An Adaptive Anti-narrowband Jamming Receiver for CI/OFDM System

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Abstract. To overcome the inherent shortcomings of orthogonal frequency division multiplexing (OFDM) system, a so-called carrier interferometry OFDM (CI/OFDM) system has been proposed. In CI/OFDM system, data symbols are spreading over all OFDM subcarriers through CI coding so that better frequency diversity gain and lower peak to average power ratio (PAPR) can be obtained. In this paper, we investigated the anti-narrowband jamming performance of CI/OFDM system. We analyzed the post-detection signal-to-jamming plus noise ratio (SJNR) of two kinds of CI/OFDM receiver schemes, which are differentiated each other based on whether the jamming subcarriers are discarded. By comparing their performance in different jamming scenarios, we concluded that each scheme can only work well under specified suitable jamming scenario, in which the one outperforms the other. According to this observation, we further propose an adaptive anti-narrowband jamming CI/OFDM receiver, which adjusts the detection scheme according to the jamming power and bandwidth, to match the corresponding jamming scenarios. Simulation results are provided to validate our scheme.

Keywords: Carrier interferometry, narrowband jamming, orthogonal frequency division multiplexing (OFDM).

1 Introduction

In orthogonal frequency division multiplexing (OFDM)[1] based wideband wireless communication systems, high speed data streams are converted to parallel sub-streams, which are simultaneously transmitted over different narrow-band subcarriers with flat fading, so that , inter-symbols interference (ISI) can be effectively avoided and then better utilization of spectrum resources can be obtained. Therefore, OFDM has been widely applied in wideband wireless systems [2]-[4]. However, OFDM also suffers from some deficiencies, such as high peak and average power ratio (PAPR) and symbol loss due to subcarrier deep fading. To overcome these drawbacks, Wiegandt introduced carrier interferometry (CI) spreading codes into traditional OFDM system, which is referred to as carrier interferometry OFDM (CI/OFDM) [5]-[6]. In CI/OFDM system, each data symbol is spreading to all OFDM subcarriers by using CI codes [7]-[8]. Then, frequency diversity gain can be fully

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utilized to improve system bit-error-rate (BER) performance [5]-[6]. Moreover, as CI/OFDM is essentially equivalent to single carrier system, there is not significant PAPR problem compared to traditional OFDM system [9].

Besides channel fading, wireless communication system may face hostile jamming in practical application environments. Therefore, anti-jamming performance is an important system metric, especially for security and military application. As each data symbol is transmitted over a unique OFDM subcarrier, one or more information symbols are likely to be lost when the corresponding subcarriers experiencing jamming, i.e., narrowband jamming. Therefore, OFDM is sensitive to jamming. On the other hand, as CI/OFDM can make better use of frequency diversity gain than traditional OFDM, it can be expected that CI/OFDM can has better anti-narrowband jamming performance than that of traditional OFDM system. For this purpose, [10] has studied the performance of CI/OFDM system under narrowband jamming via simulation, and shows that CI/OFDM system is very robust to narrowband jamming. However, our analysis shows that CI/OFDM system only has better performance than that of OFDM under some specified conditions. According to our simulation results, the CI/OFDM is only superior to OFDM when the power of the jamming is relatively small as the narrowband jamming is spreading to all subcarriers due to the CI codes dispreading at the receiver. So, a scheme, in which the subcarriers experiencing jamming are discarded at the CI/OFDM receiver, is proposed in [10]. In this paper, we call this receiver scheme as zero setting CI/OFDM (ZS-CI/OFDM) receiver, in which those subcarriers experiencing jamming are set to be zero at the receiver. Unfortunately, our preliminary research reveals that this ZS-CI/OFDM can just works well under specific narrowband jamming scenarios as significant signal power loss introduced by discarding subcarriers. Therefore, an important problem is how to make a good tradeoff between jamming spreading and signal power loss for CI/OFDM system under narrowband jamming environments.

To address the above problem, we investigated the anti-narrowband jamming performance in terms of post-detection signal-to-jamming plus noise ratio (SJNR) of CI/OFDM and ZS-CI/OFDM receiver with minimum mean square error (MMSE) equalization in this paper. By comparing SJNR of these two kinds of CI/OFDM receiver under narrowband jamming scenarios, we concluded that each scheme has its suitable jamming scenario, in which one of the receivers outperforms the other. Then, we further investigated the threshold in terms of jamming bandwidth and power to determine the suitable receiver scheme.. Based the obtained threshold, we further propose an adaptive anti-narrowband jamming receiver scheme for CI/OFDM system, which self-adaptively selects suitable receiver scheme based on jamming detection. Simulation results are also provided to validate our adaptive receiver scheme.

The rest of this paper is organized as follows. Section 2 describes the system model for CI/OFDM with and without ZS-CI/OFDM receiver under narrowband jamming. Section 3 presents the analysis and comparison of SJNR between CI/OFDM and ZS-CI/OFDM receivers with MMSE equalization under narrowband jamming. Then, the suitable narrowband jamming scenario for each receiver schemes and the selection threshold is investigated. Section 4 proposes the adaptive anti-narrowband jamming receiver for CI/OFDM system. Simulation results are presented in Section 5 to verify the analysis. Finally, this paper is concluded in Section 6.

2 System Model under Narrowband Jamming

The transmitter and receiver model of CI/OFDM system with and without ZS-CI/OFDM receivers is shown in Fig.1, where ZS means that the subcarriers experiencing jamming are set to be zero based on the results of jamming detection. At the receiver, MMSE equalization is performed to combat with the impact of channel fading and noise. Meanwhile, and represent the jamming and Additional White Gaussian Noise (AWGN) in time domain, respectively. The process of ZS is described in Fig.2, where we assume that the subcarriers suffer from jamming is located at the last part of the band without loss of generality.

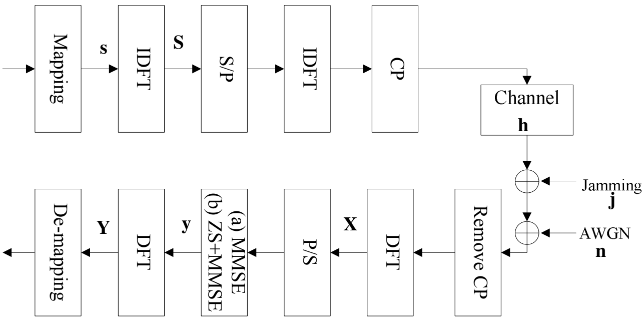

Fig. 1. System model under narrowband jamming

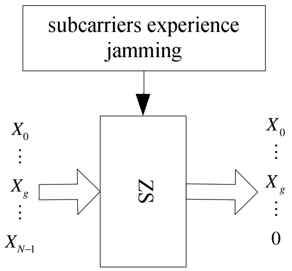

Fig. 2. The process of Zero Setting

2.1 Transmitting Signal Model

As it is depicted in [8], considering there are N data symbols to be transmitted during a OFDM symbol, the corresponding complexity baseband signal model of the transmitting signal in CI/OFDM is given by

$$S(t) = A\sum_{k=0}^{N-1}\sum_{i=1}^{N-1} s\left(k\right)e^{j2\pi i\Delta ft}e^{j\frac{2\pi}{N}ki} g\left(t\right), \tag{1}$$

where A is a constant that normalizes symbol energy to be one, $s(k)$ is the kth data symbol, $e^{j\frac{2\pi}{N}ki}$ is the CI code associate with the ith data symbol element, $\Delta f = 1/T_s$ is the subcarrier bandwidth, and $g(t)$ is a rectangular pulse of duration T_s. (1) can be further rewritten as discrete form with Nyquist sampling, i.e. ,

$$S(t) = A\sum_{k=0}^{N-1}\sum_{i=1}^{N-1} s\left(k\right)e^{j\frac{2\pi}{N}ni}e^{j\frac{2\pi}{N}ki} \qquad n = 0,\cdots,N-1 \tag{2}$$

As it is illustrated in Fig. 1, CI codes spreading is implemented by N points weighted inverse discrete Fourier transform (IDFT). Let $\mathbf{s} = \left[s(1), s(2), \cdots, s(N)\right]^T$ denote one CI/OFDM symbol vector with co-variance matrix $\mathbf{C}_s = E\left[\mathbf{s}\mathbf{s}^H\right] = E_s\mathbf{I}_N$. Here, $\mathbf{I}_N$ denotes a N by N identity matrix. After CI spreading, we can get

$$\mathbf{S} = \left[S(l)\right]_{N\times 1} = \mathbf{F}^H\mathbf{s}, \tag{3}$$

where $\mathbf{F}$ is the DFT matrix which is given by

$$\mathbf{F} = \frac{1}{\sqrt{N}}\left(f_{kl}\right)_{N\times N} = \frac{1}{\sqrt{N}}\left(e^{-j\frac{2\pi}{N}(k-1)(l-1)}\right)_{N\times N} \tag{4}$$

and the notation $(\cdot)^H$ denotes complex conjugate transposition. Meanwhile, the second IDFT operation in Fig. 1 performs the typical OFDM modulation.

2.2 Narrowband Jamming Model

The narrowband jamming is added into the received signals. For the simplicity of modeling, we assume the narrowband jamming is zero mean independent identical distributed (I.I.D.) Gaussian white noise with auto-covariance matrix $\mathbf{C}_J = \sigma_J^2\mathbf{I}_N$, where σ_J^2 is the variance of jamming .

2.3 Receiving Signal Model

Based on Fig. 1, the received signal is distorted by there factors, which are the channel fading, the narrowband jamming, and the noise. To mitigate these influences, MMSE equalization is firstly applied. Two DFT operations are used to demodulate and de-spread the signals, respectively.

According to [11], the received OFDM signal can be expressed as

$$\mathbf{X} = \mathbf{HS} + \mathbf{J} + \mathbf{W}, \tag{5}$$

where the $N\times N$ fading channel matrix $\mathbf{H}$ is given by

$$\mathbf{H} = diag\left(H_0, H_1, \cdots, H_{N-1}\right) \tag{6}$$

Let $\tilde{\mathbf{H}} = \left(H_p\right)_{N\times 1} = \mathbf{Fh}$ be the $N\times 1$ frequency response vector of the fading channel. Here, $\mathbf{h} = \left[h(0),\cdots,h(L-1),0,\cdots,0\right]_{1\times N}^{T}$ is the time domain channel impulse response of length L. $\mathbf{J} = \mathbf{Fj}$ and $\mathbf{W} = \mathbf{Fn}$ are the jamming and AWGN in frequency domain, respectively. Here, the auto-covariance matrix of $\mathbf{W}$ is $\mathbf{C}_W = \sigma_n^2 \mathbf{I}_N$. Note that there is only $D\left(D<N\right)$ nonzero elements in $\mathbf{J}$, i.e., the number of subcarriers which is subject to the jamming is D.

3 SJNR Analysis under Narrowband Jamming

In this section, we analyze the performance of CI/OFDM and ZS-CI/OFDM under narrowband jamming. Since it is very hard to analyze BER performance associated with CI/OFDM and ZS-CI/OFDM receivers under MMSE equalization, we focus the analysis on post-detection SJNR. It is well-known that the BER is a monotonically decreasing function of SJNR.

3.1 SJNR Analysis of CI/OFDM

For CI/OFDM receiver, the jamming is simply ignored. As it is illustrated in Fig.1, MMSE equalization is performed to compensate the impact of channel fading and noise. According to [12], the MMSE equalizer $\mathbf{\Lambda}$ is a $N\times N$ matrix which can be expressed by

$$\mathbf{\Lambda} = diag\left(\frac{H_0^*}{|H_0|^2 + \sigma_n^2 / E_s},\cdots,\frac{H_{N-1}^*}{|H_{N-1}|^2 + \sigma_n^2 / E_s}\right) \tag{7}$$

By applying DFT transformation to de-spread the CI code, the signal before de-mapping can be expressed by

$$\mathbf{Y} = \mathbf{F}\cdot\mathbf{y} = \mathbf{F\Lambda H}\cdot\mathbf{F}^H\mathbf{S} + \mathbf{F\Lambda I} + \mathbf{F\Lambda W} \tag{8}$$

So, the g th entry of $\mathbf{Y}$ can be expressed as

$$\begin{aligned} Y(g) = {} & \frac{1}{\sqrt{N}}\sum_{n=0}^{N-1}\frac{|H_n|^2}{|H_n|^2 + \sigma_n^2 / E_s} S(n)\exp\left(-j2\pi\frac{ng}{N}\right) \\ & + \frac{1}{\sqrt{N}}\sum_{n=0}^{N-1}\frac{H_n^*}{|H_n|^2 + \sigma_n^2 / E_s} J(n)\exp\left(-j2\pi\frac{gn}{N}\right) \\ & + \frac{1}{\sqrt{N}}\sum_{n=0}^{N-1}\frac{H_n^*}{|H_n|^2 + \sigma_n^2 / E_s} W(n)\exp\left(-j2\pi\frac{gn}{N}\right) \end{aligned} \tag{9}$$

Without loss of generality, we assume that the subcarriers influenced by the jamming are the last parts of the band, i.e. ,

$$J(n)=\begin{cases}0 & n<N-D\\ J\left(n-(N-D)\right) & N-D\le n\le N-1\end{cases} \tag{10}$$

Then, it follows (3) that (9)can be expressed as

$$\begin{aligned}Y(g)=&\frac{1}{N}\sum_{n=0}^{N-1}\frac{|H_n|^2}{|H_n|^2+\sigma_n^2/E_s}s(g)+\\&\frac{1}{N}\sum_{n=0}^{N-1}\sum_{\substack{i=0\\i\neq g}}^{N-1}\frac{|H_n|^2}{|H_n|^2+\sigma_n^2/E_s}s(i)\exp\left(j2\pi\frac{n(i-g)}{N}\right)+\\&\frac{1}{\sqrt{N}}\sum_{n=0}^{N-1}\frac{H_n^*}{|H_n|^2+\sigma_n^2/E_s}J(n)\exp\left(-j2\pi\frac{gn}{N}\right)+\\&\frac{1}{\sqrt{N}}\sum_{n=0}^{N-1}\frac{H_n^*}{|H_n|^2+\sigma_n^2/E_s}W(n)\exp\left(-j2\pi\frac{gn}{N}\right)\end{aligned} \tag{11}$$

where the first item represents the desired signal, the second item denotes the inter-carrier interference (ICI) caused by MMSE equalization, the third item is due to the contribution of jamming, and the fourth item represents the contribution of AWGN.

According to(9), we can have the overall power except jamming as

$$P_{\text{jamming-except}}=\alpha E_s, \tag{12}$$

where $\alpha=\frac{1}{N}\sum_{n=0}^{N-1}\frac{|H_n|^2}{|H_n|^2+\sigma_n^2/E_s}$. Meanwhile, the power introduced by jamming can be expressed as

$$P_{jam\min g}=\frac{\sigma_J^2}{N}\sum_{n=N-D}^{N-1}\frac{|H_n|^2}{\left(|H_n|^2+\sigma_n^2/E_s\right)}=\sigma_J^2\eta \tag{13}$$

where $\eta=\frac{1}{N}\sum_{n=N-D}^{N-1}\frac{|H_n|^2}{\left(|H_n|^2+\sigma_n^2/E_s\right)^2}$ .Then, we can have the SJNR of CI/OFDM as

$$\gamma_{\text{CI-OFDM}}=\frac{\alpha^2E_s}{\left(\alpha-\alpha^2\right)E_s+\sigma_J^2\eta} \tag{14}$$

3.2 SJNR of ZS-CI/OFDM

In order to eliminate the impact of jamming, we set the received signal to be zeros on the subcarriers influenced by the jamming at the ZS-CI/OFDM receiver. Because each of the N low-rate symbol streams is spreading across all the N subcarriers, CI/OFDM can still have the capacity to recover all the data symbols based on the remainder subcarriers in this case. It is just similar to the analysis of CI/OFDM receiver, the operations of ZS and MMSE can be expressed by

$$\mathbf{y} = \mathbf{\Lambda X} = \mathbf{\Lambda MHS} + \mathbf{\Lambda MW}, \tag{15}$$

where $\mathbf{M} = diag\left(\underbrace{1,\cdots,1}_{N-D},\underbrace{0,\cdots,0}_{D}\right)$. After de-spreading the CI codes, we can have

$$\mathbf{Y} = \mathbf{Fy} = \mathbf{F\Lambda MHS} + \mathbf{F\Lambda MW} \tag{16}$$

then, the gth entry of $\mathbf{Y}$ can be expressed as

$$\begin{aligned} Y(g) &= \frac{1}{\sqrt{N}} \sum_{n=0}^{N-D-1} \frac{|H_n|^2}{|H_n|^2 + \sigma_n^2 / E_s} S(n) \exp\left(-j2\pi \frac{ng}{N}\right) \\ &+ \frac{1}{\sqrt{N}} \sum_{n=0}^{N-D-1} \frac{H_n^*}{|H_n|^2 + \sigma_n^2 / E_s} W(n) \exp\left(-j2\pi \frac{gn}{N}\right) \end{aligned} \tag{17}$$

It follows (3) that (17) can be expressed as

$$\begin{aligned} Y(g) &= \frac{1}{N} \sum_{n=0}^{N-D-1} \frac{|H_n|^2}{|H_n|^2 + \sigma_n^2 / E_s} s(g) \exp\left(-j2\pi \frac{ng}{N}\right) \\ &+ \frac{1}{N} \sum_{n=0}^{N-D-1} \sum_{\substack{i=0 \\ i\neq g}}^{N-1} \frac{|H_n|^2}{|H_n|^2 + \sigma_n^2 / E_s} s(i) \exp\left(j2\pi \frac{n(i-g)}{N}\right) \\ &+ \frac{1}{\sqrt{N}} \sum_{n=0}^{N-D-1} \frac{H_n^*}{|H_n|^2 + \sigma_n^2 / E_s} W(n) \exp\left(-j2\pi \frac{gn}{N}\right) \end{aligned} \tag{18}$$

where the first item represents the desired signal, the second item is the inter-carrier interference (ICI) caused by MMSE equalization and ZS, and the third item denotes the contribution due to AWGN. According to(17), we have

$$E\left(|Y(g)|^2\right) = (\alpha^*)^2 E_s, \tag{19}$$

where $\alpha^* = \frac{1}{N} \sum_{n=0}^{N-D-1} \frac{|H_n|^2}{|H_n|^2 + \sigma_n^2 / E_s}$. Then, based on the methods used in [14], we can obtain the SJNR of ZS-CI/OFDM as

$$\gamma_{\text{ZS-CI/OFDM}} = \frac{\alpha^*}{1-\alpha^*} \tag{20}$$

3.3 SJNR Comparison

According to the analysis in the previous subsections, there exist two factors associate with the jamming needed to be considered, which are the ratio of jamming bandwidth versus total bandwidth, i.e., $\beta = \frac{D}{N}$, and the power of jamming, i.e., σ_J^2. In this paper, we assumed that these two factors can be detected by the jamming detection perfectly.

According to (14) and(20), we presents the numerically SJNR comparison between CI/OFDM and ZS-CI/OFDM receiver in Fig. 3, where JSR= E_s / σ_J^2 is Jamming-to-Signal Ratio. In this figure, the blue plane corresponds to the plane that $\gamma_{\text{ZS-CI/OFDM}} / \gamma_{\text{CI/OFDM}} = 1$.

From Fig. 3, it can then be seen that the curved surface which is above the blue plane illustrates that the SJNR performance of ZS-CI/OFDM receiver is better than that of CI/OFDM receiver. In this case, the influence of power loss at ZS-CI/OFDM receiver due to discarding subcarriers experiencing jamming is less than that of CI/OFDM receiver, at which jamming is spreading over all subcarriers. So, it is evidently that we should choose ZS-CI/OFDM receiver in this case. Otherwise, CI/OFDM receiver is a better choice.

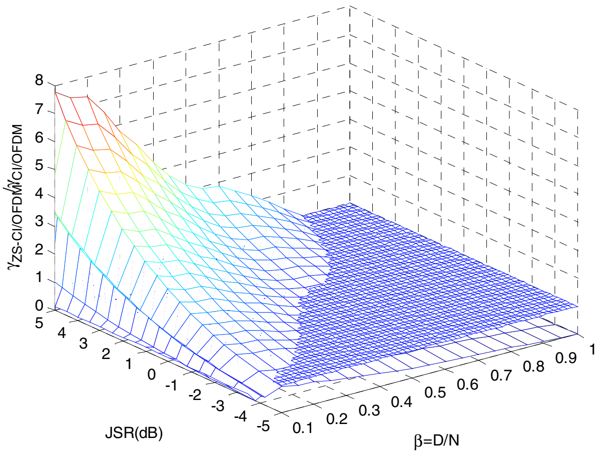

Fig. 3. Comparison of the SJNR between CI/OFDM and ZS-CI/OFDM receivers

4 Adaptive Anti-narrowband Jamming Receiver

According to the results obtained in the above Section, we can find that CI/OFDM and ZS-CI/OFDM receivers can only work well under specified jamming scenarios, respectively. Based on this observation, we propose an adaptive anti-narrowband jamming receiver which can be adjusted to match the narrowband jamming scenarios. In other words, the proposed receiver can make a good tradeoff between the jamming spreading introduced by CI de-spreading in CI/OFDM receiver and power loss due to subcarriers discarding in ZS-CI/OFDM receiver.

The proposed adaptive receiver is presented in Fig. 7. It is the combination of CI/FODM and ZS-CI/OFDM receivers. The key point is that we introduce an adaptive selection between CI/OFDM receiver and ZS-CI/OFDM receiver based on jamming detection.

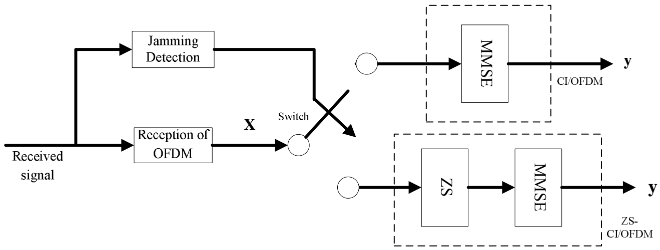

Fig. 4. The adaptive anti-Narrowband jamming receiver

The corresponding selection criterion includes two factors mentioned in the previous section, i.e., the jamming bandwidth ratio β and the jamming power σ_J^2. All of them can be obtained by jamming detection. Obviously, the optimal threshold of β and σ_J^2 should be determined based on Fig. 3. According to Fig.3, we choose ZS-CI/OFDM receiver if (β, σ_J^2) lies in the region that corresponding to $\gamma_{\text{ZS-CI/OFDM}} / \gamma_{\text{CI/OFDM}} > 1$. Otherwise, we choose CI/OFDM receiver.

5 Simulation Results

In this section, we further perform simulations to compare the BER performance of CI/OFDM, ZS-CI/OFDM and adaptive receivers under different jamming scenarios to validate the proposed receiver scheme. The channel models of "COST207TUx6" [15] are adopted in our simulations. In the simulation, Quadrature Phase Shift Keying (QPSK) is used. Signal-to-Noise Radio (SNR= E_s / σ_n^2) is set to be 20dB. The other simulation parameters used are given in Table 1. For the sake of comparison, we also provide the BER performance of OFDM system.

Table 1. Simulation Parameters in "COST207TUX6"

Subcarrier number	1024
Bandwidth	10MHz
Maximum delay	5 us
Guard interval	6.4us
Subcarrier interval	9.8kHz

In Fig. 5, we present the BER versus JSR when β =4% and 8%. It can be seen that the performance of ZS-CI/OFDM receiver is much better than that of CI/OFDM receiver and OFDM if the jamming power is large and the ratio of bandwidth of jamming β is small, i.e. , $\beta = 4\%$. This is because the jamming power is spreading across all N subcarriers due to CI de-spreading and the resulted SJNR is too small to recover the data symbols. Meanwhile, the performance of ZS-CI/OFDM receiver is not relevant to the power of jamming as all the subcarriers experiencing jamming are discarded. The recovery of data can be done by the information spreading over the other subcarriers by CI coding. However, when the jamming bandwidth becomes large, the performance of ZS-CI/OFDM also becomes worse as the power loss due to subcarriers discarding increases at ZS-CI/OFDM receiver. So, the performance corresponding to $\beta = 4\%$ is much better than $\beta = 8\%$.

On the other hand, when the jamming power is relatively small, i.e., JSR<0dB, the performance of CI/OFDM receiver is better than that of ZS-CI/OFDM receiver. This is because that the influence due to jamming power spreading for CI/OFDM receiver is less than the influence due to power loss due to subcarriers discarding for ZS-CI/OFDM receiver. So, by making an adaptive receiver selection, the proposed adaptive receiver achieves the best performance between these two receivers.

Moreover, we find that the performance of OFDM is better than that of CI/OFDM without ZS-CI/OFDM receiver when JSR is relatively large. This because the influence due to jamming power spreading for CI/OFDM receiver is larger than the influence data symbols loss for OFDM in high JSR region. So, CI/OFDM is not always superior to OFDM under narrowband jamming. But the proposed adaptive CI/OFDM receiver can always obtain the best performance.

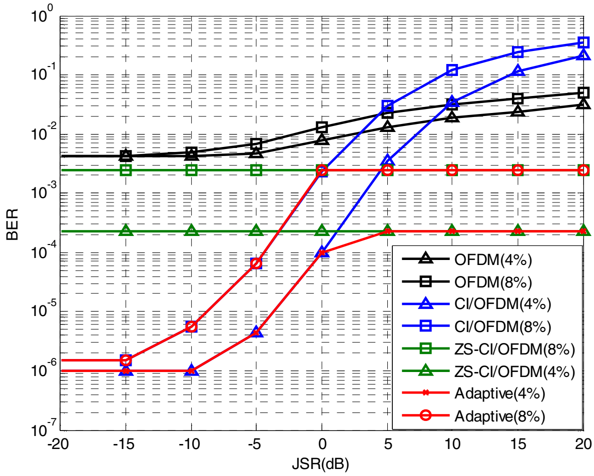

Fig. 5. BER performance comparison under different JSR (β =4% and 8%)

In Fig. 6, we further provide the performance comparison when β =20% and 40%. It can be seen that the advantage of ZS-CI/OFDM does not exist any more due to the loss of signal power and ICI interference caused by the process of ZS, especially when β is relatively large, the data can't be recovered again in the ZS-CI/OFDM system. So, CI/OFDM can not well under the environment with large jamming bandwidth. Even though, the proposed adaptive receiver can still achieve the best performance.

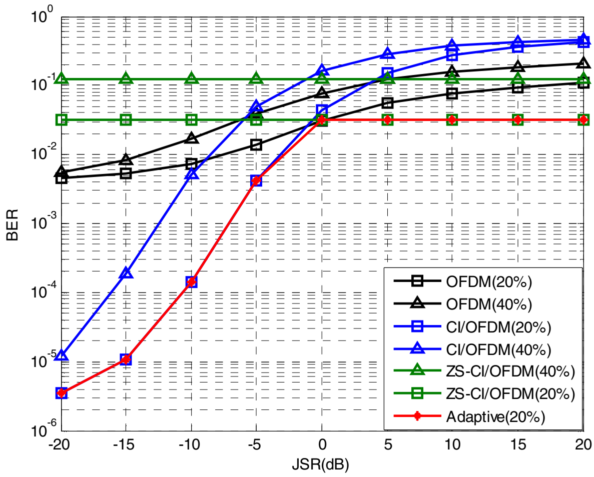

Fig. 6. BER performance comparison under different JSR (β =20% and 40%)

6 Conclusion

In this paper, we investigated the performance of CI/OFDM system with and without ZS-CI/OFDM receiver with MMSE equalization under narrowband jamming. We derived the expression of SJNR and compared the performance of two kinds of CI/OFDM receiver under different jamming scenarios. We find that each scheme can only work well in some specified jamming scenario. Then, we proposed an adaptive anti-narrowband jamming receiver for CI/OFDM system to combine these two receiver schemes so that better performance can be obtained under practical environments. Simulation results validate our proposed receiver scheme.

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