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RESEARCH ARTICLE

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A method of waveform design based on mutual information

Abstract A novel method called the general water-filling, which is suitable when clutter is not negligible, is proposed to solve the waveform design problem of broadband radar for the recognition of multiple extended targets. The uncertainty of the target's radar signatures is decreased via maximizing the mutual information between a random extended target and the received signal. Then, the general water-filling method is employed to the waveform design problem for multiple extended targets identification to increase the separability of multiple targets. Experimental results evaluated the efficiency of the proposed method. Compared to chirp signal and water-filling signal, our method improves the classification rates and even performs better at low signal-to-interference-plus-noise ratio (SINR).

Keywords waveform design, broadband radar, mutual information, target recognition

1 Introduction

A newly proposed concept for optimizing the performance of active sensors within resource-constrained and interference-limited environments is cognitive radar [1]. One of the three basic ingredients to the constitution of cognitive radar is intelligent signal processing, which builds on learning through interactions of the radar with the surrounding environment. From the moment a radar system is switched on, the system becomes electromagnetically linked to its surrounding environment in the sense that the environment has a strong and continuous influence on the radar returns. In complex electromagnetic environments, interference can be strong; meanwhile, the transmit power and energy may be limited.

Unfortunately, traditional sensors usually operate within a fixed frequency band, use a predefined suite of waveforms, and adapt to the propagation environment only through post-measurement signal processing. Thus, in many cases it has been observed that traditional sensing modalities lack the flexibility necessary to provide adequate detection, tracking, and recognition performance in difficult/complex propagation and interference environments. Therefore, intelligent illuminators are needed in the cognitive radar system and pulse shaping techniques are increasingly being employed.

A number of researchers [2–4] have considered the use of sophisticated pulse shaping techniques in order to maximize the energy reflected from the extended targets. Bell [2] has developed the theory of matched illumination for the detection of a deterministic target impulse response in the presence of additive signal-independent noise. Guerci et al. [3,4] have developed a general theory of matched illumination that includes the effects of both additive colored noise and additive colored signal-dependent clutter in the maximization of the target signal-to-interference-plus-noise ratio (SINR).

There are two primary technologies applied to waveform design problems for target discrimination. The first uses the techniques similar to that used for target detection [3,4]. Guerci and Pillai [5] have developed the theory of matched illumination for target discrimination between the deterministic target impulse responses. Unfortunately, the waveform designed in Ref. [5] focuses energy into only one or two narrow frequency bands, which may confine the bandwidth of the transmitted signal. Another important tool in such designs is the use of information theoretic techniques. Bell [2] is the first to propose a method to take advantage of the mutual information between a random extended target and the received signal to complete optimization, which is named water-filling type strategy or WF method. For convenience of the description, the water-filling method is referred to as such.

We assume that the targets are acting on the transmitted waveform as a random, linear, time-invariant system with discrete time frequency response taken from a Gaussian ensemble with known power spectral density (PSD). Denote by $\boldsymbol{h}(f) = [h(f_1),h(f_2),...,h(f_k)]^{\mathrm{T}}$ the target's radar

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signature and by $\sigma_h^2(f_k)$ its PSD at frequency f_k. A realization of the received signal is given by

$$x(f_k) = h(f_k)s(f_k) + v(f_k),\ k = 1,2,...,K, \tag{1}$$

where $s(f_k)$, $v(f_k)$ are respectively the discrete time waveform and noise at frequency f_k, and K is the number of frequency sub-bands. Under our assumptions and assuming complex envelope signaling over a sufficiently narrowband division of the transmit bandwidth, the mutual information between the target frequency response and the received signal at frequency f_k is given by

$$I_k(h(f_k),x(f_k)|s(f_k)) = \log\left(1 + \frac{|s(f_k)|^2\sigma_h^2(f_k)}{\sigma_v^2(f_k)}\right)\Delta f, \tag{2}$$

where $\sigma_v^2(f_k)$ is the noise PSD at frequency f_k, and Δf is the bandwidth used. The total mutual information between target frequency response and received signal is now given by

$$I(\boldsymbol{h},\boldsymbol{x}|\boldsymbol{s}) = \Delta f\sum_{k=1}^{K}\log\left(1 + \frac{|s(f_k)|^2\sigma_h^2(f_k)}{\sigma_v^2(f_k)}\right). \tag{3}$$

Bell proved that a water-filling strategy is required to maximize the mutual information, where the transmit PSD is given by

$$|\boldsymbol{s}(f)|^2 = \max\left[0, A - \frac{\sigma_v^2(f)}{\sigma_h^2(f)}\right], \tag{4}$$

and A is a constant chosen so that the total power constraint is met. From Eq. (4), we can see that more energy is put on the frequency range in which $\sigma_h^2(f)/\sigma_v^2(f)$ is large.

The uncertainty of the target's radar signatures is decreased by maximizing the mutual information between target frequency response and the received signal in the water-filling method. Aimed at the optimization problem of multiple target estimation and tracking, we generalize the information theoretic water-filling approach of Bell to allow optimization for multiple targets simultaneously [6]. Unfortunately, clutter cannot be neglected in the realistic system, and water-filling method does not consider the presence of clutter in the waveform design. Therefore, a general water-filling method is proposed which could optimize waveforms in the presence of additive colored noise and additive colored signal-dependent clutter, and called the GWF method.

2 General water-filling method

2.1 Calculation of mutual information in general water-filling method

We assume that the clutter is acting on the transmitted waveform as a random, linear, time-invariant system with discrete time frequency response taken from a Gaussian ensemble with known PSD. Denote by $\boldsymbol{c}(f) = [c(f_1),c(f_2),...,c(f_K)]^{\mathrm{T}}$ the clutter radar signature and by $\sigma_c^2(f_k)$ its PSD at frequency f_k. The signature of targets and noise are similar with that described above and noise is independent of clutter. For convenience, define the total noise-plus-clutter output via

$$v'(f_k) = s(f_k)c(f_k) + v(f_k). \tag{5}$$

And denote by $\sigma_{v'}^2(f_k)$ its PSD at frequency f_k. Because the noise is independent of clutter, we know that $v'(f_k)$ obeys a Gaussian distribution whose PSD has the form at frequency f_k:

$$\sigma_{v'}^2(f_k) = \sigma_v^2(f_k) + \sigma_c^2(f_k)|s(f_k)|^2. \tag{6}$$

So that the received signal vector has the form

$$x(f_k) = h(f_k)s(f_k) + v'(f_k),\ k = 1,2,...,K. \tag{7}$$

In the calculation of the mutual information, $v'(f_k)$ in Eq. (7) is similar with $v(f_k)$ in Eq. (1), the mutual information between target frequency response and received signal at frequency f_k is given by

$$I_k(h(f_k),x(f_k)|s(f_k)) = \Delta f\log\left(1 + \frac{|s(f_k)|^2\sigma_h^2(f_k)}{\sigma_{v'}^2(f_k)}\right). \tag{8}$$

The total mutual information between target frequency response and received signal is now given by

$$I(\boldsymbol{h},\boldsymbol{x}|\boldsymbol{s}) = \Delta f\sum_{k=1}^{K}\log\left(1 + \frac{|s(f_k)|^2\sigma_h^2(f_k)}{\sigma_{v'}^2(f_k)}\right). \tag{9}$$

Then what we need is to find $|\boldsymbol{s}(f)|^2$ which can maximize $I(\boldsymbol{h},\boldsymbol{x}|\boldsymbol{s})$.

2.2 General water-filling optimization method

Since $I(\boldsymbol{h},\boldsymbol{x}|\boldsymbol{s})$ is a concave function with nonnegative parameters, the maximization of $I(\boldsymbol{h},\boldsymbol{x}|\boldsymbol{s})$ is a convex problem and can be written as

$$\min_{\boldsymbol{P}} -\Delta f\sum_{k=1}^{K}\log\left(1 + \frac{p_k\sigma_h^2(f_k)}{\sigma_c^2(f_k)p_k + \sigma_v^2(f_k)}\right),$$

$$\text{subject to} \sum_{k=1}^{K}p_k = \xi, \tag{10}$$

where $\boldsymbol{P} = [p_1,p_2,...,p_K]^{\mathrm{T}}$, $p_k = p(f_k) = |s(f_k)|^2$ is the power density allocation at frequency f_k and ξ is the energy of the transmitted signal.

Using the Lagrange multiplier technique, we form the objective function

$$\Phi(\boldsymbol{P}) = -\Delta f\sum_{k=1}^{K}\log\left(1+\frac{p_k\sigma_h^2(f_k)}{\sigma_c^2(f_k)p_k+\sigma_v^2(f_k)}\right.$$
$$\left.-\lambda\left(\sum_{k=1}^{K}p_k-\xi\right)\right), \tag{11}$$

therefore, for each p_k, the KKT condition now implies that

$$\frac{\partial\Phi(\boldsymbol{P})}{\partial p_k}=\frac{\partial\log\left(1+\dfrac{p_k\sigma_h^2(f_k)}{\sigma_c^2(f_k)p_k+\sigma_v^2(f_k)}\right)}{\partial p_k}-\frac{\lambda}{\Delta f}=0, \tag{12}$$

and can be rewritten as

$$\frac{\sigma_h^2(f_k)\sigma_v^2(f_k)}{(\sigma_c^2(f_k)p_k+\sigma_v^2(f_k))(\sigma_h^2(f_k)p_k+\sigma_v^2(f_k)+p_k\sigma_c^2(f_k))}=\frac{\lambda}{\Delta f}. \tag{13}$$

1) In the absence of clutter, $c(f)=0$ and $\sigma_c^2(f)=0$, then $\sigma_{v'}^2(f_k)=\sigma_v^2(f_k)$ and Eq. (9) is the same as Eq. (3), so it can be solved by the water-filling method.

2) At the other extreme, $\sigma_v^2(f)$ is negligible compared to $\sigma_c^2(f_k)$ and Eq. (6) reduces to $\sigma_{v'}^2(f_k)=\sigma_c^2(f_k)|s(f_k)|^2$. The total mutual information between target frequency response and received signal is now given by

$$I(\boldsymbol{h},\boldsymbol{x}|\boldsymbol{s})=\Delta f\sum_{k=1}^{K}\log\left(1+\frac{\sigma_h^2(f_k)}{\sigma_c^2(f_k)}\right). \tag{14}$$

As Eq. (14) shows, the mutual information is independent of $\boldsymbol{s}(f)$ and any signal can be a transmitted signal.

3) In the most general practical situation, neither noise nor clutter is negligible and the Eq. (13) can be rewritten as

$$p_k^2(\sigma_c^4(f_k)+\sigma_h^2(f_k)\sigma_c^2(f_k))+p_k(2\sigma_c^2(f_k)\sigma_v^2(f_k)$$
$$+\sigma_h^2(f_k)\sigma_v^2(f_k))+\sigma_v^4(f_k)-\frac{\Delta f\sigma_h^2(f_k)\sigma_c^2(f_k)}{\lambda}=0. \tag{15}$$

Thus, the $\boldsymbol{P}$ that maximizes $\Phi(\boldsymbol{P})$ is

$$p_k=\sqrt{\left(\frac{b(f_k)}{a(f_k)}\right)^2+\frac{\dfrac{\Delta f\sigma_h^2(f_k)\sigma_v^2(f_k)}{\lambda}-\sigma_v^4(f_k)}{a(f_k)}}-\frac{b(f_k)}{a(f_k)}, \tag{16}$$

where

$$a(f_k)=\sigma_c^4(f_k)+\sigma_h^2(f_k)\sigma_c^2(f_k), \tag{17}$$

$$b(f_k)=2\sigma_c^2(f_k)\sigma_v^2(f_k)+\sigma_h^2(f_k)\sigma_v^2(f_k). \tag{18}$$

Since $\boldsymbol{P}$ is the magnitude squared of the transmitted signal spectrum, it must be real and nonnegative. Yet from Eq. (16),

$$|s(f_k)|^2=\max\left[0,\sqrt{\left(\frac{b(f_k)}{a(f_k)}\right)^2+\frac{\dfrac{\Delta f\sigma_h^2(f_k)\sigma_v^2(f_k)}{\lambda}-\sigma_v^4(f_k)}{a(f_k)}}-\frac{b(f_k)}{a(f_k)}\right], \tag{19}$$

where λ is a constant and the value of the constant λ is determined by the energy of the transmitted signal.

Because of the presence of clutter, the increase of the energy of the transmitted signal will not only increase the energy of the target echoes but also increase the energy of the clutter. Therefore, as shown in Eq. (19), the energy distribution in frequency of the transmitted signal, which is optimized by the general water-filling method, is not the same as that optimized by the water-filling method and does not obey an intuitional rule.

3 Application of general water-filling method in recognition of radar targets

For the recognition of radar targets taking advantage of the target echoes, the difference between the echoes of different targets can be used to identify the ID of the unknown target. Because the temporal echoes are time-shift sensitive, range aligning [7,8] is needed in the recognition which would augment the difficulty of the optimization in the waveform design. Considering that the target frequency echoes are time-shift invariant, the optimization can be done in frequency domain.

Since the general water-filling method is proposed to decrease the uncertainty of the target's radar signature, a modification of the general water-filling method is necessary in order to solve the waveform design problem of the recognition of radar targets.

Generally, we do not have the exact information of the target aspect and the target echoes vary acutely and do not follow a simple distribution in the aspect region, so we can divide the aspect region into a lot of small aspect regions in which the target echoes can be regarded as varying slowly and following a simple distribution. Assume that there are L kinds of independent targets; the aspect region is divided into N small aspect regions in which the targets are acting on the transmitted waveform as a random, linear, time-invariant system with discrete time frequency response taken from a Gaussian ensemble. Denote by $\boldsymbol{h}_{ln}(f)=[h_{ln}(f_1),h_{ln}(f_2),...,h_{ln}(f_K)]^{\mathrm{T}}$ the target frequency response of the lth class of target with an aspect in the nth small aspect region, which follows a Gaussian distribution with an expected value $\boldsymbol{m}_{ln}(f)=[m_{ln}(f_1),m_{ln}(f_2),...,m_{ln}(f_K)]^{\mathrm{T}}$ and spectral variance $\sigma_c^2(f_k)$. We can divide $\boldsymbol{h}_{ln}(f)$ into two independent frequency responses as shown in Fig. 1, a fixed frequency response $\boldsymbol{m}_{ln}(f)$ and a random frequency response $\boldsymbol{v}_{ln}(f) = [v_{ln}(f_1), v_{ln}(f_2), \ldots, v_{ln}(f_K)]^{\mathrm{T}}$ follows a zero mean Gaussian distribution with spectral variance $\sigma_{ln}^2(f_k)$. Denote by $\boldsymbol{w}_{ln}(f) = [w(f_1), w(f_2), \ldots, w(f_K)]^{\mathrm{T}}$ the filter frequency response which is useful for the feature extraction.

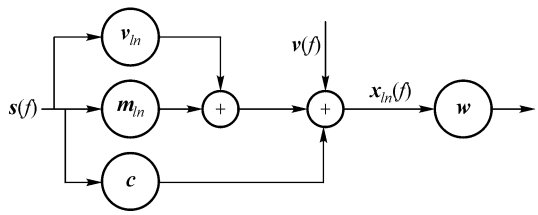

Fig. 1 Simplified transmit-receiver model of essential features

As shown in Fig. 1, the received signal at frequency f_k is given by

$$x_{ln}(f_k) = m_{ln}(f_k)s(f_k) + v_{ln}(f_k)s(f_k) + s(f_k)c(f_k) + v(f_k) = m_{ln}(f_k)s(f_k) + v'(f_k), \quad (20)$$

where

$$v'(f_k) = s(f_k)v_{ln}(f_k) + s(f_k)c(f_k) + v(f_k). \quad (21)$$

For the recognition of radar targets, the critical factor is the difference between the radar signatures of different targets; the bigger the difference, the better the identifying performance. However, the random frequency response $v_{ln}(f_k)$ makes it hard for us to identify the target and it plays the same role as clutter in the optimization, so we define the total interrupt via Eq. (21) for convenience. Because the target, clutter and noise are independent of each other, the spectral variance of the total interrupt can be written as

$$\sigma_{v'_{ln}}^2(f_k) = \sigma_v^2(f_k) + \sigma_c^2(f_k)|s(f_k)|^2 + \sigma_{ln}^2(f_k)|s(f_k)|^2. \quad (22)$$

In any small aspect region, the spectral variance of the target frequency response is small, so it can be replaced with the mean value of the spectral variances of all the small aspect regions, and the spectral variance of the total interrupt v' at frequency f_k for all targets in every small aspect region has an approximate form

$$\sigma_{v'}^2(f_k) = \sigma_v^2(f_k) + \sigma_c^2(f_k)|s(f_k)|^2 + \frac{\sum_{l=1}^{L}\sum_{n=1}^{N}|s(f_k)|^2\sigma_{ln}^2(f_k)}{NL}. \quad (23)$$

The proposed water-filling method and general water-filling method are to decrease the uncertainty of the target's radar signatures, but the intent of waveform design for the recognition is to reduce the uncertainty of the class of radar targets. Accordingly, in our optimization we aim to amplify the difference between the PSD of the fixed frequency response of different targets. For convenience of presentation, the PSD of the fixed frequency response can be called the fixed PSD for short.

The spectral variance of the fixed PSDs of all targets in the nth small aspect region is given by

$$\sigma_{dn}^2(f_k) = \sum_{l=1}^{L}\sum_{j=l+1}^{L} \mathrm{abs}\left(|m_{ln}(f_k)|^2 - |m_{jn}(f_k)|^2\right). \quad (24)$$

Considering that the slope of the decrease of error classification rates becomes smaller and smaller along with the increase of the difference between the echoes of different targets, $\sigma_d^2(f_k)$, which denotes the spectral variance of the fixed PSD of all targets in the total aspect region, can be regarded as the summation of the inverse of $\sigma_{dn}^2(f_k)$ to take more account of the separability between the classes which are difficult to identify:

$$\sigma_d^2(f_k) = \frac{1}{\sum_{n=1}^{N}\frac{1}{\sigma_{dn}^2(f_k)}}. \quad (25)$$

Replacing $\sigma_h^2(f_k)$ in Eq. (8) by $\sigma_d^2(f_k)$, the mutual information between target frequency responses of different targets and received signal at frequency f_k is now given by

$$I_k(h(f_k), x(f_k)|s(f_k)) = \Delta f \log\left(1 + \frac{\sigma_d^2(f_k)}{\sigma_{v'}^2(f_k)}\right), \quad k = 1,2,\ldots,K, \quad (26)$$

where

$$\sigma_{v'}^2(f_k) = \sigma_{c'}^2(f_k)|s(f_k)|^2 + \sigma_v^2(f_k), \quad (27)$$

$$\sigma_{c'}^2(f_k) = \frac{\sum_{l=1}^{L}\sum_{n=1}^{N}\sigma_{ln}^2(f_k)}{NL} + \sigma_c^2(f_k). \quad (28)$$

The PSD of the transmitted signal can be given by

$$|s(f_k)|^2 = \max\left[0, \sqrt{\left(\frac{b(f_k)}{a(f_k)}\right)^2 + \frac{\frac{\Delta f \sigma_d^2(f_k)\sigma_v^2(f_k)}{\lambda} - \sigma_v^4(f_k)}{a(f_k)}} - \frac{b(f_k)}{a(f_k)}\right], \quad (29)$$

where

$$a(f_k) = \sigma_{c'}^4(f_k) + \sigma_d^2(f_k)\sigma_{c'}^2(f_k), \tag{30}$$

$$b(f_k) = 2\sigma_{c'}^2(f_k)\sigma_v^2(f_k) + \sigma_d^2(f_k)\sigma_v^2(f_k). \tag{31}$$

4 Experimental results

The results presented in this section are based on the simulated data generated by some electromagnetic simulation software as the target frequency responses of three targets. The centre frequency and bandwidth of the radar are 5250 MHz and 500 MHz respectively, and the power spectral densities of noise and clutter are shown in Figs. 2 and 3, respectively. The spectral variance of target frequency response of some target is shown in Fig. 4, in the presence of clutter and noise. The PSD of the waveform optimized by general water-filling method is depicted in Fig. 5. Figure 6 presents the comparison of the mutual information between target frequency response and received signal with three different transmitted signals (chirp signal, the waveforms optimized by general water-filling method and water-filling method) changing with the signal energy.

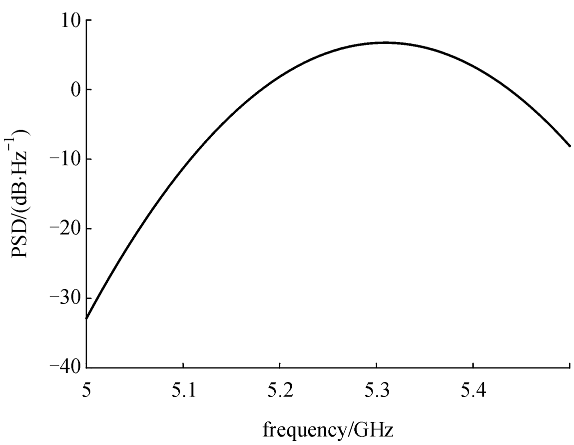

Fig. 2 PSD of noise

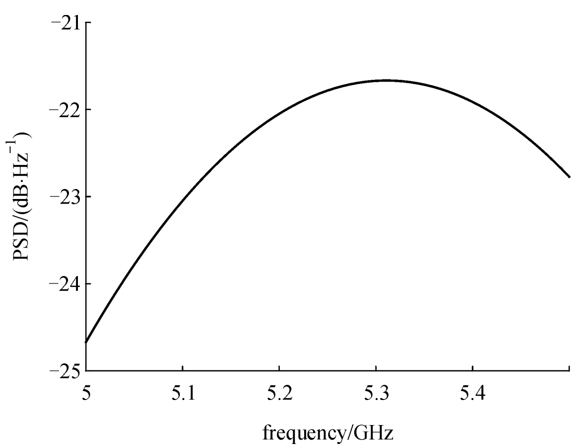

Fig. 3 PSD of clutter

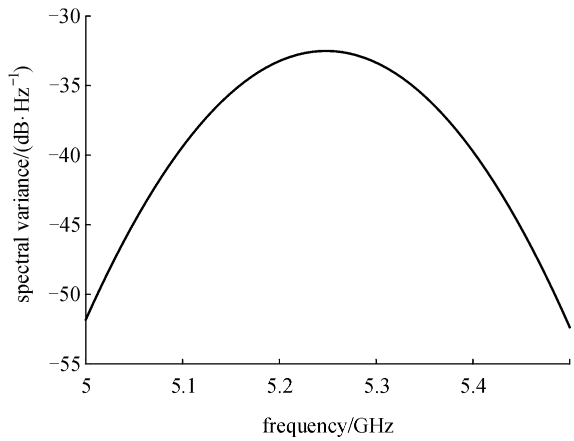

Fig. 4 Spectral variance of target frequency response

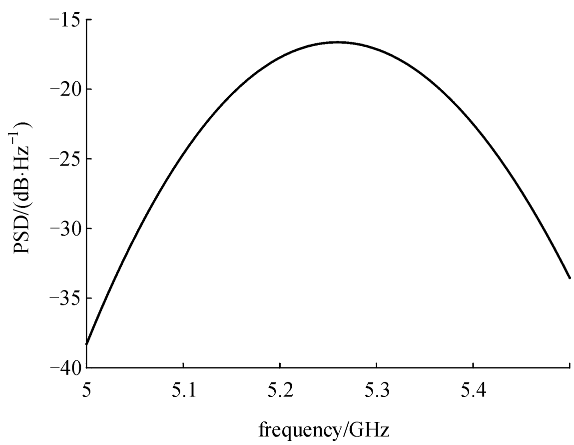

Fig. 5 PSD of waveform optimized by GWF

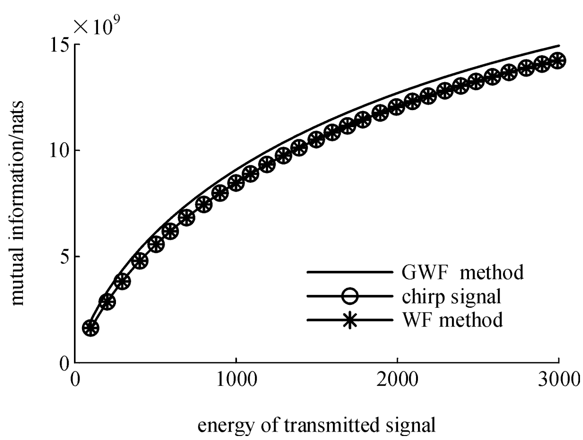

Fig. 6 Comparison of three transmitted signals

The frequency response of the three targets are generated in an aspect region of 7°, and the aspect region is divided into 16 small aspect regions, so the spectral variance of target frequency responses in any small aspect region is very small. Considering the effect of the random target frequency response is the same as clutter, we can neglect the random target frequency response. The PSD of the waveform optimized by general water-filling method for the recognition of the three targets is shown in Fig. 7.

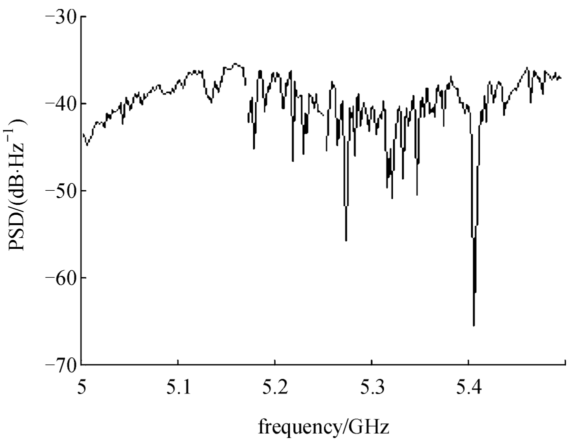

Fig. 7 PSD of waveform optimized by GWF

As shown in Figs. 5 and 7, the transmit energy of the waveform optimized by general water-filling method do not focus on minority narrow frequency bands and the advantage of broadband signal can be preserved. Figure 6 shows that the mutual information between target frequency response and received signal when the transmitted signal is the waveform optimized by general water-filling method is larger than the situation in which the transmitted signal is chirp signal or the waveform optimized by water-filling method with the same energy. According to rate distortion theory [9], we know that the uncertainty can be reduced more significantly by choosing the waveform optimized by general water-filling method as the transmitted signal.

By selecting chirp signal, the waveform optimized by water-filling method and general water-filling method as transmitted signal acting on three targets with aspect in the aspect region, and adding clutter and noise shown in Figs. 2 and 3 to the target echoes, we can get 10000 samples of received signals. Then the minimum Euclidean distance classifier can be used in the recognition in frequency domain. Taking out 4000 samples as training samples, the templates for each target in every small aspect region can be obtained using the average value of the training samples, then the remaining 6000 test samples can be identified.

The recognition rates of three kinds of transmitted signal with or without filter are shown in Table 1 and Table 2. The recognition rates indicate that, compared with the chirp signal and the waveform optimized by water-filling method, the waveform optimized by general water-filling method with the same energy can obtain better identifying performance, and the filter helps reduce the effect of the frequency band with lower SINR and increase the recognition rates.

Because the effect of clutter is neglected, the performance of the water-filling method in the simulation experiment is poor. When the clutter-to-noise ratio (CNR) is very low, the influence of clutter is very small and can even be neglected, so the recognition rates of the waveform optimized by water-filling method is close to that of the waveform optimized by general water-filling method. Along with the increase of CNR, the influence of clutter cannot be neglected and it will induce the identification performance of the water-filling method to be lower than that of the general water-filling method, just as what was shown in the simulation experiment. When CNR is very large, clutter is dominant and noise can be neglected. As Eq. (14) shows, any waveform can be chosen as transmitted signal, and the mutual information and recognition rates would be invariable.

5 Conclusions

Aimed at the problems of target estimation and identification of extended target in the broadband waveform design,

Table 1 Recognition rates of three transmitted signals with energy ξ_0/%

	without filter				with filter			
	target 1	target 2	target 3	average	target 1	target 2	target 3	average
chirp	47.70	44.65	44.35	45.57	70.60	72.30	69.70	70.87
waveform optimized by GWF	56.65	56.82	52.53	55.33	87.80	86.58	86.28	86.89
waveform optimized by WF	49.20	49.40	44.50	47.70	74.10	75.20	76.00	75.10

Table 2 Recognition rates of three transmitted signals with energy ξ_1/%

	without filter				with filter			
	target 1	target 2	target 3	average	target 1	target 2	target 3	average
chirp	73.60	69.00	72.00	71.53	93.80	92.50	91.50	92.60
waveform optimized by GWF	77.23	73.42	73.25	74.63	96.25	95.90	95.52	95.89
waveform optimized by WF	74.00	68.43	72.52	71.65	92.33	92.17	93.88	92.79

a novel method called general water-filling method is proposed in this paper and it is applied to solve the waveform design problem for the recognition of radar targets. The optimization is done by maximizing the mutual information between the target frequency responses of different targets and the received signal, which helps to increase the class separability and obtain better performance.

References

1. Haykin S. Cognitive radar: a way of the future. IEEE Signal Processing Magazine, 2006, 23(1): 30–40
2. Bell M R. Information theory and radar waveform design. IEEE Transactions on Information Theory, 1993, 39(5): 1578–1597
3. Pillai S U, Oh H S, Youla D C, Guerci J R. Optimum transmit-receiver design in the presence of signal-dependent interference and channel noise. IEEE Transactions on Information Theory, 2000, 46 (2): 577–584
4. Garren D A, Osborn M K, Odom A C, Goldstein J S, Pillai S U, Guerci J R. Enhanced target detection and identification via optimised radar transmission pulse shape. IEE Proceedings — Radar, Sonar and Navigation, 2001, 148(3): 130–138
5. Guerci J R, Pillai S U. Adaptive transmission radar: the next 'wave'? In: Proceedings of the IEEE 2000 National Aerospace and Electronics Conference. Dayton, OH, USA: IEEE, 2000: 779–786
6. Leshem A, Naparstek O, Nehorai A. Information theoretic adaptive radar waveform design for multiple extended targets. IEEE Journal of Selected Topics in Signal Processing, 2007, 1(1): 42–55
7. Zhen Y M. Study on new motion compensation methods for SAR/ISAR imaging. Dissertation for the Doctoral Degree. Xi'an: Xidian University, 2000 (in Chinese)
8. Xing M D, Bao Z. A new method for the range alignment in ISAR imaging. Journal of Xidian University, 2000, 27(1): 93–96 (in Chinese)
9. Berger T. Rate Distortion Theory. Englewood Cliffs, NJ: Prentice-Hall, 1971