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Time-Varying Single Tone Jamming Suppression Based on Frequency Interference Cancellation

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Abstract

The goal of this paper is to suppress time-varying single tone jamming (STJ) in the CDMA system by using the frequency interference cancellation method. We consider the practical scenario where STJ signal experiences time-varying fading channel. In this approach, the parameters (i.e. frequency, amplitude and phase) of the time-varying STJ are estimated in frequency domain, and then it is reconstructed and subtracted from the raw signals. The theoretical BER (bit error rate) expression is analyzed to assess the performance of the method, and computer simulations are executed. Simulation results demonstrate the effectiveness of the method in mitigating time-varying STJ and approaching the interference-free performance limit over practical ranges of STJ power levels and mobility levels.

Keywords: *CDMA, time-varying single tone jamming suppression, frequency interference cancellation, Doppler shift*

1. Introduction

It is well known that the DSSS (direct sequence spectrum spread) systems have inherent interference suppression capabilities. However, when the spreading gain is restricted (*e.g.*, time division-synchronization code division multiple access, TD-SCDMA) or the interfering signal is very strong, the anti-jamming capability is limited [1]. To solve this problem, some signal processing techniques is employed to further improve the system performance.

The problem of narrowband interference (NBI) suppression has been studied extensively over the last decades. Existing active NBI methods used in code division multiple access (CDMA) communications can be classified into time domain techniques and transform domain techniques [2].[1] Time domain adaptive filtering algorithm can fully inhibit the NBI in theory, but it not only require large convergence time to reach steadystate [3] but also distort the original signal during the interference rejection filtering [2], and time-domain techniques cannot effectively suppress the time-varying NBI [4].

Transform domain techniques have been received major attention because the methods have much merit such as faster convergence speed and more effective in time-varying NBI. [3] employs wavelet packet transform to eliminate the NBI, it has multi-resolution analysis ability and provides greater flexibility than other transforms, but it is dependent on the location of NBI frequency. [5] proposes a “frequency excision” method, where the affected frequency bins are excised. The frequency excision method is simple but it leads to significant portion loss of useful signal [6]. To avoid the useful signal loss, [4] and [7] introduced a frequency domain estimation method to suppress single tone interference, but both of them considered that the interference is time-invariant. In most practical scenarios, this assumption is not valid.

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[8] Presents an algorithm to estimate the single tone in noise. In this paper, we extend the method to suppress the time-varying single tone jamming (STJ) in CDMA system. The method is called frequency interference cancellation (FIC). In this method, the time-varying STJ is estimated according to [8], and then it is reconstructed and subtracted from the raw signals. The impact of time-varying STJ on CDMA system is analyzed, and the theoretical BER (bit error rate) expression is derived. We found that the time-varying STJ can be effectively suppressed over practical ranges of STJ power levels and mobility levels.

The rest of this paper is organized as follows. We start in Section 2 by describing the channel and signal model. In Section 3, the frequency cancellation scheme and the performance analysis are discussed. Simulation results and concluding remarks are presented in Section 4 and 5, respectively.

2. Channel and Signal Model

Consider the TD-SCDMA system. We assume that there are the NBI and additive white Gaussian noise in the system. The fading channel of the jammer is characterized as time-varying Rayleigh fading channel, the channel impulse response is represented as [9]

$$h(t) = \alpha e^{j(2\pi f_d t \cos\phi + \varphi)} \tag{1}$$

where α and f_d are the complex amplitude and the maximal Doppler shift, respectively. We assume that complex path gain α is an i.i.d (independent and identically distributed) Gaussian random variable with zero mean and variance σ_α^2. ϕ is the arrival angle of the received signal which is an i.i.d random variable. φ is uniformly distributed random phase.

The NBI is modeled as single tone jamming, which can be expressed as [7]

$$J(t) = \sqrt{P_J} e^{j(2\pi f_J t + \theta)} \tag{2}$$

where P_J is the power, f_J is the frequency and θ is the initial phase of the jamming signal.

The received baseband signal can be characterized as [10]

$$r(t) = \sqrt{P_s} x(t) + h(t) J(t) + n(t) \tag{3}$$

where

$$x(t) = \sum_{k=0}^{K-1} b(k) s(t) c(t - k \cdot SF \cdot T_c) \tag{4}$$

where P_s is the power of the transmitted signal. $b(k)$ is the transmitted signal with $E\left(|b|^2\right) = 1$. K is the number of transmitted symbols. SF is the spreading factor. T_c is the chip duration. $s(t)$ is the scrambling code, and $c(t)$ is the spreading code. $n(t)$ is the additive white Gaussian noise with variance σ^2.

Substituting (1) and (2) into (3), we can get

$$r(t) = \sqrt{P_s} x(t) + \alpha \sqrt{P_J} e^{j\left[2\pi(f_d \cos\phi + f_J)t + \varphi + \theta\right]} + n(t) \tag{5}$$

Denoted $f' = f_d \cos\phi + f_J$, $\psi = \varphi + \theta$, (5) can be rewritten as

$$r(t) = \sqrt{P_s} x(t) + \sqrt{J} e^{j\left[2\pi f' t + \psi\right]} + n(t) \tag{6}$$

where $J = P_J \left|\alpha\right|^2$.

3. STJ Elimination Scheme

After sampling, the received discrete baseband signal can be expressed as

$$r(i) = \sqrt{P_s}\,x(i) + J'(i) + n(i) \tag{7}$$

where

$$J'(i) = \sqrt{J}\,e^{j(2\pi i f'/f_s + \psi)} \tag{8}$$

where f_s is the sampling rate.

Let pf_s/M be the frequency nearest f', that is $p = round\left(Mf'/f_s\right)$. Then, $f' = (p+\Delta) f_s/M$, where $|\Delta| \le 0.5$ [8]. M is the number of DFT(discrete fourier transform). After DFT, the received signal can be expressed as

$$R(k) = \sqrt{P_s}\,X(k) + \sqrt{J}e^{j\psi} l(k) + N(k) \quad k = 0,1,\cdots,M-1 \tag{9}$$

where $X(k)$ is the DFT of the desired signal $x(i)$, and the $N(k)$ is the DFT of the noise $n(i)$,

$$l(k) = \frac{\exp\left(j\pi(p+\Delta-k)\right)}{\exp\left(j\pi(p+\Delta-k)/M\right)} \frac{\sin\left[\pi(p+\Delta-k)\right]}{\sin\left[(p+\Delta-k)\pi/M\right]} \tag{10}$$

We need to estimate the parameters of p, Δ, J ,and ψ. According to [8], we can get

$$p = \max_k \left\{R(k)\right\} \tag{11}$$

$$\Delta_+ = \frac{-B(1)}{B(0)-B(1)},\ \Delta_- = \frac{B(-1)}{B(0)-B(-1)} \tag{12}$$

where

$$B(m) = \mathrm{Re}\left(R\left[p+m\right]R^*\left[p\right]\right) \tag{13}$$

where $\mathrm{Re}(\cdot)$ denotes the real part, $*$ signifies complex conjugate. If $B(-1) > B(1)$, $\Delta = \Delta_+$, else $\Delta = \Delta_-$. The frequency f' can be obtained

$$\hat{f}' = (p+\Delta) f_s/M \tag{14}$$

The phase and power can be estimated as follows [8]

$$T = \left(1-|\Delta|\right)R\left[p\right] - |\Delta| R\left[p+\alpha\right] \tag{15}$$

$$\phi = \arg(T) - \pi\Delta \tag{16}$$

$$J = \left(\frac{|T|}{M} \frac{\left(1-|\Delta|\right)}{\left(1-2|\Delta|+2\Delta^2\right)} \frac{\pi\Delta}{\sin(\pi\Delta)}\right)^2 \tag{17}$$

where $\alpha = sign(\Delta)$, $\arg(\cdot)$ is the function for calculating the angle of complex.

With the jamming parameters being estimated accurately, we can reconstruct the jamming signal

$$\hat{J}'(i) = \sqrt{\hat{J}}\exp\left(j2\pi i\hat{f}'/f_s + j\hat{\psi}\right) \tag{18}$$

The jamming signal is subtracted from raw data, we can get

$$r'(i) = r(i) - \hat{J}'(i) = \sqrt{P_s}x(i) + n(i) + J'(i) - \hat{J}'(i) \tag{19}$$

Let $\varepsilon(i) = J'(i) - \hat{J}'(i)$, (19) can be rewritten as

$$r'(i) = \sqrt{P_s}x(i) + n(i) + \varepsilon(i), \tag{20}$$

where $\varepsilon(i)$ is the estimation error.

3.1. Theoretical Analysis of BER

The BER performance relates to the estimation error of the parameters. The MSE (mean square error) is given by

$$MSE_\varepsilon = E\left(|\varepsilon|^2\right) = \frac{1}{M}\sum_{i=0}^{M-1}|\varepsilon(i)|^2 \tag{21}$$

After despreading and descrambling, we can get [11]

$$\begin{aligned}\tilde{r}(n) &= \frac{1}{SF}\sum_{i=nSF}^{(n+1)SF-1} r'(i)c^*(i)s^*(i) \\ &= \sqrt{P_s}b(i) + \frac{1}{SF}\sum_{i=nSF}^{(N+1)SF-1} n(i)c^*(i)s^*(i) + \frac{1}{SF}\sum_{i=nSF}^{(n+1)SF-1}\varepsilon(i)c^*(i)s^*(i)\end{aligned} \tag{22}$$

The power of the desired signal P is

$$P = E\left[\left(\sqrt{P_s}b\right)\left(\sqrt{P_s}b\right)^*\right] = P_s \tag{23}$$

According to the characteristics of the spreading code and scrambling code [11], the power of the noise P_n is

$$P_n = E\left[\left(\frac{1}{SF}nc^*s^*\right)\left(\frac{1}{SF}nc^*s^*\right)^*\right] = \frac{1}{SF}E\left[nn^*\right] = \frac{\sigma^2}{SF} \tag{24}$$

The power of the estimation error ΔP is

$$\Delta P = E\left[\left(\frac{1}{SF}\varepsilon c^*s^*\right)\left(\frac{1}{SF}\varepsilon c^*s^*\right)^*\right] = \frac{1}{SF}E\left[\varepsilon\varepsilon^*\right] = \frac{1}{SF}MSE_\varepsilon \tag{25}$$

We assume that the MSE obeys the Gaussian distribution, the SINR γ is defined

$$\gamma = \frac{P}{P_n + \Delta P} = \frac{SF \cdot P_s}{\sigma^2 + MSE_\varepsilon} \tag{26}$$

The BER expression is obtained [12]

$$P_b = Q\left(\sqrt{2\gamma}\right) = Q\left(\sqrt{\frac{2SF \cdot P_s}{\sigma^2 + MSE_\varepsilon}}\right) \tag{27}$$

If the estimation is accurate, the method can achieve close to the interference-free performance limit.

4. Simulation Results

In this section, simulation results are provided to validate the theoretical analysis, and the simulation about the frequency excision (N -sigma [5]) is also shown for comparison at the same time. The setting of the sampling time T is a fundamental step, to increase the frequency resolution, an eight times oversampling in the frequency domain should be employed [13]. The simulation parameters are given in table 1. The chip rate of the TD-SCDMA is 1.28Mcps. $f_J = f_0$ (f_0 is the carrier frequency). SNR (signal-to-noise ratio) is defined as $SNR = SF \cdot P_s / \sigma^2$. JSR (jamming-to-signal ratio) is defined as $JSR = P_J / P_s$.

Table 1. Simulation Parameters

Modulation	QPSK
SF	16
M	704
T_c	$1/1.28\times10^{-6}$

Figure 1 shows the BER performance of the TD-SCDMA system with single tone jamming under the Rayleigh fading when $JSR = 10$ dB, $f_d = 100$ Hz. It is clear that the BER performance degrades significantly due to the jamming signal. When $JSR = 10$ dB, the jammer inundates the system. But the performance can be significantly improved by the frequency interference cancellation (FIC). From the figure, we can see that the FIC method achieves close to the interference-free performance limit. In addition, the simulation results match the analysis expression of (27).

Figure 2 plots the MSE performance with different SNR values when $f_d = 100$ Hz. From the figure, we can see that the MSE performance is severely degraded when the JSR increases. The reason may be explained as follows. In the theoretical analysis, we assume that the coefficient of the interference channel is a constant, in fact the channel coefficient is always changing, which result in the estimation error. When the jamming power increases, the estimation error will increases accordingly.

Figure 3 shows the BER performance as a function of the JSR when $SNR = 10$ dB, $f_d = 100$ Hz. As expected, when JSR increases, the BER performance degrades. When $JSR < 30$ dB, the performance of the FIC method approach the interference-free performance limit, which indicates that the time-varying STJ can be effectively suppressed. When $JSR > 30$ dB, the BER performance degrades, the reason is that the estimation error increases as JSR increases. From the figure, we can also see that when $JSR > 30$ dB, the performance of FIC outperforms the N -sigma. From Figure 3, it is further proved that the simulation results agree with the theoretical analysis.

Figure 4 illustrates the BER performance as a function of the JSR when $SNR = 10$ dB, $f_d = 300$ Hz. Compared with Figure 3, we can see that the BER performance degrades when f_d increases. As for FIC, this is because that when f_d increases, the channel changes faster, which result in increasing estimation error. It is different for N-sigma scheme, the reason is that the method is lack of robustness to channel conditions [14], N needs to be adjusted according to the channel conditions. From the figure, we can see that when $JSR < 20$dB, the performance of the FIC method approach the interference-free performance limit, which indicates that the time-varying STJ can be effectively suppressed. When $JSR > 20$dB, the performance of the FIC method outperforms the N-sigma. Finally, note that the simulation results approximately agree with the analytical results.

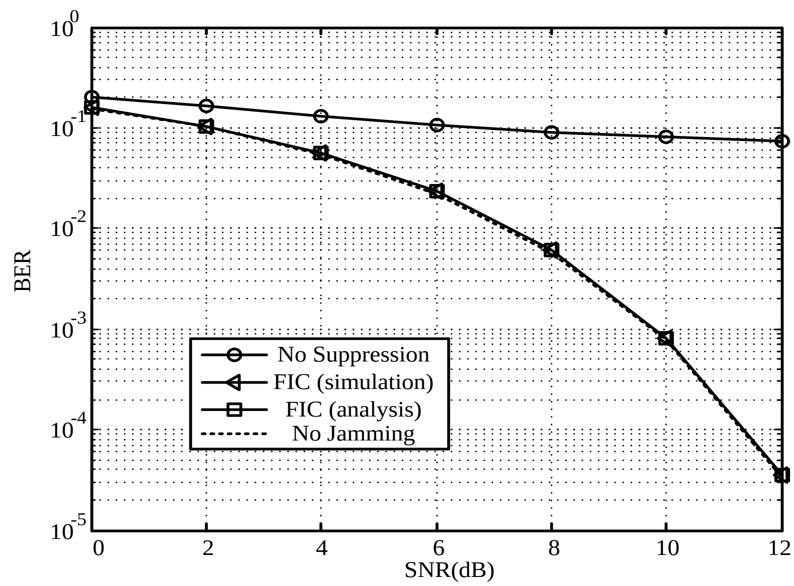

Figure 1. BER Performance under STJ Rayleigh Fading, $JSR = 10$dB, $f_d = 100$Hz

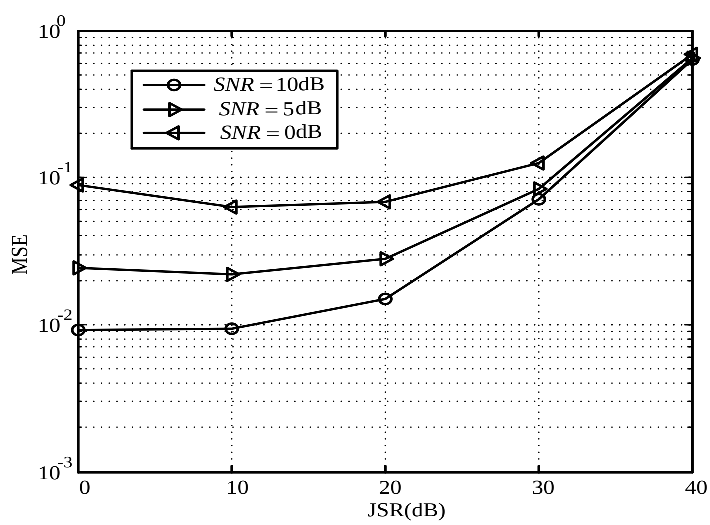

Figure 2. MSE Performance under STJ Rayleigh Fading with Different SNR Value, $f_d = 100$Hz

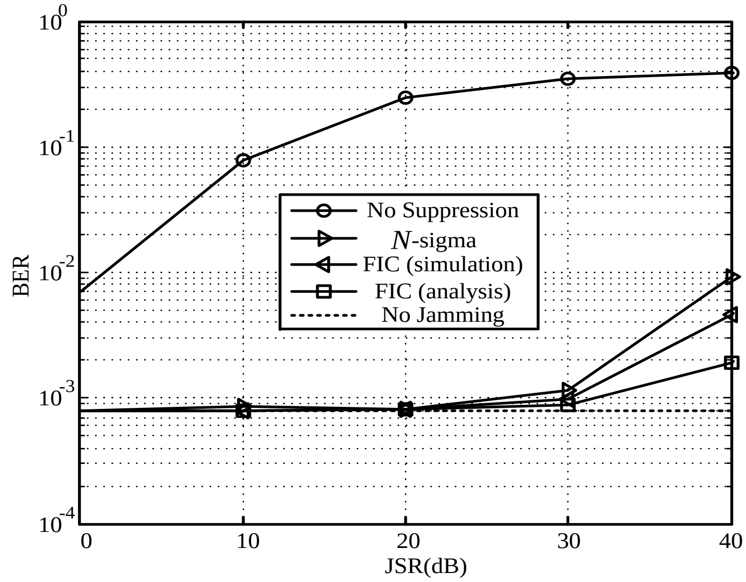

Figure 3. BER as a Function of JSR, $SNR = 10$ **dB,** $f_d = 100$ **Hz**

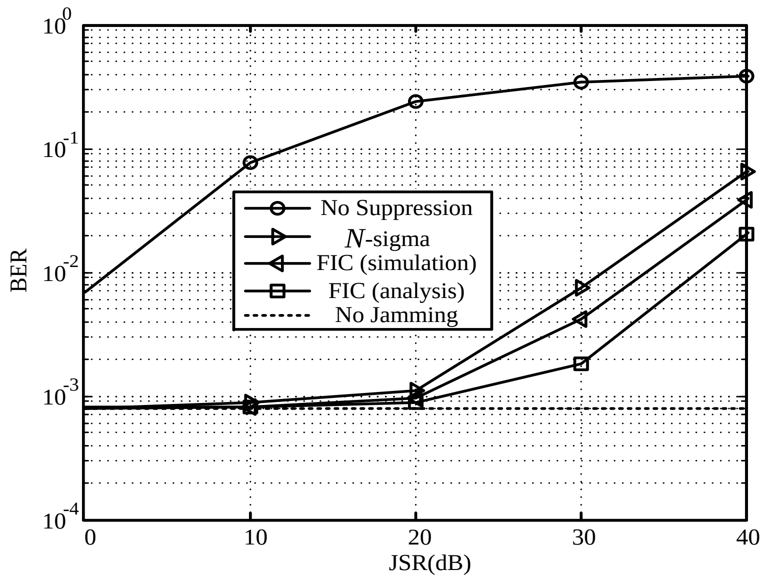

Figure 4. BER as a Function of JSR, $SNR = 10$ **dB,** $f_d = 300$ **Hz**

5. Conclusion

This paper presented the frequency interference cancellation scheme to suppress the time-varying STJ in CDMA system. The parameters of the time-varying STJ are estimated in frequency domain, and then the STJ is reconstructed and subtracted from the raw signals. The BER expression is derived to assess the performance of the method. The simulation results show that the time-varying STJ can be effectively suppressed over practical ranges of STJ power levels and mobility levels. In the future work, the performance of the proposed method in the frequency selective fading channel will be analyzed.

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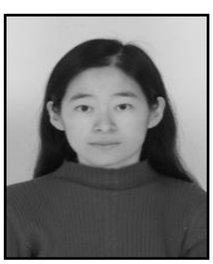

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