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CANCELLATION OF COMPLICATED DRFM RANGE FALSE TARGETS VIA TEMPORAL PULSE DIVERSITY

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Abstract—In this paper, a jamming cancelation approach based on the concept of pulse diversity is proposed to suppress some newer complicated digital radio frequency memory (DRFM) range false targets (RFT). Just repeating the intercepted radar electromagnetic signal, as done in the conventional re-transmitting jammer, is not effective because only one range false target is produced. In contrast, the newer DRFM-based RFT generation methods, especially chopping and interleaving (C&I) and smeared spectrum (SMSP) can yield a multi-lobe filter output by transforming the internal structure of the intercepted radar signal. The presented approach to overcome this challenge is based on the temporal pulse diversity technique, and it does not require parameter estimation of the jamming signal. By transmitting pulses with specific transmission pulse block and the following proper processing, it can cancel out the protruding spikes of the jammer at the price of an acceptable performance loss. Particularly, this method is applicable to broad DRFM repeat jammer in electronic warfare (EW) area.

1. INTRODUCTION

Range false targets (RFT) are employed to jam the victim radar by transmitting the signals resembling the true target echoes reasonably but positioned at different ranges. This deception jamming has been enhanced significantly in recent years with the developments of digital radio frequency memory (DRFM) techniques [1–3]. Apparently, based on the DRFM device, the jammer has the ability to generate false targets with all the qualities typical of the true targets specified. Hence,

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such jamming is liable to be detected as target and makes radar systems can not search or track properly. Consequently, the real targets can be protected and the jamming purpose is then achieved.

Furthermore, some newer types of RFTs, which are generated by transforming and processing the intercepted radar signal more subtly before transmitting rather than merely re-transmitting, have come into being. Especially, two effective types of such electronic attack (EA) — C&I and SMSP [4] — were designed to attack the LFM pulse compression radar, which made conditions much more deteriorated. These two EAs were designed specifically to aim at the radar's matched-filter, and produced a multi-lobe filter output. In practice, it is difficult for the radar to detect and recognize target with a multitude of bunched lobe spikes which are positioned ahead or behind the true targets and spaced closer than the time duration of radar signal. Moreover, it is inevitable that more sophisticated RFTs would be excogitated.

For interferences coming from different directions, the space domain filtering algorithms can be employed to suppress them [5–7]. But these algorithms may not suitable for DRFM repeat jammer, because radar echo and jammer primarily come from the same direction. For the conventional DRFM repeat jammer, it is capable of being suppressed by transmitting (quasi-)orthogonal pulses [8, 9], or by applying penalization measures to reduce the power of jammer through varying modulated parameters and a three-step matched-filtering approach [10], or by continuously emitting modified version of previous waveforms following an orthogonal structure in sequence or simultaneously [11, 12]. The performances of several sorts of CFAR processor in strong pulse jamming are investigated in [13].

All of the presented EP approaches, however, do not involve the complicated jamming types. Consequently, no suppression mechanisms against such EA have been addressed in literatures, whereas in our research, the sophisticated RFTs are taken into consideration. The proposed approach enables the radar to recover echo from jammer by using redundant codes based on temporal pulse diversity concept. Moreover, the approach is capable of dealing with certain potential jamming even if the transformation is unknown. Apparently, this is a prominent merit different from other methods. The results of the research demonstrate that this suppression approach is applicable to a wide range of DRFM repeat jammers. Certainly, these two new jamming — the C&I and SMSP — can be suppressed successfully.

The rest of the paper is organized as follows. Section 2 analyzes the jammer in details, especially the C&I and SMSP, and gives the digital representations of the jamming signal. Section 3 describes the jamming cancelation algorithm. Section 4 provides simulations. Finally, Section 5 concludes the paper.

2. JAMMING SIGNAL ANALYSIS

The DRFM techniques use a high-speed sampling digital memory for storing the intercepted radar signal and later recalling [14, 15]. Generally, in a common DRFM-based EA system, the intercepted signal is first down-converted in frequency, and then sampled and stored in a digital memory. The digital samples are then modulated in phase, amplitude or frequency. Under the control of the system, the modulated signal is later recalled and retransmitted. It follows that the signal transmitted back by the DRFM-based jammer is a simple replica of the original signal with some parameters manipulated.

Different from common DRFM-based jamming, the C&I and SMSP do not simply re-transmit the received signals, but manipulate the signal complicated before emitting the signals to the victim radar.

The C&I [4] scheme consists of two-step process. First, uniformly spaced sampling signal segments of the radar pulse are picked out. So, the selected signal segments have certain different time slots and frequencies. Second, the EA signal is created by placing (concatenating) the segments in the adjacent vacant slots. The components of the EA signal are segments of the received radar signal to which the filter transfer function is matched. Consequently, through matched-filtering, the output of this jamming shows a multi-lobe structure. Furthermore, positions of the grouped range lobes are controllable, and this makes it possible to position them ahead or behind the true targets.

Figure 1 shows an example of C&I jamming generated from the original LFM signal with 20 μs pulse width and 10 MHz bandwidth. In this example, 5 uniformly spaced sampled segments of the original LFM signal are placed in the adjacent vacant slots, and each selected segment is placed for 4 times.

The SMSP [4] scheme is another method used for generating EA signal which is comprised of certain short time duration sub-waveform. It makes one sub-waveform repeat (at least) n times, and the chirp rate of the sub-waveform is n times as the original waveform. When an SMSP signal inputs into a matched-filter with respect to the original waveform, the response amplitude looks like a comb structure (uniformly distributed spikes). Each lobe has a spectrum density distribution which is difficult to be distinguished from the target echo in practice.

Figure 2 shows an example of SMSP jamming generated from

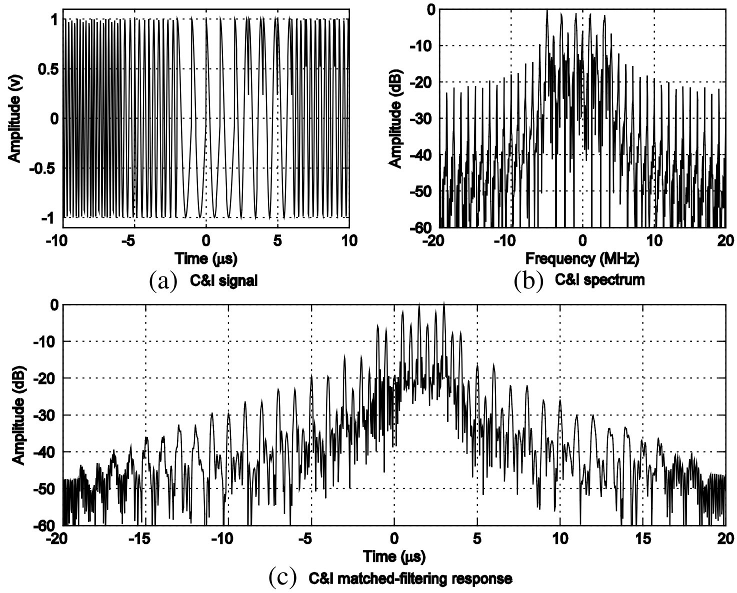

Figure 1. An example of C&I jamming.

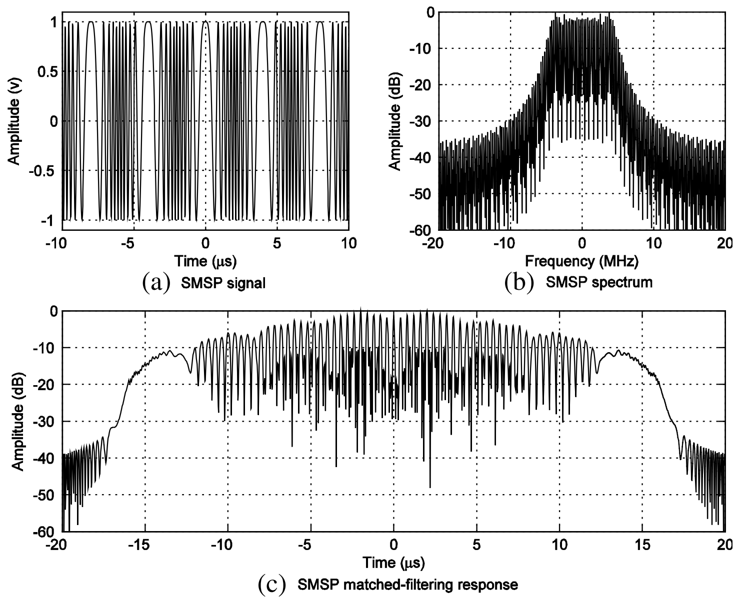

Figure 2. An example of SMSP jamming.

original LFM signal with 20 μs pulse width and 10 MHz bandwidth. In this example, the sub-waveform is transmitted for 5 times, each with 5 times chirp rate and 1/5 pulse width with regard to the original signal.

Both of the two jamming techniques exploit the properties of the matched-filter. The replica of at least a portion of the intercepted radar signal is matched to the matched-filter impulse response of victim radar. Consequently, a multi-lobe filter response is produced, and these plurality lobes can occupy exactly over the whole LFM signal frequency band and time duration. Thus, it is difficult for the radar to discriminate the true target from these complicated RFTs.

In practice, we can model both the C&I and SMSP techniques as a two-step procedure: A signal transformation and a cascade amplification process. Only the first transformation process is considered here (all the power gain is considered in received signals in victim radar), thus any complicated DRFM repeat jammer can be expressed as

$$y(t) = Tx(t) = [Tx](t) \tag{1}$$

where $y(t)$ and $x(t)$ are produced jamming signal and intercepted radar signal, respectively, and T denotes a bounded linear operator, which indicates a transforming process applied to the received radar signals. Specifically, if T is an identical transformation, i.e.,

$$[Tx](t) = x(t), \tag{2}$$

obviously it is just a conventional repeat jammer.

We assume that the received radar signal $x(t)$ is band-limited for some fixed $B > 0$, and satisfies $\mathcal{F}[x(t)] \in L^2[-B, B]$, where $\mathcal{F}$ denotes the Fourier transform. Thus the transform can be expressed from the series representation [16]

$$[Tx](t) = \sum_n x(t_n)[T\phi_n](t) \tag{3}$$

for some specific kernel ϕ. In the Hilbert space $L^2[-B, B]$,

$$\phi_n(t, w) = \frac{\sin \pi(2wt - n)}{\pi(2wt - n)}, \quad n = 0, \pm 1, \pm 2, \ldots \tag{4}$$

form a complete orthogonal basis, where w is the frequency variable. Thus, the digital representation of the transform process is given by

$$[Tx](t) = \sum_n x\left(\frac{n}{2B}\right) T \left[\frac{\sin \pi(2B(\cdot) - n)}{\pi(2B(\cdot) - n)}\right](t). \tag{5}$$

Here $(\cdot)$ denotes the independent variable. And, if T is time-invariant, which is often encountered in practice, the previous expression takes the simpler form

$$[Tx](t) = \sum_n x\left(\frac{n}{2B}\right) T\left[\frac{\sin 2\pi B(\cdot)}{2\pi B(\cdot)}\right]\left(t - \frac{n}{2B}\right). \tag{6}$$

3. PRINCIPLE OF JAMMING CANCELATION

3.1. Scenario

Pulse diversity is an effective way to suppress DRFM repeat jammer. It utilizes the fact that radar varies its transmitting pulses in the slow-time domain, so the jammer is forced to detect and analyze each updated pulse. It takes a certain period of time to complete a series of processing before it can transmit a jammer with respect to the updated pulse. Therefore, we assume the jammer lags one pulse behind the radar. This scenario is reasonable in view of the fact as follows. Even if the jammer has the ability to receive and re-transmit the current pulse at once, it can only use the previous pulse coming from the radar when it attempts to protect targets which are closer to the radar than itself. Considering the process time, the actual protection range would expand.

3.2. Radar and Jamming Signal Model

Suppose the radar transmission pulse in slow-time interval u is $P_u(t)$, where t denotes the fast-time. Thus, the jammer transmitting pulse in slow-time interval u can be expressed as $T[P_{u-1}(t)]$, where T is an operator defined in Section 2. Consequently, the received pulse of radar in slow-time interval u is as follows

$$s(t, u) = \sum_n \alpha_n(u) p_u\left[t - \tau_n(u)\right] + \sum_l \beta_l(u) T\{p_{u-1}\left[t - \tau_l(u)\right]\} \tag{7}$$

where, $\alpha_n(u)$ and $\beta_l(u)$ denote the reflectivity of the target echoes and jamming signals, respectively. And, $\tau_n(u)$ and $\tau_l(u)$ denote the time-delay of the target echoes and jamming signals relative to each pulse repetition interval (PRI), respectively. It is obvious that the received radar signals in a given slow-time interval contain both current echoes and re-transmitting jamming with respect to the previous pulse.

In some applications, coding schemes are designed to provide full diversity, simple decoding strategy and higher system performance. Here, a real transmission pulse block across four pulse intervals is defined in Table 1 [17–19], and the corresponding jamming signals are provided also.

Table 1. Transmission pulse block I.

u	0	1	2	3
Radar	$p_1(t)$	$p_2(t)$	$-p_2(t)$	$p_1(t)$
Jammer	$T[p_0(t)]$	$T[p_1(t)]$	$T[p_2(t)]$	$T[-p_2(t)]$

In the initial pulse diversity block, $p_0(t)$ may be any arbitrary pulse. Nevertheless, it is definite in subsequent blocks, just the last radar transmission pulse.

When slow-time $u = 1$ and 3, according to the transmission pulse block shown in Table 1, the received signals of radar can be expressed as

$$s(t,1) = \sum_n \alpha_n(1)p_2\left[t - \tau_n(1)\right] + \sum_l \beta_l(1)T\{p_1\left[(t - \tau_l(1)\right]\} \tag{8}$$

and

$$s(t,3) = \sum_n \alpha_n(3)p_1\left[t - \tau_n(3)\right] + \sum_l \beta_l(3)T\{-p_2\left[t - \tau_l(3)\right]\} \tag{9}$$

The radar transmission pulses in slow-time intervals 0 and 2 are also used to disturb the repeat jammer by keeping the jammer analyzing and processing the updated pulses.

3.3. Jamming Signal Cancelation

When radar works in high pulse repetition frequency (PRF), we assume the echoes reflected from the true targets and the jamming re-transmitted by the jammer are stationary due to the slight change over several short periods of PRI, and the amplitude of signals maintain constant in one transmission pulse block. Consequently, for the received signal of radar, the reflectivity notations $\alpha_n(u)$ and $\beta_l(u)$ can be reduced to α_n and β_l, respectively.

For uniform motion target, the round-trip time delay $\tau_n(u)$ and $\tau_l(u)$ can be modeled uniformly as equation below (although the jamming is single-trip actually, it can be simulated by the jammer as round-trip model)

$$\tau(t) = \frac{2(R - vt)}{c} \tag{10}$$

where R is the initial range of target, v is the relative radial velocity between radar and target, and c is the velocity of light. Actually, as we will see later, even if the assumption of uniform velocity is not fulfilled, it does not affect the performance of cancellation.

The target moves for double PRI from slow-time interval 1 to interval 3. So, the corresponding time delay difference is

$$\Delta\tau = \frac{4v}{cf_{\mathrm{PRI}}}, \tag{11}$$

where f_{PRI} denotes PRF. Because a high-repetition frequency is assumed, and v is much smaller than the light velocity c, the magnitude of $\Delta\tau$ is generally very small in the level of nanosecond. For instance, when $v = 1\,\mathrm{km/s}$ and $f_{\mathrm{PRI}} = 10\,\mathrm{kHz}$, we have $\Delta\tau = 1.33\,\mathrm{ns}$. In this example, the PRF is not extremely high. If the PRF increases much higher, which is frequently encountered in practice, the time-delay difference will be much smaller.

Because the pulse signal is processed in base band, the signal sampling rate (uniform sampling is assumed) is then relatively in a lower level, generally varying within several to tens of million samples per second (MSPS) after decimating, namely the sampling interval is greater than ten nanoseconds at least.

Accordingly, the time span with respect to the adjacent sampling points is greater than the time-delay difference by roughly an order of magnitude at least. So, the slight difference across two pulse intervals derived from target moving is no more than one sampling point in most practice cases. It is confirmed that the error introduced by the time delay difference is likely less than the error introduced in the sampling process. Hence, this error can be negligible completely on such conditions. We may notice that uniform velocity is not a necessary condition to deduce this conclusion. As a result, whether the uniform velocity is assumed or not, the conclusion is valid only if the error is less than one sampling point.

In some exceptional cases, the time-delay difference of each interesting arrival pulse can not be simply neglected. Under this condition, it can be compensated by easily multiplying the frequency response of the matched-filter by a delay factor or aligning the leading edge of received pulses over specific intervals if the time-delay difference can be estimated or obtained from other sensors, or errors will be introduced.

Accordingly, the time-delay $\tau_n(u)$ and $\tau_l(u)$ can be simply expressed as τ_n and τ_l, respectively. Where, τ_n and τ_l denote the time-delay after compensating or simply neglecting the difference. Although the Doppler shift of the target (both the true and the false) is not apparently addressed in above text, the effect aroused by it can be completely negligible in view of the high PRF and the actual acceleration of target. Thus the received signals in slow-time interval

1 and 3 are given by

$$s(t,1)=\sum_n \alpha_n p_2(t-\tau_n)+\sum_l \beta_l T\left[p_1(t-\tau_l)\right] \quad (12)$$

and

$$s(t,3)=\sum_n \alpha_n p_1(t-\tau_n)-\sum_l \beta_l T\left[p_2(t-\tau_l)\right]. \quad (13)$$

To achieve the purpose of jamming cancellation, the received signals in slow-time interval 1 and 3 pass through matched-filter separately with respect to the true targets and then add together, namely

$$\begin{aligned} s_n(t) &= p_2^*(-t)\otimes s(t,1)+p_1^*(-t)\otimes s(t,3)\\ &= p_2^*(-t)\otimes\left\{\sum_n \alpha_n p_2(t-\tau_n)+\sum_l \beta_l T[p_1(t-\tau_l)]\right\}\\ &\quad +p_1^*(-t)\otimes\left\{\sum_n \alpha_n p_1(t-\tau_n)-\sum_l \beta_l T[p_2(t-\tau_l)]\right\}\\ &= \sum_n \alpha_n \mathrm{psf}_{p_2}(t-\tau_n)+p_2^*(-t)\otimes\sum_l \beta_l T\left[p_1(t-\tau_l)\right]\\ &\quad +\sum_n \alpha_n \mathrm{psf}_{p_1}(t-\tau_n)-p_1^*(-t)\otimes\sum_l \beta_l T\left[p_2(t-\tau_l)\right] \end{aligned} \quad (14)$$

where $p_u*(-t)$ denotes the impulse response of matched-filter focused on the true targets in slow-time interval u, the asterisk denotes conjugate, $\otimes$ denotes the convolution operation, and $\mathrm{psf}(t)$ denotes point spread function (psf). It is clear that the terms 1st and 3rd which contain $\mathrm{psf}(\cdot)$ on the right side of (14) embody information of target, while the terms 2nd and 4th relate to the jammer. Since the digital representation of operator T is known, we can substitute (5) or (6) into the expression $p_2^*(-t)\otimes\sum_l \beta_l T[p_1(t-\tau_l)]$ and $p_1^*(-t)\otimes\sum_l \beta_l T[p_2(t-\tau_l)]$, respectively. Generally, $p_2^*(-t)\otimes T[p_1(t-\tau_l)]\neq p_1^*(-t)\otimes T[p_2(t-\tau_l)]$, i.e., the jammer-related terms can not be canceled. But, in a special case where $p_1(t)=p_2(t)$, the cancelation can be performed. Therefore, if $p_1(t)$ is selected identical with $p_2(t)$, (14) becomes

$$s_n(t)=\sum_n \alpha_n[\mathrm{psf}_{p_1}(t-\tau_n)+\mathrm{psf}_{p_2}(t-\tau_n)] \quad (15)$$

Evidently, the jammer terms have been canceled. On the other hand, if we focus only on the suppression of false target, a feasible transmission pulse block without full diversity can be given in Table 2.

Based on this pulse block, the cancelation result is given as follows.

$$\begin{aligned} s_n(t) &= p_2^*(-t) \otimes s(t,1) + p_2^*(-t) \otimes s(t,3) \\ &= p_2^*(-t) \otimes \left\{ \sum_n \alpha_n p_2(t-\tau_n) + \sum_l \beta_l T\{p_1[-(t-\tau_l)]\} \right\} \\ &\quad + p_2^*(-t) \otimes \left\{ \sum_n \alpha_n p_2(t-\tau_n) - \sum_l \beta_l T\{p_1[-(t-\tau_l)]\} \right\} \\ &= 2 \sum_n \alpha_n \mathrm{psf}_{p_2}(t-\tau_n) \end{aligned} \tag{16}$$

As expected, the RFTs are canceled completely. According to (14), (15) and (16), the jammer-related terms can be canceled completely when required conditions are satisfied. No other special constrains have been imposed upon the derivation. In theory, the cancelation performance of the proposed method is independent of the JSR and jamming clearance.

4. SIMULATIONS

In simulations, the LFM signal with bandwidth 10 MHz and pulse width 20 μs is employed. Besides, the sampling frequency is 40 MSPS, namely the time interval is 25 ns. A target echo is received in the presence of a C&I or SMSP jammer with jamming-to-signal ratio (JSR) equal to 15 dB. In the process of pulse compression, the matched-filtering measure is applied with a rectangle window.

4.1. Using Pulse Block I

Here, we choose the transmission pulse block I defined in Table 1. As described in Section 3.3, however, the pulse $p_1(t)$ and $p_2(t)$ must be identical here. The proposed approach is employed to cancel the jamming, and the direct matched-filtering method is used also in order to show different effect.

First, C&I jamming is tested. It can be seen clearly from Fig. 3(a) that the signal processed by direct matched-filtering still

Table 2. Transmission pulse block II.

u	0	1	2	3
Radar	$p_1(-t)$	$p_2(t)$	$-p_1(-t)$	$p_2(t)$
Jammer	$T[p_0(t)]$	$T[p_1(-t)]$	$T[p_2(t)]$	$T[-p_1(-t)]$

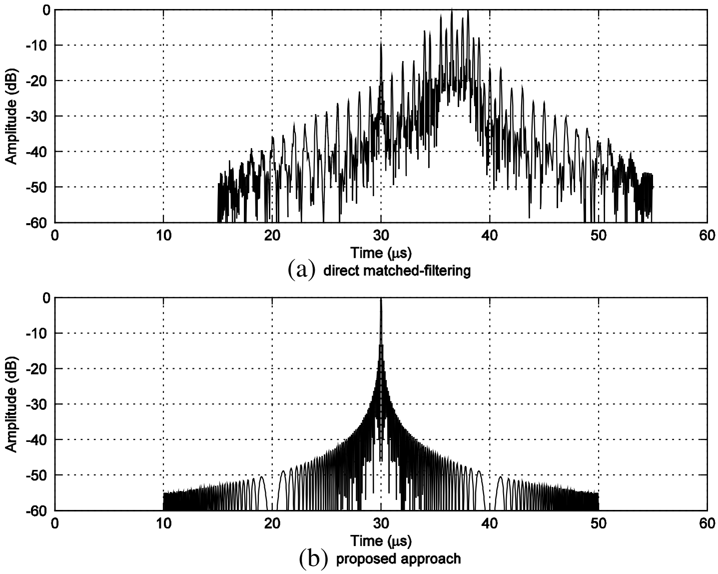

Figure 3. Cancelation of C&I jamming using transmission pulse block I.

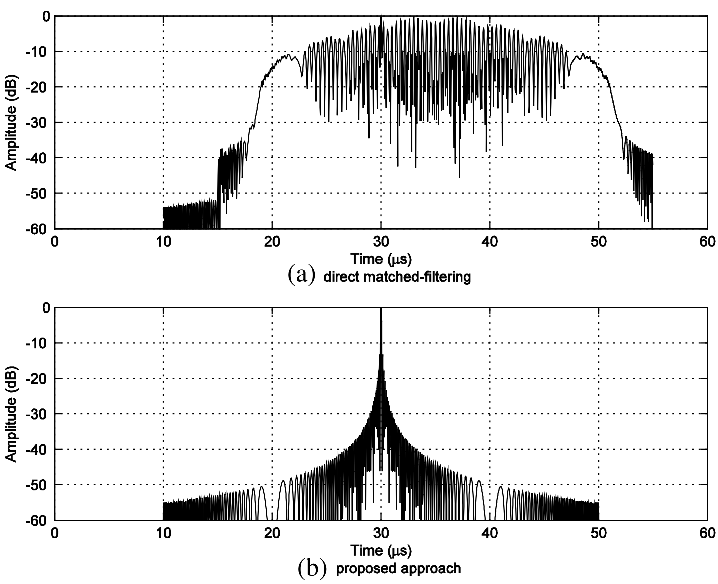

Figure 4. Cancelation of SMSP jamming using transmission pulse block I.

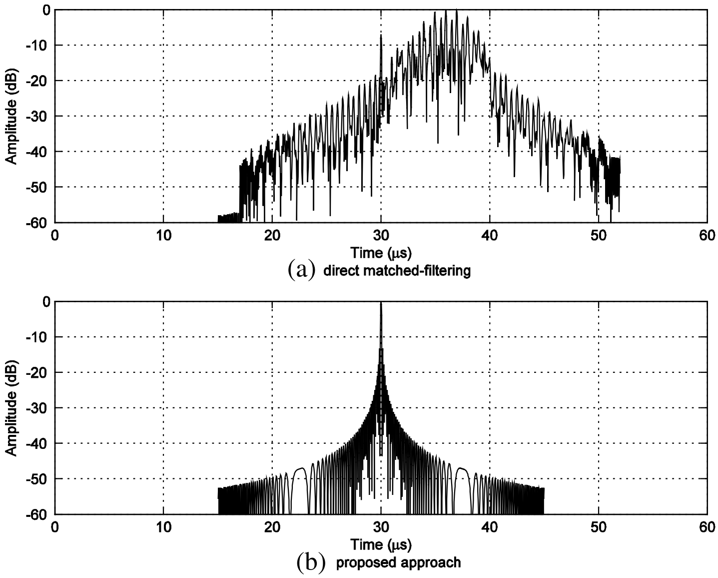

Figure 5. Cancelation of C&I jamming using transmission pulse block II.

remains a cluster of false targets. While, as shown in Fig. 3(b), the proposed approach can cancel out the jammer and focus the true target distinctly.

Second, SMSP jamming is applied to jam the victim radar. In Fig. 4(a), there are comb outputs besides the true target. Conversely, as shown in Fig. 4(b), the complicated false targets have been suppressed and the true target is obtained.

4.2. Using Pulse Block II

In this simulation, the transmission pulse block II defined in Table 2 is used. Unlike the previous case, the pulse width parameter is set to 20 μs and 15 μs while other conditions are remained. It follows that we alter simply the pulse width of the signal in transmission block, i.e., $p_1(t) \neq p_2(t)$.

In Figs. 5 and 6, the cancelation effects of C&I and SMSP are shown respectively to evaluate the algorithm based on a transmission block without full diversity. It is proved that the jamming signal can be eliminated successfully and the cancelation performance is almost identical with using transmission block I.

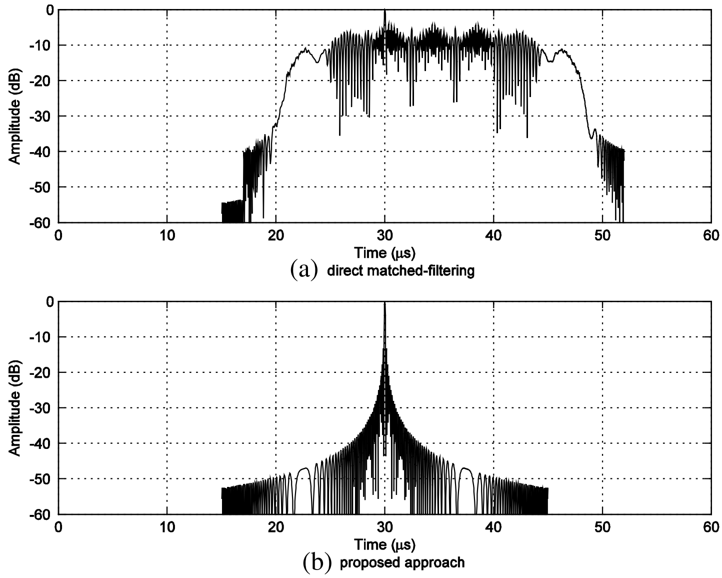

Figure 6. Cancelation of SMSP jamming using transmission pulse block II.

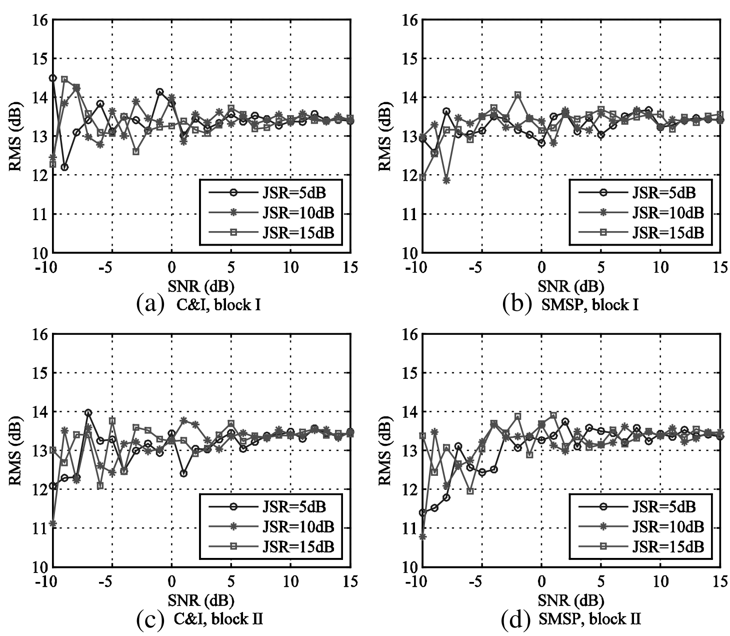

Figure 7. RMS of recovered target signal by using block I/II.

4.3. RMS of Recovered Target Signal

Here, the ratio of mainlobe to sidelobe (RMS) of recovered target signal is provided also to evaluate the performance of the presented approach. In this simulation, the signal-to-noise ratio (SNR) varies from −10 to 15 dB and the JSR varies from 5 to 15 dB. The noises are additive, Gaussian and white. Monte Carlo simulation is run 250 times.

As shown in Fig. 7, the RMS ranges from 10.8 to 14.5 dB and gradually converges to 13.4 dB (rectangle window) as the SNR increases. In addition, this simulation shows that the JSR is independent of the RMS.

5. CONCLUSIONS

This paper addresses issues about the newer types of complicated DRFM repeat jamming and presented a method to suppress them. By exploiting the redundant but essential code pulses, the proposed approach enables radar to recover the true target signals easily through jamming cancelation. Different from other methods, it is efficient to suppress complicated jamming signals besides conventional ones. The research results of the present work demonstrate that the proposed approach is applicable to a wide-ranging scope of DRFM repeat jammer, particularly the C&I and SMSP, even some potential complicated ones. It provides radar with an active strategy to counter against the repeat jammer, not just a passive anti-jamming method.

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