Impact of Timing Errors on the Performance of Double Iteration Anti-jamming Technology in Physical Layer Security

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Abstract. In physical layer security, the double iteration anti-jamming technology based on power cognition can effectively cancel the co-channel interference used in confusing eavesdroppers. This paper analyzes the theoretical performance of double iteration method and the impact of timing errors in receivers on the performance of double iteration anti-jamming technology. Theoretical and simulation results show that, over the AWGN channel, the timing errors of 0.2 chips and 0.4 chips degrade the system performance by about 1 dB and 5 dB respectively, in the interference priority mode. Thus the system performance is sensitive to the timing errors.

Keywords: Physical layer security · Timing errors · Double iteration anti-jamming technology · Co-channel interference

1 Introduction

In co-channel interference, for the purpose of jamming the eavesdroppers, the co-channel interference signal and the desired signal occupy the same frequency forming co-channel interference.

However, the co-channel interference also has an effect on the intended receiver. Therefore, cooperative interference cancellation is proposed, which can improve system reliability and significantly increase the security capacity of system. Significant solutions have been made in cooperative interference cancellation, such as time-domain prediction technology [1], transform domain suppression technology [2], code-aided technology [3]. Time-domain prediction technology, considers the interference signal as sinusoidal signal or autoregressive (AR) signal [4, 5] and obtains the optimal estimation of the signal by time-domain filtering. Such an approach is suitable for narrowband interference signal, where its data rate is much lower than the desired signal. The transform domain suppression technology utilizes the difference between the spread spectrum signal and the interference to remove the interference. However, the method is sensitive to the threshold and will damage the desired signal if the

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interference bandwidth is wide. According to the characteristics of the spreading code, the code-aided technology suppresses the narrowband interference (NBI) and the multiaccess interference (MAI) jointly and meanwhile completes dispreading detection [6]. In fact, it also relies on the prior information of the interference signal and has high computation complexity. Considering the weak self-correlation of broadband signal, the time-domain cancellation is not that acceptable.

In [7–9], the importance of the co-channel interference in physical layer security is emphasized, where the authors propose some cooperative interference power allocation schemes to improve the physical layer security. However, all the schemes are based on ideal interference cancellation, which do not take into account the timing errors. In [5], based on the method of combining power recognition technology and interference cancellation, the iteration mode is determined by sensing the desired signal to interference power ratio, which has a positive effect on broadband interference cancellation and is easy to be implemented. Furthermore, it improves the applications in anti-jamming technique of system. The performance of the schemes mentioned above is under the ideal timing synchronization assumption, but in practice, the timing errors always exist because of the asynchronized clock of the transceiver and the inaccurate estimation of the time delay.

In this paper, we analyze the theoretical performance of double iteration method and the impact of timing errors in receivers on the performance of duo-iteration anti-jamming technology.

The rest of paper is organized as follows. In Sect. 2, the system model is formed. In Sect. 3, we briefly analyze the performance of duo-iteration anti-jamming technology. In Sect. 4, we give the analysis of the system performance under the timing errors. In Sect. 5, the simulation results are presented to verify our theoretical analysis, Sect. 6 concludes this paper.

2 System Model

In Fig. 1, we give the system model. In this model, the transmitted signal consists of the desired signal and interference signal. After modulated and spread, the desired signal is transmitted to the receiver after getting through the shape filter. We consider the transmitted interference signal is a BPSK signal without spreading, and assume that the interference signal and the desired signal have the same bandwidth.

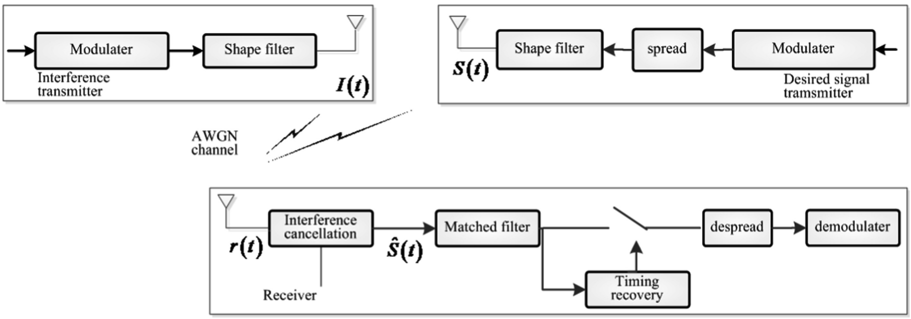

Fig. 1. System model

Denoted the users transmitter signal as $b(t) = \sum_{i=-\infty}^{+\infty} b_i p_T(t - iT_s)$, where $b_i \in \{\pm 1\}$ is the BPSK modulated desired signal. And the spreading sequence is defined as $pn(t) = \sum_{j=-\infty}^{+\infty} pn_j \cdot p_{T_c}(t - jT_c)$, where $p_T(t)$ is a rectangular pulse and its amplitude is 1 and duration is T_s. The spreading chips and the chip period are denoted by $pn_j \in \{\pm 1\}$ and T_c. The spreading gain N satisfies the relationship of $N = T_s/T_c$. And the data symbols are given by

$$S(t) = \sqrt{P_s} b(t) pn(t) g(t) \tag{1}$$

Where P_s is the desired signal power and $g(t)$ is the shaping pulse. And the interference signal takes on the form

$$I(t) = \sqrt{P_I} i(t) g(t) \tag{2}$$

The interference signal is modeled as $i(t) = \sum_{k=-\infty}^{+\infty} i_k \cdot p_{T_c}(t - kT_c)$, a random signal with the same bandwidth of the desired signal, where $i_k \in \{\pm 1\}$ is the BPSK modulated interference signal. And P_I is the energy of the interference signal. And the noise is AWGN.

The filter responses, which has the raised cosine characteristics, can be calculated as

$$h(t) = g(t) \otimes g^*(-t) = \frac{\sin(\pi t/T_c)}{\pi t/T_c} \frac{\cos(\alpha \pi t/T_c)}{1 - (2\alpha t/T_c)^2} \tag{3}$$

Where all the coefficients are normalized. T_c and α represent the duration of chips and the roll-off factor respectively. In the receiver, the received signal is first subjected to the interference cancellation. When the signal-to-interference ratio (SIR) is small, the interference cancellation is performed first. But when the SIR is large, the signal cancellation is performed first until the signal converges or completes the specified iteration times.

3 Performance Analysis of Double Iteration Anti-jamming Technology

In this part, we derive the theoretical expression and analyze the BER performance based on one iteration for the interference cancellation priority mode and the signal cancellation priority mode respectively, which do not take into account the timing errors. And we also compare and analyze the impact of the iteration times. In this section, we assume that the frequency of transceiver is perfectly synchronous. And we define the signal to noise ratio (SNR) and SIR as $SNR = P_s/\sigma_n^2$ and $SIR = P_I/\sigma_n^2$ respectively.

3.1 Performance Comparation

Performance Comparation of the Interference Cancellation Priority Mode
The joint probability distribution of signal and noise, which is conditioned on AWGN, is given by

$$f(x) = \frac{1}{2}\left[\frac{1}{\sigma_n\sqrt{2\pi}}\exp(-\frac{(x-h_1)^2}{2\sigma_n^2}) + \frac{1}{\sigma_n\sqrt{2\pi}}\exp(-\frac{(x+h_1)^2}{2\sigma_n^2})\right] \tag{4}$$

Where $h_1 = \sqrt{P_S}$ is the amplitude of the desired signal.

The cancellation of the interference priority mode is performed as follows: Firstly, the hard-decision of the received signal is given by $\hat{I}(t) = \frac{r(t)}{|r(t)|}$. And the error rate of the transmission signal b_i is calculated as

$$\begin{cases} Pe_2 = \int_{-\infty}^{-b_i \cdot h_1 - h_2} \frac{1}{\sigma_n\sqrt{2\pi}} \cdot \exp\left(-\frac{x^2}{2\sigma_n^2}\right)dx \\ Pe_{-2} = \int_{-b_i \cdot h_1 + h_2}^{+\infty} \frac{1}{\sigma_n\sqrt{2\pi}} \cdot \exp\left(-\frac{x^2}{2\sigma_n^2}\right)dx \end{cases} \tag{5}$$

Where $h_2 = \sqrt{P_I}$ is the amplitude of interference signal. Since the detection of the interference signal is not perfect. After despread, the discrete distribution of the residual interference $I(t) - \hat{I}(t)$ is shown as

$$\zeta(n) = \begin{cases} 0 & 1 - Pe_2 - Pe_{-2} \\ +2h_2 & Pe_2 \\ -2h_2 & Pe_{-2} \end{cases} \tag{6}$$

We can find that it is related not only to the transmission signal, but also to the sampling noise. Therefore, if we use the residual interference distribution as the classification criterion, the noise distribution accuracy will be improved. Denoted the equivalent noise decay factor k_σ, where its exact value can be got from the project experience. After traversing the residual interference, the final expression of BER can be expressed as

$$Pe_s = \sum_{ii=0}^{N}\sum_{jj=0}^{ii} C_N^{ii}(1 - Pe_2 - Pe_{-2})^{N-ii} C_{ii}^{jj} Pe_{-2}^{jj} Pe_2^{ii-jj} \cdot \int_{-\inf}^{N \cdot h_1 - (2 \cdot ii - 4 \cdot jj) \cdot h_2} \frac{1}{\sigma' \sqrt{2\pi}} \exp\left(-\frac{x^2}{2\sigma'^2}\right)dx \tag{7}$$

Where σ' is denoted as $\sigma' = k_\sigma \cdot \sigma_n$. It is assumed that the residual signal and the transmitter signal are unrelated, when the interference power is low and the probability of the interference detection is large. In this case, the equivalent noise power is the sum of the residual interference power and the AWGN signal power. Hence, the signal to noise ratio after dispreading is given by

$$\eta = \frac{N \cdot |h_1|^2}{4(Pe_2 + Pe_{-2})|h_2|^2 + \sigma_n^2} \tag{8}$$

According to (8) and the error rate function, we can derive the statistical error rate formula of the spread spectrum signal

$$Pe_s = Q\left(\sqrt{\eta}\right) \tag{9}$$

Performance Derivation of Signal Cancellation Priority Mode

In this mode, we detect the desired signal firstly. The error rate of the desired signal is calculated as

$$Pe_c = Q\left(\sqrt{\frac{N \cdot |h_1|^2}{\sigma_n^2 + |h_2|^2}}\right) \tag{10}$$

Assuming that we transmit a signal b_i, conditioned on whether there is the residual interference, the error rate of its canceled signal is given by

$$\begin{cases} Pe_I|C = \frac{1}{2} \cdot \left(\int_{-\infty}^{-h_2} \frac{1}{\sigma_n\sqrt{2\pi}} \exp\left(-\frac{(x-2h_1)^2}{2\sigma_n^2}\right)dx + \int_{-\infty}^{-h_2} \frac{1}{\sigma_n\sqrt{2\pi}} \exp\left(-\frac{(x+2h_1)^2}{2\sigma_n^2}\right)dx\right) \\ Pe_I|\bar{C} = \int_{-\infty}^{-h_2} \frac{1}{\sigma_n\sqrt{2\pi}} \exp\left(-\frac{(x)^2}{2\sigma_n^2}\right)dx \\ Pe_I = Pe_c \times Pe_I|C + (1 - Pe_c) \times Pe_I|\bar{C} \end{cases} \tag{11}$$

Where, if the interference cancellation is wrong, the error rate of the interference detection is $Pe_I|C$. If the interference cancellation is right, the error rate of the interference detection is $Pe_I|\bar{C}$. The first signal detection not only affects the subsequent interference detection and cancellation, but also affects the final signal detection. Therefore, we use the same method adopted in the interference cancellation priority mode, and get the expressions of the final error rate, which is calculated as

$$\begin{aligned} &\begin{cases} p_{ij} = C_N^{ii}(1 - Pe_{2|C} - Pe_{-2|C})^{N-ii} C_{ii}^{jj} Pe_{-2|C}^{jj} Pe_{2|C}^{ii-jj} \\ Pe|C = \sum_{ii=0}^{N} \sum_{jj=0}^{ii} p_{ij} \cdot \int_{-\inf}^{N \cdot h_1 - (2 \cdot ii - 4 \cdot jj) \cdot h_2} \frac{1}{\sigma'\sqrt{2\pi}} \exp\left(-\frac{x^2}{2\sigma'^2}\right)dx \end{cases} \\ &\begin{cases} p'_{ij} = C_N^{ii}(1 - Pe_{2|\bar{C}} - Pe_{-2|\bar{C}})^{N-ii} C_{ii}^{jj} Pe_{-2|\bar{C}}^{jj} Pe_{2|\bar{C}}^{ii-jj} \\ Pe|\bar{C} = \sum_{ii=0}^{N} \sum_{jj=0}^{ii} p'_{ij} \cdot \int_{-\inf}^{N \cdot h_1 - (2 \cdot ii - 4 \cdot jj) \cdot h_2} \frac{1}{\sigma_n\sqrt{2\pi}} \exp\left(-\frac{x^2}{2\sigma_n^2}\right)dx \end{cases} \\ &Pe = Pe_c \times Pe|C + (1 - Pe_c) \times Pe|\bar{C} \end{aligned} \tag{12}$$

If the first signal detection is wrong, the probability of the residual interference $Pe_{2|C}$ equals to $2h_2$. Where, just the same as $Pe_{-2|C}$, $Pe_{2|\bar{C}}$, $Pe_{-2|\bar{C}}$, $Pe_{2|C}$ is the probability after the signal cancellation, so the correlation between the interference detection and the signal declines. In addition, σ' usually can be replaced by σ_n.

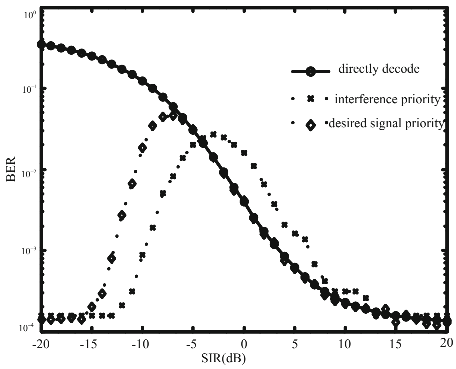

Fig. 2. Comparison of interference cancellation and direct demodulation

The simulation parameters of Fig. 2 are defined as: the spread gain $N = 15$ and $SNR = -0.5\,\text{dB}$. In Fig. 2, we can see that the performance of the signal cancellation priority is greater than the interference cancellation priority when the SIR is lower than −5 dB. Otherwise the later is greater than the former. In addition, the BER curves of the interference cancellation priority mode and the signal cancellation priority mode are both convex because as the SIR increases, the interference power decreases and the probability of the residual interference signal is increasing. Due to the spread spectrum gain, the intersection of the two curves locates at the negative half-axis of SIR. In practical applications, we can firstly obtain the critical point by numerical method and then select the iteration scheme dynamically by sensing the SIR and SNR until the performance is best.

3.2 Iteration Times Analysis

In Figs. 3 and 4, the BER performance of different iteration times in different interference cancellation modes are compared, where its parameters are defined as $SNR = -0.5\,\text{dB}$. And we can see that increasing the iteration times can hardly improve the performance. This is because the detection probability of the interference or the desired signal has a lower bound. And the effects of the noise floor and the residual interference cannot be completely eliminated.

In Fig. 3, one iteration can cancel the majority of interference signal in the higher interference power region. Therefore, increasing iteration times almost does not improve the performance significantly. As the interference signal power decreases, the probability and influence of the residual interference signal gradually increase, and it will directly affect the subsequent signal detection. Thus, the performance of signal detection cannot be improved by increasing the iteration times. Meanwhile the probability of interference detection decreases obviously when the interference power is low. Moreover, the impact of the residual interference signal will gradually reach or exceed the interference signal itself. Therefore, increasing the iteration times does not markedly improve the system performance.

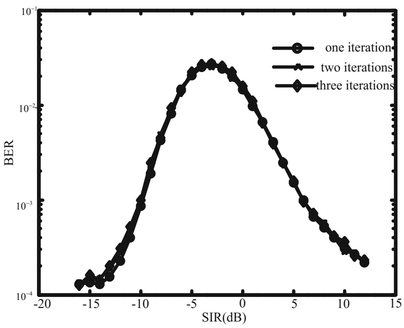

Fig. 3. Interference cancellation priority mode

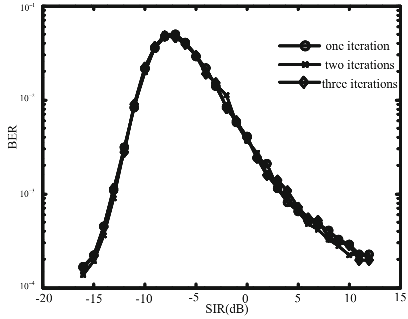

Fig. 4. Signal cancellation priority mode

Similarly, in Fig. 4, the exists of the residual interference in the signal detection makes increasing iteration times useless to improve the system performance.

4 Analysis of Timing Errors

In practice, timing errors always exist. If the sampling point is not at the optimal moment, the energy of sampled signal cannot reach the maximum, and it will introduce the ISI [10]. Ignoring the impact of carrier phase offset, the sampled signal is given by

$$r_n(\tau) = \sum_{i=-K}^{K} \hat{L}_{n-i} h(iT_s + \tau) + v_n \tag{13}$$

Where τ and v_n represent the sampling deviation of symbols and the response of noise over the matched filter respectively. And the length of the forming filter is $2k + 1$. In (13), $\hat{L}_0 h(\tau)$ is the sampled signal amplitude and $\sum_{\substack{i=-K \\ i \neq 0}}^{K} \hat{L}_{n-i} h(iT + \tau)$ is the ISI of adjacent symbols at the sampling moment. The ISI has no effect on the output mean due to $\hat{L}_i$ with mean of 0. However, the ISI, at the sampling time, will increase the output noise power [11], which is given by

$$V_I = \sum_{\substack{i=-K \\ i \neq 0}}^{K} |L_i h(iT_s + \tau)|^2 \tag{14}$$

The two major impact on the spread spectrum signal with timing errors are given by

(a) it reduces the integrated signal power, (b) it introduces the ISI power V_I, which reduces the system performance.

5 Simulation Results

The proposed above schemes have been simulated numerically by using MATLAB software, where the spreading gain $N = 15(11.76\,\text{dB})$, and the roll-off factor of match filter $\alpha = 0.22$, and $SNR = -0.5\,\text{dB}$.

In Fig. 5, the BER performance curves of 0.2 chips and 0.4 chips timing errors and ideal timing synchronization are compared. And we give their theoretical derivations and simulation results respectively. We can see that the theoretical derivations and simulation results are the same. In the interference cancellation priority mode, timing errors increase the BER and accelerate the deterioration of the performance. The timing errors of 0.2 chips degrades performance by about 1 dB. In addition, the performance decreases about 5 dB when the timing error is 0.4 chips, so the interference cancellation priority mode is sensitive to timing errors.

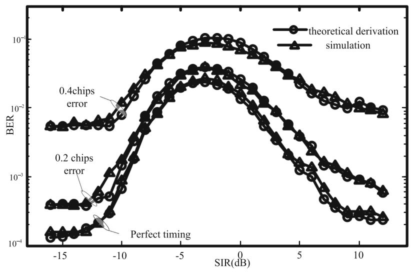

Fig. 5. The interference cancellation priority mode

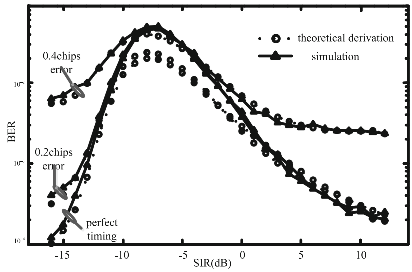

Fig. 6. The signal cancellation priority mode

In Fig. 6, in the signal cancellation priority mode, the timing errors affect the BER performance significantly when the interference power is large. However, when the interference power is low, the small timing errors has little influence on the BER performance, but the large timing errors enlarge the error platform significantly.

6 Conclusions

In physical layer security, for the double iteration anti-jamming technology based on power recognition, we derive the theoretical expressions for BER with timing errors and analyze the impact of performance. The derivations are verified in simulations. Studies show that timing errors deteriorate the performance of system, but the impacts are different under the different iteration schemes, which requires a sufficiently time delay estimation at the receiver. This paper can provide a theoretical maximum time synchronization error allowed by co-channel interference anti-jamming technology in practical.

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