The Journal of Engineering

IET International Radar Conference (IRC 2018)

Deceptive multiple false targets jamming recognition for linear frequency modulation radars

eISSN 2051-3305
Received on 26th February 2019
Accepted on 2nd May 2019
doi: 10.1049/joe.2019.0766
www.ietdl.org

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Abstract: This study considers the problem of deceptive multiple false targets jamming recognition. Due to the different modulation patterns, there is a great difference in fast-time frequency spectrum or slow-time Doppler spectrum between the different types of jammings. The proposed algorithm first extracts the received sample matrix, then computes left and right similarity (LR-similarity) by fast-time-slicing or slow-time-slicing process and finally recognises the samples according to template matching classifier. Experimental results demonstrate that the accuracy recognition probability of the proposed method is >95%, when jamming-to-signal ratio is above 3 dB.

1 Introduction

Deceptive multiple false targets jamming (DMFTJ) is a chain of false targets based on digital radio-frequency memory (DRFM) technology, which generated by high fidelity-replicated victim radar transmitting signals followed by a series of modulation in the digital domain. Therefore, the DMFTJ is correlative with the target echo signal and partial processing gain can be achieved from signal processing such as pulse compression (PC) and coherent accumulation, thus carrying out effective density jamming against the coherent radar [1–4]. The so-called density is relative to range cells of radar. Its main influence on radar detection is to reduce the detection performance of constant false-alarm rate radar detector by forming a series of false targets that are attenuated to both sides so that the real target being covered [5].

With the development of advanced radar jamming technology, various DMFTJ styles are constantly emerging. Generally, there are two modes of DMFTJ including full-pulse storage and pulse slice storage, mainly used by a DRFM. Under the full-pulse storage mode, the full-pulse dense transmit jamming (FDTJ) is generated, which can achieve the largest signal processing gain. However, since the forwarding delay is usually greater than the pulse duration, the jamming can only be transmitted in the next pulse repeat interval for self-defensive jamming. Moreover, due to time–frequency coupling characteristics for linear frequency modulation (LFM) signals, DRFM also tends to modulate in frequency domain and hence achieve velocity deception dense transmit jamming (VDTJ) [6]. Considering the different characteristic between FDTJ and the target echo, a large number of jamming recognition algorithms have emerged, yet many shortages are observed in recognition, for example the correlation sample selection of jamming samples combined with adaptive side-lobe cancellation is adopted for jamming discrimination in [7]; unfortunately, this method will fail when the jamming is not related to the target. On the other hand, the partial-pulse dense transmit jamming (PDTJ) using pulse slice storage is more suitable for radar using large time-width and bandwidth product transmitting signals, but the power losses caused by the mismatch will weaken the jamming performances [8]. Hence, a DMFTJ named interrupted-sampling repeater jamming (ISRJ) is proposed (in [9], it was referred as Chopping and Interleaving, C&I). This kind of jamming can not only shorten the sampling-to-interference delay but also produce sub-false targets symmetrical to the main false targets. However, the number and quality of the false target are influenced by the sampling cycle and sample pulse width, wherein a reasonable parameters setting is also required [9, 10]. Interrupted-sampling directly jamming (ISDJ) and interrupted-sampling circularly jamming (ISCJ) are also proposed in [6]. Compared with ISRJ, ISDJ forwards the intercepted slices for only one time and ISCJ has the relatively high storage capacity. Besides, more researches are involved in [11], where ISRJ can be identified by calculating the variance of a time-varying energy function, which is obtained by calculating the square of the absolute value of the time–frequency domain function. However, the decision threshold of this method needs to be pre-set according to experience, without consideration of environmental clutter and target fluctuation.

In this paper, we consider the problem of the DMFTJ mode recognition including FDTJ, PDTJ, ISRJ, and VDTJ. To this aim, we model the DMFTJ in Section 2 and a coefficient called LR-similarity in frequency spectrum and Doppler spectrum introduced in Section 3 to recognise the DMFTJ, while Section 4 presents the recognition scheme based on template-matching classifier. Finally, Section 5 shows the numerical results and some analysis and conclusions are given in Section 6.

2 Jamming signal model

The LFM signal is a large time-bandwidth product signal whose bandwidth is normally ranged from units MHz to hundreds MHz, and even units GHz to some. It takes into account both radar range resolution and velocity resolution, and it has good clutter suppression performance. Therefore, it is often used in PC radars. For wideband LFM radar, suppose the transmitted signal $s(t)$, and it can be expressed as

$$s(t) = \mathrm{rect}\left(\frac{t}{\tau}\right)\exp\left[j2\pi\left(f_c t + \frac{1}{2}\mu t^2\right)\right], \tag{1}$$

where $\mathrm{rect}\left(\frac{t}{\tau}\right) = \begin{cases} 1, & |t| \le \frac{\tau}{2} \\ 0, & \text{otherwise} \end{cases}$, τ denotes the time width of $s(t)$, f_c, and μ are the carrier frequency and the chirp rate.

Among the DMFTJs, the convolution modulations and/or production modulations in time domain are always utilised. Moreover, the jamming signals have a comparable power with the target echo signals and have an appropriate frequency-shift to accurately submerge the real targets. Therefore, the DMFTJ's unified expression can be written as

$$s_J(t) = s(t - \tau_R) \times p_1(t) \times p_2(t), \tag{2}$$

where * is meant to convey convolution, τ_R is the propagation time from the jammer to the radar, $p_1(t)$ is the product modulation function and $p_2(t)$ is the convolution modulation function. Through proper selection for the parameters in (2), various types of the DMFTJ can be generated by the jammer. FDTJ, PDTJ, ISRJ, and VDTJ can be set according to Table 1.

For FDTJ, we can control the amplitudes and the delays of each false target to cover the real target by changing A_k and T_k. In this paper, we define $A_k = A_J$, $T_k = kT_J$ to guarantee the pulse uninterrupted. PDTJ can start transmitting as soon as DRFM receive a part of the pulse and do not require to wait for receiving the whole segment of pulse, which can effectively shorten the system reaction time. Similarity, τ_J is the slice width and A_k, T_k is always given in A_J, kT_J. Instead of intercepting and repeating the whole radar pulse, ISRJ divides one radar pulse into multiple segments. Each segment corresponds to either receive or transmit mode and the two modes appear alternately, so the interrupted sampling function $p_1(t)$ is assumed to be a rectangular envelope pulse train. Different from PDJT, ISRJ first convolutes the rectangular envelope, and it is multiplied with the intercepted signal. Moreover, since the LFM signal has time–frequency coupling characteristics, i.e. the frequency domain offset is equivalent to the delay in the time domain, Doppler modulation of the LFM signal will also generate a series of random bursts before and after the real target.

In this paper, suppose the real target echo has the delay τ_s and Doppler shift f_d, then it can be written as

$$s_E(t) = s(t - \tau_s) \times \exp(j2\pi f_d), \tag{3}$$

and the received signal is written as

$$r(t) = s_E(t) + s_J(t) + n(t), \tag{4}$$

where $n(t)$ is complex Gaussian noise whited in processing bandwidth with variance σ^2.

3 LR-similarity

The distance metrics between two vectors $\boldsymbol{s}_1$ and $\boldsymbol{s}_2$ can be seen as the similarity of two vectors, there are many standard of distance metrics to weigh the similarity between two signals. In this paper, we define the cosine similarity

$$\mathrm{sim}_{s_1,s_2} = \frac{\left|\boldsymbol{s}_1^H\boldsymbol{s}_2\right|}{\|\boldsymbol{s}_1\| \times \|\boldsymbol{s}_2\|}, \tag{5}$$

as the standard of similarity [12].

Equation (5) characterises the correlation between $\boldsymbol{s}_1$ and $\boldsymbol{s}_2$, and its value is only related to the overlapping degree of the two signals. If the value of sim_{s_1,s_2} equals 1, then the two signals are completely overlapped or proportional, indicating that the signal $\boldsymbol{s}_1$ is completely similar to the $\boldsymbol{s}_2$. Whereas with the gradual decrease in the overlapping part of the two signals, the value of sim_{s_1,s_2} is gradually reduced, indicating the signal $\boldsymbol{s}_1$ is partially similar to $\boldsymbol{s}_2$ until completely separated.

It is assumed that a two-dimensional data matrix is formed by the baseband data of the M pulse echo within a CPI after coherent demodulation, and it corresponds to a two-dimensional horizontal section of the radar three-dimensional data block. For a single-aperture antenna system, or a certain position of the array antenna, only a two-dimensional data matrix as shown in Fig. 1 can be formed [13].

Assuming that $\boldsymbol{S}_{f1}$ and $\boldsymbol{S}_{f2}$ are the frequency spectrum of the two signals $\boldsymbol{s}_1$ and $\boldsymbol{s}_2$, respectively, the coefficients called frequency spectral similarity can be defined as

$$\mathrm{sim}_{\boldsymbol{S}_{f1},\boldsymbol{S}_{f2}} = \frac{\left|\boldsymbol{S}_{f1}^H\boldsymbol{S}_{f2}\right|}{\|\boldsymbol{S}_{f1}\| \times \|\boldsymbol{S}_{f2}\|}. \tag{6}$$

The greater the frequency spectral similarity, the higher the frequency spectrum overlap between the two signals are. (6) suggests that the frequency spectral similarity represents not only the degree of frequency spectral similarity between two complete signals but also the degree of frequency spectral similarity between the complete signal and part of the signal.

If the radar transmitted signal vector in fast time is used as the reference signal $\boldsymbol{s}_1 = [s(0)\ s(1)\cdots s(L-1)]^{\mathrm{T}}$, and the radar received signal vector in fast time is used as the signal to be sliced $\boldsymbol{s}_2 = [r(0)\ r(1)\cdots r(K-1)]^{\mathrm{T}}$ where $\boldsymbol{s}_2$ using only the data recorded by the radar during the time-on-target (ToT), where K is the number of samples collected by the radar during a single pulse and

Table 1 Jammer modulation parameters for DMFTJs

$s_J(t)$	$p_1(t)$	$p_2(t)$
FDTJ	1	$\sum_{k=1}^{N} A_k\delta(t - T_k)$
PDTJ	$\mathrm{rect}\left(\frac{t}{\tau_J}\right)$	$\sum_{k=1}^{N} A_k\delta(t - T_k)$
ISRJ	1	$\mathrm{rect}\left(\frac{t}{\tau_J}\right) \times \sum_{k=1}^{N} A_k\delta(t - T_k)$
VDTJ	$\sum_{k=1}^{N} A_k\exp(j2\pi f_k)$	1

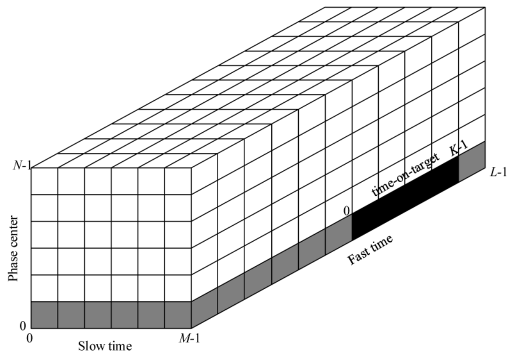

Fig. 1 *Radar data block diagram*

an even number. Then, we define the coefficients sim_L and sim_R as the frequency spectral LR-similarity

$$\mathrm{sim}_L = \frac{\left|\boldsymbol{S}_{f1}^H \boldsymbol{S}_{fL}\right|}{\| \boldsymbol{S}_{f1} \| \times \| \boldsymbol{S}_{fL} \|}, \tag{7}$$

$$\mathrm{sim}_R = \frac{\left|\boldsymbol{S}_{f1}^H \boldsymbol{S}_{fR}\right|}{\| \boldsymbol{S}_{f1} \| \times \| \boldsymbol{S}_{fR} \|}, \tag{8}$$

where $\boldsymbol{s}_L = [s(0)\cdots s((K/2)-1)]^{\mathrm{T}}$, $\boldsymbol{s}_R = [s(K/2)\cdots s(K-1)]^{\mathrm{T}}$. We denote frequency spectral left-similarity and frequency spectral right-similarity between $\boldsymbol{s}_1$ and $\boldsymbol{s}_2$ by sim_L and sim_R, respectively. The frequency spectral LR-similarity can reflect the frequency spectrum similarity between the radar transmitted signal and the radar received signal which is left-sliced or right-sliced in time domain, respectively. It is assumed that the radar transmitted signal is a chirp signal and the PC ratio is far >1, the radar received signal is an ideal target echo signal, the frequency spectral left-similarity and frequency spectral right-similarity can be calculated, respectively, as $\sqrt{2}/2$. That is, the difference between the frequency spectral left-similarity and frequency spectral right-similarity is about 0. The frequency spectral LR-similarity result has been reported for FDTJ, PDTJ, and ISRJ as some kinds of DMFTJ recognition. Fig. 2 shows the frequency spectral LR-similarity for JSR = 3 dB.

On the other hand, if the transmitted signal in fast time is used as the $\boldsymbol{s}_2$, and the received signal in fast time is used as the $\boldsymbol{s}_1$. Since the mid-point of the transmitted signal is easy to obtain, the difference between sim_L and sim_R can be used to judge the frequency spectrum symmetry of the radar received signal more accurately. In this case, the frequency spectral LR-similarity result can be shown in Fig. 3 under the condition of JSR = 3 dB. The template set shows that the left and right frequency spectrum of PDTJ is significantly different after slicing, and the frequency spectrum of ISRJ is basically symmetrical. This is because if the ISRJ is sliced in time domain, it is equivalent to the equal proportion slicing in the frequency domain of the interference signal owing to the time–frequency coupling properties. Then, the frequency spectral LR-similarity of FDTJ has no obvious difference. The FDTJ is the superposition of multiple transmitted signals that its amplitude spectrum width is like the echo signal. This fits the mathematical expressions in the frequency domain of Section 3.

As shown in Fig. 1, assume $\boldsymbol{S}_{\mathrm{d}1}$ and $\boldsymbol{S}_{\mathrm{d}2}$ are the Doppler spectrum of the two data vectors $\boldsymbol{s}_{\mathrm{d}1}$ and $\boldsymbol{s}_{\mathrm{d}2}$ in slow time dimension, respectively, the coefficients called Doppler spectral similarity can be defined as

$$\mathrm{sim}_{S_{\mathrm{d}1},S_{\mathrm{d}2}} = \frac{\left|\boldsymbol{S}_{\mathrm{d}1}^H \boldsymbol{S}_{\mathrm{d}2}\right|}{\| \boldsymbol{S}_{\mathrm{d}1} \| \times \| \boldsymbol{S}_{\mathrm{d}2} \|}. \tag{9}$$

The greater the Doppler spectral similarity is, the higher the Doppler spectrum overlap between the two signals are. The slow time snapshot of the two-dimensional data matrix have $2M$ pulses used as the reference signal $\boldsymbol{s}_{\mathrm{d}1}$ and the signal to be sliced $\boldsymbol{s}_{\mathrm{d}2}$, The Doppler spectral LR-similarity can be defined as

$$\mathrm{sim}_{dL} = \frac{\left|\boldsymbol{S}_{\mathrm{d}}^H \boldsymbol{S}_{\mathrm{d}L}\right|}{\| \boldsymbol{S}_{\mathrm{d}} \| \times \| \boldsymbol{S}_{\mathrm{d}L} \|}, \tag{10}$$

$$\mathrm{sim}_{dR} = \frac{\left|\boldsymbol{S}_{\mathrm{d}}^H \boldsymbol{S}_{\mathrm{d}R}\right|}{\| \boldsymbol{S}_{\mathrm{d}} \| \times \| \boldsymbol{S}_{\mathrm{d}R} \|}, \tag{11}$$

where $\boldsymbol{s}_d = [s(0)\cdots s(2M-1)]^{\mathrm{T}}$, $\boldsymbol{s}_{dL} = [s(0)\cdots s(M-1)]^{\mathrm{T}}$, $\boldsymbol{s}_{dR} = [s(M)\cdots s(2M-1)]^{\mathrm{T}}$, f_d is the Doppler frequency, T is the pulse repetition interval of radar. sim_{dL} and sim_{dR} are called Doppler spectral LR-similarity between $\boldsymbol{s}_1$ and $\boldsymbol{s}_2$. Doppler spectral LR-similarity can reflect the fluctuation between adjacent pulses, and the closer the value is to 1, the smaller the target fluctuation is.

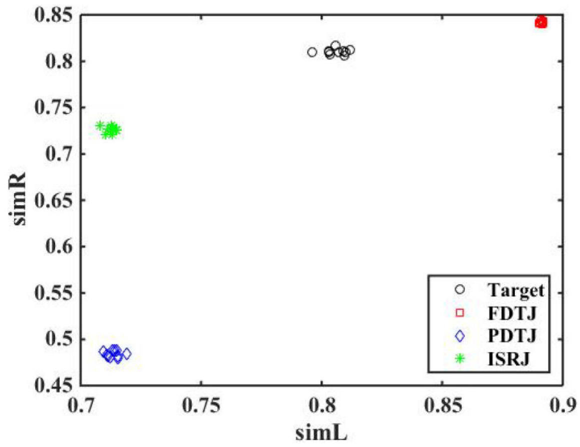

Fig. 2 *Frequency spectral LR-similarity if the radar received signal is used as the $\boldsymbol{s}_2$ for JSR = 3 dB*

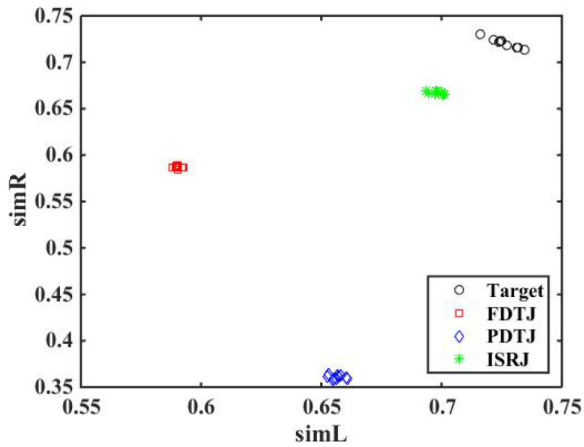

Fig. 3 *Frequency spectral LR-similarity if the radar transmitted signal is used as the $\boldsymbol{s}_2$ for JSR = 3 dB*

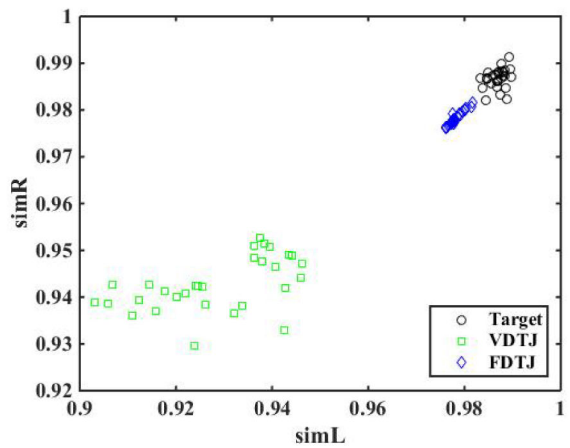

Fig. 4 *Template set of block diagram of the Doppler spectral LR-similarity for JSR = 3 dB*

The VDTJ has the smallest value, the target echo signal has the largest, and the other kinds of jamming such as FDTJ are between them. Fig. 4 illustrates the difference between them.

4 Recognition scheme

Thanks to the frequency spectral LR-similarity, the DMFTJ recognition block diagram is shown in Fig. 5, and the specific algorithm procedure is in algorithm 1 (Fig. 6).

The DMFTJ recognition block diagram based on the Doppler spectral LR-similarity is shown in Fig. 7, and the specific algorithm procedure is in algorithm 2 (Fig. 8).

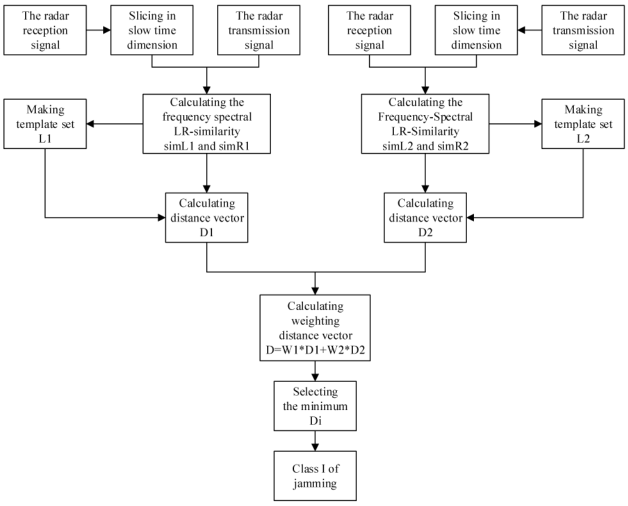

Fig. 5 *Block diagram of DMFTJ recognition based on the frequency spectral LR-similarity*

1) Passing the received signal through the matched filter, the pulse compressed signal is obtained by the over threshold detection. Corresponding interception of the received signal through the location of the pulse compressed signal to get the $\mathbf{s_2}$. Then the radar transmitted signal is considered as the $\mathbf{s_1}$.

2) By slicing the obtained signals in fast time domain, $\mathbf{s_2}=[s(0)\ \cdots\ s(K\text{-}1)]^T$ is sliced into $\mathbf{s_L}=[s(0)\ \cdots\ s(\frac{K}{2}\text{-}1)]^T$ and $\mathbf{s_R}=[s(\frac{K}{2})\ \cdots\ s(K-1)]^T$.

3) After DFT transformation of two samples after slicing and the reference sample, they are transformed from fast time domain to frequency domain, and the results obtained by normalization are recorded as $\mathbf{S_{fL}}$, $\mathbf{S_{fR}}$, $\mathbf{S_{f1}}$, respectively. The frequency spectral LR-similarity can be obtained respectively according to the formula (10) (11).

4) Similar to the procedure as (2) (3), the radar received signal is used as the $\mathbf{s_1}$, and the radar transmitted signal is used as the $\mathbf{s_2}$. The frequency spectral LR-similarity can be obtained respectively.

5) The frequency spectral LR-similarity feature vectors as the characteristic parameters of the jamming recognition to make two-dimensional template sets L_1, L_2 of $\{sim_{L1}, sim_{R1}\}$ and $\{sim_{L2}, sim_{R2}\}$, respectively. The statistical distance D_1, D_2 that in L_1, L_2 template sets can be calculated by using the template matching recognition algorithm, and then combined D_1 and D_2 to recognize the jamming.

Fig. 6 *Algorithm 1: DMFTJ recognition algorithm based on the frequency spectral LR-similarity*

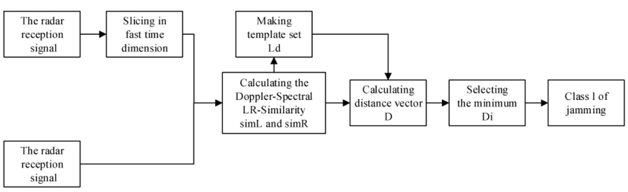

Fig. 7 *Block diagram of DMFTJ recognition based on the Doppler spectral LR-similarity*

1) $\mathbf{s_d}=[s(0)\ \cdots\ s(2M-1)]^T$ is formed by the baseband data of the 2M pulse echo within a CPI after coherent demodulation. $\mathbf{s_{dL}}=[s(0)\ \cdots\ s(M-1)]^T$ and $\mathbf{s_{dR}}=[s(M)\ \cdots\ s(2M-1)]^T$ are obtained by slicing in the slow time dimension.

2) After DFT transformation of two samples after slicing and the reference sample, they are transformed from slow time domain to Doppler domain , and the results obtained by normalization are recorded as $\mathbf{S_d}$, $\mathbf{S_{dL}}$, $\mathbf{S_{dR}}$, respectively.

3) According to the formula (13) (14), the Doppler spectral LR-similarity of the radar received signal are obtained.

4) The Doppler spectral LR-similarity feature vectors as the characteristic parameters of the jamming recognition to make a two-dimensional template set L_d of $\{sim_L, sim_R\}$. The statistical distance D that in the L_d template set is calculated by using the template matching recognition algorithm to recognize the jamming.

Fig. 8 *Algorithm 2: DMFTJ recognition algorithm based on the Doppler spectral LR-similarity*

Table 2 Simulation parameters for wideband LFM radar

Symbol	Quantity	Value
f_c	radio frequency	1.8 GHz
f_0	intermediate frequency	55 MHz
f_s	sampling frequency	200 MHz
B	bandwidth	20 MHz
T_p	pulse repetition interval	200 μs
τ	pulse width	30 μs
N	number of pulses	64

5 Numerical results

The jamming recognition simulation of four kinds of dense false target interference established by Section 3 is carried out according to Table 2 parameters.

Suppose that the target echo signal satisfies Swerling II distribution and the jamming signal is a pulse sequence with fixed amplitude. By using Table 1 parameters, radar received signal is sliced in fast-time dimension in the case of SNR = 10 dB according to the method in Section 3. Assuming that τ_J is 2.5 μs and N is 6. Under the conditions of JSR = 3 dB to calculate the frequency spectral LR-similarity, there is little overlap between the target echo signal and the various kinds of jamming. The frequency spectral LR-similarity of various jamming signals varies little with the change of JSR when the radar received signal as the $\boldsymbol{s}_2$, except for the PDTJ follow the left path procedure of Fig. 5. Correspondingly, when the radar transmitted signal as the $\boldsymbol{s}_2$, we can better distinguish the target and PDTJ follows the right path procedure of Fig. 5. Hence, we set weight value of the left path algorithm to 1 and the right path algorithm to 0.7, which can better distinguish different kinds of DMFTJ. We choose template matching method as the recognition algorithm and the Euclidean distance is selected as the distance measurement, then the various kinds of jamming are identified. Under the condition of JSR = 3 dB and 300 template samples, the template matching recognition test is carried out to recognise 100 experimental samples, and the recognition probability is shown in Fig. 9. Similarity, DMFTJ can be identified according to the procedure of Fig. 7 based on Doppler spectral LR-similarity and the recognition probability is shown in Fig. 10.

As can be seen from Figs. 9 and 10, the recognition probability of all kinds of dense false targets is not high when the jamming power is less than the signal power. This is due to the radar

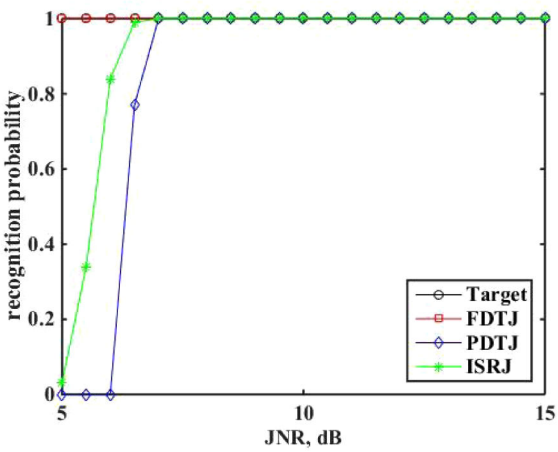

Fig. 9 *Probability of jamming recognition based on the frequency spectral LR-similarity*

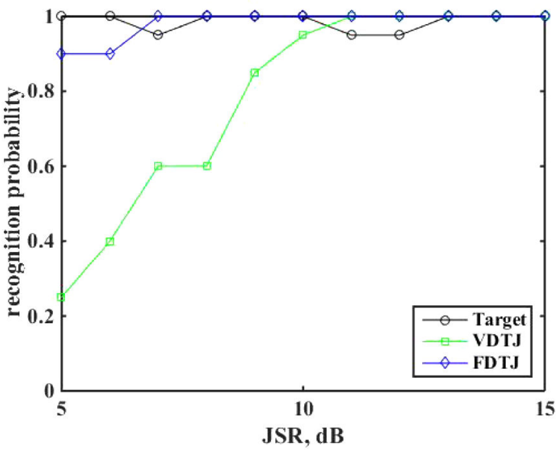

Fig. 10 *Probability of jamming recognition based on the Doppler spectral LR-similarity*

received signal's frequency spectrum or Doppler spectrum mainly shows the characteristics of the target echo signal in the case of low JSR, which leading to the frequency spectrum or Doppler spectrum of radar received signal is similar to that of target echo signal and the LR-similarity has small distinction. With the increase of JSR, the parameters tend to be stable. When the data in the case of JSR = 3 dB is used as a matching template, the probability of recognition is >95% when JSR is above −3 dB based on the method with frequency spectral LR-similarity and the probability of recognition is >95% when JSR is above 3 dB based on the method with Doppler spectral LR-similarity.

6 Conclusion

Radar DMFTJs are formulated into four distinct modes according to the different modulation patterns. With the aid of theoretical analysis on the frequency spectrum and Doppler spectrum LR-similarity, this paper makes use of the differences between the DMFTJs and the target echo signals after slicing in frequency spectrum and Doppler spectrum, further extracts frequency spectral LR-similarity and Doppler spectral LR-similarity. The template matching method is then selected as the classifier to simulate the jamming recognition. The proposed algorithms will help to identify distinct jamming pattern and hence achieve the recognition goals in advanced radar schemes.

7 References

[1] Schleher, D.C.: '*Electronic warfare in the information age*' (Artech House, Inc., Norwood, MA, USA, 1999)

[2] Roome, S.J.: 'Digital radio frequency memory', *Electron. Commun. Eng. J.*, 1990, **2**, (4), pp. 147–153

[3] Li, Y., Luo, X.M., Lv, G.H.: 'The study of multi-false targets synthesizing technology against chirp ISAR'. Int. Conf. on Microwave and Millimeter Wave Technology, Nanjing, China, 2008, pp. 802–805

[4] Berger, S.D.: 'Digital radio frequency memory linear range gate stealer spectrum', *IEEE Trans. Aerosp. Electron. Syst.*, 2003, **39**, (2), pp. 725–735

[5] Levanon, N.: 'Detection loss due to interfering targets in ordered statistics CFAR', *IEEE Trans. Aerosp. Electron. Syst.*, 1988, **24**, (6), pp. 678–681

[6] Zhong, L.: 'Jamming technique for countering LFM pulse compression radar based on digital radio frequency memory'. PhD thesis, National University of Defence Technology, 2006

[7] Cai, G., Shao, Y., Li, R.: 'A method for countering dense false target jamming based on correlation sample selection'. 2017 IEEE Int. Conf. on Signal Processing, Communications and Computing (ICSPCC), Xiamen, China, 2017, pp. 1–5

[8] Hong, L.I., Zheng, G.Y., Yang, Y.K., *et al.*: 'The performance analysis of multi-false targets jamming of part copying radar pulse', *Electron. Inf. Warfare Technol.*, 2010, **25**, (3), pp. 39–44

[9] Sparrow, M.J., Cikalo, J.: 'ECM techniques to counter pulse compression radar'. US, US 7081846 B1, 2006

[10] Feng, D., Xu, L., Pan, X., *et al.*: 'Jamming wideband radar using interrupted-sampling repeater', *IEEE Trans. Aerosp. Electron. Syst.*, 2017, **53**, (3), pp. 1341–1354

[11] Yang, S.Q., Tian, B., Zhou, R.Z.: 'ECCM against interrupted sampling repeater jamming based on time–frequency analysis', *J. Signal Process.*, 2016, **32**, (10), pp. 1244–1251

[12] Greco, M., Gini, F., Farina, A.: 'Radar detection and classification of jamming signals belonging to a cone class', *IEEE Trans. Signal Process.*, 2008, **56**, (5), pp. 1984–1993

[13] Richards, M.A.: '*Fundamentals of radar signal processing*', (McGraw-Hill, New York, NY, USA, 2005)