



Linear Companding Scheme to Reduce PAPR and Spectral Regrowth in T-OFDM System with HPA

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Abstract:

As illustrated in literature, T-OFDM achieved a lower clipping probability and reduces the side-lobe values of the autocorrelation function of the input vector then suppressing the high peak power of the transmitted samples with non-Gaussian distribution. Moreover, the high diversity features of the proposed structure led to substantial improvements in the system performance with frequency selective fading channel. Nevertheless, peak reduction is decreased with the Gaussian distribution of subcarrier numbers, as well as, the in-band distortion is susceptible to non-linearity of high power amplifiers (HPAs). Consequently, the smaller clipping probability and lower block error rate characteristics of T-OFDM are embedded with a new linear companding (LC) technique to construct a structure of T-OFDM-LC system. In the proposed T-OFDM-LC scheme, low-amplitude samples are enlarged, while high-amplitude samples are compressed linearly in the time domain. This linear amplitude transformation is designed to reduce the peak-to-average power ratio (PAPR) while preserving the average power of the transmitted signal. The proposed T-OFDM-LC system acquires preferable achievement in PAPR reduction and spectral regrowth decreasing comparable with the T-OFDM system when using under the negative ramification of HPAs.

Keywords:

Bit error rate (BER); High power amplifier (HPA); Linear Companding; Orthogonal frequency division multiplexing (OFDM); Peak to average power ratio (PAPR); OFDM with T-transform (T-OFDM)

Highlights:

- A new linear companding technique was presented.
- PAPR reduction BER performance over frequency selective fading channel of T-OFDM with linear companding were presented.
- The effect of HPA was considered by using SSPA.

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1. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is a modulation technique that has been adopted with a numerous high bits rate wireless communication systems. However, the widely emerging of OFDM systems have been impact with some challenges issues such as high pea to average power ratio (PAPR) and low immunity against high dispersive channel. The high PAPR can drive the transmitted signal into the nonlinear operating region of the high-power amplifier (HPA), resulting in signal distortion [1-3]. In the sequel, many approaches have been developed to reduce the negative impact of high peak power and suppressed performance of OFDM signals in frequency selective fading channel with trade-off high complexity, bandwidth losses and performance distortion. Basically, PAPR reduction methods can be classified into two major categories: distortionless techniques, such as precoding techniques [4-11], selective mapping (SLM), and Partial Transmission Sequence (PTS) [12-15], and distortion-based techniques, such as nonlinear companding [16-21], iterative clipping and filtering [22, 23]. Based on precoding schemes, [4-9] proposed new algorithms of joint Walsh-Hadamard, Cosine and Haar transforms with IFFT to construct single unitary transforms, which give lower PAPR and better bit error rate (BER) performance. As shown in [5, 6], T-OFDM is an attractive technique that achieved an outstanding BER performance over frequency selective fading channel and a noticeable PAPR reduction comparing with the conventional OFDM. In contrast, nonlinearity of HPA caused a deleterious in-band distortion on the transmitted samples of T-OFDM. Therefore, in order reduce such a degradation in BER performance of T-OFDM system the high peak power need to be clipping. In this work, a new linear companding (LC) technique is utilized with T-OFDM to acquire more PAPR reduction and to diminish the in-band distortion resulting from the nonlinearity effect of HPA. The

proposed T-OFDM-LC technique achieves a noticeable PAPR reduction further to attractive BER performance improvement even in the presence of HPAs. The rest of this paper is organized as follows. Section 2 addresses block-diagram and signal analysis of the proposed system. Section 3 quantifies the PAPR and spectral efficiency of T-OFDM with linear companding. In Section 4, a novel linear companding technique which is related to the proposed structure is stated. Simulation results are illustrated in Section 5. Lastly, section 6 mentions the conclusions of this work.

2. PROPOSED T-OFDM-LC SYSTEM DESCRIPTION

As a consequence of the superposition of set of modulated signals through the IFFT, one of the main disadvantages of utilizing OFDM system is the PAPR. Despite the low probability of such superposition, these large peaks negatively affect overall system performance. Additionally, the nonlinearity of the HPA causes distortion, resulting in both in-band distortion and out-of-band radiation [24]. Thus, the proposed T-OFDM-LC system merges the T-transform's advantages with a novel LC technique to eliminate the deleterious effect of non-linearity of HPAs. Figure 1 depicts the main parts of T-OFDM-LC schemes.

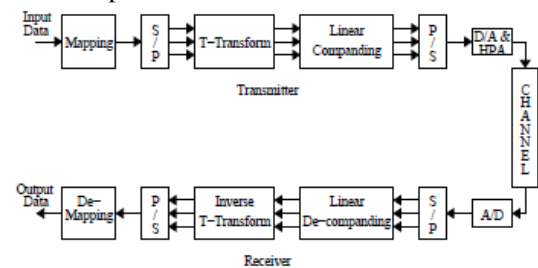


Fig. 1 T-OFDM-LC Block Diagram.

As observe in Fig. 1, modulated symbols are penetrated into T-transform (which described in details in [4] as the combination of WHT and IFFT characteristics). Consequently, the output data sequences of T transform are computed as:

$$x(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} \sum_{m=0}^{N-1} X(m) e^{j\pi \left(\left(\sum_{s=0}^{N-1} m_s n_s \right) + \frac{2nk}{N} \right)} \quad (1)$$

Where, $\frac{1}{\sqrt{N}}$ is the normalization value with data size equal to N, X is the transmitted samples in frequency-domain. After LC, x signals are feed into digital-to-analog (D/A) converter and HPA then transmitted over the channel. By considering the effect of both additive white Gaussian noise (AWGN) and fading channel, the received samples can be computed as $r(t) = x(t) \otimes h(t) + w(t)$, where $h(t)$ is the channel

impulse response (CIR), $w(t)$ is the AWGN noise, and $\otimes$ denotes circular convolution.

At the receiving end, the samples should be de-companded first according to the criteria which will illustrated in section IV to acquire the de-companded samples $r'(t)$. Then, $r'(t)$ feeds into inverse T transform to obtain the signal in dyadic-domain. As a result, the resultant samples can be expressed as:

$$Y(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} \sum_{m=0}^{N-1} r'(m) e^{j\pi \left(\left(\sum_{s=0}^{N-1} m_s n_s \right) - \frac{2nk}{N} \right)} \quad (2)$$

Accordingly, it still needs to be equalized. Thus, channel equalization in the proposed T-OFDM-LC system are performed in dyadic domain. Consequently, based on dyadic convolution theorem [25], the channel equalization in T-OFDM-LC system is performed as:

$$Y'(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} Y(n \oplus k) E_q(n) \quad (3)$$

Where, $n \oplus k$ denotes the bitwise X-OR, Y is the output sequence of inverse T-transform, and E_q is the equalizer samples that can be computed in dyadic-domain as:

$$E_q(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} Q(k) W(n, k) \quad (4)$$

where, W is the Walsh-Hadamard matrix with n and k index, and Q is an optimization values based on either minimum mean square error (MMSE) or Zero-Forcing (ZF) criterion. Although an equalizer is used in such a system in the Walsh-Hadamard domain, it can be utilized before inverse T-transform (in time domain) by accomplishing a linear convolution among the received signals in time domain and the impulse response of the equalizer sequence.

3. QUANTIFYING THE PAPR AND SPECTRAL EFFICIENCY OF THE PROPOSED T-OFDM-LC SYSTEM

Basically, MC criterion is based on the carrying symbols over N subcarriers. Consequently, each of the N output samples from IFFT operation involves the superposition of N complex samples. Based on the central limit theorem, particularly for large N , the resulting output can be regarded as a complex Gaussian distributed variables with variance $\sigma^2 = |x(k)|^2/2$. Thus, the characteristic function of $x(k)$ is $\psi(jv) = e^{-(1/2)v^2\sigma^2}$, where v is real. The IFFT of this characteristic function yields the probability density function (PDF) of $x(k)$ as:

$$Pr(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{|x|^2}{2\sigma^2}} \quad (5)$$

Moreover, the Rayleigh distribution is commonly utilized to obtain modeling signal

statistics. Such a distribution employs close relationship with the central chi-square distribution, that is derived from Gaussian-distributed variables. Thus, the PDF of Rayleigh distribution signal is:

$$Pr(x) = \frac{x^2}{2\sigma^2} e^{-\frac{x^2}{2\sigma^2}} \quad (6)$$

In general, the PAPR of the transmitted signal can be defined as [4]:

$$PAPR[x(k)] = \frac{\max_{0 \leq t \leq N-1} |x(k)|^2}{E[|x(k)|^2]} \quad (7)$$

where, $E[.]$ represents the expectation operator $\{E[x] = \int_{-\infty}^{\infty} x Pr(x) dx\}$ which can be computed in the frequency domain because IFFT is a unitary transform, and N is the subcarriers number. The PDF or the synonym cumulative distribution function (CDF) is the statistical description of the PAPR which is commonly used essentially when the theoretical maximum PAPR value occurs. Consequently, CDF of the signal $x(k)$ is $CDF(x) = \int_{-\infty}^x Pr(u) du = 1/2 \left(1 + \operatorname{erf}\left(\frac{x}{\sqrt{2}\sigma}\right)\right)$, with Gaussian distribution

and $CDF(x) = 1 - e^{-\frac{x^2}{2\sigma^2}}$ with Rayleigh distribution, where $\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$.

Almost, complementary cumulative distribution function (CCDF) is commonly evaluated as $CCDF(x) = 1 - CDF(x)$. As shown in Fig. 4 and sustained in [4], employing T-transform with OFDM system reduces the values of the side-lobe of the autocorrelation function of the input vector. Thus, the sequence with low out-of-phase periodic correlation values can be used to construct low-peak factor signals (i.e. reducing the PAPR of the system).

On the other hand, in order to quantify the performance of ZF combiner in fading channels, average BER computed by first finding the BER conditional on the subcarrier numbers equal to Walsh length. Following [4], the conditional BER of QPSK can be computed as:

$$Per_{QPSK}(n) \{BER\}_{\{h_i(n)\}_i}^N = \eta_1 Q(\sqrt{2\eta_2\gamma}) \quad (8)$$

Where η_1, η_2 are the normalization values, the Q-function is defined as $\{Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-\frac{t^2}{2}} dt\}$, $h_i(n)$ is a slowly varying frequency selective Rayleigh fading channel response and γ is the instantaneous signal-to-interference plus noise power ratio (SINR) at the output of ZF combiner. Assuming free inter-carrier interference ($\sigma_{ICI}^2 = 0$), thus the value of SINR with QPSK modulation is computed as:

$$\gamma(n) = \frac{E_c (\sum_{i=1}^N h_i(n) E_{q_i}(n))^2}{(N_0 \sum_{i=1}^N |E_{q_i}(n)|^2)} \quad (9)$$

Where E_c is the average energy per chip, N is the subcarrier number which is equal to Walsh-

Hadamard size, E_q is the ZF combiner values, and N_0 is the noise power. Substituting (4) into (9) as:

$$\gamma_{ZF}(n) = \frac{E_c}{\frac{2N_0}{N^2} \sum_{i=1}^N \left(\frac{1}{|h_i(n)|^2}\right)} \quad (10)$$

By substituting (10) into (8), the conditional BER of the signal is equivalent to:

$$Per_{QPSK,ZF}(n) = \eta_1 Q\left(\sqrt{\frac{\eta_2 E_c}{\frac{2N_0}{N^2} \sum_{i=1}^N \left(\frac{1}{|h_i(n)|^2}\right)}}\right) \quad (11)$$

Due to the effect of frequency selective fading channel, each subcarrier has a different BER. In

order to mitigate this phenomenon, the proposed scheme has been employed to minimize the influence of deep fading on certain subcarriers. This reduction comes from the effect of high diversity characteristics of the proposed T-OFDM-LC structure.

4. PROPOSED T-OFDM-LC ALGORITHM

T-OFDM system is an attractive scheme due to its outstanding performance (including BER and PAPR reduction), further to the simple of implementation regardless the number of subcarriers and the modulation type. Furthermore, there is no any bandwidth expansion. However, the elements with Gaussian distribution are increased as a consequence of increasing the number of subcarriers with high data rate systems, while the numbers of non-Gaussian elements remain the unchanged. In the sequel, the overall distribution of T-OFDM system will be closer to Gaussian distribution which is by default more analogous to probability of the traditional system. Eventually, the high peak power of the

T-OFDM signals will be clipped when passing through HPA. Such a clipping fades the signal power and produces a distortion in both in and out of band. As a result, performance of T-OFDM system will be degraded seriously. Therefore, the proposed LC technique utilizes to acquire more PAPR reduction in the T-OFDM system as well as increasing resilience of small power samples against the deleterious effect of noise. By using the proposed LC technique, the amplitude of the output signals for each branch in T-Transform is either enlarged or compressed before fed to the digital-to-analog (D/A) converter then amplified by a HPA. The linear companding technique is based on compressing the large signal while enlarging the small signal linearly for each unit of T-OFDM. The design criteria for the linear companding technique are given as:

- Computing the amplitude and phase of T-transform output signal in (1) for each unit as:

$$|x(k)_U| = \sqrt{(\Re(x(k)_U))^2 + (\Im(x(k)_U))^2}, U = 1 \dots \log_2 N - 1 \quad (12)$$

$$\phi(k)_U = \arctan \left(\frac{\Im(x(k)_U)}{\Re(x(k)_U)} \right) \quad (13)$$

where, N is the length of data frame, U is the number of uncorrelated T transform unit that computed vertically, k is the number of symbols per each unit, and $\Re$, $\Im$ are the real and imaginary values of $x(k)$.

- Selecting the maximum and minimum power in each unit of T transform. That is,

$$l_{max,U} = \arg \max |x(k)|^2 \quad (14)$$

$$l_{min,U} = \arg \min |x(k)|^2 \quad (15)$$

- Calculating the mean of power for selected values in each unit and evaluate the new companding values of power as:

$$mean_U = \frac{|x(l_{max,U})|^2 + |x(l_{min,U})|^2}{2} \quad (16)$$

$$\mu_U = \frac{|x(l_{max,U})|^2}{mean_U} \quad (17)$$

$$\begin{aligned} P(l_{max,U})_{compressing} &= P(l_{min,U})_{expanding} \\ &= mean_U \end{aligned} \quad (18)$$

- Evaluating the new complex values of transmitted signal as:

$$x(l_{max,U}) = \sqrt{P(l_{max,U})_{compressing}} e^{j\phi(l_{max,U})} \quad (19)$$

$$\begin{aligned} &x(l_{min,U}) \\ &= \sqrt{P(l_{min,U})_{expanding}} e^{j\phi(l_{min,U})} \end{aligned} \quad (20)$$

- Computing the side information for each unit which has to transmit (suppose optimal transmission) to the receiver:

$$S_U = [l_{max,U}, l_{min,U}, \mu_U] \quad (21)$$

Thus, the size of side information for each frame with N subcarriers is:

$$S_{frame} = 3(\log_2 N - 1) \quad (22)$$

At the receiving end of the de-companded block in Fig. 1 and according to the same criteria of transmitter, the received symbols have to be de-companded by:

- Computing the mean of received signal power which has been selected depending on the side information and de-companding as:

$$mean'_U = \frac{|r'(l_{max,U})|^2 + |r'(l_{min,U})|^2}{2} \quad (23)$$

$$\begin{aligned} P'(l_{max,U})_{de-compressing} &= \mu_U * mean'_U \end{aligned} \quad (24)$$

$$\begin{aligned} P'(l_{min,U})_{de-expanding} &= mean'_U (2 - \mu_U) \end{aligned} \quad (25)$$

- Evaluating the output signal of de-companding block as:

$$x'(l_{max,U}) = \sqrt{P'(l_{max,U})_{de-compressing}} e^{j\phi'(l_{max,U})} \quad (26)$$

$$x'(l_{min,U}) = \sqrt{P'(l_{min,U})_{de-expanding}} e^{j\phi'(l_{min,U})} \quad (27)$$

These signals will pass to inverse T-transform to turn back the constellation symbols.

It interesting to mention, if we need more PAPR reduction, more iterations of LC will be

performed with a trade-off of increasing the side information.

5.SIMULATION RESULTS AND DISCUSSION

5.1.T-OFDM without Linear Companding Technique

Figure 2 shows the CCDF of the T-OFDM, and the conventional OFDM systems with different data size. Due to lower superposition of T-OFDM, the values of the autocorrelation function side lobe are decrease. As a result, the T-OFDM signals have lower PAPR than OFDM signals. As clearly shown, 12dB PAPR reduction is achieved by using T-OFDM instead of the traditional OFDM system. However, with high data rate systems that require more subcarriers, the clipping probability of the T-OFDM system increases and moves closer to Gaussian distribution of OFDM system. Therefore, adopting new scheme with T-FDM system in

order to achieve more PAPR reduction is crucial. Figure 3 depicts that the BER performance of T-OFDM outperforms outstandingly that of traditional OFDM in the frequency selective fading channel with quadrature phase shift keying (QPSK) modulation. It should be noticed that at low signal-to-noise ratio (SNR), the performance of T-OFDM system will worse lower than that of conventional OFDM. In contrast, at high SNR and owing to the frequency spreading property, T-OFDM system performance outperforms that of OFDM system by 7dB. This issue arises because, in a Rayleigh fading channel, there exists an optimal distribution of the total received SNR among the diversity signals. Consequently, the curve of conventional OFDM crosses the curve for the T-OFDM system, which has high diversity, in the low SNR region.

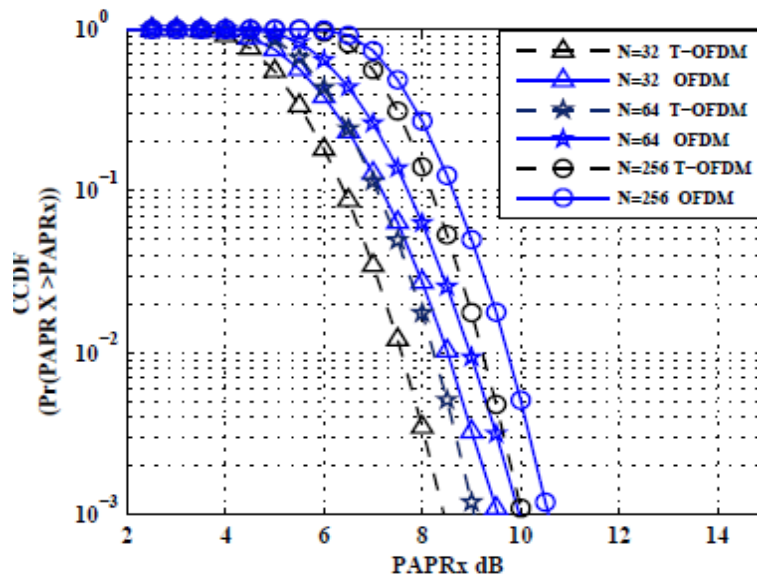


Fig. 2 CCDF for T-OFDM and OFDM Systems with Different Data Size.

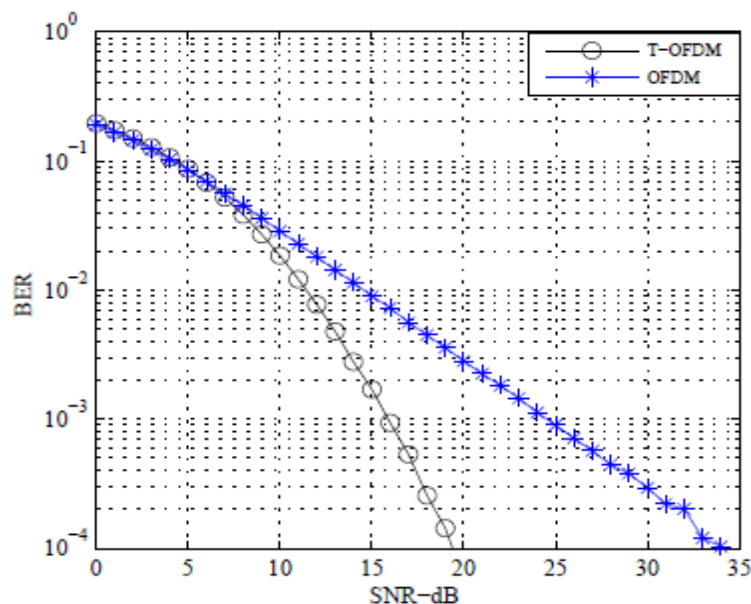


Fig. 3 BER for T-OFDM, and Conventional OFDM, with SSPA, QPSK and Rayleigh Fading Channel.

5.2. T-OFDM with Linear Companding Technique

Practically, HPAs, such as solid-state power amplifier (SSPA) [24] are used with radio transmission systems. In this work, the parameters of SSPA have been set to be the typical value ($P=2$ and $A_s=1.25$). Figure 4 compares the CCDF of transmitted signals for the proposed T-OFDM-LC, T-OFDM and the traditional OFDM systems. As clear from this figure, T-OFDM-LC achieves a noticeable about 3.5 dB and more than 2 dB of PAPR reduction comparing with the conventional OFDM and T-OFDM systems, respectively. This reduction comes from the ability of the proposed LC technique to clip the peak values of the transmitted signals further to the reduction of

the peak power that essentially results from reducing the superposition of the transmitted samples by using T-transform. Consequently, T-OFDM-LC is an efficient approach to provide lower peak power while maintaining the average power. Figures 5 and 6 illustrate the BER performance of the proposed T-OFDM-LC system comparing with the T-OFDM and traditional OFDM systems over multipaths fading channel with QPSK and 16-QAM modulations, respectively, and the presence of SSPA. Apparently, the T-OFDM-LC outperforms other systems as a consequence of its ability to eliminate the nonlinear effect of HPA by reducing the peak power of the transmitted signal further to the spreading features of T-transform.

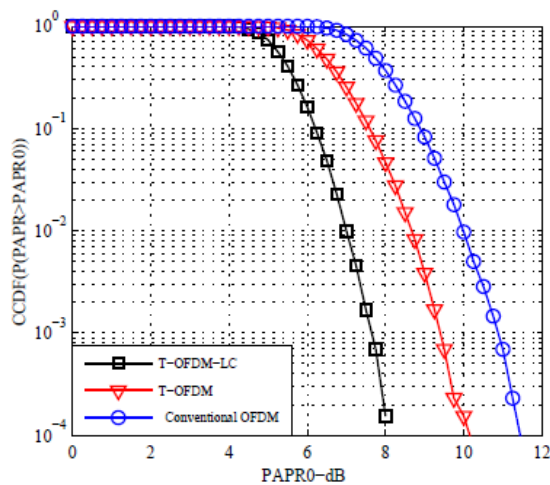


Fig. 4 CCDF for Proposed T-OFDM-LC, T-OFDM, and Conventional OFDM.

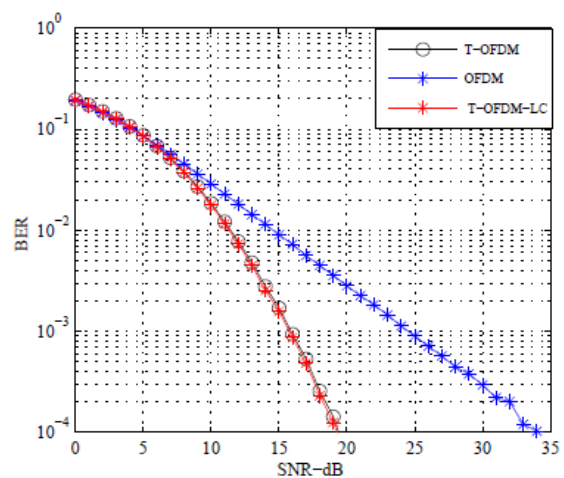


Fig. 5 BER for T-OFDM-LC, T-OFDM, and Conventional OFDM, with SSPA, QPSK and Rayleigh Fading Channel.

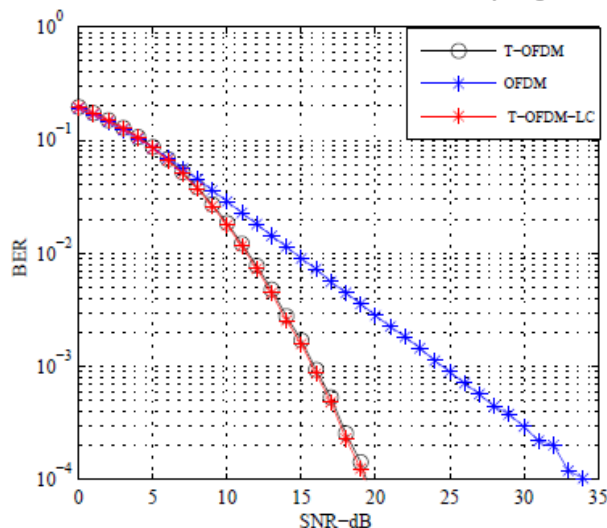


Fig. 6 BER for T-OFDM-LC, T-OFDM, and Conventional OFDM, with SSPA, 16-QAM and Rayleigh Fading Channel.

6. CONCLUSION

The proposed T-OFDM-LC scheme that utilized T-transform with a novel linear companding (LC) technique achieved attractive BER performance even with the presence of HPAs and an outstanding PAPR reduction. Thus, it

can be adopted in the multicarrier communication systems. The proposed T-OFDM-LC system eliminated the deleterious effect of the HPAs nonlinearity by reducing the peak power that inherited in the transmitted signal of OFDM further to reduce the factual

influence of fading channel on the performance of such a system. The proposed T-OFDM-LC schemes achieved an efficient PAPR reduction technique (about 8dB) with the same average power in the transmitted signals further to its dexterous structure to combat the HPAs in-band signal distortion particularly with frequency selective fading channels.

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