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Radar Phase-Modulated Waveform Design for Extended Target Detection*

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Abstract: Extended target detection performance can be enhanced by using phase-modulated waveform designs in band-limited radar systems. Unlike waveforms designed for the total energy constraint, phase-modulated waveforms can fully exploit the transmit power in the pulse duration, which is more suitable for practical radar systems. An alternating iterative algorithm was developed to optimize the phase-modulated baseband waveform by maximizing the signal-to-noise ratio (SNR) at the receiver filter output. The output SNR increases continuously with the number of iterations and the algorithm is guaranteed to converge. Simulations validate the effectiveness of this approach. The waveforms designed by this method outperform other commonly used waveforms for extended target detection.

Key words: cognitive radar; waveform design; phase-modulated waveform; extended target detection

Introduction

Cognitive radar is a recently proposed radar system concept, with one of the most important characteristics being the feedback structure from the receiver to the transmitter. Waveforms based on prior knowledge about the targets and environments can be adaptively optimized to improve system performance and efficiency[1]. Many adaptive waveform design techniques have been developed for extended target detection during the past decade. Bell[2] used a known target impulse response to design transmit-wave-form/receiver-filter pairs for the optimal detection of extended targets. Bell[2] maximized the output signal-to-noise ratio (SNR) to derive a transmit eigenwaveform solution for extended target detection. Pillai et al.[3] considered signal-dependent clutter in the transmit waveform and receiver filter designs for extended target detection. An iterative solution was used to maximize the output signal-to-interference-plus-noise ratio (SINR) because of the highly nonlinear nature of the problem. The solution for extended target detection has also been heuristically extended to the N-target identification problem[4-6]. All these results show the theoretical benefits of adaptive waveform design for extended target detection and recognition.

However, the arbitrary waveform assumption[2-6] is inappropriate for practical radar systems. Existing radar systems can only emit band-limited signals because of restrictions on the antenna structure and the linear amplifier[7]. Thus, methods using arbitrary waveforms are difficult to implement. Even if such waveforms could be transmitted, the frequency difference due to atmospheric attenuation and its uncertainty will make the optimization of little value[8]. The band limitation must be considered to exploit the waveform diversity in practical systems. In addition, the total energy constraints used in waveform design problems[2-6] is also not very useful. Since the constraint in most real radar

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systems is not on the total energy of the transmit waveform, but rather on the waveform power, the maximum waveform modulus constraint is more suitable for practical radar systems[9]. Phase-modulated waveforms are used here because they can fully exploit the transmit power in the pulse duration given the maximum modulus constraint. The assumption is also suitable for systems that can only transmit signals with a constant envelope.

With the band limitation and modulus constraint, the waveform design problem becomes nonlinear and nonconvex. Therefore, an alternating iterative algorithm was introduced to find the phase-modulated baseband waveform that maximizes the output SNR in band-limited radar systems. The waveform is optimized by sequentially updating each phase of the signal. This gives a higher SNR than for other common phase-modulated waveforms, which represents the target detection performance in a radar system using either Neyman-Pearson or Bayes decision rules[2].

1 Problem Statement and System Model

1.1 Targets

The system seeks to estimate target parameters such as distance and speed from the target echo signal. The time difference between echoes reflected from different points across the target is determined by the radial distance between these reflection points (which depends on the target aspect angle). The maximum time difference is given by $\tau_{\max}=2d/c$ where d is the range span of the target and c is the speed of light[10]. When the signal bandwidth is very narrow so that the inequality $B\tau_{\max} \ll 1$ holds, the different delays can be modeled as phase shifts, and the target can be treated as a single point[11]. For high resolution applications, modern radar systems transmit wideband signals, so the inequality $B\tau_{\max} \ll 1$ is no longer valid. A target with multiple reflection centers must then be considered, with the impulse response modeled as

$$h(t)=\sum_{i=1}^{K} h_i \delta(t-t_i) \tag{1}$$

where $0 \leqslant t_i \leqslant \tau_{\max}$ with t_i as the different delays of the reflection centers and h_i as the reflection coefficients[11]. In general the extended target impulse response $h(t)$ can be assumed to be any function defined between 0 and $\tau_{\max}$. The echo signal is then given by

$$y(t)=\int_0^{\tau_{\max}} h(\tau)x(t-\tau)\mathrm{d}\tau \tag{2}$$

where $x(t)$ is the transmit signal.

1.2 System model

Consider a band-limited radar system model as shown in Fig. 1.

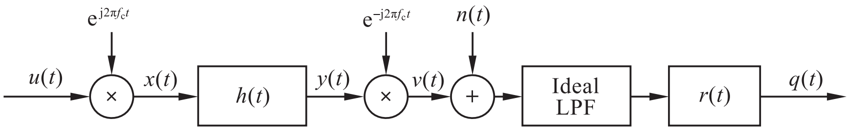

Fig. 1 Radar system model

A complex-valued finite duration baseband waveform $u(t)$, which is confined to the frequency interval $[-B/2, B/2]$, is modulated to the transmit frequency f_c and transmitted. Strictly speaking, the Fourier transform of a finite duration signal cannot be limited to a deterministic bandwidth. Assume that the band $[-B/2, B/2]$ is selected so that only negligible energy resides outside the frequency interval[2]. The echo signal $y(t)$ can be calculated from the transmit signal $x(t)$ and the extended target impulse response $h(t)$ using Eq. (2). Actually, the physical transmit signal is the real part of the complex-valued signal $x(t)$ and $y(t)$ is recovered from the real echo signal using the Hilbert transformation. The baseband echo signal $v(t)$ is filtered by an ideal linear time-invariant low-pass filter (LPF) to pass only frequencies in the band $[-B/2, B/2]$. The low-pass filter is just a statement of the fact that the baseband transmit signal $u(t)$ has no significant energy outside the frequency interval[2]. Then, $v(t)$ also does not, since it is the response of a linear time-invariant system to the transmit signal[2]. The power spectral density of the zero-mean additive Gaussian noise $n(t)$ is $P_{nn}(f)$, which represents the sum of the thermal noise in the multi-stage amplifier. The transmit waveform $u(t)$ and the receiver-filter $r(t)$ must be jointly optimized to maximize the SNR at the receiver output $q(t)$, where the SNR represents the target detection performance in the radar system.