of 8dB.



(a) (b)

(c) (d)

Fig. 6. BER performance versus the number of users in specific SIR condition

(a) SIR=-40dB (b) SIR=-30dB (c) SIR=-20dB (d) SIR=-10dB

As shown in **Fig. 6**, the BER performance of the hybrid MUD receiver approximately remains unchanged as the increase of the number of transmitters, when compared with that of the matched filter receiver. In most cases, the number of transmitters is not more than 20 in the DS-UWB communication system. Therefore, under the specific SIR condition, the hybrid MUD receiver is still able to get a superior detective performance when there are many transmitters occupying the same channel simultaneously. It indicates that the BER performance of the hybrid MUD receiver is not sensitive to the channel capacity. This is one of the greatest advantages of the proposed MUD algorithm.

4.2 Recognition Rate

In the *K*-means clustering, recognition rate is a significant criteron that can directly reflect the capability of a classifier. In this paper, the recognition rate is equivalent to what proportion of wrong codes in the candidate set **b** that can be recognized. The wrong codes recognition rate of the *K*-means clustering with different number of users and SIR conditions is shown in **Table 3** as follows (SNR=8dB):

Table 3. Recognition rate of K-means clustering with different SIR and user numbers

SIR **User Number**	**-40dB**	**-30dB**	**-20dB**	**-10dB**
2	4.42%	26.4%	43.5%	21.4%
4	6.25%	37.8%	66.9%	61.4%
6	6.01%	55.7%	84.4%	85.6%
8	1.46%	76.3%	91.4%	93.1%
10	3.33%	72.9%	93.4%	96.0%
12	3.40%	68.9%	96.8%	97.8%
14	3.73%	76.7%	96.8%	97.8%
16	3.68%	75.4%	96.9%	98.2%
18	4.35%	79.0%	97.2%	98.4%
20	5.12%	81.8%	97.4%	98.6%

From **Table 3**, we can see that the recognition rate of the *K*-means clustering in the hybrid multiuser detector increases with the increment of the number of users and the SIR. However, in the low SIR conditions, the recognition rate of the *K*-means is less than 10%, which means that the NBI is main interference source of the DS-UWB system and the hybrid MUD does not bring much improvement regarding the BER performance. When the SIR is relative high (e.g., more than -30dB), the recognition rate increases with the increment of the number of users, which illustrates that the hybrid MUD algorithm can obtain very good detection performance, especially when there are large number of users transmitting in the same UWB channel simultaneously.

5. Conclusion

In this paper, we have proposed a hybrid approach for multiuser detection of the DS-UWB signal. The algorithm embraces four steps. First, as the output of matched filters, the candidate codes set is mapped into a one-dimensional feature space by the code mapping. The purpose is to make the right codes and wrong codes easy to be distinguished. Second, the amplitude judgment is made to identify the error bits by using the *K*-means clustering. Third, the sign judgment is performed for preventing the right codes being classified wrongly. Finally, the wrong codes are corrected by the sign reversal. The simulation results have shown that the BER performance of the hybrid MUD algorithm is superior to that of the matched filter and MMSE detector. Its performance is very close to that of OMD, thanks to the wrong code recognition feature from the *K*-means clustering classifier. Compared to the OMD, the hybrid MUD has lower computational complexity that increases linearly with the number of users. In addition, in the condition of strong narrowband interference, the hybrid MUD algorithm has been shown to have good BER performance, which illustrates that the hybrid MUD algorithm has strong robustness against the strong NBI. Hence, we conclude that the hybrid MUD can achieve superior detection performance in either strong AWGN or strong NBI conditions. The proposed algorithm could be a powerful and an ideal choice for the physical layer design of the ad-hoc wireless network, especially when it is applied for formation flying. Furthermore, the performance of the hybrid MUD receiver can hardly be influenced by the change of the number of users. This means that the proposed hybrid approach can be an efficient method to solve the interference problem when there are large quantities of transmitters occupying the same channel simultaneously.

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