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PAPR REDUCTION IN ACO-OFDM FOR VISIBLE LIGHT COMMUNICATION SYSTEM

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Abstract

Visible Light Communication (VLC) is gaining popularity in optical wireless. In conventional OFDM, bi-polar signals having both positive and negative values are considered. However, in optical OFDM uni-polar signals, which have only positive values, are used. Therefore, suitable changes have to be done in conventional OFDM to make it compatible with O-OFDM. These modifications lead to the generation of asymmetrically clipped optical Orthogonal Frequency Division Multiplexing (ACO-OFDM) technology. In ACO-OFDM systems Peak to Average Power Ratio (PAPR) is a detrimental effect and should be suppressed. In ACO-OFDM, the estimation of probability density function (pdf) is not straightforward; therefore, a very limited literature is available. In this paper, an attempt is made to estimate pdf and Complimentary Cumulative Distribution Function (CCDF) expression for an ACO-OFDM with intensity modulation and direct detection (IM/DD), and its validity is checked by using simulation results. For ACO-OFDM scheme PAPR reduction methodology is used by applying various clipping strategies along with non-linear μ-law companding scheme. The results presented in the paper are obtained through computer simulation using MATLAB software. As clipping increases Bit Error Rate (BER), therefore, at various clipping mechanism BER are also obtained. It has been found, that by choosing suitable clipping along with non-linear companding scheme, PAPR can be reduced significantly while maintaining reasonable good BER performance. It is found, that with the proposed technique, PAPR is reduced by 76.10% as compared to raw ACO-OFDM.

Keywords: ACO-OFDM, BER, CCDF, O-OFDM, PAPR, pdf.

1. Introduction

Visible Light Communication is emerging as a promising solution for indoor wireless communication. In VLC as a transmitter, LED is used. The use of LED in VLC provides two principal benefits; one is the illumination of the local area and other as a communication device. The main advantages are low cost, simple in implementation, good BER performance and no electronic interference. The only problem with LED is the limited modulation bandwidth; therefore, transmission data rate is limited. To enhance data transfer rate O-OFDM can be used. In traditional communication, OFDM is used efficiently. In RF communication, both bi-polar and complex-valued signals are coherently transmitted [1-3]. In VLC, intensity modulated direct detection (IM/DD) is used to generate a non-negative real signal through LEDs [4, 5]. Therefore, the RF-based system cannot be directly applied to the VLC system. In order to overcome the negative values, DC biased is added. The value of DC is chosen such that the minimum value is zero. Therefore, all the signals values are now either positive or zero. The OFDM, which is now obtained as a result, is known as DCO-OFDM. In the second approach, negative values are clipped and this approach is known as Asymmetric Clipped Optical OFDM (ACO-OFDM) [5]. In O-OFDM systems, ACO-OFDM is preferred over DCO-OFDM due to less power requirement and in ACO-OFDM, only odd–sub-carrier are transmitted, therefore, it is less vulnerable to noises. In ACO-OFDM, as a negative part of the signal is clipped and only odd sub-carriers are transmitted, therefore, total signal power reduces, and in turn BER increases.

In this paper, an attempt has been made to model CCDF function for ACO-OFDM, along with PAPR reduction analysis. Pdf and CCDF estimation are important in studying the performance of OFDM system at various power levels and more general in the estimation of BER performance. As the clipping of signal increases the BER, therefore, in this work, three types of clipping schemes are considered in association with the μ-law companding technique to obtain lower PAPR with a reasonably good BER performance.

2. Related Works and Preliminaries

VLC based O-OFDM is a novel area of research, especially, DCO and ACO-OFDM and therefore, the available literature are limited [6-10]. Dissanayake and Armstrong [6] performed the comparison of ACO-OFDM and DCO-OFDM. According to Armstrong and Schmidt [7], a performance comparison of these two techniques in presence of Added White Gaussian Noise (AWGN) noise is illustrated. Dissanayake et al. [8] proposed a simultaneous transmission of these techniques. Mossaad et al. [9] proposed the use of ACO-OFDM in Visible Light Communication, while Wang et al. [10] presented the PAPR reduction technique in the VLC application. Probability density function estimation is an open area in both OFDM and O-OFDM; still in case of conventional OFDM system Rayleigh distribution is close to simulated results. van Nee and Prasad [11], the researcher, developed an approximation to address the probability of PAPR by approximated N subcarriers and a factor α for oversampling distribution, and they mention that when $\alpha = 2.8$ is the best value to reach better PAPR when the number of subcarriers follow $N \geq 64$ as it is very cumbersome to obtain exact power distribution.

In both conventional OFDM and ACO-OFDM for PAPR, reduction both clipping non-linear companding techniques are separately proposed [12-16]. In the similar direction, piecewise companding function for the distribution of modulus of amplitude is presented in [12], and they obtained a minimum PAPR of 2.5 dB in case of conventional OFDM. Jiang et al. [17] attempted to model pdf and CCDF functions ACO-OFDM, but the accuracy of the proposed function is limited. Zhang et al. [18] recently proposed a PAPR reduction method based on Toeplitz matrix based Gaussian blur method. In this method, the Gaussian kernel is convolved with ACO-OFDM signal and resulting signal is formed as a Toeplitz matrix whose elements are Gaussian random with zero mean and variance. In this method, lesser numbers of sub-carriers are transmitted, therefore, PAPR reduces. For more details, readers can refer to [18]. In this method, with the Crest Factor (CF), which is the ratio of peak power to the average power of the signal of 0.8, PAPR is nearly 10 dB.

Zhang et al. [18] work is compared to the work proposed in this paper, a hybrid companding scheme, which is proposed to reduce PAPR while maintaining BER and from the obtained results, it is found that our results are better in comparison to the earlier work.

2.1. Basic OFDM

In OFDM bitstream first mapped into a complex value signal vector, $S = [S_0, S_1, ..., S_{N-2}, S_{N-1}]^T$, where N is the number of sub-carriers, which is transmitted in parallel. In the discrete time domain, the nth IFFT symbol is given by:

$$s_n = \frac{1}{N}\sum_{k=0}^{N-1} s_k . \exp\left(j\frac{2\pi nk}{N}\right), \quad n = 0,1,..., N-1 \tag{1}$$

For $N \geq 64$, then symbols are random variables, which are independent and identically distributed. Using the result of the famous central limit theorem (C.L.T.), the real and imaginary parts of the symbols follow Gaussian distribution each having mean zero and variance σ^2. Considering, $z = x + iy$, where x, y are Gaussian distributed having pdf.

$$f_X(x) = \frac{1}{\sqrt{2\pi\sigma^2}}\exp\left(-\frac{x^2}{2\sigma^2}\right) \text{ and } f_Y(y) = \frac{1}{\sqrt{2\pi\sigma^2}}\exp\left(-\frac{y^2}{2\sigma^2}\right)$$

and respectively.

$|z| = \sqrt{x^2 + y^2}$, then the joint pdf is given by:

$$f_{|Z|}(z) = \frac{2z}{\sigma^2}\exp\left(-\frac{z^2}{2\sigma^2}\right), z \geq 0 \tag{2}$$

This pdf is known as Rayleigh distribution. The cumulative distribution function $|z|$ is given by:

$$F_{|Z|}(z)=\int_0^z \frac{2y}{\sigma^2}\exp\left(-\frac{y^2}{2\sigma^2}\right)dy=1-\exp\left(-\frac{z^2}{2\sigma^2}\right), z\geq 0 \tag{3}$$

The experimental verification of the above pdf is shown in Fig. 1. In pdf creation, N (bin) is considered to be 4096. Here, both the real, Fig. 1(a), and imaginary parts, Fig. 1(b), of distribution follow a Gaussian distribution with mean value zero. It is also shown that the modulus of total distribution follows Rayleigh distribution, Fig. 1(c). It is also noted that the fitted curve (shown with red colour) exactly pass through the middle point of each bin histogram, therefore, fitting is exact. In OFDM, system PAPR of a particular block is defined by:

$$PAPR_S=\frac{\max(|s_n|^2)}{E(|s_n|^2)}, 0\leq n\leq N-1 \tag{4}$$

Assuming the average power of $|s_n|$ is equal to one, i.e., $E(|s_n|^2)$. Then $\{z_n\}$ has the pdf.

$$f_{|Z_n|}(z)=2z\exp\left(-z^2\right), n=0,1,2,...,N-1 \tag{5}$$

$E\left(|Z_n|^2\right)=2\sigma^2=1$. The maximum value of $\{Z_n\}$ is equal to Crest Factor and defined by $CF=\sqrt{PAPR}$. Assume that the maximum value of the Crest Factor of $\{Z_n\}$ is defined as Z_{max} and CDF is given by:

$$\begin{aligned} F_{Z_{\max}}(z) &= P(Z_{\max}<z) \\ &= P(Z_0<z).P(Z_1<z)...P(Z_{N-1}<z) \\ &= (1-e^{-z^2})^N \end{aligned} \tag{6}$$

The CCDF function is given by:

$$\tilde{F}_{Z_{\max}}(z)=P(Z_{\max}>z)=1-P(Z_{\max}\leq z)=1-(1-e^{-z^2})^N \tag{7}$$

However, the above CCDF formula used a correction term α and final expression is given by:

$$\tilde{F}_{Z_{\max}}(z)=1-(1-e^{-z^2})^{\alpha N} \tag{8}$$

In Fig. 2, CCDF vs. PAPR for conventional OFDM is presented with a varying number of subcarriers (N). In the figure, the dotted line represents the simulation results, while the solid line represents theoretical results using Eq. (8), while considering α = 2.8. It is clear from the figure, that as N increases the agreement between simulation and theoretical results also increases. The field of VLC based communication is relatively new, still, there are many challenges, which need to address before it can be used in high-speed communication.

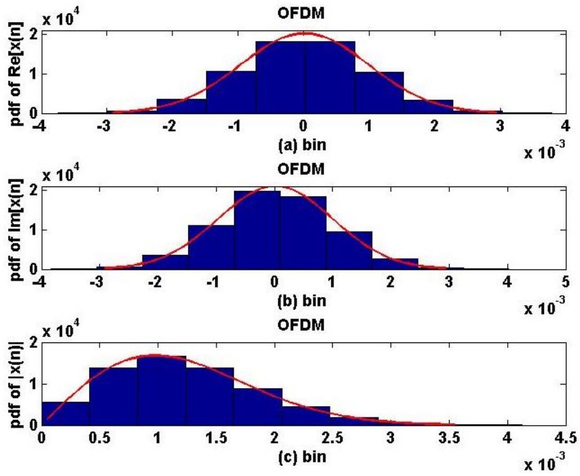


Fig. 1. OFDM probability distributions.

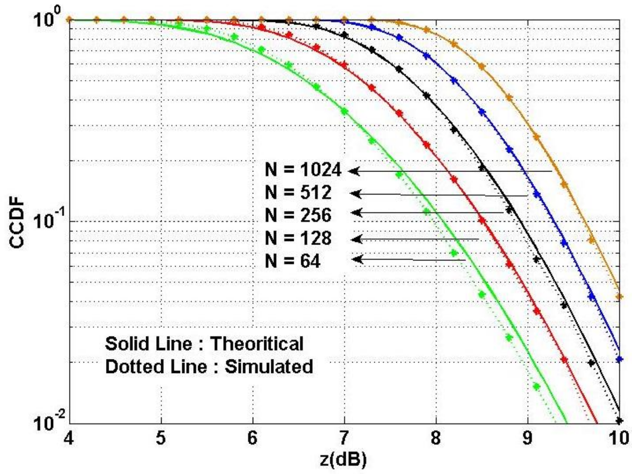


Fig. 2. CCDF vs. PAPR for conventional OFDM.

3. ACO-OFDM

In ACO-OFDM, first of all, the negative part is clipped and then odd-subcarriers, carry data symbols. The clipping noise falls on even sub-carriers, however, they are set to zero. Therefore, data symbols on odd subcarriers are not affected by clipping noise. However, a trade-off exists is between power and spectral efficiency. Let the symbols of ACO-OFDM define as:

$$S = \left[0, S_1, 0, ..., S_{\frac{N}{2}-1}, ..., 0, S_1^* \right] \tag{9}$$

Taking the IFFT, the obtained time-domain signal for $n = 0, ..., N - 1$ is:

$$s_n = \frac{1}{\sqrt{N}} \sum_{k=1}^{N-1} S_k . e^{j\frac{2\pi kn}{N}} = \frac{2}{\sqrt{N}} \sum_{k=1}^{\frac{N}{2}-1} \mathrm{Re}\left\{ S_k . e^{j\frac{2\pi kn}{N}} \right\}$$
$$s_n == \frac{2}{\sqrt{N}} \sum_{t=1}^{N/4} \mathrm{Re}\left\{ S_{2t-1} . e^{j\frac{2\pi(2t-1)n}{N}} \right\} \tag{10}$$

Using symmetric property, we have:

$$s_{n+\frac{N}{2}} = \frac{2}{\sqrt{N}} \sum_{t=1}^{N/4} \mathrm{Re}\left\{ S_{2t-1} . e^{j\frac{2\pi(2t-1)\left(n+\frac{N}{2}\right)}{N}} \right\} = -s_n, \quad n = 0,..., \frac{N}{2}-1 \tag{11}$$

Therefore, by only transmitting the positive part of S_n information can be transmitted without losing any information. The ACO-OFDM system is shown in Fig. 3 [14, 15]. Here, input data S_n is first mapped into the required modulation scheme, after adding zero padding (ZP) then IFFT of modulated data is performed.

Clipping is performed at this level and clipped signal is defined as S_n^c on this clipped signal cyclic pre-fixed (CP) is added. It is noticeable, that both ZP and CP ensure symbol recovery while suppressing inter-symbol-interference (ISI).

At this level, compander is used to compress the signal S_n^{co}, thereafter parallel to serial (*P/S*) conversion is performed. Finally, electrical to optical (*E/O*) conversion is done, and optical information is transmitted. It is assumed that the channel is corrupted by noise; therefore, noise is inserted in channel part. At the receiver side, the above-mentioned steps are performed in reverse order to recover originally transmitted data.

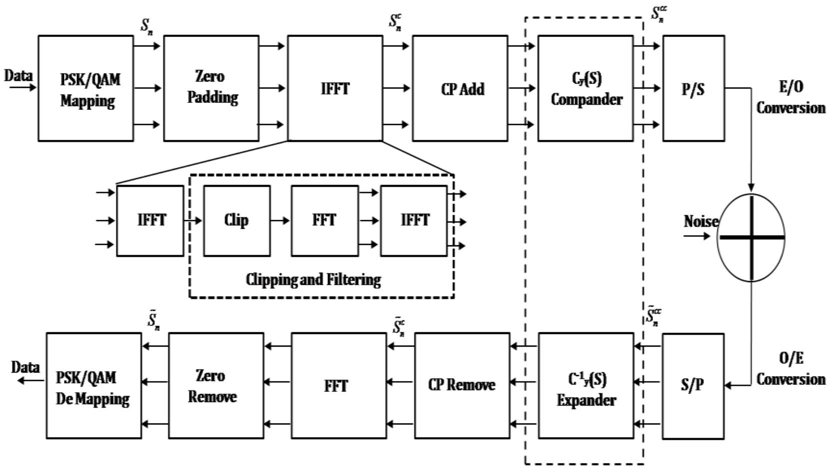


Fig. 3. Block diagram of ACO-OFDM mechanisms with clipping and companding.

3.1. Clipping of ACO-OFDM

To reduce PAPR clipping is the easiest of the phenomenon, where subcarriers peak values are clipped to pre-decided level, thus peak power decreases, and consequently, PAPR decreases. In the clipping, three different types of clipping are assumed, when the amplitude of subcarriers, which are more than pre-defined level '*A*' are clipped and we define this process as a clip (CF) and defined as:

$$s_n^c = Clip[s_n] = \begin{cases} A, & s_n \geq A \\ s_n, & 0 < s_n < A \\ 0, & s_n \leq 0 \end{cases} \tag{12}$$

In the traditional clipping, the Crest Factor is used to define clipping $CF=A/\sigma$, where, A is the upper clipping level as defined above and σ is the standard deviation of original ACO-OFDM symbols. This type of clipping brings down PAPR to a low level, but BER increases significantly. So, we define another clipping level, where the amplitude of subcarriers, which are more than 1.4 times of mean values of total subcarriers are clipped, we define this process as a clip (*m*) and defined as:

$$s_n^c = Clip[s_n] = \begin{cases} 1.4E\{s_n\}, & s_n \geq A \\ s_n, & 0 < s_n < A \\ 0, & s_n \leq 0 \end{cases} \tag{13}$$

where $E\{s_n\}$ is the mean value of amplitude subcarriers.

In the third type of clipping, amplitude of subcarriers, which are more than pre-defined level '*A*' are clipped and we define this process as a clip (*P*) and defined as:

$$s_n^c = Clip[s_n] = \begin{cases} 0.7Peak\{s_n\}, & s_n \geq A \\ s_n, & 0 < s_n < A \\ 0, & s_n \leq 0 \end{cases} \tag{14}$$

where Peak $\{s_n\}$ is the peak value of amplitude in all subcarriers.

3.2. *μ*-Law companding

μ-Law Companding is a technique where low amplitude signals are amplified while higher amplitude signals remain somewhat constant. This is a non-linear companding scheme. The other companding scheme is *A*-Law, mapping scheme, but PAPR and BER performance of this scheme are poorer to *μ*-Law scheme [19]. Therefore, in this work, *μ*-Law companding scheme is considered. The main use of the companding scheme is to reduce variability in the amplitude of the signals. In the *μ*-law companding, the signal at the transmitter side is compressed according to the following formula:

$$s_n^{'} = \frac{\max(s_n)\ln\left(1 + \frac{\mu|s_n|}{\max(s_n)}\right)}{\ln(1+\mu)} \tag{15}$$

where μ is the μ-law compression parameter whose value is considered to be 255.

At the receiver site, the original signal is obtained by reverse operation of expanding using:

$$s_n = \frac{\max(s_n)}{\mu}\left(e^{\left|s_n^{'}\right|\frac{\ln(1+\mu)}{\max(s_n)}} - 1\right) \tag{16}$$

The companding scheme performs better than clipping method due to the absence of clipping noise.

In this work, we have used both clipping and companding techniques to reduce PAPR. In general, the amplitude of IFFT bins is small except for few bins whose amplitude is comparatively larger. Therefore, larger amplitude bins can be clipped to bring down maximum value, thus PAPR also reduces. However, clipping introduces distortion and increases BER. To further reduce, the difference amongst amplitudes non-linear companding scheme can be used. Using these two techniques first clipping then companding reduce the variability of the amplitude to a great extent, thus a very low PPAR can be obtained while maintaining the BER.

4. Results

In the first part of the work, ACO-OFDM is simulated and histogram plot is obtained. The histogram plot, which shows that it looks like Gaussian with negative bins is clipped (Fig. 4). Further considering $E\left(\left|X_n\right|^2\right) = \sigma^2 = 1$, we can approximate pdf as:

$$f_{|X_n|}(x) = A\exp\left(-\frac{x^2}{2}\right)u(x) \tag{17}$$

where, $u(x)$ is step function. In other words:

$f_{|X_n|}(x) = A\exp\left(-\frac{x^2}{2}\right), x \geq 0$ by using the fundamental property of pdf, we get

$\int_0^\infty f_{|X_n|}(x)dx = 1 \Rightarrow A = \sqrt{\frac{2}{\pi}}$ and CDF as:

$$F_{|X_n|}(x \leq z) = \int_0^z \sqrt{\frac{2}{\pi}}\exp\left(-\frac{x^2}{2}\right)dx \tag{18}$$

It is to note that this equation can be solved using numerical integration. In the case of ACO-OFDM, it has been found that CCDF is shifted with respect to the above expression as given in Eq. (17), so we re-write Eq. (18) as:

Using elementary mathematics, we get

$$F_{|X_n|}(x \leq z) = \int_m^{z+m} \sqrt{\frac{2}{\pi}}\exp\left(-\frac{x^2}{2\sigma^2}\right)dx \tag{19}$$

$$F_{|X_n|}(x \le z) = \int_0^z \sqrt{\frac{2}{\pi}} \exp\left(-\frac{(x-m)^2}{2\sigma^2}\right) dx \tag{20}$$

The simulated results for CCDF vs. PAPR are shown in Fig. 5 and simulation is performed for a wide range of values of *N* varying from 1024 to 4096. After shifting of theoretical results using Eq. (20), the simulated and theoretical are in good agreement with each other, through simulation experiment the value of *m* is found to be 2.25. Therefore,

$$F_{|X_n|}(x \le z) = \int_0^z \sqrt{\frac{2}{\pi}} \exp\left(-\frac{(x-2.25)^2}{2\sigma^2}\right) dx \tag{21}$$

Using Eq. (21), the CCDF of ACO-OFDM can be evaluated using numerical simulation.

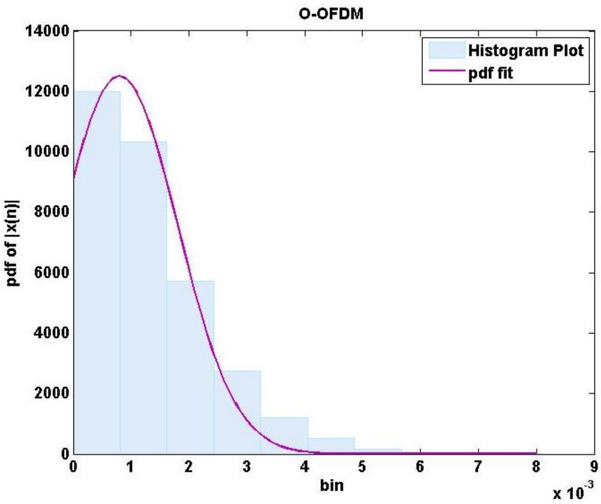


Fig. 4. ACO-OFDM probability distributions.

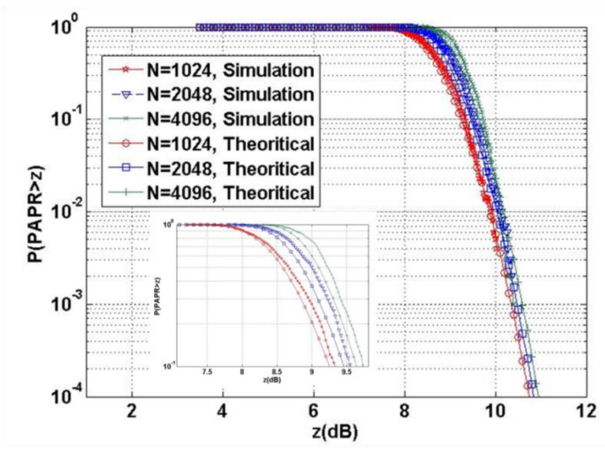


Fig. 5. CCDF vs. PAPR for conventional ACO-OFDM.

In Fig. 6, amplitude vs. bin is plotted. In the simulation, 8096 bins are considered, and in the figure, amplitudes are plotted in increasing order with a peak value of 0.42. When peak amplitude clipping is applied, only a small number of subcarrier amplitudes are clipped. Now, the maximum amplitude value of the clipped symbol is 0.2945. Similarly, with traditional clipping, amplitude level goes down to a very low level of 0.0465. It is clear from the figure, as we increase the clipping level more numbers of subcarriers have clipped amplitude, thus amplitude distortion decreases, but this lowering of amplitude increases the BER.

In Fig. 7, CCDF vs. PAPR for ACO-OFDM under various schemes are shown. Here, PAPR of original ACO-OFDM is 14.69 dB. First, we discuss, PAPR under only three clipping schemes. In case of the clip (*P*), the PAPR is 14.05 dB, which is very close to original ACO-OFDM, while for clip (*m*) scheme PAPR is 3.543 dB. Finally, in the case of clip (CF) scheme, the PAPR is 2.937 dB. Now, when clip (*P*) and companding schemes are used simultaneously, PAPR of 3.543 dB is obtained, thus PAPR is improved by 10.5 dB. If clip (*m*) and compading schemes are used together then obtained PAPR is 1.283 dB, finally with clip (CF) and companding schemes the obtained PAPR is 0.4925 dB. Zhang et al. [18] work obtained a result and it is also shown that the PAPR is nearly 9.6 dB. Thus, compared to Zhang et al. [18] work, the proposed method is superior.

In Fig. 8, BER vs. SNR is plotted for various OFDM schemes while considering only clipping techniques. The BER for conventional OFDM is better than ACO-OFDM scheme. Using peak clipping, the BER performance is the same as an original ACO-OFDM signal. The BER performance for CF based clipping is poorest, while for the clip (*m*) BER performance is moderate.

In Fig. 9, BER vs. SNR is plotted for various OFDM schemes while considering both clipping and companding techniques. Now the BER for ACO-OFDM is very close to conventional O-OFDM signals. This happens because the companding technique improves SNR and thus BER. While comparing the results of Fig. 8, and Fig. 9, results improve in terms of BER, due to the SNR improvement.

In Fig. 10, subcarrier amplitudes under various schemes are shown. In Fig. 10(a) original ACO-OFDM subcarriers are shown, here amplitude variations are huge, with a minimum value of 1.148×10^{-5} and the maximum value is 0.42. After applying peak clipping, the maximum amplitude is 0.2945.

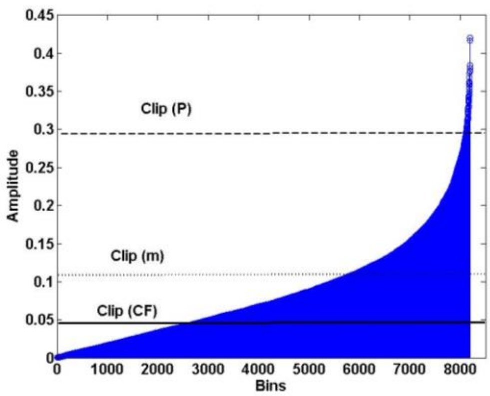


Fig. 6. Amplitude vs. bin under various clipping schemes.

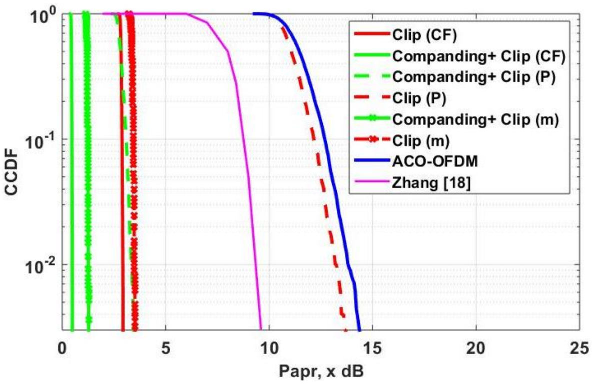


Fig. 7. CCDF vs. PAPR for ACO-OFDM under various schemes.

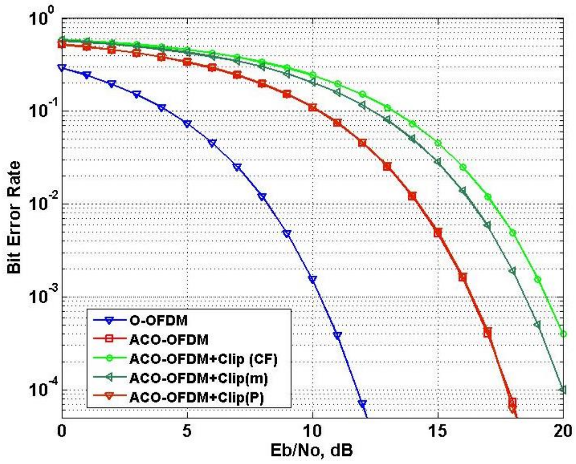


Fig. 8. BER vs. SNR under various clipping schemes.

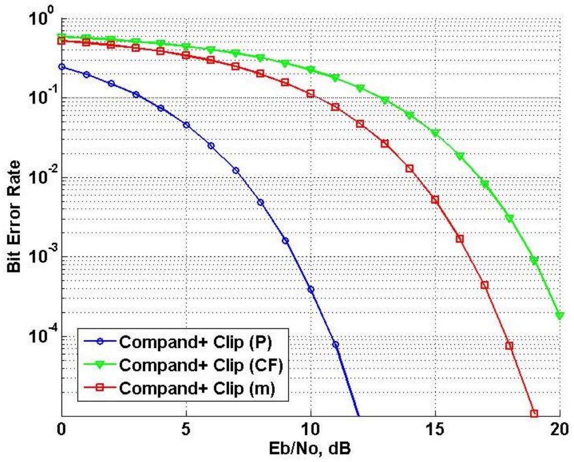
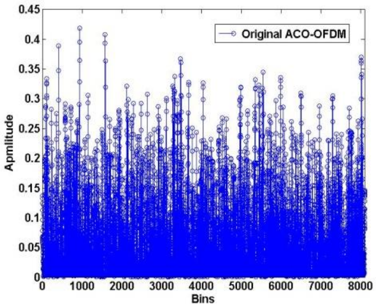
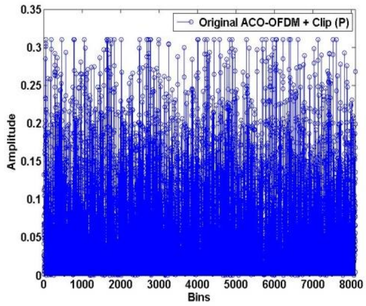


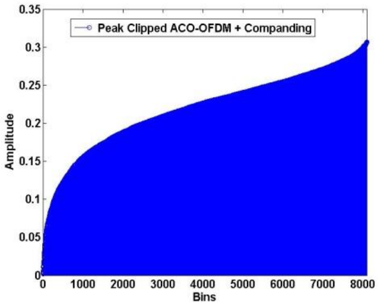
Fig. 9. BER vs. SNR under companding and various clipping schemes.



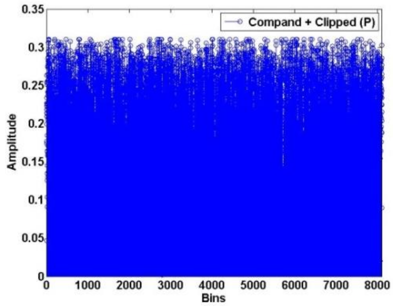
(a) Original ACO-OFDM.



b) Original ACO-OFDM + Clip (*P*).



(c) Non-linear companding.



(d) Peak clipped ACO-OFDM companding.

Fig. 10. Subcarrier amplitude under various schemes.

After applying non-linear, companding the chance in amplitude is in a non-linear fashion as shown in Fig. 10(c). The amplitude of the companded signal with peak clipping has a minimum value of 5.25×10^{-4} and the maximum amplitude is 0.30, thus, the lowest value of amplitude increases by a factor of more than 45 times while maximum amplitude remains nearly same. Hence, companding schemes are a better choice in ACO-OFDM for reduction of PAPR while maintaining BER.

In Table 1, comparison with recent paper [18] is done. From the table, different parameters along with their values are shown. In this work, various clipping is considered, therefore, in the results, a range is given in some parameters. It is clear that our method is better to recent work, with little distortion, in contrast to earlier work, which is distortion free.

In the future, we will work on a novel non-linear companding scheme using Fig. 6, such that the linear and non-linear part of the curve can be well represented. This mapping will be more useful in further PAPR reduction.

Table 1. Comparison with reference [18].

Parameter	Zhang, T	Proposed
Original ACO-OFDM PAPR	15.8 (dB)	14.7 (dB)
Final PAPR	9.6 (dB)	0.5-3.5 (dB)
Original SNR for BER (10^{-4})	20.5 (dB)	18 (dB)
Final SNR for BER (10^{-4})	22 (dB)	12-20.5 (dB)
Distortion	Free	Lesser
PAPR improvement %	39.24	76.10

5. Conclusions

Invisible Light Communication, ACO-OFDM can be used effectively. In ACO-OFDM only half of the subcarriers are transmitted whose negative part is clipped. Therefore it is very power efficient technique. Some of the concluding remarks as follows:

- ACO-OFDM cumulative distribution function is half Gaussian and means shift.
- The clipping of amplitude reduces distortion and thus PAPR in the expense of increase BER.
- Non-linear companding technique reduces the variability in amplitudes.
- Using both clipping and companding technique, PAPR can be reduced significantly while maintaining BER at the acceptable level.
- The proposed scheme shows an improvement of 76.10% in PAPR as compared to earlier work where an improvement of 39.24% is observed.

Nomenclatures

A	Clipping level
E	Expected value (mean)
F	Cumulative distribution function
f	Probability distribution function
N	Number of subcarriers
S_i	Symbols
s_n^c	Clipped symbols
s_n^{co}	Clipped and companded symbols
X	Random variable
Y	Random variable

Greek Symbols

α	Oversampling factor
μ	Law parameter, 255
σ	Standard deviation

Abbreviations

ACO	Asymmetric Clipped Optical
AWGN	Added White Gaussian Noise
BER	Bit Error Rate
CCDF	Complementary Cumulative Distribution Function
CF	Crest Factor
DCO	DC-biased Optical
IFFT	Inverse Fast Fourier Transform
IM/DD	Intensity Modulated/Direct Detection
LED	Light Emitting Diode
OFDM	Orthogonal Frequency Division Multiplexing
PAPR	Peak to Average Power Ratio
VLC	Visible Light Communication

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