A Method of JTIDS Feature Extraction Based on Nonlinear Transformation of High Order Cumulant

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Abstract. In the view of the target dense region, the features of different target’s time difference are not obvious, which leads to the problem of JTIDS multi-user sorting useless based on time difference. A nonlinear transformation sorting algorithm of high-order cumulant based on doppler frequency shift is proposed: First of all, make the nonlinear transformation based on the second order cumulant, the sixth order cumulant, the normalized skewness and the normalized kurtosis for single station signals respectively, achieve a sharp rise occurs in the degree of the frequency shift; Then, build the eigenvector according to the transformation; Finally, use spectral clustering algorithm to cluster the datasets. Simulation experiments were carried out based on four targets which could not be sorted by the time difference. The result showed that compared with the traditional method, the success rate of our method was significantly improved, and the effectiveness of the algorithm was verified.

1. Introduction

JTIDS (Joint Tactical Information Distribution System) is a set of information distribution system which includes navigation, communication, identification and other functions[1]. With the advantages of anti-interference and high confidentiality, JTIDS is the main battlefield information distribution system now and in the future. Currently, the terminal of JTIDS system has been applied to various scenarios, such as shipborne, airborne and stable stations, and its distribution situation directly reflects the battlefield target situation, realizing the positioning of the terminal has important significance for master the battlefield situation information.

Passive positon of JTIDS signals mainly includes direction finding and long baseline time difference position, among which time difference method is widely used due to its high positioning accuracy. However, since JTIDS is a multi-user data link, problems are still existed in the time difference positioning system, such as the interweaving of multi-target flight paths and the inability to track close-range multi-target groups. Hence, multi-user sorting becomes one of the problems to be solved in the time difference positioning system, which also determines the performace and application scope of the time difference positioning system.

2. Related Work

Currently, there are two ways to achieve multi-user sorting of JTIDS including label sorting and no label sorting. In the study of no label sorting, several authors used the time difference feature and the position of signal time slots for sorting[2], but this method failed when the time difference was not obvious. In the study of label sorting, JTIDS’s bispectral feature and rician channel feature are adopted to identify and sort the target through SVM, clustering and neural network in the researches[2][3], and
the recognition rate is over 90%. However, in the actual scene, the channel of moving target changes rapidly that make the feature unobvious, also the blind sorting is not achieved. In the research[4], a pulse extraction and clustering algorithm based on SVM was proposed, and DOA, RF, PW, PRI, TOA of radar emitter signals were used as sorting features. The authors[5][6]proposed a time-frequency information sorting method and a frequency-hopping signal sorting method based on sparse Bayesian learning. When the SNR was larger than 6dB, the sorting recognition rate reached 95%. However, these methods are not applicable to JTIDS signal for the fast hopping speed and wide frequency band, also the carrier frequency information is constantly changing with time, so it is difficult to extract the features mentioned above. Currently, many researches about label sorting have been studied while the blind sorting is not. When the numbers of JTIDS targets can’t be obtained from the other way, blind sorting becomes an indispensable way because JTIDS is a multi-user data link. Consequently, this paper focuses on the multi-user blind sorting method of JTIDS.

For the moving target, the most obvious measurable feature is the Doppler frequency shift. As a result of this, the Doppler frequency shift can be used to sort the users. However, the Doppler frequency shift measured by the multi-users in the process of motion is not easy to distinguish. This paper proposed a method uses Doppler frequency shift as sorting parameters and do the nonlinear transformation based on the high order cumulant. According to the extracted Doppler frequency shift, the method makes the nonlinear transformation due to the second order cumulant, the sixth order cumulant, the normalized kurtosis and the normalized skewness, the result is the features change into another 2d coordinate space after transformation when the Doppler frequency shift is not easy to distinguish. this method leads a difference on high similarity features which improves the success rate of multi-user sorting.

3. The Introduction Of Algorithm
This section elaborates our proposed algorithms. First, we introduce the main algorithm. Then, the clustering algorithms are presented briefly. Finally, the steps of sorting are presented.

3.1. Nonlinear Transformation Of High Order Cumulant
Aiming at the situation of time difference and Doppler frequency shift, the transformation based on the second order cumulant ($C_2$), the sixth order cumulant ($C_6$), the normalized kurtosis ($g_1$) and the normalized skewness ($g_2$) is carried out, and new clustering features are constructed.

3.1.1. Features Based On The Second Order Cumulant And The Sixth Order Cumulant. For a single random variable, assume that the probability density function of the random variable $x$ is $p(x)$, and its characteristic function is defined in (1).

$$
\Phi(\omega) = \int_{-\infty}^{\infty} p(x) e^{i\omega x} dx = E[e^{i\omega x}]
$$

Extended to multiple random variables $X = [x_1, x_2, \ldots, x_k]$, and its characteristic function is defined in (2).

$$
\Phi(\omega_1, \omega_2, \ldots, \omega_k) = E[e^{i(\omega_1 x_1 + \omega_2 x_2 + \cdots + \omega_k x_k)}]
$$

According to the textbook[7], we can get the following expression.

$$
\frac{\partial^r \Phi(\omega_1, \omega_2, \ldots, \omega_k)}{\partial \omega_1^{\alpha_1} \omega_2^{\alpha_2} \cdots \omega_k^{\alpha_k}} = i^r E[x_1^{\alpha_1} x_2^{\alpha_2} \cdots x_k^{\alpha_k} e^{i(\omega_1 x_1 + \omega_2 x_2 + \cdots + \omega_k x_k)}]
$$

Set $\omega_1 = \omega_2 = \cdots = \omega_k = 0$, and set $\Psi(\omega_1, \omega_2, \ldots, \omega_k) = \ln \Phi(\omega_1, \omega_2, \ldots, \omega_k)$ and take the derivative of $r = \nu_1 + \nu_2 + \cdots + \nu_k$, we can get the function as follows.

$$
C_{\nu_1 \nu_2 \cdots \nu_k} = (i)^r \frac{\partial^r \Psi(\omega_1, \omega_2, \ldots, \omega_k)}{\partial \omega_1^{\alpha_1} \omega_2^{\alpha_2} \cdots \omega_k^{\alpha_k}} |_{\omega_1 = \omega_2 = \cdots = \omega_k = 0}
$$
Then we can get the $k$ order cumulant.

$$C_k = C_{k_1, \cdots , k_l} = \text{Cum}(x_1, x_2, \cdots , x_k) \quad (5)$$

Assume that $x(n)$ is a zero mean stationary random process, it’s $k$ order cumulant is expressed in (6).

$$C_{k_1}(\tau_1, \tau_2, \cdots , \tau_{k_1}) = \text{Cum}[x(n), x(n+\tau_1), \cdots , x(n+\tau_{k_1})] \quad (6)$$

Thus, the nonlinear transformation based on the second order cumulant and the sixth order cumulant can be got, take the transformation based on the $C_{20}$ as an example, $N$ donates the whole power of the noise and the signal model is $S(n) = e^{j\theta(n)/2} e^{j2\pi f_0 n} e^{j2\pi f_d (n)(n-1)T+1} + N(n) \quad (7)$

$$f_d$$ donates the Doppler frequency shift, $T$ donates the signal’s quasi-periodic. Then the result is showed in (7).

$$C_{20} = \text{Cum}(S(n), S(n)) = E[S^2(n)] - E[S(n)] \cdot E[S(n)] = E[e^{j2\theta(n)/2} e^{j2\pi f_0 n} e^{j2\pi f_d (n)(n-1)T+1} + N^2(n)]$$

$$- E[e^{j\theta(n)/2} e^{j2\pi f_0 n} e^{j2\pi f_d (n)(n-1)T+1} \cdot E[e^{j\theta(n)/2} e^{j2\pi f_0 n} e^{j2\pi f_d (n)(n-1)T+1} + N(n)]$$

$$= \frac{1}{N-2N^2} \sum_{n=1}^{N} \cos(2\theta(n) + 2\pi f_d (n)(n-1)T+1) + N$$

Equation (7) has showed that the $\theta(n)$ donates several fixed value, and $f_d$ is the reference carrier frequency, it donates a fixed value, $N$ is the power of the Gaussian white noise, so $f_d$ donates the main change in the expression. And so on, we can get the expression of the nonlinear transformation based on $C_{60}$ in (8).

$$C_{60} = \text{Cum}(S(n), S(n), S(n), S(n), S(n), S(n)) = E[S^6(n)] - 15E[S^4(n)]E[S^2(n)] + 30E[S^2(n)]^3 \quad (8)$$

3.1.2. Features Based On The Normalized Kurtosis And The Normalized Skewness. The expressions of the transformation based on the normalized kurtosis and skewness are showed in (9)(10). take the transformation based on the $g_1$ as an example.

$$g_1 = \frac{C_{3x}(0,0)}{[C_{2x}(0,0)]^{3/2}} \quad (9)$$

$$g_2 = \frac{C_{4x}(0,0,0)}{[C_{2x}(0,0)]^2} \quad (10)$$

And the expression of $C_{2x}(0,0), C_{3x}(0,0)$ and $C_{4x}(0,0)$ is in (11)(12)(13).

$$C_{2x}(0,0) = E[S^2(n)] \quad (11)$$

$$C_{3x}(0,0) = E[S^3(n)] \quad (12)$$

$$C_{4x}(0,0) = E[S^4(n)] - 3C_{2x}(0,0)^2 \quad (13)$$

Thus, the result of the transformation based on the normalized kurtosis are showed in (14).
\[ g_n = \frac{E(S^3(n))}{[E(S^2(n))]^{3/2}} \]
\[ = \frac{1}{N} \sum_{n=1}^{N} \cos(3\theta_n + 2\pi f_c(n)((n-1)T+1)) + N \]
\[ = \frac{1}{N} \sum_{n=1}^{N} \cos(2\theta_n + 2\pi f_c(n)((n-1)T+1)) + N \]

Equation (14) has showed that the \( \theta_n \) donates several fixed value, and \( f_c \) is the reference carrier frequency, it donates a fixed value, \( N \) is the power of the Gaussian white noise, so \( f_d \) donates the main change in the expression.

3.2. Brief Introduction Of Clustering Algorithm

After the processing above, we can get the new features, hence, the clustering algorithm is urgent need to achieve multi-user sorting. Kmeans clustering algorithm[8][9] and DBSCAN clustering algorithm[10] is the most commonly used. The spectral clustering algorithm is a kind of new method to cluster. So, our experiment uses the spectral clustering algorithm to verify the features’ effectiveness.

The spectral clustering algorithm is a kind of method based on the Graph theory[11], by constructing the similarity matrix and adopting the method of graph cutting, the algorithm can use the J-k curve method to determine the number of clusters.

3.3. Steps Of Sorting

After the the statement mentioned above, a conclusion come to the sorting method’s steps as follows:

a) Get intermediate frequency data of single station.

b) Calculate the Doppler frequency shift of single station, and judge whether it can be sorted.

c) If the Doppler frequency shift can’t sorted, then calculate the cumulant.

d) Make the nonlinear transformation due to the expression(7)(8)(10)(14), and get the new features.

e) Cluster the new features.

4. Experiments

This section elaborates our experiment. The simulation parameters: 4 targets, the coordinates of observatory 1 is (0,-10000)(m), the coordinates of observatory 2 is (0,-10000)(m), the modulation mode of the signal is MSK, the bandwidth is 200MHz, the Fh interval is 3MHz, frequency hopping patterns were randomly selected to generate 258 pulses, symbol rate is 5Mbps and the instantaneous bandwidth is 3.5MHz, take a slot of (258 pulses) as a sample, 100 samples were picked for per group of targets, extracted the new features \( C_{20}, C_{60}, g_1 \) and \( g_2 \) respectively. Use the spectral clustering algorithm to cluster under the condition of the unknown targets’ numbers.

4.1. The Comparison Of Two Types Of Features

4.1.1. Experiment 1. The coordinates of 4 targets are all the same (5000,8000)(m), the velocity of the 4 targets are (-35,185)(m/s), (-35,180)(m/s), (-35,190)(m/s), (-35,197)(m/s) and the accelerations are (7,3)(m²/s), (-5,10)(m²/s), (5,-15)(m²/s), (-5,-25)(m²/s), the SNR is 10dB. Extract the targets’ features of time difference, Doppler frequency shift, as the Figure 1(a), Figure 1(b) shows. This experiment makes the transformation based on the second order cumulant and the sixth order cumulant to get the new features, as the Figure 1(c) shows.
The Features Of Single Doppler Frequency Shift And Nonlinear Transformation

The result is showed in Figure 2.

Figure 1. The Features Of Single Doppler Frequency Shift And Nonlinear Transformation

The result of the Figure 1 showed that the transformation makes the similar features more different, the simulation uses the new features to cluster, by using the J-k curve method to determine the number of the clusters, and using the k-nearest neighbours to construct the similar matrix, the result is showed in Figure 2.

Figure 2. Clustering And Sorting Results Of Three Methods

A conclusion can be drawn form the Figure 2 that the value of k is 4 for the point where the curvature changes the most, then the cluster result shows the samples of every group of targets are: 100, 100, 100, 100, the sorting accuracy rate is 100%. This experiment showed that the new features have high rate of sorting accuracy when transformation happen to the uneasy sorting features.

4.1.2. Experiment 2. The coordinates of 4 targets are all the same (5000,8000)(m), the velocity of the 4 targets are (-35,185)(m/s), (-35,180)(m/s), (-35,190)(m/s), (-35,197)(m/s) and the accelerations are(7,3)(m²/s), (-5,10)( m²/s), (5,-15)( m²/s), (-5,-25)( m²/s), the SNR is 8.5dB, 9dB, 9.5dB, 10dB. Extract the targets’ features of time difference, Doppler frequency shift, as the Figure 3(a), Figure 3(b)shows. This experiment makes the transformation based on the normalized kurtosis and the normalized skewness, as the Figure 3(c)shows.

Figure 3. The Features Of Single Station Doppler Frequency Shift And Nonlinear Transformation
The result of the Figure 3 showed that the transformation makes the similar features more different, the simulation uses the new features to cluster, by using the J-k curve method to determine the number of the clusters, and using the k-nearest neighbors to construct the similar matrix, the result is showed in Figure 4.

![J-k curve method based on the spectral clustering](image1)

Figure 4. Clustering And Sorting Results Of Three Methods

A conclusion can be drawn form the Figure 4 that the value of k is 4 for the point where the curvature changes the most, then the cluster result show the samples of every targets are: 101, 103, 99, 97, the sorting accuracy rate is 98%. This experiment showed that the new features have high rate of sorting accuracy when transformation happen to the uneasy sorting features.

4.2. The Simulation Of Different Datasets

4.2.1. Experiment 3. This experiment extracts the experiment1 and the experiment2’s Doppler frequency shift, and makes the transformation. The result is showed in Figure 5 and Figure 6.

![Comparison Of Feature Data In Experiment 1](image2)

Figure 5. Comparison Of Feature Data In Experiment 1

From the result of Figure 5, our experiment shows that the feature $g_1$ and $g_2$ can’t sort the targets while the feature $C_{20}$ and $C_{40}$ achieve the purpose.

![Comparison Of Feature Data In Experiment 2](image3)

Figure 6. Comparison Of Feature Data In Experiment 2
From the result of Figure 6, our experiment shows that all the feature $g_1$, $g_2$, $C_{20}$ and $C_{60}$ can sort the targets. The datasets of experiment2 have different SNR, so the feature $g_1$ and $g_2$ can sort the targets. Hence, if the targets’ SNRs are different, we can use the $g_1$ and $g_2$ as sorting features.

4.3. The Experiment Result

From the above experiments conclusions can be drawn that the feature of Doppler frequency shift, which is not easy to distinguish, is highly differentiated by the algorithm proposed in this paper. Compared with the traditional time difference sorting method, it can distinguish the targets with no obvious time difference and has high accuracy.

5. Conclusion

In this paper, aiming at multi-user sorting problem where the time differences of the moving targets are not obvious. Firstly, the signal received by a single station is transformed based on the second order cumulant, the sixth order cumulant, the normalized kurtosis and the normalized skewness, this step leads a difference on high similarity features of the Doppler frequency shift. Then, the transformed features can be got and use to cluster, and finally the spectral clustering algorithm is adopted to cluster the feature datasets, so as to achieve the sorting case. The simulation results showed that the proposed method can significantly improve the differentiability of the unsorted Doppler frequency shift eigenvectors and has high accuracy. Also, the feature vectors of time difference which can’t be sorted achieve sorting by the proposed method and the results verified the validity of the proposed method.

References

[1] Mei WH and Wang SB 2005 Fh Communication (Beijing: National Defense Industry)
[2] Wang LX 2009 Study And Implementation Of JTIDS Signal Feature Extraction And Integrated Processing Based On Space-time association Master
[3] Fang XY 2009 Research And Implementation Of JTIDS Signal User Sorter Master
[4] Yang S and Hou C and Si W 2017 Extract Pulse Clustering in Radar Signal Sorting International Applied Computational Electromagnetics Society Symposium Italy (ACES)
[5] Guo HZ and Zhang SS 2016 Application Of Sparse Bayesian Model In Frequency Hopping Signal Ratio Separation The Signal Processing 06 pp733-738
[6] Guo HZ 2016 Frequency Hopping Signal Detection, Parameter Estimation and Sorting Algorithm Research Master
[7] Wang Z and Wu J 2016 Modern Digital Signal Processing (Changsha: University Of National Defence Science And Technology)
[8] Sun JX 2008 Modern Pattern Recognition (Higher Publishing House Education)
[9] Mackay and David An Example Inference Task: Clustering ( Cambridge University pp 284-292)
[10] Martin E, Kriegel and Hans-Peter A density-based algorithm for discovery clusters in large spatial databases with noise Proceeding of the Second International Conference in Knowledge Discovery and Data Mining AAAI pp 226-231
[11] Shi J and Malik J 2000 Normalized Cuts and Image Segmentation IEEE Transaction on PAMI 22 8