A New Concept of Clipping without Spectrum Broadening for Carrier Interferometry OFDM System

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***Abstract*—This paper proposes a new technique for peak-to-average-power ratio (PAPR) reduction without spectrum broadening for Carrier Interferometry orthogonal frequency division multiplexing (CI/OFDM) system. Recently, Carrier Interferometry (CI) code is becoming an interesting code for reducing the PAPR of OFDM system. However, for guaranteeing the low PAPR as the PAPR of single carrier (i.e. by about 4 - 6dB with *roll-of-factor* of 0.2 - 0.5), we propose low complexity clipping technique for CI/OFDM system. However, it can be easily adapted for other OFDM systems. The main contribution of this paper is the introduction of a new clipping technique with low complexity frequency domain filtering (FDF) which is employed prior to the IFFT. The benefits of the proposed technique are low complexity of FDF and no spectrum broadening. Our results confirm that the PAPR of clipped CI/OFDM can be reduced by about 1dB better than that of the conventional clipped OFDM signals. We clarified that the PAPR is now similar to the PAPR of single carrier system. In the frequency selective fading channel, the bit-error-rate (BER) performance is also improved by about 7dB better than that of the traditional OFDM system due to the frequency diversity benefits in CI/OFDM system.**

***Index Terms* — clipping, spectrum broadening, frequency domain filtering (FDF), carrier interferometry (CI), OFDM, down-sampling**

I. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) has been used for the modulation scheme of terrestrial digital TV broadcasting and is one of the promising techniques for the next generation mobile communications. OFDM multiplexes narrow band and realizes the broadband data transmission by sending the information in parallel mode. OFDM also has superior and unique feature of high frequency efficiency and prevents signal distortion affected by multi-path fading environment. However, it has substantially high peak-to-average power ratio (PAPR) and the transmission performance degrades through the nonlinear channel.

A recent complex spreading code, called Carrier interferometry (CI) code has been introduced in [1] and [2] for reducing the PAPR of OFDM signals. However, the reduction of CI alone is not significant because the PAPR of OFDM by employing the CI codes is only by about 8-9dB. In our work in [3], it is shown that this PAPR level is still higher than the PAPR of single carrier system i.e. 4 - 6dB for *roll-of-factor* of 0.2 - 0.5. In this paper, we intend to use clipping technique due to its simplicity of implementation. Though clipping can reduce PAPR, it affects the unwanted spectrum broadening. Therefore, we performed frequency domain filtering (FDF) as in introduced in [4] and [5].

In this paper, we improve our work in [5] by proposing a new clipping technique without impact of spectrum broadening. The basic principle of the proposed technique is described as follows.

When we remove the spectrum broadening using FDF, in fact we can obtain the same performance using FFT without oversampling by selecting only the odd subcarrier and ignoring the other subcarrier value (especially when oversampling factor L is 2). When L is 4, the same performance can be obtained by selecting only the subcarrier $4n$, $n = 0, 1, 2, \ldots, N-1$ where N is the FFT point. Generally FDF with oversampling factor of L and FFT point of NL, can be performed with FFT point of N and input data selection of Ln, $n=0, 1, 2, \ldots, N-1$.

Because of the FFT point can be reduced by a factor of L, the complexity of our proposal is lower than that of the technique in [4] and [5]. In contrast to the proposal in [5], our clipping technique can be viewed as like clipping before the IFFT of OFDM modulator. As a consequence, no spectrum broadening is introduced by the proposed technique.

In addition, we consider the FFT-based Carrier Interferometry Codes, called CI-IFFT, as introduced in [5]-[8] so that the complexity of our proposed clipping for CI/OFDM can be addressed as a technique with more low complexity design.

Our results clarified that the PAPR performance has been improved and no spectrum broadening is affected by the clipping process. We also show the BER performance result of CI/OFDM and OFDM in additive white Gaussian noise (AWGN) channel and frequency selective fading channel. Both of them show the improvement by about 2dB at bit-error-rate (BER) level of 10^{-5} and 9dB at BER level of 10^{-5}, respectively.

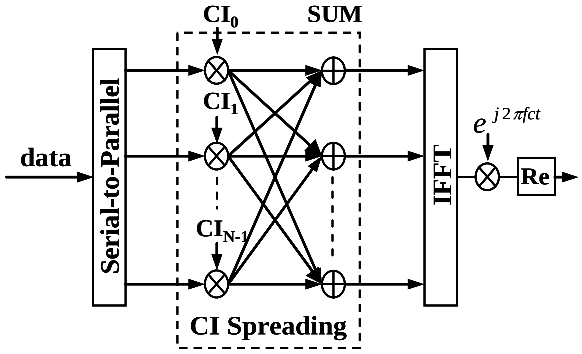


Fig. 1. CI/OFDM transmitter

II. SYSTEM MODEL

The original configuration of CI/OFDM transmitter is shown in Fig. 1. Modulated data are converted from serial to parallel, then spread over N subcarriers using CI spreading codes. The spreading codes of k-th symbol are shown as

$$CI(k,n) = e^{j(2\pi / N)k \cdot n} \tag{1}$$

where k is the number of data symbol and n is the number of subcarrier. In CI/OFDM system, each low-rate symbol stream is spread onto all of the N subcarriers. It is carefully selected to allow symbol stream k to be separable from the other symbols located on identical carriers. The spreading sequence applied to symbol stream k is selected to ensure orthogonality between $K=N$ transmitted symbol streams, even though symbol stream occupy the same carriers at the same time.

The conventional clipping technique with FDF is shown in Fig. 2. After serial-to-parallel conversion, data are spread using CI codes and FFT-ed. We then performed a clipping and FDF for removing the out band noise. Here, the complexity of FDF is high, because the FFT size of the FDF is LN, where L is an oversampling factor. We can observe that $N(L-1)$ data is removed from the FFT of FDF. It is a wasting computation. Starting from this point, we propose how to design an efficient FDF without removing the some output, but performing the same results.

Based on the principle as shown in Fig. 3, we obtain the similar output of IFFT or FFT only by doing a process of selecting the appropriate subcarriers. Then we call it as down-sampling. Suppose that in Fig. 3(a), we have 4 subcarriers and oversampling factor of L = 2. Input data are {D1, D2, …, D8}, while the output are {A, B, C, D, E, F, G, H}. In a FDF, output {C, D, E, F} should be removed because it is an out-band noise. Therefore, the total output are only {A, B} and {G, H}.

However, the same result can be obtained by using the principle as described in Fig. 3(b). We select the input data as {D1, D3, D5, D7} and further it is called as down-sampling. By this selection, though without an oversampling, we can obtain the same output as {A, B, G, H} (only with the different scaling). Based on this principle, we propose the new clipping with non oversampled-FDF but have the same result to that of FDF with oversampling.

The structure of our proposed clipping and non-oversampled-FDF is shown in Fig. 4. After clipping process, we perform a down-sampling with a selection rule as

$$S_{new}[n] = S_{conventional}[Ln] \tag{2}$$

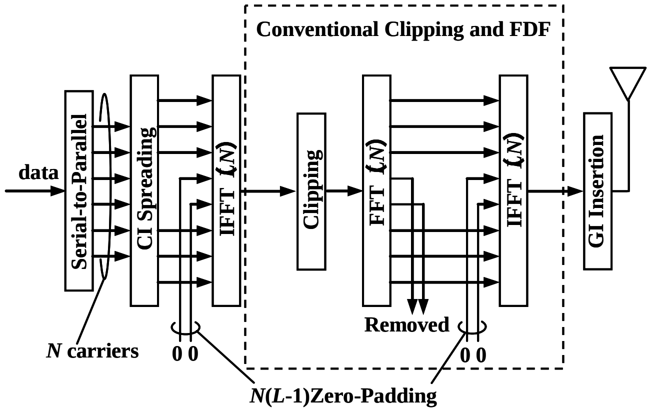
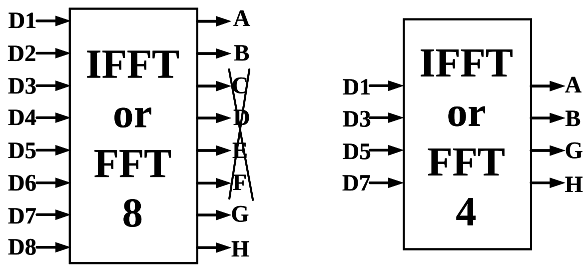


Fig. 2 Conventional clipping technique with FDF



(a). with oversampling (b). without Oversampling

Fig. 3 A principle of reducing the FFT size in FDF

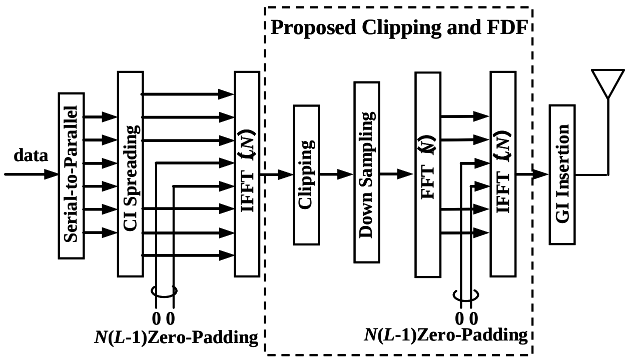


Fig. 4 Proposed clipping technique with new FDF

where n = 0, 1, …, N-1, S_{new} is the input signal with new samples of N and $S_{conventional}$ is the conventional signal with number of sample is LN.

As a consequence, the number of input data of FFT is only N so that the computational complexity of the new FDF is only $N/2\ log_2(N)$, while conventional FDF complexity is $LN/2\ log_2(LN)$. It can be concluded that our proposed clipping with new FDF has the computational complexity of

$$rf = \frac{1}{L \times \left(\frac{\log_2(L)}{\log_2(N)} + 1 \right)} \tag{3}$$

times lower than that of the conventional FDF in Fig. 2. Here, rf is the computational complexity reduction factor with FFT-radix of 2. Because the true PAPR should be computed with oversampling, we insert $N(L-1)$ of zeros to the IFFT at the FDF before guard interval (GI) insertion as shown in Fig. 4. Suppose we have N=64, and L=4, the computational complexity reduction is 81.25%.

III. Clipping and PAPR

PAPR is used as the measure for evaluating peak power of the transmitted signal. Mathematically, PAPR is defined as the ratio between the maximum power and the average power of the transmitted signal and it is expressed as

$$PAPR = \frac{\max_{0<t<ts} |x(t)|^2}{E\left\{ |x(t)|^2 \right\}} \tag{4}$$

where $|x(t)|^2$ is the power of transmitted signal and ts is OFDM symbol duration.

Fig. 5 is the envelope of CI transmit signal from the new design of CI/OFDM in [8]. By carefully observing Fig. 5, when one part of CI signals are added coherently, other parts of signal do not add coherently. This is the main reason why PAPR decreases when CI codes are employed as reported in [3] and [5]-[11].

Let $x(t)$ is a CI/OFDM signal. Considering to the clipping at amplitude A_{max}, we describe the output of the clipped signals as

$$y(t) = \begin{cases} |x(t)|, |x(t)| < A_{\max} \\ A_{\max}, |x(t)| \geq A_{\max} \end{cases} \tag{5}$$

where $y(t)$ is a clipped CI/OFDM signal. In this paper, clipping is considered as a kind of soft limiter, so that does not affect to a phase distortion. We define a parameter called clipping ratio (CR) is in [10] and expressed as

$$CR = \frac{A_{\max}}{\sigma} \tag{6}$$

where σ is a root-mean-square (rms) level of one CI/OFDM symbol. The clipped CI/OFDM signal, *ClippedTX* is then expressed as

$$ClippedTX = CR * Average\ Amplitude \tag{7}$$

If CR increases, the portion of signal which is larger than *ClippedTX* decrease. On the other hand, if CR decreases, the size that the signal is cut-off increase.

Fig. 6 shows CI/OFDM signal before and after clipping with CR=1.2. It is easy to confirm that with this clipping level the maximum peaks are less than 3×10^{-3} (W). If we send the clipped signal just as it is, the spectrum broadening appear. This is the reason of why a filter is required.

IV. MMSE Combiner

To maximize frequency diversity benefits, minimize the noise and restore orthogonality because of multi-path fading effects, a combiner should be performed at the receiver. In additive white Gaussian noise (AWGN) channel, or flat fading channel, the optimal combiner is equal gain combining (EGC).

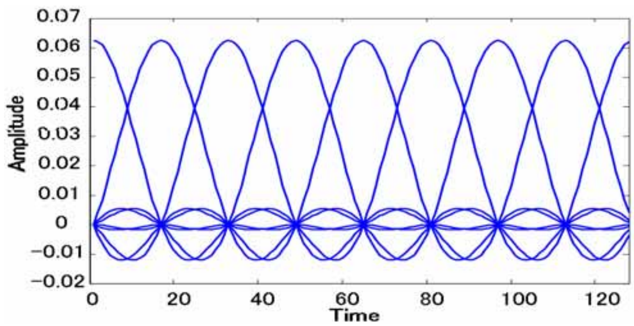


Fig. 5 Envelopes of CI transmit signal

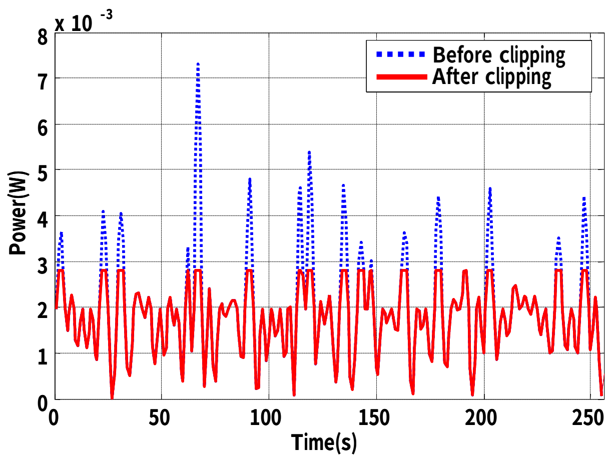


Fig. 6 Power of CI/OFDM signals with original and CR=1.2

However, EGC is not an optimal strategy in frequency selective fading channel. In this paper, we select minimum mean square error (MMSE) combiner [12], an optimum solution for multi-path fading channel. Weighting values are derived from MMSE criteria as

$$W(k) = \frac{H^*(k)}{|H(k)|^2 + \mathrm{var}(N0)} \tag{8}$$

where $H(k)$ is channel impulse response (obtained from channel estimation module, for easy in presentation we assume a perfect channel estimation), $H^*(k)$ is the conjugate complex of $H(k)$, and $var(N0)$ is variance of the noise.

V. Performance Results

In this section, we present the performance results of our proposed technique with the simulation parameters as shown in Table 1. Fig. 7 describes the power delay profile of Bad Urban (BU) COST-207 fading model. Here, *Ts* is the time distance between two samples of the power delay profile.

Fig. 8 shows PAPR performance for CI/OFDM and OFDM systems with only one CR value (CR=1.2). It is clear that with clipping, the PAPR of CI/OFDM is 0.5-1dB better than that of clipped OFDM signals at complementary cumulative distribution function (CCDF) of 10^{-4}. In this figure, PAPR is improved by implementing CI spreading code on OFDM signal.

In Fig. 9, we present the power spectral density (PSD) of CI/OFDM, clipped CI/OFDM, OFDM and clipped OFDM system. We use the *CR*=1.2 for performing the PSD of clipped CI/OFDM and clipped OFDM signals. Obviously, it can be seen the PSD of the clipped CI/OFDM and clipped OFDM is same as that of without clipping. This result confirms that our proposed clipping exactly does not introduce spectrum broadening.

Figs. 10 and 11 describe the BER performance in AWGN and multi-path fading channel. In AWGN channel, BER performance of clipped CI/OFDM is 2dB better than BER of clipped OFDM at average BER level of 10^{-5}. This is because the number of distorted signals in clipped CI/OFDM is smaller because of lower PAPR level.

In Fig. 11, clipped CI/OFDM outperforms clipped OFDM with improvement of 7dB at BER level of 10^{-5}. in the case of without clipping, BER performance of CI/OFDM is 6dB better than that of conventional OFDM system. The reason is the improvement by the frequency diversity of CI spreading codes.

TABLE 1
SIMULATION PARAMETERS

Transmitter	Modulation	QPSK
	Number of Subcarriers	52
	Guard Interval (GI) Length	16
	FFT Points	256
	Oversampling (*L*)	4
	Error coding	Off
	Spreading Code	FFT-based Carrier Interferometry [6]-[8]
	Clipping Ratio (CR)	1.2
Channel	AWGN	
	Bad Urban of COST-207 Fading Model	
Receiver	Combiner	MMSE

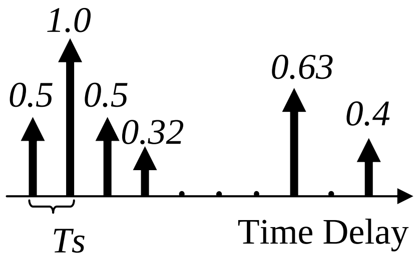


Fig. 7. Power delay profile of Bad Urban (BU) COST-207

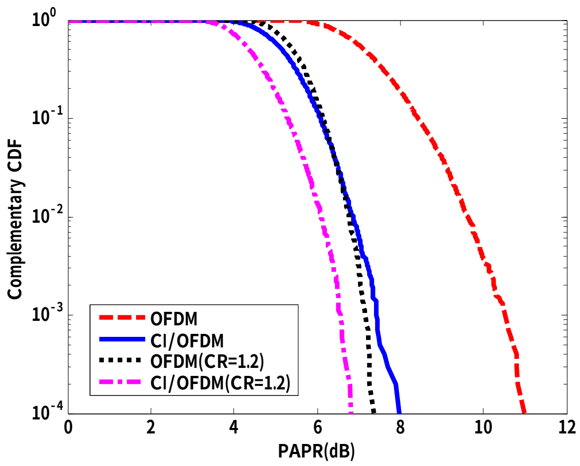


Fig. 8. Complementary CDF (CCDF) of PAPR with clipping (CR=1.2) and without clipping

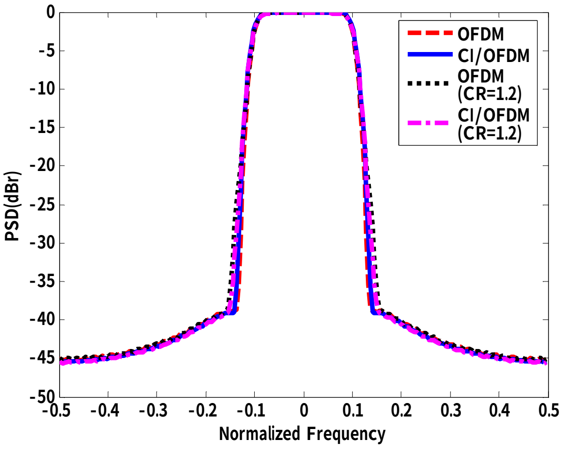


Fig. 9. Power spectral density (PSD) with clipping (CR=1.2) and without clipping

In Fig. 12, we resume the PAPR performance (in dB) for several CR of 0.6, 0.8, 1.0, 1.2, 1.4 and 1.6. It can be seen that PAPR level of clipped CI/OFDM is always lower by about 1dB than the PAPR level of clipped OFDM.

Fig. 13 plots the average of BER performance of the clipped CI/OFDM and clipped OFDM in AWGN and multipath fading channel for several CR of 0.6, 0.8, 1.0, 1.2, 1.4 and 1.6. Both in AWGN and multipath fading channel, clipped CI/OFDM outperforms clipped OFDM significantly. With CR=1.0 in AWGN, BER level of clipped CI/OFDM is 1.3×10^{-4}, while clipped OFDM is 5.2×10^{-4}. Setting CR=1.0 in multipath fading channel, BER level of clipped CI/OFDM is 1.7×10^{-4}, while BER level of clipped OFDM is 1.9×10^{-3}. It is clearly shown that CI/OFDM with clipping can perform both low PAPR and high performance than conventional OFDM.

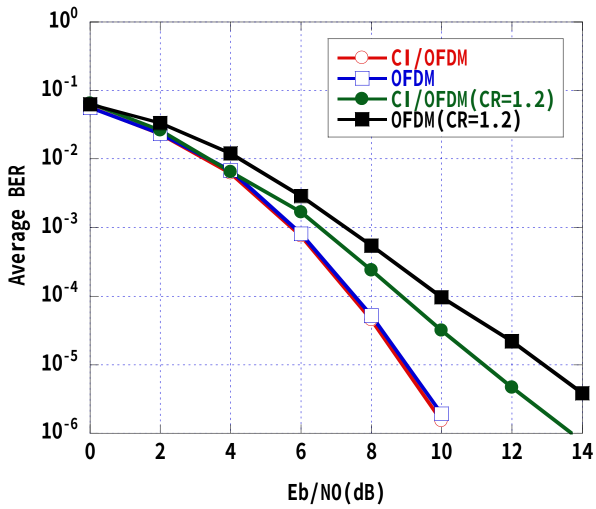


Fig. 10. BER performance in AWGN channel

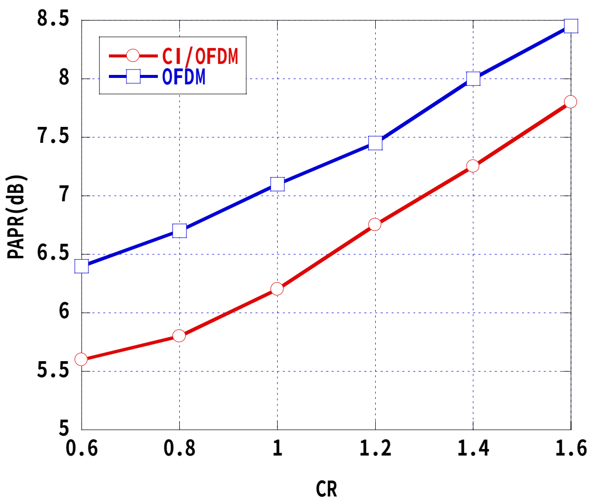


Fig. 12. PAPR level OFDM and CI/OFDM on CDF of 10^{-4} with various CR

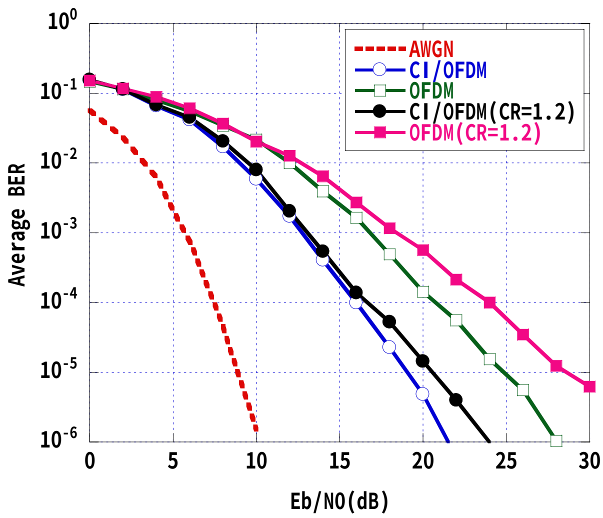


Fig. 11. BER performance in multi-path fading channel

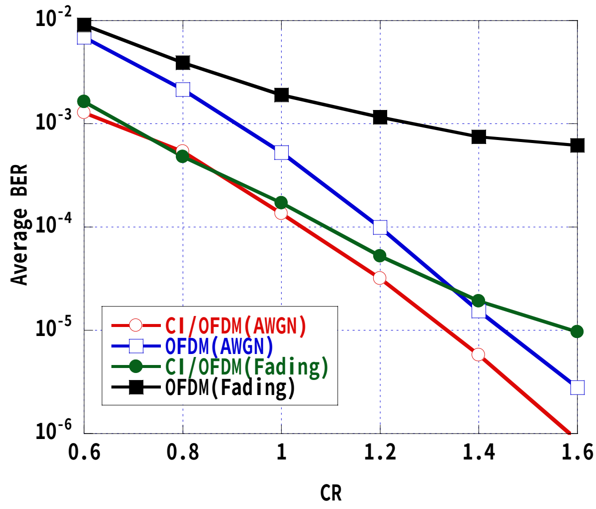


Fig. 13. BER performance of OFDM and CI/OFDM with various CR

VI. CONCLUSIONS

A new concept of low complexity clipping without spectrum broadening has been proposed. In this proposal, we perform clipping and new frequency domain filtering (FDF), so that no spectrum broadening is introduced by the clipping. Computational complexity of our proposed FDF is only $N/2 \log_2(N)$ while the complexity of the conventional FDF is $NL/2 \log_2(LN)$. By this new FDF, we can reduce the computational complexity of the conventional FDF by about 81.25% on N=64 subcarriers with oversampling factor of L=4. We obtained PAPR improvement by about 1dB better than that of traditional OFDM without CI spreading codes at CR=0.6-1.6. Here, we obtain the PAPR of clipped CI/OFDM similar to the PAPR level of single carrier system with roll-of-factor of 0.2, i.e. PAPR level is by about 6dB at CCDF of 10^{-4}. The BER performance of clipped CI/OFDM is improved by about 2dB in AWGN channel and 7dB in frequency selective fading channel at average BER level of 10^{-5} when compared to the clipped of traditional OFDM signals.

ACKNOWLEDGEMENT

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