Postprint of Interference Suppression Method Based on Frank Code

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Abstract

When interference enters from the radar' s mainlobe direction, employing adaptive beamforming algorithms leads to issues such as mainlobe beam distortion and pointing error. To address this mainlobe interference problem, an anti-jamming method based on transmit waveform design is proposed. By transmitting Frank-coded signals and exploiting the orthogonality property of Frank coding, a matched filter and a blocking filter are constructed. The received data is processed through both filters separately to obtain two signal channels, and adaptive cancellation is then utilized to suppress the interference, thereby achieving mainlobe interference suppression. Simulation results demonstrate that the waveform design approach can effectively suppress interference entering from the mainlobe.

Full Text

Preamble

Title: Anti-Interference Method Based on Frank Coding

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Abstract: When interference enters from the radar's main-lobe direction, adaptive beamforming algorithms can cause main-lobe beam distortion, offset, and other problems. To address this issue of main-lobe interference, this paper proposes an anti-jamming method based on transmitted waveform design. When transmitting signals encoded by Frank codes, the orthogonality of Frank coding is exploited to construct matched and blocking filters. The received data is passed through both filters to obtain two signal paths, and then adaptive cancellation is used to suppress the interference, thereby achieving main-lobe interference suppression. Simulation results verify that the waveform design approach can effectively suppress interference entering through the main-lobe.

Keywords: anti-mainlobe interference; phase encoding; matched filtering; blocking filtering

0 Introduction

Radar serves as the “eyes” of modern warfare, and its importance is self-evident. The performance of radar target detection in complex electromagnetic environments and radar survivability have become critical factors determining war outcomes. In combat, both adversaries engage in a series of jamming and anti-jamming measures to gain electromagnetic air superiority. Based on the angle at which interference enters the radar antenna, interference can be classified as main-lobe interference or sidelobe interference. For sidelobe interference, adaptive cancellation algorithms, ultra-low sidelobe antennas, and sidelobe blanking techniques can achieve good anti-jamming effects. However, when interference enters from the main-lobe direction, the target signal and interference signal cannot be distinguished in the spatial domain, and adaptive algorithms can cause main-lobe distortion, elevated sidelobe levels, and antenna pattern offset.

Main-lobe interference has become a primary factor threatening radar detection performance and survivability. Current anti-jamming techniques address this problem primarily in the time domain, spatial domain, frequency domain, polarization domain, and through multi-domain joint processing. R.Wu et al. studied a multi-linear constraint-based anti-mainlobe interference method that adds additional constraints during adaptive beamforming with main-lobe interference to maintain the main-lobe pattern while suppressing interference. However, this method cannot estimate the target’ s spatiotemporal parameters. Compton first proposed using polarization arrays for anti-jamming, and domestic researchers such as Wang Xuesong and Chao Shuyuan conducted in-depth studies on this method, providing theoretical performance analysis and evaluation metrics for polarization filters. However, because external interference and target signals are not ideally polarized, the signal after polarization filtering in auxiliary channels still contains partial target echoes, preventing effective interference suppression while also weakening the target signal. Zhou Qingsong et al. studied blind source separation-based anti-mainlobe interference methods, but after echo signals undergo blind source separation, the signal phase information is destroyed, creating difficulties for subsequent parameter estimation. Su Baowei, Wang Qiang et al. proposed blocking matrix preprocessing-based anti-mainlobe interference methods, but these require accurate knowledge of the main-lobe interference signal’ s direction of arrival (DOA). Estimating the interference signal requires algorithms like MUSIC, which have high computational complexity. Moreover, when interference and target signals arrive from the same angle, the constructed blocking matrix filters out both target signals and main-lobe interference, causing algorithm failure. Wang Qiang et al. studied a four-channel main-lobe interference suppression algorithm that constructs an additional difference beam compared to traditional monopulse angle measurement, forming a special sidelobe cancellation structure to suppress main-lobe interference. However, this system is relatively complex and can only cancel one main-lobe interference signal.

This paper proposes a blocking filter-based anti-mainlobe interference method for radar under main-lobe interference conditions. First, Frank coding matrices are used for phase encoding the transmitted signal. Due to the zero cross-correlation property of each row in Frank coding, this characteristic is exploited to design a blocking filter that removes the target signal, leaving only interference and noise in that path. Simultaneously, a matched filter is designed for the other signal path, which contains the target signal, interference, and noise. The signal processed by the blocking filter serves as the auxiliary channel, while the signal processed by the matched filter serves as the main array channel. Finally, adaptive beamforming is applied to form beams that suppress main-lobe interference. The algorithm concept is illustrated in [Figure 1: see original paper].

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1 Frank Coding and Signal Model

1.1 Frank Coding Introduction

Frank coding was jointly proposed by Heimiler and Frank. A Frank code of length m^2 can be composed of a Frank matrix:

$$\begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1m} \\ C_{21} & C_{22} & \cdots & C_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ C_{m1} & C_{m2} & \cdots & C_{mm} \end{bmatrix}$$

where the element in row p, column q is:

$$C_{pq} = \exp\left[j2\pi(p-1)(q-1)/m\right]$$

The Frank coding matrix is orthogonal, and its coding sequences are also orthogonal sequences. The rows of the Frank coding array have zero cross-correlation properties, meaning the cross-correlation function between row p and row q of the array is:

$$R_{pq}(k) = \sum_{n=1}^{m} C_{pn} C_{qn}^{*} = 0 \quad (p \neq q)$$

Based on this property of coding signals, a filter bank orthogonal to the transmitted Frank-coded signal can be designed to filter out the target signal from the received signal.

1.2 Signal Model

Using Frank coding for phase encoding of the transmitted signal yields the radar transmission signal. The specific encoding rules are shown in [Figure 2: see original paper]. Assume each pulse period is T_m and the pulse group period is T_R. Each pulse has width τ, which is uniformly divided into m sub-pulses. Row i of the Frank coding matrix is used to encode the i-th pulse, where the element in row i, column k corresponds to the k-th phase of the i-th sub-pulse.

Let the amplitude modulation function of the multi-phase coded signal be $A(t)$. The transmitted signal can be written as:

$$S_T(t) = A(t)\exp\left[j2\pi f_0 t + j\phi(t)\right]$$

where ϕ_{in} represents the phase coding of the n-th sub-pulse in the i-th pulse of a pulse group, m is the number of sub-pulses (identical to the dimension of the Frank coding matrix), f_0 is the carrier frequency, τ_{sub} is the sub-pulse width, and $\mathrm{rect}(t/\tau_{sub})$ is a rectangular pulse of width τ_{sub}.

Assume a target at distance R_0 moving radially toward the radar with velocity v_i. The echo signal of the i-th coded pulse is:

$$S_{echo}(t) = A(t-\tau)\exp\left[j2\pi f_0(t-\tau) + j\psi(t-\tau) + j\phi(t-\tau)\right]$$

where $\tau = 2R_0/c + 2v_i t/c$ is the time delay.

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2 Main-Lobe Interference Suppression Signal Processing Modules

The signal processing flow of the blocking matrix anti-mainlobe interference suppression system is shown in [Figure 3: see original paper]. The system consists of three main modules: matched filtering processing module, blocking filtering processing module, and adaptive cancellation processing module.

2.1 Matched Filtering Processing Module

The purpose of the matched filtering processing module is to maximize the output signal-to-noise ratio. The output signal contains the target signal, interference, and noise. The impulse response function of the matched filter is related to the transmitted signal $S_T(t)$ and can be expressed as:

$$h(t) = kS_T^*(t_0 - t)$$

where t_0 is the pulse accumulation time.

2.2 Blocking Filtering Processing Module

The blocking filtering processing module aims to filter out the target signal from the echo signal to obtain data containing only interference and noise. The blocking filter utilizes the zero-correlation property between rows of the Frank coding matrix. Any row of sub-codes in the coding matrix is orthogonal to other sub-codes. Therefore, any sub-code row other than itself can serve as the impulse response for that sub-code' s blocking filter. Consequently, the impulse response function of the blocking filter is uncorrelated with that of the matched filter and can be expressed as:

$$h_b(t) = k' S_T'^*(t_0 - t)$$

where t_0 is the pulse accumulation time and $S_T'(t)$ is a signal orthogonal to the transmitted signal $S_T(t)$. The encoding rule is shown in [Figure 4: see original paper].

When the received data passes through the blocking filter, and the data from each sub-code after blocking filtering is aligned and accumulated in time, the target signal in the filtered echo information is suppressed, leaving only external interference and noise.

2.3 Adaptive Sidelobe Cancellation Algorithm

Assume the signals received by N array antennas $x_n(k)$ $(n = 1, 2, \dots, N)$ serve as the main channel for signal processing. To avoid increasing system hardware complexity, all signals received by the antenna array are used as the auxiliary channel for signal processing, denoted as $y(k)$. The data after main channel matched filtering is denoted as $X(k)$, and the data after auxiliary channel blocking filtering is denoted as $Y(k)$. The main channel after matched filtering processing is $X(k) = [x_1(k), x_2(k), \dots, x_N(k)]^T$, where k is the number of sampling points. According to the minimum mean square error criterion, the optimal weight vector is:

$$\mathbf{w}_{opt} = \mathbf{R}_{XX}^{-1}\mathbf{r}_{XY}$$

where $\mathbf{R}_{XX} = E[\mathbf{X}\mathbf{X}^H]$ and $\mathbf{r}_{XY} = E[\mathbf{X}Y^*]$.

3 Simulation Experiments

Assume an ideal uniform linear array with $N = 16$ elements and element spacing $d = \lambda/2$. Assume one desired signal and two jamming signals entering from the main-lobe direction exist in space. The expected signal has an azimuth angle of 0°. Assume the target is 225 km from the radar. The radar transmitted signal is a rectangular pulse signal modulated by Frank coding with carrier frequency $f_0 = 2000$ MHz. The Frank coding matrix is 8×8. Jamming signal 1 has carrier frequency $f_{J1} = 2000$ MHz (same frequency as the transmitted signal), and jamming signal 2 has carrier frequency $f_{J2} = 2200$ MHz. Both jamming signals are at 0° angle. The noise in each channel is Gaussian white noise. To reduce the sidelobe level during pulse compression, a Chebyshev window is applied to suppress sidelobe levels.

[Figure 5: see original paper] shows the range-Doppler frequency map obtained from received data after matched filtering. The target signal is covered by jamming signals. On the same channel across 100 Doppler frequency range gates, false target signals are generated in the range dimension, adversely affecting radar target detection. [Figure 6: see original paper] shows the range-Doppler frequency map obtained from the received signal after processing by the constructed blocking filter. Compared with the matched filter, the target signal is suppressed after blocking filter processing, and the resulting signal contains only interference and noise.

[Figure 7: see original paper] shows the range-Doppler frequency map after beamforming following matched filtering. [Figure 8: see original paper] shows the range-Doppler frequency map after cancellation processing, demonstrating that the cancellation processing can effectively suppress interference entering from the main-lobe.

[Figure 9: see original paper] shows the Doppler frequency slice at the target' s range cell. After cancellation processing, both same-frequency and different-frequency interference entering from the main-lobe are effectively suppressed, while the target signal energy remains essentially unchanged. [Figure 10: see original paper] shows the range slice at the target' s Doppler frequency cell. Before cancellation processing, the jamming signal exceeds 30 dB, completely overwhelming the target signal. After cancellation processing, the target signal power reaches 20 dB while the interference signal is about 5 dB, allowing clear identification of the target' s range gate.

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4 Conclusion

By phase-encoding the transmitted signal using Frank coding matrices and exploiting the orthogonality of Frank coding to construct matched and blocking filters, the matched filter output contains target, interference, and noise, serving as the main channel for signal processing. The signal processed by the blocking filter contains only interference and noise, serving as the auxiliary channel. Finally, adaptive cancellation is used to cancel interference and noise from the auxiliary channel. Simulation results verify that the proposed algorithm can suppress both same-frequency and different-frequency interference entering from the main-lobe direction. Compared with other methods, the proposed algorithm offers advantages such as no need for additional hardware and low computational complexity, providing a new approach for anti-mainlobe interference.

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