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Detection Performance of DS/FH Hybrid Signals for TT&C under Repeater Jamming*

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Abstract: Studying the performance deterioration of DS/FH signals for TT&C(Telemetry Tracking & Command) in interfered environment is of great importance to this novel system. Expressions for probability of detection and false alarming of DS/FH(Direct Spread/Frequency Hopping) signals for TT&C under repeater jamming are deduced. The probability of false alarming, PSLR(Peak Side lobe Level Ratio) and Correlation Coefficient are simulated and analyzed with different configuration of DS(Direct Spread) and FH(Frequency Hopping) spreading gain based on Matlab/Simulink. It is concluded that victim's receiver is suffered "deception jamming" as long as relative delay time is less than frequency hop duration, which denotes correctness of deduce and offers references for following work.

Key words: DS/FH; TT&C; repeater jamming; PFA; PSLR; correlation coefficient; detection performance

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转发干扰下 DS/FH 混合扩频测控信号检测性能

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摘 要:分析直扩/跳频(DS/FH)混合扩频测控信号在干扰环境下的性能对该新测控体制的研究具有重要的意义。推导了转发干扰环境下 DS/FH 测控信号的检测概率和虚警概率表达式。以 Matlab/Simulink 为平台搭建了检测性能仿真系统,对检测概率、主副旁瓣比和相关系数进行了仿真分析,指出只要转发时延小于一个跳频驻留,就能实现"欺骗"干扰,验证了理论推导的正确性,为进一步研究提供了参考。

关键词:DS/FH;TT&C;转发干扰;虚警概率;主副旁瓣比;相关系数;检测性能

1 Introduction

Combining the advantages of Direct Sequence Spread Spectrum (DSSS) system and Frequency Hopping Spread Spectrum (FHSS) system, DS/FH hybrid spread spectrum system has high viability and good reliability in complexly electronic environment, which is deemed to be best anti-jamming system for TT&C. The synchronization of DS/FH signals for TT&C has been analyzed to a certain degree in AWGN channel[1], which is not enough to demonstrate its superiority on DS or other systems. In order to find out pertinent anti-jamming measures and offer advices for setting DS/FH system parameter[2-3], it is necessary to explore its performance under jamming.

As we all know that DS/FH hybrid spread spectrum system is hardly interfered by blanket jamming because of its high processing gain. Repeater jamming is all of the same as the real signal but time delay or Doppler frequency, so it can obtain the system's processing gain and interfere victim's receiver effectively with lesser jamming power, which indicates great threat. Repeater jamming is

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usually based on DRFM (Digital Radio Frequency Memory), by current types of which enough delay could be obtained for TT&C signals[4].

Reference [5] analyzed respectively the performance of acquisition and demodulation, converting jamming effect to the degradation of SNR, but the supposition that repeater jamming was a reverse replica is not prevalent all the time. The effect of repeater jamming depends on the relative time delay, which is deemed to be not better exceed PN code chip duration[5-6], but the reality is that the receiver doesn't actually know the code phase of the real signal and makes judgment only by peak correlation value. When the relative time delay is shorter than chip duration, the existence of repeater jamming will promote acquisition of the signal if there is no further jamming measures[7].

Though repeater jamming has partial correlation with local PN code[8] for TT&C signals, partial peak correlation value is possibly large enough to affect receiver's judgment and deteriorates the performance of acquisition, because the jammer could increase the power of interfering signal. So the relative delay time should be less than hop frequency duration other than chip duration to obtain effective jamming. Besides probability of detection and false alarming, PSLR (Peak Side Lobe Level Ratio) and correlation coefficient could also be used as parameters to characterize effect of jamming.

Based on former study, the performance of detection of DS/FH signals for TT&C is discussed here. This paper is organized as following. Section 2 introduces the detection and acquisition model, simulation parameters are introduced in section 3, including probability of detection and false alarming, PSLR as well as correlation coefficient. Some cases are simulated in section 4, and conclusions are presented in last section.

2 Acquisition and Detection Model

Assuming that local hop frequency has synchronized with the receiver signals, the problem turns to be the detection performance of DSSS under repeater jamming. Correlation operation and square rule are usually adopted in the model, just as shown in Fig.1, where T is integral time, equaling to one period of the stochastic code usually.

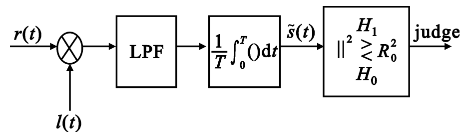

Fig.1 Acquisition and detection for DSSS
图 1　直扩捕获检测原理图

The received signal $r(t)$ and local intermediate frequency signal $l(t)$ are:

$$r(t) = s(t) + j(t) + n(t)$$

$$l(t) = \sqrt{2}Pn(t)\exp(-j2\pi f_{IF}t) \tag{1}$$

$$s(t) = \sqrt{2P}D(t-\tau)Pn(t-\tau)\cos[2\pi(f_{IF}+f_d)t+\theta_S]$$

$$j(t) = \sqrt{2J}D(t-\tau-\tau')Pn(t-\tau-\tau')\cos[2\pi f_J t+\theta_J] \tag{2}$$

where $s(t)$ is real signals and $j(t)$ is repeater jamming signal; $n(t)$ is Gauss white noise with limited band whose mean value is zero and two-side power spectral density is $N_0/2$; P is signal power, and $D(t)$ is transferred data with 1 as assumed value in acquisition phase; $Pn(t)$ is stochastic codes, and m codes is adopted here; f_{IF} is intermediate frequency; f_d is remaining Doppler frequency after coarse acquisition with θ_S as remaining phase; J is jamming signal power with f_J as frequency and θ_J as phase; τ and τ' are real time delay and relative time delay, respectively.

3 Simulation Parameters

3.1 Probability of detection and false alarming

Previously assuming that local hop frequency has synchronized with the received signals, repeater jamming has more delay time than real signals, which leads to the delay of hop frequency and only has partial correlation during DS acquisition. The output of the complex correlator $\tilde{S}$ in Fig.1 is

$$\tilde{S} = \sqrt{P}\exp(j\theta_S)\tilde{R}(\tau,f_d) + \tilde{J} + \tilde{\eta}$$

$$\tilde{R}(\tau,f_d) = \frac{1}{T}\int_0^T Pn(t-\tau)Pn(t)\exp(j2\pi f_d t)\,dt$$

$$\tilde{\eta} = \frac{\sqrt{2}}{T}\int_0^T n(t)Pn(t)\exp(-j2\pi f_{IF}t)\,dt \tag{3}$$

$$\tilde{J} = \frac{\sqrt{J}}{T}\int_{\tau'}^T j(t)Pn(t)\exp(-j2\pi f_{IF}t)\,dt = \frac{\sqrt{J}}{T}\int_{\tau'}^T Pn(t-\tau-\tau')Pn(t)\exp(j2\pi(f_J-f_{IF})t)\,dt \tag{4}$$

where $\tilde{\eta}$ is complex Gauss random variable obeying $N(0, N_0/T)$; $\tilde{R}$ is the ambiguity function of periodic random sequence $Pn(t)$, which can be described as $\tilde{R}=\bar{R}+R^r$ considering its stochastic property[10], where $\bar{R}$ is the mean value, R^r is stochastic variable:

$$\bar{R}_i(\tau,f_d)\approx\begin{cases}\exp(\mathrm{j}\pi f_d T)(1-|\rho|)\\ \dfrac{\sin(\pi f_d T)}{N\sin(\pi f_d T_c)}, & |\tau|<T_c \quad H_{i=1}\\ 0, & \text{others} \quad H_{i=0}\end{cases}$$

$$G_i(\tau,f_d)\approx\begin{cases}\rho^2/N, & H_1\\ \rho^2/N+(1-|\rho|)^2/N, & H_0\end{cases} \tag{5}$$

where ρ equals to $\Delta\tau/T_c-[\Delta\tau/T_c]$, $[\cdot]$ denoting the integer portion of a number. N is the length of $Pn(t)$ and T_c is chip duration of $Pn(t)$.

Assuming $\tau=kT_c+\varepsilon, 0\leqslant\varepsilon\leqslant T_c, \tau'=k'T_c, k, k'$ is an integer, namely the real signal and repeater jamming have integral chip delay time, $f_J-f_{\mathrm{IF}}=f_d$,

$$\begin{aligned}\tilde{J}&=\frac{\sqrt{J}}{NT_c}\int_0^{(N-k')T_c}Pn(t-kT_c-\varepsilon)\cdot\\&Pn(t+k'T_c)\exp(\mathrm{j}2\pi f_d(t+k'T_c))\mathrm{d}t=\\&\frac{\sqrt{J}}{NT_c}T_c\sum_{i=0}^{N-k'-1}Pn(iT_c-kT_c-\varepsilon)\cdot\\&Pn(iT_c+k'T_c)\exp(\mathrm{j}2\pi f_d(iT_c+k'T_c))\end{aligned} \tag{6}$$

So the mean value of $\tilde{J}$, which is the peak value of the correlation between repeater jamming and local signal is:

$$E[\tilde{J}]\approx\begin{cases}\sqrt{J}\exp(\mathrm{j}\pi f_d T)\left(1-\dfrac{|\varepsilon|}{T_c}\right)\dfrac{\sin[\pi f_d(N-k')T_c]}{N\sin(\pi f_d T_c)},\\ \qquad\left|k+k'+\dfrac{\varepsilon}{T_c}\right|\leqslant 1\\ 0, \quad \text{others}\end{cases} \tag{7}$$

Equation (7) shows that there is always peak of correlation between repeater jamming and local signal, whose height depends on jamming power and relative delay time τ'. The more the jamming power is and the less the relative delay time is, the higher the peak is. It is because of existence of the peak that repeater jamming increases probability of false alarming remarkably, deteriorating system's performance, but doesn't affect probability of detection. Therefore it is doable to study effect of repeater jamming by analyzing changes of probability of false alarming. Repeater jamming is all the same as the real signal but the time delay, so peak after correlation must have jitter too, which is supposed as that of real peak in (5). Only special case when $\varepsilon=0$ is discussed here.

Here come the two hypotheses:

$$\begin{aligned}&H_0: z=|\tilde{J}+\tilde{\eta}|, \text{phase dosen't match}\\&H_1: z=|\tilde{R}+\tilde{\eta}|, \text{pahse matches}\end{aligned} \tag{8}$$

It is easy to see that the output of the complex correlator nearly obeys Rice distribution, the probability density function of decision variable $x=|z|^2$ is[9]:

$$f(x|H_i)=\frac{1}{2\sigma_i^2}\exp\left(-\frac{x+m_i^2}{2\sigma_i^2}\right)I_0\left(\frac{m_i\sqrt{x}}{\sigma_i^2}\right) \tag{9}$$

where $I_0(\cdot)$ is zero Bessel function.

$$m_1=|E(z)|_{i=1}=\sqrt{P}\,|\bar{R}_1(\Delta\tau,\Delta f_d)|$$

$$\sigma_1^2=\mathrm{var}(z)_{i=1}=\frac{1}{2}(PG_1(\Delta\tau,\Delta f_d)+N_0/T)$$

$$m_0=|E(z)|_{i=0}=|E[\tilde{J}]|$$

$$\sigma_0^2=\mathrm{var}(z)_{i=0}=\frac{1}{2}(JG_0(\Delta\tau,\Delta f_d)+N_0/T)$$

Here are obtained the probability of detection, P_d, and false alarming, P_{fa}, of DS/FH signal for TT&C under repeater interference:

$$\begin{aligned}P_d&=\int_{R_0^2}^{+\infty}f(x|H_1)\mathrm{d}x=\\&\int_{R_0/\sigma_1}^{+\infty}x\exp\left(-\frac{x^2+\gamma^2}{2}\right)I_0(\gamma x)\mathrm{d}x=\\&Q(\gamma_1,R_0/\sigma_1)\\P_{\mathrm{fa}}&=Q(\gamma_0,R_0/\sigma_0)\end{aligned} \tag{10}$$

$$\gamma_1=\frac{m_1}{\sigma_1}=|\bar{R}1(\Delta\tau,\Delta f_d)|\sqrt{2N\frac{E_c}{N_0}\sqrt{1+\frac{E_c}{N_0}\rho^2}^{\,-1}}$$

$$\gamma_0=\frac{m_0}{\sigma_0}=|E[\tilde{J}]|\sqrt{2N\frac{E_c}{N_0}\sqrt{1+\frac{E_c}{N_0}\rho^2}^{\,-1}}$$

$$\frac{R_0^2}{\sigma_0^2}=C\left(1+\frac{E_c}{N_0}\mu_1\right)^{-1}, \frac{R_0^2}{\sigma_0^2}=C\left(1+\frac{E_c}{N_0}\mu_2\right)^{-1}$$

$$C=\frac{R_0^2}{N_0/2T}, \mu_1=\rho^2, \mu_2=\rho^2+(1-|\rho|)^2 \tag{11}$$

where E_c/N_0 is chip signal power to noise power density ratio, C is normalizing threshold. Considering range of normalizing threshold[10] and existence of interference, it is reasonable to set 10 as the value of C, which nearly is the value in AWGN channel when P_{fa} is 10^{-3} and E_c/N_0 is -10 dB-Hz.

3.2 PSLR and Correlation Coefficient

The effect of jamming was gained by deteriorating the correlation performance, because its existence doesn't only reduce the real main lobe, but increases side lobes. Repeater jamming is so alike with the real signal that they are highly correlative with each other, and there are two peaks in correlation figure, just as shown in Fig. 2, in which the real one is located at nearly 150 chips. Thus the study of changes in correlation under jamming is of great importance.

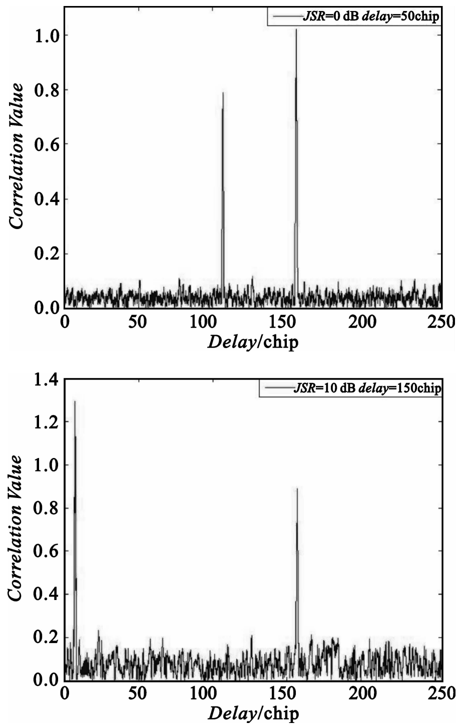

Fig.2 Correlation value under different condition
图 2　不同环境下的相关图

$$PSLR(\text{dB}) = 20\lg \frac{|Largest\ Sidelobe|}{|Mainlobe\ Peak|} \tag{12}$$

$$\zeta = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} f(\Delta\tau_i, \Delta f_d j) g(\Delta\tau_i, \Delta f_d j)}{[\sum_{i=1}^{m}\sum_{j=1}^{n} f^2(\Delta\tau_i, \Delta f_d j) * \sum_{i=1}^{m}\sum_{j=1}^{n} g^2(\Delta\tau_i, \Delta f_d j)]^{1/2}} \tag{13}$$

where $f(\Delta\tau_i, \Delta f_d j)$ and $g(\Delta\tau_i, \Delta f_d j)$ stand for Time-Doppler two-dimensional correlation figure.

PSLR stands for the peak of side lobe and main lobe ratio in correlation figure, defined in (12), which describes effect of jamming on correlation. The smaller the *PSLR* is, the better the performance is. *PSLR* equals to $-20\lg N$ in ideal situation, and approximately is -48 dB when $N = 255$.

Usually used in study of imaging radar to evaluate effect of jamming, the Correlation Coefficient (CC) describes the correlation degree between two images which are correlation figures before and after being jammed. Similarly, correlation coefficient can be adopted here, defined in (13). The more closely the value of CC approaches 1, the less the jammed effect is. Only time dimension is considered here.

4 Simulation and Analysis

The aforementioned deduction is simulated in numerical and Mote Carlo ways here based on Matlab/Simulink. In order to lower the sampling frequency and simulation time, the period of stochastic code, T, is set to 1 ms, moreover, the remaining Doppler frequency after coarse acquisition and T have relationship of $f_d * T = 0.3$. It surely makes no difference to conclusion under these assuming factors. E_c/N_0 is set to -10 dB-Hz in the following simulations.

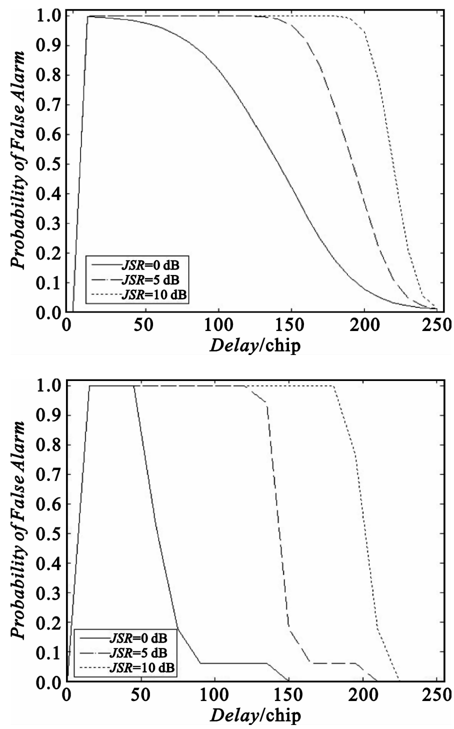

Fig.3 Probability of false alarming versus relative time delay with different *JSR*
图 3　不同时延下的虚警概率

4.1 Probability of false alarming

As shown in Fig.3, P_{fa} nearly equals to 0 with relative delay time τ' less than chip duration, denoting jamming doesn't worsen system's performance, but promotes the acquisition of real signals; P_{fa} increases quickly up to 1 when τ' is little more than chip duration, because repeater jamming obtains almost all the processing gain comparing real signal, which results in the highest jamming power; peak side lobe slowly decreases with τ' increasing, because FH pattern delays largely and only partial correlation exists between repeater jamming and local PN code, that is why P_{fa} keeps decreasing. When τ' increases to hop duration, FH pattern of repeater jamming is completely stagger with that of local signal, so repeater jamming can't be dehoped and deteriorates to common blanking jamming, then P_{fa} is back down nearly to 0 when *JSR* is not large enough.

Fig.4 shows that P_{fa} always approximately equals to 0 when τ' is little, here just the special case $\tau' = 0$ is considered. Repeater jamming doesn't deteriorate system's performance, contrarily promotes acquisition in this situation. When τ' becomes a little larger than chip duration, P_{fa} is increasing with *JSR* larger and larger. Moreover, the longer repeater jamming delays, the more power needed to increase P_{fa}, because partial correlation peak is smaller under the same conditions when relative delay time is larger.

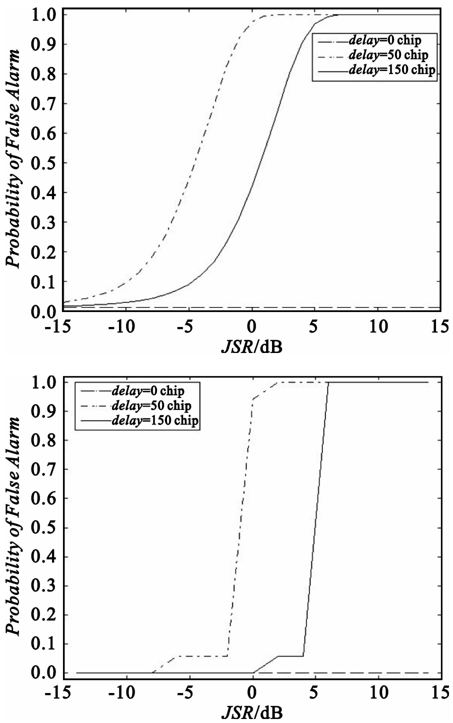

Fig.4 Probability of false alarming versus *JSR* with different relative time delay

图 4 不同干信比下的虚警概率

4.2 PSLR and Correlation Coefficient

Fig.5 shows that the correlation coefficient and *PSLR* are almost the same value with that of no jamming situation when τ' is smaller. The larger the *JSR* is, the more slowly the performance get better with increasing τ'. When jamming power is little enough, *PSLR* is around -20 dB in Fig.5, which has much difference with theoretical value (-48 dB), because of the existence of noise.

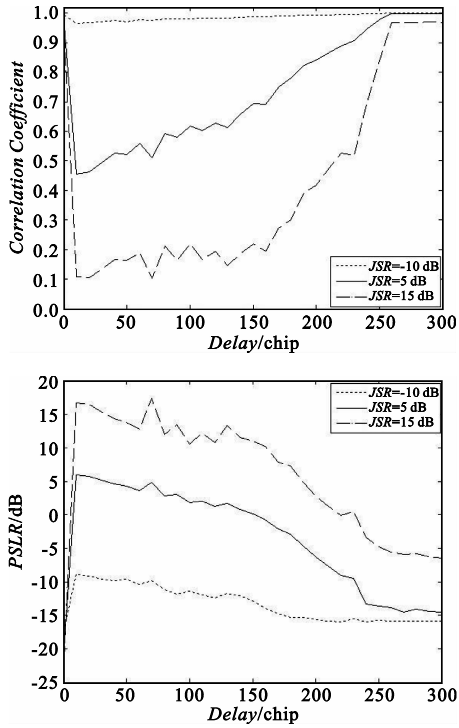

Fig.5 Correlation coefficient and *PSLR* versus relative time delay with different *JSR*

图 5 不同时延下的相关系数

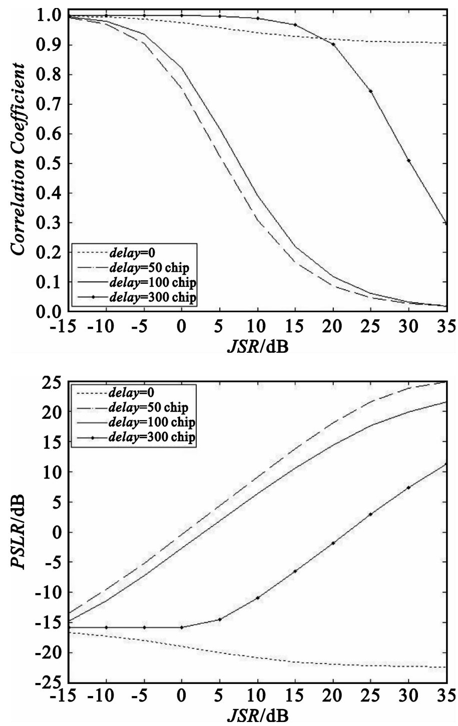

Fig.6 Correlation coefficient versus *JSR* with different relative time delay

图 6 不同干信比下的相关系数

Fig.6 shows that correlation coefficient is decreasing while *PSLR* is increasing with *JSR* becoming larger and larger when τ' is less than hop duration. Correlation coefficient and *PSLR* could be worsened with large enough jamming power when τ' exceeds hop duration, because repeater jamming has deteriorated to common blanket jamming now.

5 Conclusions

This paper analyzed the performance of DS/FH signals for TT&C under repeater jamming. Existence of repeater jamming will promote acquisition of real signal when relative delay time τ' is less than chip duration. Whereas FH patterns of repeater jamming and local signals will miss a little and become partially correlative with each other when τ' is a little larger than chip duration, but as long as the jammer enhances jamming power enough, it is also possible to worsen system's performance, including Correlation Coefficient decreasing while P_{fa} and *PSLR* increasing quickly. If τ' is too large, FH pattern will miss so much and peak of partial correlation will become so little or even to zero that repeater jamming will deteriorate to common blanket jamming which is to be spread seriously by DS/FH system and couldn't interfere effectively.

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