Research on cognitive signal waveform technology based on artificial intelligence algorithm

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Abstract: With the continuous development of communication measurement and control technology, the communication environment is increasingly complex and changeable, and the traditional communication technology has been unable to meet people's communication needs. The proposal of cognitive dynamic system (CDS) provides a new direction for the development of wireless communication technology. At present, the two main application directions of cognitive system are cognitive radio (CR) and cognitive radar (CR)[1][2]. Considering the innovative combination of cognitive system and TT&C communication scene, this paper studies the cognitive transmission performance under various environmental noises based on chirp signal, and uses BP neural network to optimize the system performance. The simulation results show that the adaptive waveform technology can improve the anti-jamming ability, and the BP algorithm has good prediction effect and reduces the computational complexity of the system.

1. Introduction
In recent years, the measurement and control communication technology develops rapidly, but the traditional communication technology can not match the changes of the current environment in real time, clutter and noise interference will reduce the anti-jamming performance of the system[3].

After Simon Haykin first proposed the concept of cognitive radar[4], scholars at home and abroad have carried out research on cognitive system. Guerci et al. Proposed the concept of complete adaptation, defined cognitive characteristics as perception, learning and adaptation[5][6]. Based on the particle filter algorithm, Sira SP et al studied the adaptive waveforms of narrow-band radar, broadband environment and dense sea clutter environment[7][8][9]. In reference[10], MIMO radar technology is proposed, which uses space time adaptive processing (STAP) method to suppress clutter and jamming signals.

At present, cognitive technology is rarely used in TT&C communication system. In addition, the adaptive system will waste a lot of computing resources. Therefore, this paper constructs an adaptive system based on a variety of noise environments in TT&C communication system. At the same time, the system is optimized based on BP (Back Propagation) neural network algorithm. The simulation results show that the adaptive algorithm has good communication error performance, and the BP algorithm effectively reduces the computational complexity, and has good prediction effect.

2. System Model
Cognitive dynamic system is a kind of dynamic intelligent system with human brain cognitive ability. It includes perception action cycle, memory, attention and intelligence[11]. It will gradually form the cognition of the environment, reflecting the dynamic processing ability of information. The basic structure of cognitive dynamic system is shown in Figure 1.
2.1. Linear frequency modulation

Linear frequency modulation (LFM) is a signal whose instantaneous frequency changes linearly with time. It keeps the characteristics of continuous signal and pulse at the same time. LFM signal is also known as chirp signal. The mathematical expression of LFM signal is as follows:

\[
s(t) = A \cdot \text{rect}\left(\frac{t}{T}\right) \cdot \exp\left[j \left(2\pi f_c t + \frac{Kt^2}{2}\right)\right]
\]

Where \(A\) is the signal amplitude, \(f_c\) is the signal carrier frequency, \(t\) is the time, \(T\) is the pulse width, \(K\) is the frequency modulation slope, \(\varphi(t) = 2\pi f_c t + \frac{Kt^2}{2}\) is the signal phase.

Another expression of LFM signal transmitting waveform is as follows:

\[
s_T(t) = \sqrt{2} \text{Re}\left[\sqrt{E_T} \tilde{s}(t) \exp(j2\pi f_c t)\right]
\]

Among them, \(E_T\) is the energy of the transmitted signal waveform, \(\tilde{s}(t)\) is the complex envelope of the normalized signal, and \(\text{Re}(\cdot)\) is the real part of the signal.

2.2. Influence of transmitting waveform on SNR

In the process of cognitive transmission, the echo signal needs to be processed by the receiver filter. Under the background of clutter and noise, the signal expression after filtering is as follows:

\[
y_R(t) = h_R(t) * [s(t) * h(t) + s(t) * h_c(t) + n(t)]
\]

Where, \(h_R(t)\) is the impulse response of the receiver, \(s(t)\) is the transmitted signal, \(h(t)\) is the target impulse response, \(h_c(t)\) is the impulse response of clutter interference, and \(n(t)\) is interference signal. \(y_s(t)\) represents the signal part after matched filtering, and \(y_n(t)\) represents the noise part after matched filtering. Then the \(SINR\) at \(t_0\) can be expressed as:

\[
SINR_{t_0} = \frac{|\tilde{s}(t_0)|^2}{E[|y_n(t_0)|^2]} = \frac{\int_{-\infty}^{\infty} |H_R(f)S(f)H(f)\exp(j2\pi f_0 t)df|^2}{\int_{-\infty}^{\infty} |H_R(f)|^2 |S(f)|^2 T(f)df}
\]

\[
|T(f)|^2 = P_c(f)|S(f)|^2 + P_n(f)
\]

It can be seen from formula (4) that the \(SINR\) of cognitive transmission system is related to the transmitted signal waveform.

3. Problem Formulation

3.1. Ambiguity function

Ambiguity function (AF) refers to the resolution characteristics of two targets when their velocity and distance are different. The ambiguity function formula is defined as the square of the output signal amplitude after matched filtering:

\[
A_f(\tau, f_d) = \frac{1}{(\int_{-\infty}^{\infty} |\tilde{s}(t)|^2 dt)^2} \left| \int_{-\infty}^{\infty} \tilde{s}(t)\tilde{s}^*(t - \tau) \exp(-j2\pi f_d t) dt \right|^2
\]
In formula (6), $\tau$ is the time delay, $f_d$ is the Doppler shift. It can be seen from equation (6) that the ambiguity function of LFM signal is a two-dimensional correlation function of distance and velocity. Therefore, the communication performance of cognitive transmission can be improved by adjusting the LFM slope, pulse width and other related parameters.

### 3.2. Adaptive optimization strategy of waveform parameters

Cognitive technology can change the waveform parameters, and improve the anti-interference ability of the system. Cramer Rao lower bound (CRLB) is an important basis for error measurement and estimation of target signal delay and Doppler frequency shift, and can calculate the best estimation accuracy of unbiased estimation. The expression of Fisher information matrix is as follows [12]:

$$J = \frac{2E_s}{N_0} \left[ \frac{f^2 - (\bar{f})^2}{f \cdot \bar{t} - \bar{f} \cdot \bar{t}} - \frac{f^2 - (\bar{f})^2}{f \cdot t - \bar{f} \cdot \bar{t}} - \frac{f^2 - (\bar{f})^2}{f \cdot t - \bar{f} \cdot \bar{t}} \right]$$

(7)

Where $2E_s/N_0$ is the signal-to-noise ratio, $E_s$ is the signal power, $N_0$ is the power spectral density of the complex noise envelope, $f$ is the signal frequency, and $t$ is the signal time.

Each element of the Fisher information matrix is the second-order partial derivative of the ambiguity function of the signal $s(t)$ with respect to the two-dimensional plane origin position of the time delay $\tau$ and Doppler frequency shift $f_d$ [13]. Therefore, Fisher information matrix can be expressed as:

$$J = \frac{2E_s}{N_0} \begin{bmatrix} \frac{\partial^2 A_f(\tau, f_d)}{\partial \tau^2} |_{\tau=0, f_d=0} & -\frac{\partial^2 A_f(\tau, f_d)}{\partial \tau \partial f_d} |_{\tau=0, f_d=0} \\ -\frac{\partial^2 A_f(\tau, f_d)}{\partial \tau \partial f_d} |_{\tau=0, f_d=0} & \frac{\partial^2 A_f(\tau, f_d)}{\partial f_d^2} |_{\tau=0, f_d=0} \end{bmatrix}$$

(8)

TT & C system it needs to obtain the range and velocity of the target signal, the measurement noise covariance formula of distance velocity dimension can be expressed as:

$$R_{\tau R} = M J^{-1} M^T$$

(9)

$$M = \text{diag} \left( \frac{c}{T}, \frac{c}{2f_c} \right)$$

(10)

Based on the above theory, it is assumed that the signal of cognitive transmission system is Gaussian envelope LFM signal, the signal expression is as follows:

$$s(t) = \frac{1}{\sqrt{T \pi}} \exp \left[ -\left( \frac{1}{2T^2} - jK \right) t^2 \right]$$

(11)

$T$ is the pulse duration of the signal and $K$ is the frequency modulation slope of the signal, which together constitute the parameter vector $\theta = [T, K]^T$ of the LFM signal in cognitive transmission system. The measurement noise covariance matrix of LFM transmitting waveform signal is as follows:

$$R_{T-K}(\theta) = \begin{bmatrix} \frac{c^2 T^2}{2SNR} & \frac{c^2 K T^2}{2 \pi f_c SNR} \\ \frac{c^2 K T^2}{2 \pi f_c SNR} & \frac{c^2}{(2\pi f_c)^2 SNR} \left( \frac{1}{2T^2} + 2K^2 T^2 \right) \end{bmatrix}$$

(12)

In formula (12), the measurement noise covariance matrix $R_{T-K}(\theta)$ of LFM transmitting signal is related to signal-to-noise ratio $SNR$, pulse width $T$, frequency modulation slope $K$ and signal carrier frequency $f_c$. In the process of cognitive signal transmission, the carrier frequency $f_c$ is constant.

### 3.3. Cognitive waveform technology based on BP neural network

Back Propagation Neural Network is a multi-layer feedforward neural network trained according to the error back propagation algorithm. BP algorithm takes the square of the network error as the objective function and uses the gradient descent method to calculate the minimum value of the objective function. BP network has input layer, hidden layer and output layer. The basic unit of neural network is neuron. The structure of BP neural network is shown in Figure 2.
4. Simulation Results

The adaptive waveform technology of cognitive dynamic system is applied to TT&C communication scene. This paper studies the influence of chirp signal waveform parameters and environment parameters on BER performance in Gaussian white noise environment. The simulation results are as follows:

As shown in Figure 3, with the increase of SNR, the BER $P_e$ becomes smaller and smaller; when SNR is constant, the BER of chirp signal is slightly higher than 2FSK. The communication environment is extended to complex environment. The simulation results are as follows:
In Figure 4, it can be seen that when the $SNR$ is constant, the BER performance is the best in Gaussian noise environment; when the $SNR$ is small, the BER performance is the worst in Weibull noise environment; when the $SNR$ is large, the BER performance is the worst in tone noise environment; the influence of $SNR$ on tone noise environment is less than the other three noise environments.

The adaptive waveform system is used to obtain the training sample data set, and the BP adaptive waveform parameter learning network is constructed by training and learning data rules. Among them, $SNR$ is used as the input of neural network, and BER $P_e$ is used as the prediction output. BP neural network is used to build BER prediction network through training and learning, and the BER curve under different $SNR$ is studied. The simulation results are as follows:

Figure 5. The curve of BER prediction value of BP network changing with $SNR$

As shown in Figure 5, when the pulse width $t$ is constant, with the increase of $SNR$, the BER $P_e$ becomes smaller and smaller. BP neural network has a good prediction effect on the bit error rate of chirp signal, and the prediction curve of BP neural network is closer to the theoretical bit error rate curve.

The pulse width $T$ of chirp signal is used as the input of neural network, and the bit error rate $P_e$ is used as the prediction output. The BP neural network is used to construct the bit error rate prediction network through training and learning, and the bit error rate curve under different pulse width $t$ is studied. The simulation results are as follows:

Figure 6. The curve of BER prediction value of BP network changing with $T$
As shown in Figure 6, when SNR is constant, with the increase of pulse width T, the BER $P_e$ is smaller and smaller. BP neural network has a good prediction effect on the BER of chirp signal, and the prediction curve of BP neural network is more smooth.

5. Conclusion

This paper studies the cognitive waveform optimization of communication measurement and control system. Considering the computational complexity and cost of adaptive waveform system, this paper proposes a cognitive signal waveform technology based on BP neural network algorithm, and studies the BER performance under various environmental noise background. The simulation results show that the adaptive waveform technology based on BP neural network algorithm can effectively reduce the computational complexity of the system, and the predicted value is closer to the real theoretical value.

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