Research on Adaptive Waveform Optimization Design of Anti-jamming Radar

Zhixiang Zhao, Jiali Yuan, Minxing Li

Department of Computer and Communication Engineering, Northeastern University at Qinhuangdao, Qinhuangdao, Hebei, 066004

Abstract. With the rapid development of science and technology, the development of radar in China has entered a new stage, but the signal interference problem is still a bottleneck restricting the accuracy of radar detection. Based on this, this paper conducts waveform optimization design research on radar anti-interference and improved detection accuracy. Firstly, the radar is outlined, then six commonly used radar anti-jamming technologies are introduced. Then the characteristics of modern radar anti-jamming technology are analyzed. Finally, the radar waveform is optimized. Through the waveform design adaptive mechanism and simulation, we find that as the number of adaptive iterations increases, the detection probability of interest targets is increasing.

1. Introduction
Based on the relative relationship between radar bandwidth and target physical size, the target model of radar detection includes point target and extended target [1]. The number of targets that radar detects is also likely to contain multiple [2]. Thanks to the development of advanced hardware technologies such as digital arbitrary waveform generators, solid-state transmitters and high-speed signal processing hardware, real-time adaptive design waveforms and received signal processing have been realized, which has greatly promoted the intelligent development of radar [3]. At present, in the complex radar environment, in addition to the target information, the ultra-wideband radar echo has a lot of clutter and interference. Due to the attenuation of various obstacles, the echo signal of the target is usually weak and easily submerged in background clutter and noise. If effective clutter suppression is not performed, it will cause great trouble to target detection [4].

2. Radar Introduction
Radar is an abbreviation for Radio Detection And Ranging. In general, radar systems use modulated waveforms and direction lines to emit electromagnetic energy into a large area of space to search for targets. Targets in the contraction domain reflect some of the energy (radar reflections or echoes) back to the radar, which are then processed by the radar receiver to extract information about the target, such as distance, velocity, angular position, and other target recognition characteristics [5].

The general radar consists of five components: transmitter, transmitting antenna, receiver, receiving antenna and display, as well as auxiliary equipment such as power supply equipment, data acquisition equipment, anti-jamming equipment [6]. The transmitter provides a radar-modulated power RF signal for the radar, which is radiated by the antenna via the feeder and the transceiver switch. The receiver selects the weak high-frequency signal received on the antenna by appropriate filtering from the
background of noise and interference. The radar terminal display uses the target information and intelligence obtained by the display radar, and the displayed content includes the position of the target and its motion, various characteristic parameters of the target, and the like. The basic working principle of the radar is that the radar transmitter generates enough electromagnetic energy to radiate into the atmosphere through the antenna, concentrate in a narrow direction to form a beam, and propagate forward. After the electromagnetic wave encounters the target in the beam, it will generate reflection along all directions. A part of the electromagnetic energy is emitted back to the direction of the radar, and is acquired by the radar antenna and sent to the receiver to form an echo signal of the radar. Since the electromagnetic wave will attenuate with the propagation distance during the propagation process, the radar echo signal is very weak and is almost submerged by the noise. The receiver is placed in a weak echo signal, processed by the signal processor, and extracts the information contained in the echo, and sends it to the display to determine the distance, direction, speed, etc. of the target.

![Radar system schematic](image)

**Figure 1** Radar system schematic

3. Radar Anti-Jamming Technology

Radar anti-interference technology is a measure to ensure the effective use of the electromagnetic spectrum to deal with electronic interference [7]. Radar anti-jamming is a resource struggle in the electronics field. Any radar can interfere, and any interference can be prevented. This depends mainly on the technical resources of the people who are hostile to both sides. The purpose of radar anti-jamming is to reduce the various interference signals that affect the normal operation of the radar to a tolerable level, and to ensure the normal operation of the radar.

In view of the new characteristics of radar anti-jamming technology, the future development of radar anti-jamming technology mainly has the following directions.

3.1. Phased Array Technology

Phased array antenna is the most attractive form of antenna in electronic scanning antenna. This kind of antenna changes the phase distribution on the aperture surface of the antenna through electronic control instructions to achieve beam steering or beamforming control [8]. The outstanding advantages of phased array antennas compared to other antennas are:

1) The antenna aperture remains fixed in space, so no heavy mechanical rotating device and rotating space are needed, thereby greatly improving the stability of the antenna beam, and the antenna is small in size and light in weight;

2) With electronic scanning technology, the antenna beam control is flexible, and the beam can instantaneously point to any position in the designated area or sweep the large space in a very short time, thereby greatly saving the scan search time which is susceptible to interference;

3) The scanning process has no inertia and the reaction time is short, so more data can be obtained on the target track, which can adapt to the dense signal environment;
4) Flexible and fast beam pointing, which can simultaneously search and track multiple targets with the same antenna aperture in a specified space;
5) A high power amplifier can be used because of multiple array elements or subarrays consisting of array elements. Therefore, the entire antenna array can provide a large effective radiation power, which can effectively reduce the signal-to-noise ratio and weaken the influence of interference;
6) A large number of array elements in the phased array antenna can control the aperture illumination to obtain a more ideal radiation pattern. If some of the array elements fail, although the antenna array performance is degraded, it can still perform reliable work.

3.2. Multi-Beam Technology
Such a multi-beam system utilizes a multi-beam network (such as a Butler matrix network) or a multi-beam lens (such as a Rotman lens) to form a plurality of independent mutually adjacent high-gain beams in space [9].
The advantages of multi-beam antennas are: each beam has the full gain of the antenna array aperture; it can cover a wide range of sectors and frequencies; it can scan spatially without interruption with high angular resolution; When an independent low-power microwave amplifier is added, the array can generate huge effective radiated power, so that the most effective anti-interference power can be used to deal with the interference threat.

3.3. Millimeter Wave Countermeasure Technology
The millimeter band usually refers to a radio band having a wavelength of 1 to 10 mm (the corresponding frequency is 30 to 300 GHz), and the lower limit is adjacent to the centimeter wave, and the upper limit is adjacent to the light wave. Because millimeter wave has the advantages of narrow beam, low side lobes, high directionality, wide frequency band and strong anti-interference ability, especially frequency agility, pulse compression, frequency diversity technology, etc., so they are widely used in millimeter wave radar, so that millimeter wave radar has a stronger anti-interference ability.

3.4. Low Intercept Probability Technique
By using coding spread spectrum and reducing peak power, the radar signal is designed as a low intercept probability signal, making it difficult for the reconnaissance receiver to detect and even detect such signals, thus protecting the radar from electronic interference.

3.5. Sparse Array Integrated Pulse Aperture Technology
This is a new system radar technology that uses a large aperture sparse array, wide pulse transmission, and digital technology to form narrow pulses and antenna array beams in the meter band. It has the advantages of wide frequency band, high working frequency and low probability of interception. It is a new radar system with strong anti-interference ability.

3.6. Passive Detection Technology
This is a detection technique that does not transmit a signal by itself and transmits a signal by a receiving target to find a target. Therefore, it will not be scouted or interfered.

4. New Features Of Modern Radar Anti-Jamming Technology
With the rapid development of military high technology, the core supporting role of electronic technology in military weapons and equipment has become more and more obvious, and the new radar system has been rapidly emerging and widely used to adapt to the fierce confrontation of military electronics and high technology [10]. Under the general situation of increasing radar confrontation and increasing intensity, modern radar anti-interference should have the following characteristics:
1) The radar antenna should have high gain, low sidelobe, narrow beam, low cross-polarization response, sidelobe cancellation, sidelobe blanking, electronic scanning phased array, single pulse angle measurement technology;

2) The transceiver system design shall have high effective radiated power, pulse compression waveform, wideband frequency hopping, wide dynamic range, image rejection, channel matching of single pulse/auxiliary receiving system;

3) In the frequency domain, the radar system should occupy more and wider electromagnetic spectrum to deal with the threat of radar countermeasure systems that have expanded the frequency band. In terms of energy, the advantage of the energy concentration of the radar in the airspace, time domain and frequency domain must be exerted as much as possible to weaken the limited radiated power of the electronic interference;

4) The radar system must use the computer as the core to carry out fast digital information processing, control and transmission, so as to improve the system's high-speed information processing capability, response speed, tracking accuracy and adaptability to the electromagnetic environment, and improve the recognition ability of small echoes of target echoes. At the same time, multi-target, multi-unit tracking, clutter suppression, in order to adapt to the dense electromagnetic signal environment;

5) The radar system should have power management capability to quickly detect, intercept, sort and identify threat signals in a dense signal environment, automatically select the best anti-interference pattern according to the threat level to obtain the best detection effect, and can always interfere with the interference point positioning;

6) The radar system should have comprehensive multi-functional capabilities, that is, it can cope with positive interference, and can identify negative interference in time. It is necessary to comprehensively utilize radar technology resources and improve all-round anti-interference ability;

7) The radar system should have omnidirectional, full-band, high-power, multi-function and multi-beam capability to cope with multiple targets;

8) The radar system needs to be highly integrated, so that the system can be quickly converted into different functions and different performance devices according to different mission requirements to adapt to the ever-changing threats. At the same time, the use of modular hardware and software to achieve on-site replacement to reduce electronics effect of interference signals;

9) Radar systems should be developed in the direction of solid-state and integration, using microwave integrated circuits, ultra-large-scale and ultra-high-speed circuits, fault-tolerant circuits, redundant devices, and in-machine test circuits that can perform self-tests on faults to improve radar anti-jamming technical reliability and equipment survivability.

5. Waveform Adaptive Optimization Based On Information Theory
In order to improve the detection ability of interest targets and strengthen the suppression effect on clutter targets, this paper proposes an adaptive waveform optimization design method based on information theory from the perspective of waveform design. The method is mainly divided into two steps: waveform optimization and waveform power optimization.

5.1. Radar Signal Waveform Design Considerations
The radar transmitting signal not only determines the signal processing method, but also directly affects the main tactical indicators such as the power, accuracy, resolution and anti-interference performance of the system. Therefore, radar signal design has become a comprehensive consideration of radar systems, and is an important part of radar design. The radar signal design is to select the appropriate signal according to the target environmental conditions given by the tactical requirements, set the radar signal type and related parameters to meet the radar tactical performance and realize the radar functions. In general, the radar signal waveform should be able to meet the following requirements at the same time:

(1) Have sufficient energy to ensure that the target is found and the target parameters are accurately measured;
(2) It has a certain time width and bandwidth to meet the accuracy of ranging and speed measurement;
(3) Has sufficient target resolution;
(4) Good suppression ability for unwanted clutter;
(5) Has low interception characteristics, improves anti-reconnaissance ability, and thus improves anti-electronic countermeasure capability.

5.2. Waveform Optimization Guidelines
Optimization criteria for improving radar signal resolution, measurement accuracy, clutter suppression, and immunity to electrical interference are:
1) Minimize the weighted integrated sidelobe level (WISL) or weighted peak sidelobe level (WPSL) criteria: the smaller the WISL or WPSL, the smaller the sidelobe energy returned by the strong target (clutter), the larger the criterion is to control the shape of the waveform blur function or the MIM radar emission pattern, reduce the mutual interference between multiple targets, and improve the multi-target detection performance;
2) Minimize template matching error criterion: It is mostly used for pattern matching, fuzzy function, and waveform spectrum template matching. The smaller the matching error, the better the fitting effect and the stronger the anti-interference ability.

Waveform constraints mainly include the following four types:
1) Energy Constraint: Constrains the transmitted waveform energy in a certain interval, usually determined by the radar system transmitter or the radar's maximum detection distance;
2) Constant modulus constraint or peak-to-average power ratio (par) constraint: limits the dynamic range of the waveform amplitude, designed to operate the radar nonlinear amplifier in the maximum efficiency state (saturated or near-saturated state) to avoid nonlinear distortion of the output waveform;
3) Similarity constraints: Constraint design waveforms are similar to a reference waveform to obtain certain characteristics of the reference waveform;
4) Spectral Constraints: Constrain the energy transmitted by certain frequency bands in a radar waveform to ensure that the radar coexists with the spectrum of certain electronic systems.

It should be pointed out that in some cognitive radar waveform optimization problems, the above optimization criterion function can be modeled as a constraint, and some constraints can also be included in the optimization criterion.

5.3. Waveform Optimization
Based on the target prior information, the beamforming technique is used to weight the echoes from the interest target and the clutter target. According to the information theory, any two vectors satisfy statistical independence, and their mutual information values are minimized. If the two vectors represent the echo signals from the interest target and the clutter target, respectively, the amount of information acquired by the radar from the interest target and the clutter target is larger when the mutual information value is the smallest.

5.4. Waveform Power Optimization Assignment
According to the optimization criteria, the most suitable transmission waveforms for the current environment can be selected in the waveform set to obtain the most interest target and clutter target information. Next, in view of the rich frequency domain characteristics of UWB signals, this paper considers the frequency domain energy optimization allocation method to further improve the suppression effect on clutter. According to the information theory, the interaction information between the echo signal of the interest target and the reception beam can be obtained, whereby the total mutual information value between the interest target and the reception beam can be obtained. Of course, different targets have different cost functions, and the designed waveform is unlikely to meet the needs of all targets. In order to solve this problem, this paper considers multiple sets of waveform joint
design methods, the number of groups depends on the number of interest targets existing in the channel.

According to Bell’s water injection theory design principle, when the echo target echo response amplitude is large and the detection target echo response amplitude is small, the signal power in the frequency is reduced; and when the clutter target echo response amplitude is small, the detection is small. When the target echo response amplitude is large, it is necessary to strengthen the signal power within the frequency. Of course, the method of optimizing the power distribution is different for different interest targets. A corresponding adaptive optimized transmit waveform can be generated according to the number of interest targets.

5.5. Waveform Design Adaptive Mechanism

According to the above, the adaptive waveform design of this paper is a waveform optimization method based on the optimization detection. The process is as follows:

1) Generating transmit waveforms with good correlation characteristics, setting these waveforms into a set R;
2) Estimated based on the measurement of the continuous time of the received signal $R_{Qr}$, $R_{Ql}$, $R_{N}$;
3) According to the estimated value, the emission waveform most suitable for the current environment $S_{t+1}$ in the signal set R is selected;
4) Adjusting the transmitted signal $S_{t+1}$ according to the difference in the magnitude of the frequency domain echo response of each target at time t obtained. The power spectral density achieves the purpose of suppressing the clutter target and improving the probability of detecting the target of interest;
5) Optimized signal $S'_{t+1}$ as the transmitted signal at time t+1, the received signal and the target and environmental parameters are subsequently updated.
6) Repeat steps 2)~5).

6. Signal Power Optimization Distribution Simulation

The feasibility and advancement of the above adaptive waveform optimization design method are verified by simulation experiments. First, a radar model with 8 rounds was established. Eight transmitting antennas were distributed arrays, and eight receiving antennas were concentrated and linear arrays. The transmit signal has a bandwidth of 500 MHz and a sampling frequency of 2.4 GHz. For the convenience of analysis, it is assumed that there are only two targets in the detection environment, and the interest target and the clutter target are respectively located at the 35° and 45° directions of the receiving element. The echo signals of the two targets can be separated at the receiving end by beamforming techniques.

In the waveform design phase, the transmit waveform is first optimized by minimizing the mutual information criterion. As shown in Figure 2, the amount of information decreases as the number of iterations increases, and the amount of information under different signal-to-noise ratios is also different. The larger the signal-to-noise ratio, the smaller the amount of information and the faster the rate of reduction. This is because as the signal to noise ratio increases, the estimation accuracy $R_{Qr}$ versus $R_{Ql}$ is also gradually increasing, resulting in a decrease in mutual information. The signal energy spectral density is then optimized based on the difference in the target frequency domain response amplitude. Setting the target fluctuations to satisfy the Gaussian model and the lengths are 30 m and 20 m, respectively. Assuming that the interest target is large and the clutter target is small. As shown in Figure 3 (a), the smaller target time domain response is lower in the middle and the higher in the middle. The target frequency domain response is completely opposite. As shown in Figure 3 (b), the larger target shows a narrower frequency domain response, that is, the amplitude of the large target
in the low frequency band is greater than the amplitude of the small target, the high frequency band is the opposite. The transmitted signal energy is not concentrated in the place where the clutter power is the smallest, but in the place where the power difference between the interest target and the clutter target is the largest.

![Figure 2](image)

**Figure 2** Mutual information minimization process under different SNR

![Figure 3](image)

**Figure 3** Time domain and frequency domain response of different targets

The analysis shows that as the number of adaptive iterations increases, the probability of detecting interest targets is increasing. And as the number of iterations increases, the increase in detection probability is also gradually reduced, and the corresponding value tends to a limit. By comparison, we find that the detection probability of using this method is significantly higher than the detection probability of not using this method.

**7. Conclusion**

With the rapid development of new generation information technology, radar has more and more application prospects. In addition to traditional meteorological, navigation, remote sensing, surveying and mapping, radar is gradually coming to the ordinary consumers, phased array technology, millimeter wave technology is applied in 5g communication equipment and vehicle radar. At present, we are in the historical intersection of the world's scientific and technological revolution and military revolution, collaborative detection, integration, quantum, microwave photon, terahertz, micro-system, fine processing, etc. Emerging technologies have become a research hotspot in the radar industry at home and abroad. Which technologies can become the subversive technology of the next-generation radar, and which technologies are fogs and traps, it requires us to think deeply and continue to study.
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