An Improved Radar ECCM Method Based on Orthogonal Pulse Block and Parallel Matching Filter

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Abstract —In this paper, a Radar Electronic Counter Countermeasure (ECCM) scheme is considered to enhance the concept of pulse diversity which makes use of the orthogonal pulse block code. This is achieved by employing all the received signals in the matching filter operation at slow-time intervals based on parallel matching filters, which improves the Signal to Noise Ratio (SNR) of real targets. This algorithm has been verified by simulations.

Index Terms—DRFM repeat jamming; ECCM; matched filter; pulse diversity

I. Introduction

For radar systems under deception jamming, Electronic Attacks (EA) will not work sufficiently due to the high Jamming-to-Signal Ratio (JSR). In particular, a Digital Radio Frequency Memory (DRFM) repeat jammer creates a false target, which has the same property of the target echoes. It stores the transmitting signal from the radar and regenerates a skin similar to the target with different range position making it difficult to distinguish true and false targets. The DRFM delays the stored pulse until a fixed time before the expected arrival of the next incoming radar pulse, as predicted by the measurement of the radar's Pulse Repetition Interval (PRI) [1].

Current Radar Electronic Counter Countermeasure (ECCM) techniques [2]-[8] mostly rely on the concepts of the pulse diversity. In Ref [2], [3] the concept of pulse diversity and two pulses coding techniques are presented, both methods work efficiently and give a good performance. However, an unfavorable aspect is that, only half of the receiving echoes are employed in the matched filter operation. Full-rate orthogonal pulse block design schema is presented in Ref [4].

Even though this method employs all signal of the receiving echoes in the matching filter operation at slow-time interval. Nevertheless repeating the same pulses to achieve the full rate orthogonal pulse block makes it easy for the DRFM repeat jammer to indicate/find out that, the victim radar is using pulse diversity. In Ref [6] such a method is proposed where the diversified pulses are phase-perturbed, i.e., a phase shift is introduced to Linear Frequency Modulation (LFM) signals.

In this paper, parallel matched filters are employed. This ensures that, all the received echoes are employed in the matched filter operation to suppress out the repeated jamming. Furthermore, improves the SNR of real target.

II. Radar and Jamming Signal Model

Consider a setup where the radar transmits new or modified pulses during each slow-time step. The pulse emitted during slow-time interval is consequently expressed by $p_m(t)$. The jammer is henceforth assumed to lag one pulse behind the radar, i.e. at slow-time, it transmits pulse $p_{m-1}(t)$.

The received signal at radar can be modeled as the sum of two reflective blocks with two different pulses.

$$\begin{aligned} s_r(t,u_m) &= S(t,u_m)_{Actual\ signal} + S(t,u_m)_{ECM\ signal} \\ s_r(t,u_m) &= \sum_n \sigma_n p_m(t-\Delta_n(u_m)) + \sum_l \rho_l p_{m-1}(t-\Delta_l(u_m)) + n_m(t) \end{aligned} \quad (1)$$

where μ_m denotes the slow-time domain at placement m and t is the fast-time domain. σ_n denotes the reflectivity levels of real targets whereas $\Delta_n(\mu)$ denotes the delay associated with each reflector.

Analogously, ρ_l represents the false reflectors imitated by the jammer, with mimicked delays given by $\Delta_l(\mu)$. $n_m(t)$ denotes the corresponding noise. Obviously, the received radar signals in a given slow-time interval contain both current echoes and re-transmitting jamming with respect to the previous pulse.

When radar emits pulse with a high repetitive frequency, there are only just slight changes in system geometry over short adjacent periods of slow-time intervals [2], [5]. Under these instances the reflectors normally do not raise a big change and almost remain stationary. For this algorithm we therefore assume that over T slow-time intervals the reflectors and their reflectivity levels can be considered to be stationary.

According to Ref [4], the target motion should be properly compensated; otherwise radar would suffer from the residual repeat jamming and the loss in Signal to Noise Ratio (SNR) of real targets. Two-dimensional frequency domain motion compensation algorithm is used to overcome the limitation of One-dimensional range frequency domain motion compensation and match

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filtering. Schema in Ref [4] obtains a good performance and fully removes the impact of target motion on matched filtering, However, the paper presented in Ref [5] indicates that, because the pulse signal is processed in base band, the signal sampling rate (uniform sampling is assumed) is then relatively in a lower level. 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 completely neglected on such conditions. In some exceptional cases, the time-delay difference of each interesting arrival pulse cannot be simply neglected. Under this condition, it must be compensated. J. Li, H. Liu, and Z. He [9] described a technique to compensate the motion, based on shifting the matching weight coefficients. It is useful when the signal bandwidth is much wider and the target velocity is much higher. For simplicity, we assumed in this paper that, the time-delays associated with reflectors are more liable to minor alterations across slow-time positions and can be modeled with a linearly increasing offset as a function of μ [3]. Therefore, the delays can be approximated as

$$\Delta_n(u_m+k)=\Delta_n(u_m)+k\delta, \quad 0\le k\le T \tag{2}$$

$$\Delta_l(u_m+k)=\Delta_l(u_m)+k\delta, \quad 0\le k\le T \tag{3}$$

where δ is a stationary constant for the duration of the one coherent integration interval, T =3 is assumed. Furthermore, δ is also assumed to be a parameter which is already known or can be estimated.

III. Principle of Jamming Suppression

To achieve the purpose of jamming suppression, the radar system transmits a different sequence of equal length pulses at each slow-time interval, starting at u=0, the pulses sequence of the radar and the repeat jammer are illustrated in Table I. To compare the pulses in Ref. [4] to our proposed method, the multiple identical pulse blocks within a Coherent Processing Interval (CPI) are shown in Fig. 1. CPI is a statistical measure of the time duration over which the received signal pulses responses are essentially invariant.

TABLE I. Pulse Sequence

U	0	1	2	3
Radar	$p_1(t)$	$p_2(t)$	$-p_2(t)$	$p_1(t)$
Repeat Jammer	$p_0(t)$	$p_1(t)$	$p_2(t)$	$-p_2(t)$

$p_0^*(-t)$: is a time reverse conjugate pulse of $p_0(t)$ which is useful in matched filter operation. $p_0(t)$ can be any arbitrary pulse, which the jammer may already have in memory, from for example some previous radar transmission. Nevertheless, it is used in full-rate orthogonal pulse, just as the last radar transmission pulse, e.g. p_2.

From Fig. 1, it is clear that, p_2 and p_1 are repeated many times and no reverse conjugate pulses are used. Furthermore, in all CPIs (PRI stationary blocks) at each slow-time μ =0 the pulses are similar to that of slow-time μ =2 pulses. In addition at each slow time u=1,the pulses are negative to the slow time μ =3 pulses, which makes the DRFM repeat jammer easily distinguish the pulse diversity applied to counter the jamming, thus, the jammer can overcome this issue and generate the false target properly to blind the victim radar. Therefore, in the proposed method the order of negative and different pulses are varied as long as the diverse pulses combinations occur on the same CPI. Moreover, the pulses or their parameters, should be modified whenever a new CPI is started in order to confuse the jammer and to keep it busy trying to estimate the incoming pulses.

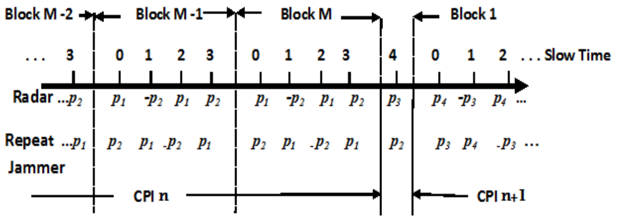

Fig. 1. Pulse Sequence of the full-rate orthogonal pulse block design.

To employ all the received signals /echoes in the matching filter operation, parallel matched filters are used. The emitted pulses of the radar at positions u=1 and μ =3 make it certain that signals received on $S(t,1)$ and $S(t,3)$ follow the orthogonal block structure, but the pulses emitted from radar at positions μ =0 and μ =2 are not ,thus , the jammer related terms cannot be completely canceled. However, in special cases where the pulses are chosen perfectly, the cancelation can be performed [5]. Parallel matched filter is used to receive the signals at slow-time interval 1 and 3 with respect to the true targets and then add together. The same step used above is applied for the received signals at slow-time interval 0 and 2, and then, the output from both parallel matched filters is summed up together. The delays between the pulses are approximated using 2 and 3.

Accordingly, the received signal at slow-time positions μ =1 and μ =3 can be expressed as:

$$S(t,1)=\sum_n \sigma_n p_2(t-\Delta_n)+\sum_l \rho_l p_1(t-\Delta_l)+n_1(t) \tag{4}$$

$$\begin{aligned} S(t,3)=&\sum_n \sigma_n p_1(-(t-\Delta_n-2\delta)) \\ &+\sum_l \rho_l\{-p_2\}(-(t-\Delta_l-2\delta))+n_3(t) \end{aligned} \tag{5}$$

Based on the first matched filter, the output signal can be expressed as:

$$S_{1out}=p_2^*(-t)\otimes S(t,1)+p_1^*(-t)\otimes S(t,3)+n_{1,3}(t) \tag{6}$$

where $\otimes$ denotes the convolution operation, $n_{1,3}(t)$ represents the corresponding noise, $p_2^*(-t), p_1^*(-t)$ are the impulse response of matched filter focused on the true targets signals.

Thus S_{1out} can be simplified below:

$$S_{1out} = p_2^*(-t)\otimes\left\{\sum_n \sigma_n p_2(t-\Delta_n)+\sum_l \rho_l p_1(t-\Delta_l)\right\}$$
$$+\,p_1^*(-t)\otimes\left\{\begin{array}{l}\sum_n \sigma_n p_1(-(t-\Delta_n-2\delta))\\ +\sum_l \rho_l\{-p_2\}(-(t-\Delta_l-2\delta))\end{array}\right\}+n_{1,3}(t) \qquad (7)$$

$$S_{1out} = \sum_n \sigma_n(PSF_{p_2}(t-\Delta_n)+PSF_{p_1}(t-\Delta_n-2\delta))$$
$$+p_2^*(-t)\otimes\left\{\sum_l \rho_l p_1(t-\Delta_l)\right\}-p_1^*(-t)\otimes \qquad (8)$$
$$\left\{\sum_l \rho_l p_2(t-\Delta_l-2\delta)\right\}+n_{1,3}(t)$$

Generally, the jammer terms cannot be canceled. But, in a special case where the pulses are chosen perfectly i.e. $p_1 = p_2$ and the delay can be estimated, the cancelation can be performed [5]. Therefore, the output of the first matched filter reduces into the sum of two point spread function (PSF).

$$S_{1out} = \sum_n \sigma_n(PSF_{p_0}(t-\Delta_n)+PSF_{p_1}(t-\Delta_n))+n_{1,3}(t) \quad (9)$$

For the received signals at μ =0 and μ =2, using the same step derivation, the second matched filter output can be express as:

$$S_{2out} = \sum_n \sigma_n(PSF_{p_1}(t-\Delta_n)+PSF_{p_2}(t-\Delta_n))+n_{0,2}(t)+I_s \quad (10)$$

In (10) I_s denotes a small interference signal since the jamming terms are not totally cancelled. This interference will be acceptable at the exact matched filter position.

IV. Simulations

In order to evaluate the performance of the method, we introduce the signal-to-jamming-plus-noise -ratio Improvement factor IF_{SJNR} as $SJNR_{out}/SJNR_{in}$, where $SJNR_{out}$ and $SJNR_{in}$ are the output and input $SJNR$ corresponding to the suppression, respectively.

At first, the matching filter output results of the received signal before and after cancellation are given to illustrate the effectiveness of the method. In simulations, the LFM signal with bandwidth 10MHz, pulse width 10 µs, carrier frequency 2.5 GHz and the target echo and the repeat jammer are assumed to have equal power, additionally, δ=0 is assumed.

Fig. 2 shows the matching filter output with respect to true target during slow-time interval $S(t,1)$, whereas Fig. 3 shows the outcomes after adding $S(t,3)$ to $S(t,1)$ and the proposed scheme for pulse diversity has been employed and the jamming signal has been suppressed. Fig. 4 shows the improvement of the overall system after summing the first parallel matched filter output $(S(t,1)+S(t,3))$ to the output of the second parallel matched filter $(S(t,0)+S(t,2))$. As per the simulation result from Fig. 4, this method can improve the SNR. Furthermore, the output power is four times that of the input power.

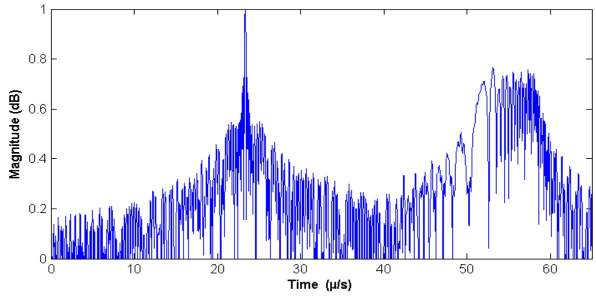

Fig. 2. Matched filter output at slow time μ =1, $(S(t,1))$.

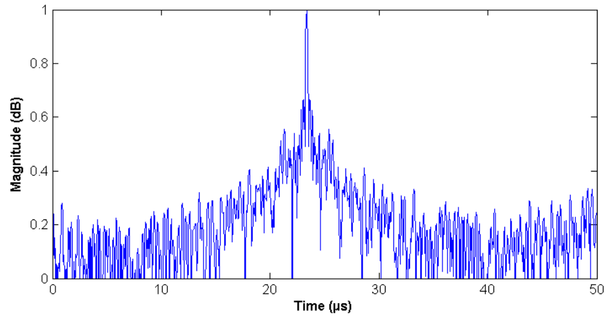

Fig. 3. Matched filter output of $(S(t,1)+S(t,3))$.

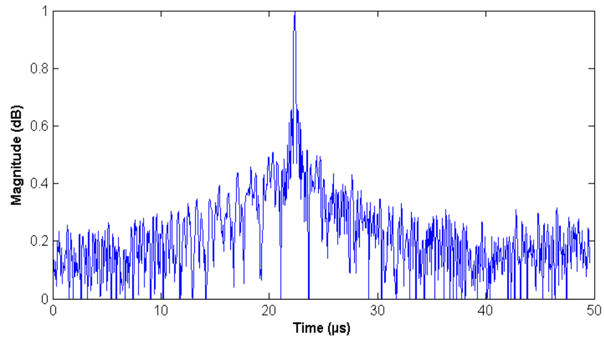

Fig. 4. The summation of the two parallel matched filters.

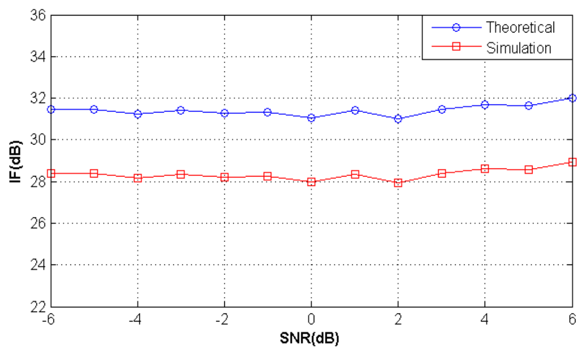

Fig. 5. IF_{SJNR} Vs. SNR.

Secondly, the influence of SNR on suppression performance is analyzed. The plot of the IF_{SJNR} under different SNR is shown in Fig. 5. The simulation is run as follows: the input SNR is varied from -6dB to 6dB, JSR is 0dB, and other parameters are the same as above.

Theoretically, the jamming signal must be completely removed after adding ECCM techniques, but there is an unavoidable remaining jamming signal due to signal processing. Due to this fact, to indicate the robustness of the proposed method we compare it to the theoretical results (the jammer terms are completely removed).

It can be seen from Fig. 5 that, this method can improve Signal-to-Jamming- plus- noise- Ratio. The proposed method has high performance for jamming suppression of up to 28 dB, while it is about 32 dB theoretically. Moreover, it does not have high influence on noise and only suppresses the jamming, thus there is no remarkable enhancement with increasing SNR, thus, as SNR increase from -6 to 6 dB, IF_{SJNR} slightly improves as well by about 1 dB.

V. Comparison to the Existing Algorithms

In order to favorably compare the proposed scheme to the existing methods in Ref. [2]-[4], we define the following properties:

- Robustness: Robustness means that the ECCM technique is not designed to address the flaws of a specific ECM system. The designer makes use of fundamental principles or general limits of available technology, such as time delay through a repeater jammer. As applied to ECCM, robustness applies to whether the technique works when the jammer is either off or on. A technique that introduces a large performance penalty if busy when no jammer signal is present would be non-robust.
- Perishability: The concept of perishability involves two aspects. The first relates to how easy it is for the enemy to find out what ECCM is being employed. The second aspect is how easy it is for the enemy to counter the ECCM even when its characteristics are known.
- SNR: is a measure of the ability of the victim radar to detect targets. It is also an indication of the weakness of the radar to certain jamming techniques. Therefore, SNR describes how much noise is in the output of a device after adding ECCM techniques.

Accordingly, we analyze and compare these properties in the form of a table. Table II shows the comparison between the methods.

TABLE II: Comparison between the Proposed Method and Existing Methods

Properties	Methods		
	Akhtar [2]	Xia et al [4]	Our method
Robustness	High	High	High
Perishability	High	Moderate	High
SNR	Moderate	High	High

From Table II above it is clear that the proposed algorithm has performed better than [2]-[4]. This is achieved by employing all the received signals as used in Ref. [4], which enhances the SNR of the real targets. However, this is not done in [2] and hence a moderate SNR is achieved as compared to our method. Furthermore, the proposed method has good perishability similar to Ref. [2], since it does not repeat the same pulses to achieve the full rate orthogonal pulse block. Thus, the repeated jamming will not easily find out that ECCM is being employed.

VI. Discussion

In proposed method, there is no need to plot the output with respect to true target during slow-times $S(t,3)$, $S(t,0)$ and $S(t,2)$ as it looks similar to $S(t,1)$. No plot for matched filter output after adding $S(t,2)$ to $S(t,0)$ using the same manner.

After transmitting and processing the first block (Table I), the radar system can iterate the process with the identical block structure. In the derivation of the schemes, no special constraints have been imposed upon the pulses. The waveforms should however be chosen to ensure that the reflectors magnitude is invariant under both pulses and the diverse properties are achievable. The pulses, or their parameters, should be modified whenever a new pulse sequence is started in order to confuse the jammer and to keep it busy trying to estimate the incoming pulses. Emitting an extra pulse between two blocks is also useful to start the new sequence of pulses with a pulse which is not known to the jammer.

The strategy proposed requires integration over several pulses to separate the incoming signals. However, it can also be based on the transmission of pulses which are themselves composed of two, to decrease the integration over several pulses.

Finally, we assumed that the jammer lags by only one pulse behind the radar. Once the jammer lags behind by more than one pulse, the system can overcome this constraint by utilizing higher order block codes [11].

VII. Conclusion

From the above description, we observed that using parallel matched filters can enhance the immunity of concept of pulse diversity and improve the SNR of real targets. This has been achieved by using parallel matching filters to employ all the signal information of the received echoes in the matching filter operation at slow-time interval and fully detecting the true target and suppressing the repeat jammer.

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