



# Optimizing the Reduction of PAPR of OFDM System Using Hybrid Methods

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Accepted: 22 March 2022 / Published online: 7 April 2022

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## Abstract

Orthogonal Frequency Division Multiplexing (OFDM) is a multi-carrier modulation, which transfers multimedia data in both wired/wireless communications. It suffers from high Peak to Average Power Ratio (PAPR) which slows down the implementation of OFDM in practical communication systems due to the nonlinear operation of High-power amplifier. It makes the OFDM system design more complex and costlier. Many authors presented different strategies to mitigate the high PAPR. One of them is companding which lowers the out-of-band interference in OFDM, but it degrades the Bit Error Rate (BER) performance. The other one is the Selected mapping (SLM) which improves the BER performance, but the system complexity is increased for large values of phase rotation factor. Hence, a new hybrid algorithm is proposed in this paper which is the combination of SLM with different types of companding techniques to acquire the advantages of both the techniques. With this proposed scheme, the PAPR is reduced by a large amount compared to conventional OFDM and OFDM with SLM techniques. Also, it enhances the spectral efficiency and reduces system complexity. The outcome of the proposed hybrid techniques is encouraging; hence this technique can be used in LTE, Fourth Generation (4G), Fifth Generation (5G) and beyond wireless communication systems.

**Keywords** Companding · OFDM · PAPR · SLM

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## 1 Introduction

As the world is moving towards high data rates, the Orthogonal Frequency Division Multiplexing (OFDM) is a promising technology which provides better performance in terms of upgrading the channel capacity, efficient utilization of bandwidth and improving the quality of the service [1]. To meet these requirements, some modifications need to be done not only at the physical layer level but also at other layers. Hence, an efficient configuration like Multi-Input Multi-Output (MIMO) is initiated to attain higher speeds and low latency [2, 3]. When OFDM is combined with MIMO, the frequency selective channel will be converted into a frequency flat fading channel which inclines the minimization of receiver complexity and cost. Hence, LTE-OFDM is a key technology that supports future wireless systems as it reduces the cost and complexity.

OFDM supports wireless standards like IEEE 802.11a/g/n/ac WLAN, Digital Audio Broadcasting (DAB), Digital Video Broadcasting-Terrestrial (DVB-T), Digital Subscriber Line (DSL), Long Term Evolution (LTE) and 4G communications.

OFDM also supports WiMax (802.16) standard and 3<sup>rd</sup> Generation Partnership Project (3GPP) to increase the system performance even if there is no end-to-end line of sight path [4]. Fifth Generation (5G) technologies provide better data rates that are equal to 1000 times of the current 4G communications, and the number of Internet of Things (IoT) devices connected to a system is also increased by a large factor.

5G communications place a vital role in emphasizing spectral as well as energy efficiency [5]. As there is tremendous growth in data traffic, IoT places a vital role in minimizing the system cost and complexity [6]. Hence, OFDM is the prevalent multi carrier modulation technique considered as the backbone for all upcoming (5G and beyond) wireless technologies to provide three major scenarios like Ultra Reliable and Low Latency Communications (URLLC), Enhanced Mobile Broadband (eMBB) and Massive Machine Type Communications (mMTC) [7].

Even though OFDM scheme is an enticing technique to all modern wireless communication technologies, it suffers from one of the major challenging issues i.e., high Peak to Average Power (PAPR). In an OFDM signal,  $N$  data symbols are modulated with the help of  $N$  subcarriers that are orthogonal in nature. When all the modulated signals are appended to the same phase, the resultant peak amplitude will be high as the cumulative addition is done using Inverse Fast Fourier Transform (IFFT) operation. In this case, the peak amplitude is  $N$  times the average amplitude. According to the definition, PAPR is the ratio of maximum power to average power [8]. In OFDM, the cumulative addition of multiple sub carriers is done using Inverse Fast Fourier Transform (IFFT) operation due to which high peak value arises. This high PAPR ushers the High-Power Amplifier (HPA) to be operated in the nonlinear region which is the most crucial threat in both uplink and downlink [9] of wireless communications. The nonlinearity of the HPA effectuates the Inter Carrier Interference (ICI), high out of band radiation and deteriorates the Bit Error Rate (BER) performance of the communication system [10]. The efficiency of the HPA is crucial due to the limited battery power of mobile handset. For example, in [7], it was projected that in upcoming 5G mobile handsets, PAPR reduction is the more important thing to improve the battery power and efficiency of Millimeter wave (mmWave) HPAs.

Many authors proposed different types of PAPR reduction strategies in the literature to achieve low complexity and to decrease the non-linear distortion of HPA. Some of them are clipping and filtering, companding, Selected Mapping (SLM) and Partial Transmit Sequence (PTS) etc. [11]. Among all these schemes, SLM is the powerful and popular

technique [12] which does not introduce distortion while reducing the PAPR and the implementation is less complex. In SLM, a set of OFDM symbols are generated which represents the same data block and the symbol with lowest PAPR [13] is selected for transmission. Companding is also a good contender to SLM which provides better PAPR with less complexity, good BER and no bandwidth expansion. Companding attenuates high peaks while amplifying the low amplitude values to get better PAPR results [14–16].

A new category of hybrid technique combines two or more reduction techniques which gives better PAPR [17–20] reduction than single technique. Nowadays, hybrid methods have gained interest as they hold the advantages of all techniques used in them. Even though they achieve better results like improved PAPR reduction with an increase in BER performance of the system, it increases the system complexity by a very little amount. In this paper, a combination of low complexity SLM with different types of nonlinear companding techniques like Rooting Companding Technique (RCT), Logarithmic Rooting companding (LogR), Hyperbolic Tangent Rooting companding (TanR) and Exponential (EXP) companding are projected to mitigate the PAPR by a large amount with less complexity [21–24]. The proposed hybrid techniques acquire the advantages of both SLM and companding techniques used in this paper. They have the advantages of increasing the Signal to Noise Ratio (SNR) as the companding retains the signal level beyond the noise level during the entire processing. Also, these techniques have the advantages of reduced PAPR, increased BER performance, increased spectral efficiency and no bandwidth expansion. Hence the system complexity and cost are reduced. But as the side information of SLM is not reduced in the proposed technique, the complexity is little bit increased compared to SLM without side information technique, but the complexity is reduced compared to single PAPR reduction techniques.

The rest of the paper is organized as follows: Introduction to OFDM and significance of PAPR are presented in sect. 2. Section 3 presents various PAPR reduction techniques available in the literature and their limitations. Proposed SLM-Companding technique is provided in sect. 4. In sect. 5, the simulation results of the hybrid PAPR reduction techniques, which are the combination of SLM with different types of companding techniques are projected and finally section VI summarizes the outcome of this work and concludes the paper.

## 2 Generation Of OFDM and Significance Of PAPR

### 2.1 Orthogonal Frequency Division Multiplexing (OFDM)

OFDM divides the procurable bandwidth into multiple number of sub carriers, which are orthogonal in nature. Transmitting these subcarriers with uniform intervals will give several advantages like reduction of multipath distortion, improving the spectral efficiency of the system and ease of incorporation with Multi-Input-Multi-Output (MIMO) technology. OFDM converts the wideband signal with bandwidth  $B (= 1/T)$  and symbol time  $T$  into  $N$  non-overlapping narrow band signals with each signal bandwidth of  $B'$  as [25]:

$$B' = \frac{B}{N} = \frac{1}{NT} \quad (1)$$

The block diagram of OFDM is depicted in Fig. 1. Here, the symbol generation can be done with the help of digital modulation techniques like M-ary Quadrature Amplitude

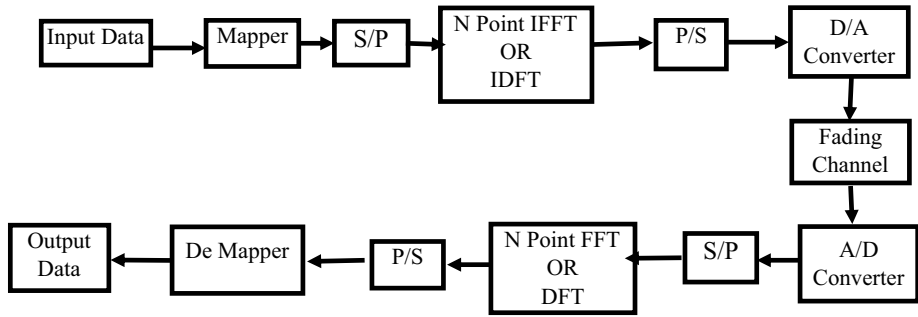


Fig. 1 Block diagram of OFDM

Modulation (M-ary QAM) or M-ary Quadrature Phase Shift Keying (M-ary QPSK). Now the Serial to Parallel (S/P) converter preserves [9]  $N$  constellation points which can be used for the purpose of modulation. To get profusely accurate PAPR values, the output of S/P converter should be passed through an N-point IFFT which gives the time domain representation of OFDM signal as [26]:

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k)e^{j2\pi \frac{k}{N}n} \tag{2}$$

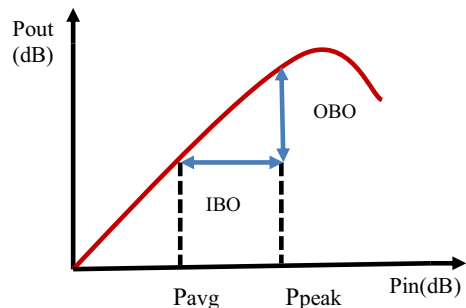
where  $n$  is the time,  $k$  is the frequency indices and  $X_k$  is the data transmitted on  $k$ th subcarrier with the value of  $k = \{0, 1 \dots N-1\}$ .

### 2.2 Significance of Peak to Average Power Ratio (PAPR)

As the efficiency of HPA is critical due to its nonlinear characteristics [27], high PAPR in OFDM obstructs the implementation of OFDM for battery operated mobile handsets. Central limit theorem states that for higher and sufficient values of  $N$ , the complex (real and imaginary) OFDM symbol supports Gaussian distribution whereas its amplitude and power follow the distributions like Rayleigh and exponential distributions respectively. The expression for PAPR of baseband OFDM signal is given by:

$$PAPR(x[n]) = \max_{0 \leq n \leq N-1} \frac{|x[n]|^2}{E[x[n]^2]} \tag{3}$$

Fig. 2 Input/Output characteristic curve of a Power Amplifier



The Cumulative Distribution Function (CDF) of the envelope of a signal is expressed by a threshold level  $F(z)$  as:

$$F(z) = 1 - \exp(-Z) \tag{4}$$

The probability of PAPR outside the level  $F(z)$  is evaluated by using Complementary Cumulative Distribution Function (CCDF)

$$F_z(z) = 1 - (1 - e^{-z})^n \tag{5}$$

As the manufacturing of a linear HPA is difficult and costly, high PAPR is a major problem in an OFDM system [18]. When the HPA is operated at or below the saturation region, the OFDM system works well in the piece-wise linear region. Figure 2 depicts the characteristic curve of a Power Amplifier. From the figure, if the HPA works near the saturation, the IOB/OOB distortions may be increased. The formulas of IOB/OOB distortions which decides the non-linearity of PA is given by:

$$IBO = 10 \log_{10} \left( \frac{A_s^2}{\text{Average input power}} \right) \tag{6}$$

$$OBO = 10 \log_{10} \left( \frac{A_0^2}{\text{Average output power}} \right) \tag{7}$$

From the above equation, the maximum input voltage is denoted as:  $A_s^2$  and the maximum throughput value is indicated as:  $A_0^2$ .

The HPA will be driven to non-linear region due to the high peaks resulted by the IDFT/IFFT [28]. This creates the problems like poor coverage due to wastage of power in out of band radiations, harmonic generation, and the decay in power efficiency. Many authors proposed different strategies to reduce the PAPR, and in this paper, PAPR is reduced by a large amount by using proposed hybrid methods.

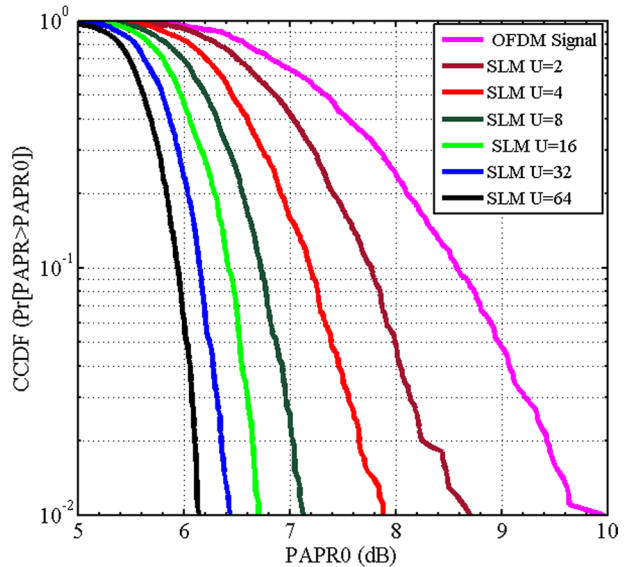
### 3 Literature Review on PAPR Reduction Techniques

#### 3.1 Selected Mapping

Even though Selected Mapping (SLM) was proposed in the year 1996, [29] it is the most prominent PAPR reduction technique which gains substantial improvements compared to the remaining techniques. In SLM, a data block from the output of the serial to parallel converter i.e.  $X = [X_0, X_1, \dots, X_{k-1}]^T$  is multiplied by phase rotation factor  $U$ . The different phase sequences are given by  $Pu = [P^u_0, P^u_1, \dots, P^u_{k-1}]^T$ . Consequently,  $U$  sequences  $[Xu_1, Xu_2, \dots, Xu_{k-1}]$  are generated which are having statistically independent nature [11]. The  $U$  number of sequences are belonging to the same data block, which can be fed to the IFFT block to produce  $U$  statistically independent sequences. Lastly, among all sequences, the one with lowest PAPR is preferred for serial transmission [12].

The  $U$  number of sequences, which are also called as side information, is required at the receiver to reconstruct the original data block. This is the first drawback of SLM [29]. In

**Fig. 3** Performance of PAPR with SLM



addition to that,  $U$  IFFT operations are needed at the transmitter to apply the SLM process which makes the system more computationally complex [13]. To get rid of these drawbacks, many researchers put their efforts in reducing several algorithms [12, 13, 26, 28] were proposed with low complexity and without using side information. In this SLM technique, the mapping method used is 16-QAM with 64 sub carriers and the number of symbols considered for this simulation are 1024.

The distribution function  $CCDF = \text{Prob} (PAPR > PAPR_0)$  was used with respect to cut off level  $PAPR_0$  to express the range of PAPR of OFDM. PAPR values of OFDM and the reduction technique SLM for different values of route numbers that is from  $U=2$  to 64 are plotted in Fig. 3. The value of PAPR of OFDM signal without applying any PAPR reduction technique is equal to 10 dB at a CCDF of  $10^{-2}$ . When SLM reduction technique is applied to OFDM, the PAPR is reduced to 8.7 dB for phase factor  $U=2$ , 7.9 dB for  $U=4$  and 6.7 dB for  $U=16$ . Further increment in  $U$  value results in reduction of PAPR by a large amount i.e., for  $U=64$ , PAPR is reduced to 6.1 dB. But enhancing the value of phase factor ( $U$ ) causes the transmitter design more and more computationally complex due to the increment in number of IFFT blocks. Hence in proposed hybrid methods, SLM is combined with different types of companding techniques with which one can achieve less PAPR without increasing  $U$  value.

### 3.2 Clipping and Filtering

The PAPR can be diminished by a signal amplitude distortion method. Clipping and filtering decreases the peak amplitude of the input signal to a pre-defined threshold level [30].

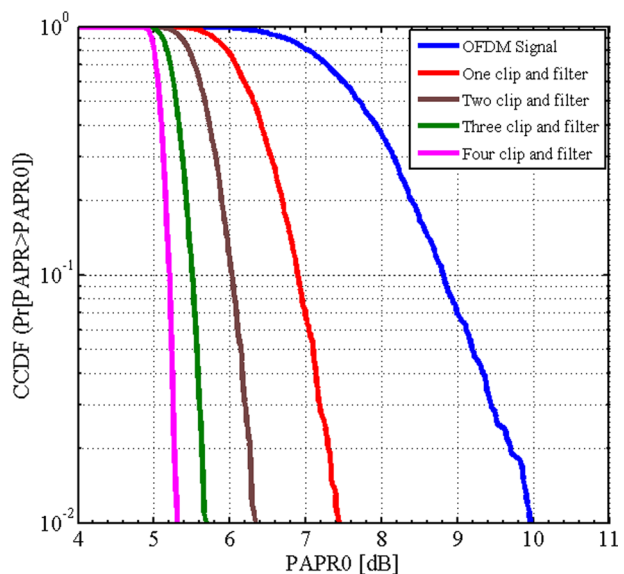
$$C(x) = \begin{cases} Ae^{j\phi(x)} & ;|x| \geq A \\ x & ;|x| < A \end{cases} \tag{8}$$

where, clipping level is denoted by A which is a positive integer, and the phase of the input signal x is  $\phi(x)$ . However, clipping alone creates distortions like in-band radiations and out-of-band radiations result in BER performance degradation and effects the power efficiency of HPA [8]. To overcome the drawback of out-of-band radiation, frequency domain filtering is introduced but this technique also fails in reducing in-band radiations. When the signal is passed through filtering, the band pass filtering induces peak regrowth [31]. Thus, many authors suggested repeated clipping and filtering as an alternative way to reduce the peak regrowth at a cost of increasing computational complexity and degradation in the performance of BER [32]. In this repeated clipping and filtering method, first IFFT operation is done to convert the frequency domain signal into time domain signal which can be clipped as given below.

$$C = \begin{cases} \sqrt{C_R * E[|x|^2]} * \frac{x}{|x|} & ;x^2 > c_t \\ x & ;x^2 \leq c_t \end{cases} \tag{9}$$

where C represents the output signal,  $C_t$  is threshold level, C is the output of the clipper,  $|x|^2$  and  $E[|x|^2]$  are the signal and mean powers respectively. In this clipping process, high peaks whose value is greater than clipping level is decreased to the allowable level without affecting the input signals phase angle. Initially, input data vector  $(a_0, a_1, \dots, a_{N-1})$  whose length is N need to be converted to time domain from frequency domain using IDFT/IFFT. Clipping ratio ( $C_R$ ) decides the clipping percentage of IFFT signal, but larger values of  $C_R$  increase the value of BER.

Fig. 4 PAPR performance of clipping and filtering of OFDM



The clipped signal is converted to frequency domain using DFT/FFT and then the actual filtering processing will be done with the help of IDFT to reduce the out-of-band radiation. In this Repeated Clipping and Filtering (RCF) technique, iteration number is considered as 4, hence the above clipping and filtering process can be repeated 4 times and the  $C_R$  is assumed to be 3 dB. As shown in Fig. 4, the PAPR achieved at CCDF value  $10^{-2}$  is 7.4 dB for one RCF, 6.3 dB for two RCF, 5.7 dB for three RCF and 5.3 dB for four RCF. Further decrement in PAPR is possible by increasing  $C_R$  value and iteration number. But larger values of  $C_R$  increases BER and the system complexity increases for the higher values of iteration number.

### 3.3 Companding

One of the popular signal distortion techniques is non-linear. Companding which diminishes the high peak values by distorting the OFDM signal prior to amplification process. Like clipping technique, companding also suffers from in-band and out-of-band distortions and complexity. But it does not need any side information like SLM technique. Basic companding techniques are classified as  $\mu$ -law and A-law [14] which compress the signal logarithmically at the transmitter and expands the same at the receiver.

#### 3.3.1 A-law Companding

The A-law compressor maintains linear curve for low input levels and logarithmic curve for high level inputs as given by the following equation [24].

$$y(x) = \begin{cases} y_{max} \frac{A \frac{|x|}{x_{max}}}{(1+A)} \operatorname{sgn}(x); & 0 < \frac{|x|}{x_{max}} \leq \frac{1}{A} \\ y_{max} \frac{\left[1 + \log_e \left[A \frac{|x|}{x_{max}}\right]\right]}{(1 + \log_e A)} \operatorname{sgn}(x); & \frac{1}{A} < \frac{|x|}{x_{max}} \leq 1 \end{cases} \quad (10)$$

The Consultative Committee for International Telephony and Telegraphy (CCITT) decided the value of A as 87.6 used by the countries like Russia, India, and China to compand the speech signal in telecommunications.

#### 3.3.2 $\mu$ -law Companding

Like A-law,  $\mu$ -law is also linear at low level inputs and logarithmic at high input signal levels. The mathematical expression for  $\mu$ -law is defined as [13]:

$$y(x) = V \frac{\log \left(1 + \mu \frac{|x|}{V}\right)}{\log(1 + \mu)} \operatorname{sgn}(x) \quad (11)$$

As per CCITT, the countries like USA and Japan use the value of  $\mu$  as 255 in Voice Coder and Decoders (VOCODER).



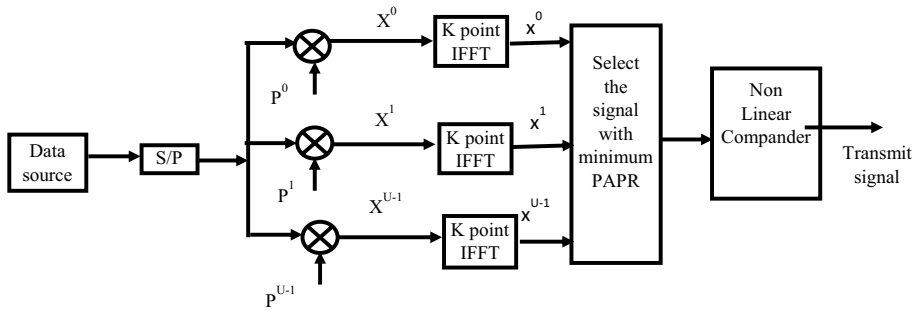


Fig. 5 Block diagram of the proposed method

## 4 Proposed PAPR Reduction Method

The proposed method is a combination of SLM and companding schemes that give better results compared to the existing techniques. Figure 5 depicts the block diagram of proposed hybrid method (SLM + Companding).

The algorithm of the proposed hybrid method is as follows:

- (1) The modulation of input data stream is done by Quadrature Amplitude Modulation (QAM)
- (2) The mapped QAM signal is multiplied by different phase factors from  $U=2$  to 64 to assess the lowest PAPR value
- (3) Each sub block signal is converted to time domain with the help of IFFT which acts as a modulator, hence the complexity is reduced
- (4) The signal is over sampled by a factor of  $L$ , and finally the optimum peak signal is chosen
- (5) The compression of output signal is done by different types of nonlinear companding techniques like Rooting Companding Technique (RCT), Logarithmic Rooting companding (LogR), Hyperbolic Tangent Rooting companding (TanR) and Exponential (EXP) companding
- (6) Finally, the one with optimum PAPR is chosen for transmission

In this proposed one, for lesser values of phase rotation factor, a lower PAPR is obtained as the nonlinear companding techniques are appended to the SLM technique. As the proposed techniques give less PAPR for lesser values of phase rotation factor, the computational complexity of the system decreases. The following non-linear companding techniques are used in the proposed method.

### 4.1 Exponential Companding (EXP)

The EXP companding equation relies on the Exponential function whose characteristic equation at the transmitter is given by [33]:

$$h(x) = \text{sgn}(x)^d \sqrt{\alpha \left[ 1 - \exp\left(x - \frac{|x|}{\sigma}\right) \right]} \quad (12)$$

The inverse exponential companding function at the receiver section is given by

$$h^{-1}(x) = \text{sgn}(x) \left| \sqrt{-\sigma^2 \log\left(1 - \frac{|x|^d}{\alpha}\right)} \right| \quad (13)$$

where  $\alpha$  is a positive integer and is also known as average output signal power.

## 4.2 Rooting Companding Technique (RCT)

In this technique, the amplitude is only altered based on the following equation [14] and the phases remain constant before the signal is processed by digital to analog converter.

$$f(x) = |x|^y * \text{sgn}(x) \quad (14)$$

where,  $y$  decides the amount of variation in amplitude value whose range is from 0.1 to 0.9 and  $\text{sgn}(x)$  is used to maintain the constant phase. Choosing the lower values of  $y$  reduces the PAPR by a large amount. Similarly, the de-companding is used at the receiver to get back the original amplitude values.

The mathematical expression for de-companding is given by

$$f(x)^{-1} = |x|^{\frac{1}{y}} * \text{sgn}(x) \quad (15)$$

Rooting technique converts the statistical Rayleigh distributed OFDM signals into Gaussian distribution, and it changes the values of mean and variance of OFDM signals. This technique reduces the PAPR by lowering the peak amplitude value.

## 4.3 Hyperbolic Tangent Rooting Companding (TanR)

Hyperbolic Tangent rooting companding technique distributes the large envelope signals into tangent distribution and this is decided by the function Tangent. This conversion can be established by using the following companding equation [22]

$$f(x) = \tanh(|x| * k^y) * \text{sgn}(x) \quad (16)$$

where  $k$  is a positive number ranging from 5 to 25, which controls the companding level in an effective manner and  $\text{sgn}(x)$  is used for phase of the OFDM signal. The decompanding equation which can be used at the receiver is given as:

$$f(x)^{-1} = \left| \left( \text{atanh}\left(\frac{|x|}{k}\right) \right)^{\frac{1}{y}} \right| \text{sgn}(x) \quad (17)$$

### 4.4 Logarithmic Rooting Companding Technique (LogR)

Logarithmic Rooting companding (LogR) depends on the logarithmic function [20] to achieve companding process. The LogR companding at the transmitter and inverse companding at the receiver are as follows:

$$f(x) = \log(|x| * k_2)^y + 1) * \text{sgn}(x) \tag{18}$$

where  $k_2$  is a positive constant which determines the degree of companding.

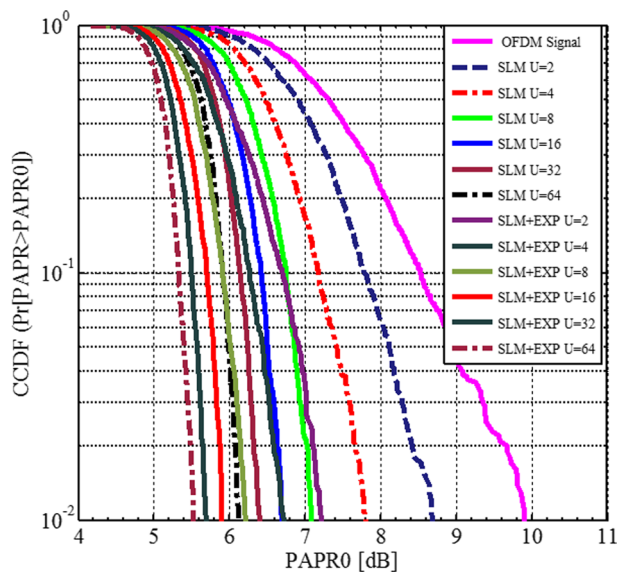
$$f(x)^{-1} = \left| \left( \exp\left(\frac{|x|}{k_2}\right) - 1 \right)^{\frac{1}{y}} \right| \text{sgn}(x) \tag{19}$$

Several simulations were done in MATLAB for the proposed hybrid methods for making comparisons of their performance with respect to PAPR and the results obtained for the proposed techniques are presented in the next section.

## 5 Results and Discussion

Hybrid techniques are more popular as they acquire the advantages of all methods used in the PAPR reduction process. To enhance the capacity of the system in terms of reducing PAPR, the combination of SLM with different nonlinear companding techniques are proposed in this paper. 1024 symbols are used in the proposed scheme with 64 sub carriers and the mapping method used is 16-QAM which is simulated by generating the data randomly. For all proposed PAPR reduction techniques, the PAPR value is evaluated for different phase rotation factors i.e. for  $U=2$  to 64. The complementary

**Fig. 6** Comparison of OFDM, OFDM-SLM & OFDM-SLM-EXP Techniques

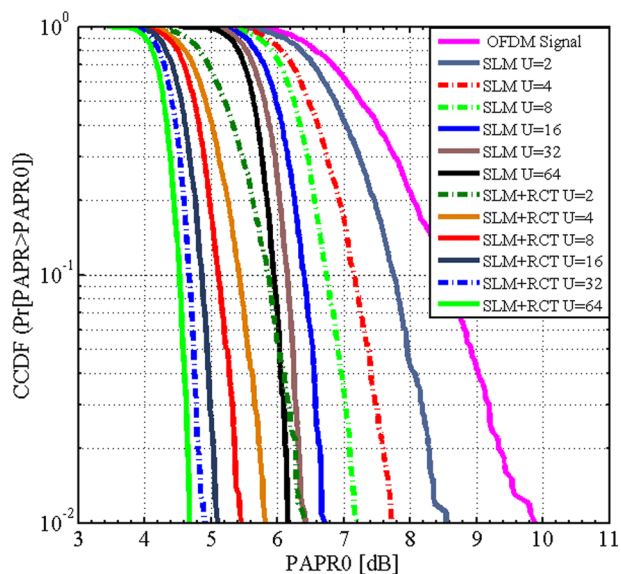


cumulative distribution function,  $CCDF = \text{Prob} \{PAPR > PAPR_0\}$  is used to express the range of PAPR in terms of a probability of occurrence with respect to its cut-off value.

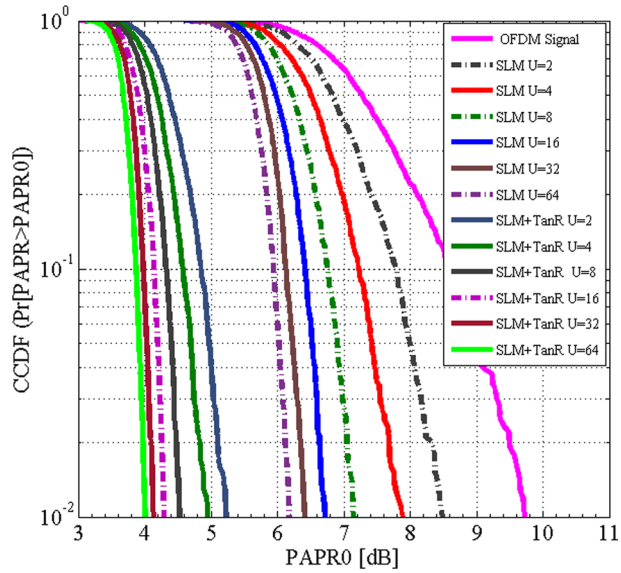
### 5.1 SLM with Exponential Companding

Figure 6 shows the comparison of OFDM, OFDM-SLM and SLM-EXP techniques with number of bits equal to 1024 which are mapped using 16-QAM. PAPR is assessed at CCDF value of  $10^{-2}$  of actual OFDM signal which is equal to 9.9 dB. SLM reduction method reduces PAPR to 8.7 dB for route number  $U=2$  and 7.8 dB for  $U=4$ . When  $U$  is increased, PAPR is reduced and for  $U=64$ , the PAPR is decreased to 6.1 dB. Hence, PAPR reduces by increasing  $U$ . But when the value of  $U$  is increased, it increases the system complexity and cost. With the proposed SLM with EXP technique, it is observed that  $U$  value need not be increased to achieve less PAPR. SLM-EXP technique reduces the PAPR to 7.2 dB for  $U=2$  and it decreases gradually with increasing  $U$  and for  $U=64$ , it is reduced to 5.5 dB. Increasing the value of  $U$  results in increasing the computational complexity. Hence to reduce the complexity, consider  $U$  as 8 and when PAPR is calculated for  $U=8$ , OFDM with SLM is having PAPR of 7.1 dB and it is reduced to 6.2 dB for hybrid SLM with EXP technique with a major difference of 3.7 dB compared to original OFDM signal. When SLM-EXP technique is compared with SLM technique, the performance of SLM-EXP is improved by 1.5 dB for  $U=2$ . As the EXP companding technique uses both cosine and sine functions, the compression is better at the transmitter which helps in reducing the PAPR compared to OFDM and SLM techniques.

**Fig. 7** Comparison of OFDM, OFDM-SLM & OFDM-SLM-RCT Techniques



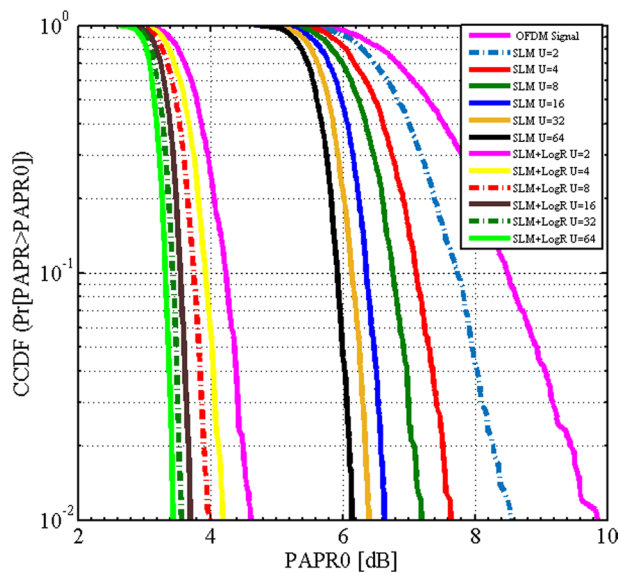
**Fig. 8** Comparison of OFDM, OFDM-SLM & OFDM-SLM-TanR Techniques



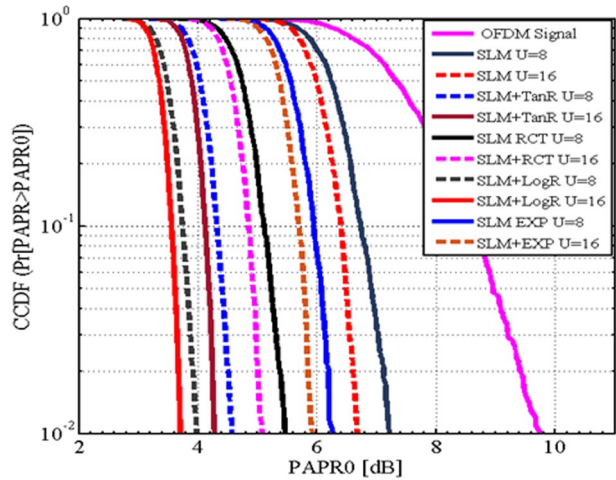
**5.2 SLM with RCT**

Figure 7 presents the comparison of PAPR of OFDM, OFDM-SLM and SLM-RCT comparing techniques. As shown, the actual OFDM signal’s PAPR is equal to 9.9 dB. By using SLM PAPR reduction technique, PAPR is reduced to 8.5 dB for U=2, and 6.2 dB for U=64. For the proposed SLM-RCT method, the value of PAPR is 6.4 dB for U=2 and it decreases gradually with increasing U and for U=64, it is reduced to 4.7 dB. It

**Fig. 9** Comparison of OFDM, OFDM-SLM & OFDM-SLM-LogR Techniques



**Fig. 10** Comparison of OFDM with Hybrid techniques



**Table 1** Comparison of OFDM with hybrid techniques for U=8 and 16

S.No	Method	PAPR (dB) at CCDF = 10 <sup>-2</sup>
1	OFDM	9.8
2	OFDM with SLM for U=8	7.2
3	OFDM with SLM for U=16	6.6
4	OFDM with SLM+EXP for U=8	6.2
5	OFDM with SLM+EXP for U=16	5.9
6	OFDM with SLM+RCT for U=8	5.4
7	OFDM with SLM+RCT for U=16	5.1
8	OFDM with SLM+TanR for U=8	4.6
9	OFDM with SLM+TanR for U=16	4.3
10	OFDM with SLM+LogR for U=8	4.0
11	OFDM with SLM+LogR for U=16	3.7

is observed that the proposed SLM-RCT technique reduces the PAPR by a large amount without increasing U value to achieve less PAPR. To reduce the complexity, consider U as 8 and when PAPR is calculated for U=8, hybrid SLM-RCT reduces PAPR to 5.4 dB with a major difference of 4.5 dB compared to original OFDM signal and 1.8 dB compared to SLM. Compared to the SLM-EXP technique, which produces the PAPR of 6.2 dB for U=64, SLM-RCT technique reduces the PAPR to 4.7 dB with a difference of 0.8 dB. The PAPR of Rooting technique is less compared to SLM-EXP technique.

### 5.3 SLM with TanR Companding

As shown in Fig. 8, PAPR is evaluated for OFDM, OFDM-SLM and SLM-TanR companding for different values of U. PAPR of OFDM signal is equal to 9.7 dB, SLM method reduces the PAPR to 8.5 dB for route number U=2 and 6.2 dB for U=64. The proposed

SLM-TanR reduces the PAPR to 5.2 dB for  $U=2$  and 4 dB for  $U=64$ . When  $U=8$ , OFDM with SLM is having PAPR of 7.2 dB and it is reduced to 4.5 dB for hybrid SLM with TanR technique with a major difference of 2.7 dB compared to SLM and 5.2 dB compared to conventional OFDM signal. It is observed that the SLM-TanR technique is better compared to SLM-EXP and SLM-RCT techniques as it reduces the PAPR to 4 dB which is better than SLM-EXP whose PAPR is 5.5 dB and SLM-RCT with a PAPR of 4.7 dB.

## 5.4 SLM with LogR Companding

Figure 9 illustrates the PAPR of OFDM, SLM and SLM-LogR techniques. As shown, the OFDM signal is with PAPR value 9.8 dB. The proposed SLM with LogR technique reduces PAPR to 4.6 dB for  $U=2$  and it decreases gradually with increasing  $U$  and for  $U=64$ , it is reduced to 3.4 dB. To reduce the complexity, consider  $U$  as 8 and when PAPR is calculated for  $U=8$ , OFDM with SLM is having PAPR of 7.2 dB and it is reduced to 4 dB for hybrid SLM with LogR technique with a major difference of 3.2 dB compared to SLM and 5.8 dB compared to original OFDM signal. When the SLM-LogR technique is compared to the remaining proposed reduction techniques, SLM-EXP method gives PAPR of 6.2 dB, SLM-RCT technique provides 5.4 dB, SLM-TanR gives 4.5 dB and SLM-LogR is with PAPR of 4 dB for  $U=8$ . It proves that the Logarithmic companding (LogR) is better than EXP, TanR and RCT techniques. Hence, among all techniques, SLM-LogR gives better performance in reducing PAPR and reduces the system complexity and computational cost. The comparison of conventional OFDM with all proposed hybrid techniques is shown in Fig. 10. The phase rotation factor is considered as  $U=8$  and 16. All techniques are having better results in reducing PAPR compared to the conventional OFDM and OFDM-SLM reduction techniques.

For further discussion, Table 1 gives the clear idea about all the proposed companding techniques. Conventional OFDM is having PAPR of 9.8 dB and the PAPR of OFDM with SLM is reduced to 7.2 dB for  $U=8$  and 6.6 dB for  $U=16$ . The PAPR of SLM with EXP companding technique is 6.2 dB for  $U=8$  and 5.9 dB for  $U=16$ , SLM-RCT technique is 5.4 dB for  $U=8$  and 5.1 dB for  $U=16$ , SLM-TanR companding is 4.6 dB for  $U=8$  and 4.3 dB for  $U=16$ , and finally, SLM-LogR technique is 4 dB for  $U=8$  and 3.7 dB for  $U=16$ . Hence, all proposed techniques reduce the PAPR by a large amount compared to OFDM as well as SLM by reducing the system complexity and cost. Finally, it is observed that, LogR technique reduces the PAPR by a great amount compared to conventional OFDM, SLM and the remaining companding techniques.

## 6 Conclusions

The bottleneck of OFDM technique is high PAPR which makes the system more complex as it moves the HPA to be operated in the nonlinear region. Hence, in this paper, hybrid PAPR reduction techniques have been proposed and implemented to out-strip the performance of the system by decreasing the PAPR at lower complexity by choosing lower phase rotations of SLM i.e., for  $U=8$ . When compared to original OFDM and SLM, all proposed hybrid techniques give less PAPR and Logarithmic companding gives better performance among all of them proposed in this work.

All the proposed techniques reduce the PAPR value with less hardware required which leads to the decrement in computational complexity of the system. Also, the proposed

techniques improve the system efficiency, reduces the PAPR, increases the BER performance and SNR. As the PAPR reduces, the overall complexity can be reduced as the HPA works in linear region. But compared to SLM without side information technique, the complexity is increased by little bit. Hence, in future, the proposed techniques complexity can be further reduced by using the SLM without side information technique. Due to the above advantages, the proposed hybrid techniques can be employed in future wireless communication systems, and they can be incorporated in standards like Interoperable Public Safety (IPSC) and waveforms like Universal Networking Waveform (UNW) and Wideband network Waveform (WNW). Also, OFDM plays a vital role in LTE, 4G, 5G and beyond wireless communications technologies where battery operated handsets are used for broadband applications.

**Funding** The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

**Data availability of material** The datasets generated during and/or analyzed during the current study are not publicly available right now but are available from the corresponding author on reasonable request.

## Declarations

**Conflict of interest** We confirm that this work is original and has not been published elsewhere, nor is it currently under consideration for publication elsewhere/The authors have no relevant financial or non-financial interests to disclose.

**Code availability** (Software application or custom code)-Code is written in Matlab and it is not publicly available.

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