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Research on detection performance of passive detection system based on troposcatter

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ABSTRACT

Electromagnetic (EM) wave propagated via troposcatter is a valuable candidate for beyond line-of-sight (b-LoS) detection. In this paper, the probability of detection is firstly analyzed. Aiming at acquiring signal-to-noise ratio (SNR), we present two approaches including statistical model and time-varying model. Hopfield model is employed to establish the relationship between SNR and time-varying meteorological parameters. Simulations demonstrate the availability of above models. Finally, a cognitive system is introduced to improve the performance of passive detection system. The uncontrollable factors including meteorological parameters, elevation angle and frequency of EM wave are firstly studied, and then the controllable parameters will be regulated on the basis of conclusions deduced in this paper.

1. Introduction

Detecting enemy early-warning radar plays an important role in the modern warfare. Because geography and curvature of the earth may impede electromagnetic (EM) wave propagation, satellite system can be employed for beyond line-of-sight (b-LoS) detection. However, satellite link has security problems and may be exposed to hostile jamming. Image recognition technology generally used in the satellite system is relatively powerless to detect radars in disguise or located in blind areas [1,2]. EM wave of hostile radar propagated via troposcatter can be utilized for b-LoS detection [3–6]. This passive mechanism can also make hostile anti-radiation missile unavailing to attack the detection system.

Nowadays, passive detection system based on troposcatter has already been well studied. Professor Wang and his group improve the traditional Multiple Signal Classification (MUSIC) algorithm to process the troposcatter signal [3,4]. And they also investigate the fading correlation for troposcatter link under an uncooperative circumstance [5]. In [6], a computational method for the rotational loss in the passive detection system is proposed. The unique characteristics of troposcatter obviously affect EM wave propagation [7]. In [8], a cognitive troposcatter link is proposed to improve the quality and capacity, physical awareness objects including geometry, meteorological conditions are studied and then the optimal frequency is calculated.

To study detection performance of passive detection system based on troposcatter, probability of detection with respect to several factors is analyzed. Two approaches are presented to precisely estimate the key signal-to-noise ratio (SNR). In addition, Hopfield model is proposed to describe time-varying tropospheric refractivity, relationship between meteorological conditions and propagation loss is deduced. Aiming at improving detection performance under different circumstances, we introduce a cognitive system. The uncontrollable factors including meteorological conditions, elevation angle and carrier frequency are studied, and then controllable parameters are regulated.

The remaining of this paper is organized as follows. Signal detection technique focusing on energy detection is described in next Section. Section 3 introduces methods to estimate the SNR and tropospheric refractivity. In Section 4, several concrete examples and cognitive system are described. The conclusions are drawn in Section 5.

2. Signal detection theory

Currently, signal detection techniques mainly focus on matched filter detection, cyclostationary feature detection and energy detection. Matched filter detection can maximize the SNR. However, demand for priori knowledge of the received signal results in an evident drawback. Passive system has few chances to acquire sufficient information of enemy devices, which will obviously aggravate this problem. The huge calculation complexity of cyclostationary feature detection can bring a relatively long running time [8–11]. Therefore, energy detection becomes a preferred

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candidate for processing the unknown signal received by a passive system. This paper employs the conventional energy detection algorithm to analyze the detection performance of passive system. Detection problem can be transformed into a binary hypothesis test, which can be presented as [9]

$$\begin{cases} H_0 : r[n] = w[n], & n = 0, 1, \ldots, N-1 \\ H_1 : r[n] = s[n] + w[n], & n = 0, 1, \ldots, N-1 \end{cases} \tag{1}$$

where $s[n]$, $w[n]$ stand for the unknown deterministic signal and the additive white Gauss noise (AWGN), respectively. H_0 denotes the situation that signal is absent, H_1 the situation that signal is present, $w[n] \sim \aleph(0, \sigma^2)$. After processing the received signal, the final output can be expressed as Y. If $Y > \tau$, the signal is present, otherwise it is absent. Here, the predefined threshold can be expressed as τ. Probability of false alarm and detection can be expressed as P_{FA} and P_D. Energy detection gives them as [10]

$$\begin{cases} P_{FA} = \frac{\Gamma(u, \tau/(2\sigma^2))}{\Gamma(u)}, \\ P_D = \Pr(Y > \tau | H_1) = Q_u\left(\sqrt{k\gamma/\sigma^2}, \sqrt{\tau/\sigma^2}\right), \end{cases} \tag{2}$$

where $Q_u(.,.)$ stands for the generalized Marcum Q-function, $\Gamma(x)$ the gamma function, γ the SNR, u the time bandwidth product, $k\gamma$ the non-centrality parameter for conditionally non-central chi-square distribution. Considering the signal propagated by troposcatter, which be approximated as a Rayleigh fading channel [5,11], we can acquire the PDF of average SNR as [8,12]

$$f(\gamma) = \frac{1}{\Gamma(1)} \left(\frac{1}{\bar{\gamma}}\right) e^{-\frac{\gamma}{\bar{\gamma}}}, \tag{3}$$

where $\bar{\gamma}$ is the average SNR. P_D with no diversity follows

$$P_D = \int_0^{\infty} Q_u\left(\sqrt{k\gamma/\sigma^2}, \sqrt{\tau/\sigma^2}\right) f(\gamma) \mathrm{d}\gamma, \tag{4}$$

where $Q_u\left(\sqrt{k\gamma/\sigma^2}, \sqrt{\tau/\sigma^2}\right)$ can be expressed as

$$Q_u\left(\sqrt{k\gamma/\sigma^2}, \sqrt{\tau/\sigma^2}\right) = 1 - e^{-\frac{k\gamma+\tau}{2\sigma^2}} \sum_{n=u}^{\infty} \left(\frac{k\gamma}{\tau}\right)^{k/2} I_n\left(\frac{\sqrt{k\gamma\tau}}{\sigma^2}\right). \tag{5}$$

Therefore, we can found P_D under a Rayleigh fading channel following

$$P_D = \left(\frac{\bar{\gamma}}{\bar{\gamma}+1}\right)^{1-u} \left[e^{\frac{-\tau}{2(1+\bar{\gamma})}} - e^{\frac{-\tau}{2}} \sum_{n=0}^{u-2} \frac{1}{u!} \left(\frac{\tau\bar{\gamma}}{2(\bar{\gamma}+1)}\right)^n \right]. \tag{6}$$

The $\bar{\gamma}$ of passive detection system based on troposcatter can be given by

$$\bar{\gamma}(dB) = P_r + G - P_n, \tag{7}$$

where P_n denotes the power of noises, G the gain of receiver, P_r the received power. According to Eq. (7), the key to acquire $\bar{\gamma}$ lies in estimating the value of P_r.

3. Method for estimating SNR

3.1. Transmission loss

Power received by a passive detection system follows

$$P_r(\mathrm{dB}) = P_t - L_\Sigma, \tag{8}$$

where L_Σ is the propagation loss of a troposcatter link. Zhang method is internationally accepted to estimate L_Σ [13–15]. The main propagation loss of troposcatter can be given by

$$L = F + 30\lg f + 30\lg\Theta_0 + 10\lg d + 20\lg(5 + \chi H) + 4.34\gamma h_0 + L_c, \tag{9}$$

where $\Theta_0 = \theta_t + \theta_r + 1000d/r$ refers to the least scatter angle (mrad) [14,15], r the median effective earth radius (km), $\theta_t(\theta_r)$ the elevation angle (mrad) of TX(RX), F the meteorological factor (dB), χ the atmospheric structure coefficient (km^{-1}). The values of F and χ can be determined according to a digital map [15]. f is the carrier frequency (MHz), d the path length (km) between TX/RX. $H = 10^{-3}\Theta_0 d/4$ denotes the height (km) between lowest scattering point and horizontal line between TX/RX. h_0 denotes the height (km) between lowest scattering point and ground, it can be calculated as

$$h_0 = r/\cos\left[0.5\left(\frac{d}{r} - \arccos\frac{r}{r+h_r} - \arccos\frac{r}{r+h_t}\right)\right] - r, \tag{10}$$

where $h_t(h_r)$ denotes the height of TX(RX). L_c denotes the aperture-to-medium coupling loss (dB), which follows

$$L_c = 0.07 \times e^{0.055 \times (G_t + G_r)}, \tag{11}$$

where G_t (G_r) stands for the antenna gains, which can be approximated as

$$G_{t,r} = 10\lg[4.5 \times (D/\lambda)^2], \tag{12}$$

where D is the diameter of a parabolic antenna (m). L_{bR} stands for the loss related with height of antenna. It can be given by [14]

$$L_{bR} = 10\lg\left\{1 + \left[\frac{(5+\gamma H)}{4\pi\Theta_0 h_r/\lambda}\right]^2\right\}. \tag{13}$$

As stated above, L_Σ can be calculated as

$$L_\Sigma = L + L_{bR} - (G_t + G_r). \tag{14}$$

Without L_{bR}, Fig. 1(a) presents L_Σ variation with d under parameters: f = 4.5 GHz, $D_t = D_r$ = 2.5 m, $\theta_t = \theta_r = 0.5°$, d = 150 km, other parameters are same as above, L_Σ variation with f and θ_r are presented in Fig. 1(b) and (c), respectively.

Although Zhang method can effectively estimate the propagation loss, it depends on statistical data and cannot expose the time-varying characteristics. Theoretically P_r of a troposcatter link follows

$$P_r = P_t \int_V \frac{\lambda^2 g_t g_r G_t G_r \sigma_v \rho}{(4\pi)^3 (r_1 r_2)^2} dV, \tag{15}$$

where λ denotes the wavelength, σ_v the scattering cross-section, $r_1(r_2)$ the distances between scatterer to TX(RX), $g_t(g_r)$ the antenna directivity function, $L_c = -10\lg\rho$. Because of good directivity and narrow beam of the antenna, V can be simplified as [16]

$$V = 1.206 \frac{r_1^2 r_2^2 \delta_t \delta_r \phi_t \phi_r}{\sqrt{r_1^2\phi_t^2 + r_2^2\phi_r^2}\sin\Theta}, \tag{16}$$

where $\delta_t(\delta_r)$ is the half power beam width in vertical direction, $\phi_t(\phi_r)$ the half power beam width in horizontal direction. Both of them can be written as

$$\delta_{t,r}(\phi_{t,r}) = (70° \sim 75°) \times \lambda/D. \tag{17}$$

The antenna directivity function can be expressed as

$$\begin{cases} g_t = \exp\{-a_t(\varphi_t - \varphi_{t0}) - b_t(\theta_t - \theta_{t0})\}, \\ g_r = \exp\{-a_r(\varphi_r - \varphi_{r0}) - b_r(\theta_r - \theta_{r0})\}, \end{cases} \tag{18}$$

where $\varphi_t(\varphi_r)$ denotes the azimuth, $\theta_{t0}(\theta_{r0})$ the beam elevation, $\varphi_{t0}(\varphi_{r0})$ the beam azimuth. $a_t = 4\ln 2/\psi_{ht}^2$, $a_r = 4\ln 2/\psi_{hr}^2$, $b_t = 4\ln 2/\psi_{vt}^2$, $b_r = 4\ln 2/\psi_{vr}^2$. Here, $\psi_{vt}(\psi_{vr})$ denotes the vertical beam width, $\psi_{ht}(\psi_{hr})$ the horizontal beam width. Elevation deviation loss accompanying with azimuth deviation loss are caused by the situation that elevation angle and azimuth deviate from the optimal link. g_t, g_r have obvious relationship with azimuth and ele-