IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received December 26, 2019, accepted January 17, 2020, date of publication January 28, 2020, date of current version February 6, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2970022

Analysis of Hybrid PAPR Reduction Methods of OFDM Signal for HPA Models in Wireless Communications

SRAVANTI THOTA [1], YEDUKONDALU KAMATHAM [2], (Senior Member, IEEE), AND CHANDRA SEKHAR PAIDIMARRY [3], (Member, IEEE)

[1]Department of ECE, University College of Engineering, Osmania University, Hyderabad 500007, India
[2]Department of ECE, CVR College of Engineering, Hyderabad 501510, India
[3]Department of ECE, University College of Engineering, Osmania University, Hyderabad 500007, India

Corresponding author: Sravanti Thota (sravanti23@gmail.com)

This work was supported by AICTE, New Delhi under Research Promotion Scheme (RPS), under the project entitled "Study and Implementation of Self-Organized Femtocells for Broadband Services to Indoor Users in Heterogeneous Environment" under Grant 8-30/RFID/RPS/POLICY-1/2016-2017.

ABSTRACT Orthogonal Frequency Division Multiplexing (OFDM) suffers from a high Peak-to-Average Power Ratio (PAPR). Designing a High Power Amplifier (HPA) with high PAPR is not a wise technique as it roots the amplifier to operate in a non-linear region which is intricate. Linearity and power efficiency are important constraints of HPA which cannot be achieved at the same time. Therefore, perfect linearity is observed when efficiency is low or vice versa and efficiency can be improved by decreasing the PAPR. In this paper, the PAPR is mitigated by using Partial Transmit Sequence (PTS), Selected Mapping (SLM), Hybrid and proposed methods. Analysis of OFDM with high PAPR passing through different HPA models is evaluated in terms of Power Spectral Density (PSD), gain and efficiency for all PAPR reduction methods considered in this work. The results are encouraging by using hybrid PAPR reduction method, HPAs can be operated in a linear region to provide higher efficiency compared to non-hybrid PAPR reduction methods. Hence, hybrid PAPR reduction methods can be used even in future wireless communications systems including 5G and beyond.

INDEX TERMS Companding, high power amplifier models, orthogonal frequency division multiplexing, peak to average power ratio, partial transmit sequence, selected mapping.

I. INTRODUCTION

Due to the popularity of gaming, multimedia services, and others, new wireless communication technology has been growing with higher data rates which naturally leads to higher bandwidths with low latency and high Quality of Service (QoS) [1]. An example in [2], projected that 5G technology can attain a higher data rate, the capacity of the system more than 1000 times, cell throughput more than 25 times and spectral efficiency more than 10 times than the present 4G technologies. The Long-Term Evolution (LTE) and OFDM are the key tasks and central over previous systems.

OFDM is a widespread modulation technique which triggers all 4G wireless communication systems such as WLANs like IEEE 802.11 a/g/n/ac, Digital Video Broadcasting-Second Generation by Terrestrial (DVB-T2), Digital Audio Broadcasting (DAB), Digital Video Broadcasting by Satellite-Second Generation (DVB-S2) and IEEE 802.11 WiMAX (Worldwide Interoperability for Microwave Access). Faraway in broadband wireless schemes, in the case of higher data transmission, the complexity is reduced by combining OFDM with Multiple-Input-Multiple-Output (MIMO) wireless communications [3]. OFDM is a flavorful technique with several merits such as low complexity, easy assimilation with MIMO and soon is adopted by multifarious inventions and strongly persuades 5G NR choosing OFDM as the heart for designing new waveform [4]. The OFDM is the new waveform for isolation and multiplexing for efficient support of 5G and the spectrum efficient from the physical layer perception. To balance implementation complexity and

The associate editor coordinating the review of this manuscript and approving it for publication was Zhong Fan.

concert the low cost, low complication IoT devices are the solution for 5G communications. Hence OFDM is the backbone of many future wireless accessing systems.

OFDM is united of many synchronized carriers and when they are added in the same time domain leads to high PAPR. In terms of linearity range and coverage, the most significant problem in the uplink of wireless communications is PAPR [5], [6]. This high PAPR causes signal degradation like increased BER and out of band radiation on the transmitter side when conceded through HPA due to its non-linearity property and efficiency of HPA is very critical because of limited battery power. As probed in [7] for future 5G, the deprived battery presentation and overall low power efficiency of mmWave Power Amplifier (PA), the PAPR reduction is considered. To evade the non-linear distortion the Input Backoff (IBO) of HPA should be higher than PAPR. Since at the transmitter side most of the power is consumed by HPA and other devices [8], [9], the power can be saved by improving the efficiency of HPA.

Many PAPR saving methods have been proposed in the literature to decrease non-linear distortion of HPA and operate in a linear range. These methods are classified into signal distortion, coding, and probabilistic techniques. Signal distortion techniques like clipping and filtering [10] increases BER directing to in-band and out-band radiations. Companding is a technique applied to speech signal having high peaks is the distorting method is also applied to OFDM signal as this signal has high peaks. Two types of companding transform like μ-law and A-law [11], [12] are implemented to reduce PAPR by compressing the OFDM signal with a tolerable increase in BER and low complexity. The OFDM signal can also be modified by adding or multiplying phase or optimization factors called a probabilistic method. In this method, a set of different OFDM symbols is generated and the symbol having low PAPR is selected called Selected Mapping (SLM) [13], [14]. If the OFDM symbol is divided into disjoint subblock and each subblock is figured by weighting phase factor are merged and the phase factors are elected to produce minimum PAPR of the combined signal which is a Partial Transmit Sequence (PTS) [15], [16]. As per the requirements of the system, anyone of the methods is combined with other, called hybrid methods. For example, PTS is combined with linear or non-linear companding techniques [17], SLM is combined with PTS [18] which reduces the hardware and computational complexities by reducing PAPR than single methods.

In this paper, a low complex PAPR reduction method is proposed and is compared with the other hybrid methods in terms of efficiency, complexity, and PAPR. The new hybrid method is the cascade of two stages. In the first stage, the SLM is combined with PTS reduction technique and in the second stage, the PTS technique is combined with companding methods. The combination of SLM with companding, PTS with companding which are existing method and new hybrid (SLM with PTS) with companding are projected in terms of PSD and PAPR.

Though there is an enormous literature tackling the PAPR reduction, no reviews have associated the distortions triggered by different HPA models of an OFDM system with PAPR reduction procedures. In this paper, it is proposed to investigate the effects of these PAPR reduction methods for dissimilar types of frequency-independent HPA models.

The remainder of this paper is organized as follows: Section II introduces OFDM, PAPR, and various PAPR reduction techniques. Section III presents the HPA analysis. The performance of HPA models is compared through simulations in section IV. Finally, conclusions are drawn in section V.

II. OFDM SYSTEM

A. OFDM

These days, the discrete-time models are applied in all systems. Here the discrete-time OFDM is derived from continuous-time by sampling T_s with a sampling period of T_N for each symbol which is sampled N times with N subcarriers.

$$T_s = NT_N = \frac{N}{BW} \tag{1}$$

An OFDM symbol is the sum of N individual signal modified with M-QAM or M-QPSK onto subchannels of equal bandwidth (BW), which is proficiently implemented using Inverse Discrete Fourier Transform/ Inverse Fast Fourier Transform (IDFT/IFFT) operation [19]. Henceforth, the time domain OFDM signal x[n] is

$$\mathrm{x}[n] = \frac{1}{\sqrt{N}} \sum_{k=0}^{n-1} \mathrm{X}_k \mathrm{e}^{\frac{j2\pi kn}{N}}; \quad 0 \le n \le N-1 \tag{2}$$

where n is time and k is the frequency indices and X_k is frequency-domain OFDM signal with $k = \{0, \ldots.., N-1\}$ subcarriers.

B. PAPR

The PAPR of the OFDM signal can be estimated as:

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

In literature, the occurrence of PAPR is assessed by a mathematical tool called Complementary Cumulative Distribution Function (CCDF). The probability of PAPR of OFDM signal surpassing definite threshold α_{th}[20] is the result of CCDF. Therefore, the CCDF for OFDM signal is:

$$\mathrm{P}(\mathrm{PAPR} > \alpha_{\mathrm{th}}) = 1 - \mathrm{P}(\mathrm{PAPR} \le \alpha_{\mathrm{th}}) \tag{4}$$

C. PAPR REDUCTION METHODS

A large PAPR would push the HPAs into saturation, making interference among the subcarriers at the transmitter which degrades the performance of BER. The average power of the OFDM signal can be reduced to alleviate lashing the HPAs into saturation which reduces the performance of BER and Signal-to-Noise Ratio (SNR). Therefore, the solution is to reduce the peak power i.e., the high peak of the signal.

Many reduction schemes have been proposed in the literature. These methods are categorized into three types: signal distortion, probabilistic and hybrid techniques.

i) Companding Method: The distortion technique with low complexity, better BER performance without expansion of bandwidth offering better low PAPR than clipping method is a companding method [21]–[26]. The A-law and μ-law are the two companding methods which are applied to the proposed method.

ii) Selected Mapping (SLM): It was proposed in 1996 [27], which has been used extensively for PAPR reduction. In this, the OFDM is multiplied with different U phase sequences which are statistically detached, and these sequences are operated by IFFT producing U OFDM independent phase sequences. Finally, the series has the lowest PAPR, is considered. When U is greater, the PAPR reduction is better but a substantial number of IFFT blocks are required which increases hardware complexity. The main drawback of this technique is to transmit side information along with each data block for informing the receiver about the sequence selected. This side information is $log_2^U\, bits$. Le Goff et al. [30] proposed an SLM technique without side information and many SLM algorithms with low complexity have been proposed [28]–[31].

iii) Partial Transmit Sequences (PTS): The OFDM is partitioned into V subblocks, each subblock is operated by IFFT and each IFFT series is multiplied by a set of rotation factors W. All the sequences are summed and PAPR is calculated. This process is continued until the lowest PAPR is obtained. As the number of subblocks increases better PAPR reduction and therefore to find the optimum set of phase factors W^{V-1} set of factors have to be searched which increases the computational complexity exponentially with the number of subblocks and requires $log_2^{W^V}\, bits$. The OFDM is divided into subblocks by different methods [32], [33].

iv) Hybrid Methods: In recent literature, based on the system requirements like low complexity, better BER performance, etc., two or more existing PAPR methods are combined [34]–[37] to reduce PAPR called hybrid methods. In this paper, the hybrid method is the combination of SLM and PTS in which the PAPR is reduced with low hardware and computational complexity.

The hardware complexity in SLM and computational complexity (the number of search iterations) in PTS is reduced because the optimum PAPR is achieved by using only eight-phase sequences (U) and two subblocks (V), phase factors $W = [1 - 1\, j - j]$ i.e., four iterations than the conventional SLM and PTS techniques. The side information for SLM is 3 *bits* and PTS is *4* bits only.

A new hybrid method [38] from the literature, companding is the low complex PAPR reduction technique and also doesn't expand bandwidth, therefore without increasing complexity i.e., with same side information and expanding the bandwidth, the optimum PAPR of OFDM system can be achieved with hybrid method by combining PTS with A-law (A = 87.6) and μ-law (μ = 255) companding transforms, SLM with A-law and μ-law companding transforms and a hybrid method with A-law and μ-law companding transforms as shown in Fig.1.

TABLE 1. Simulation parameters.

S No	PARAMETERS	Quantity
1	SYMBOLS	500
2	SUBCARRIERS	64
3	MODULATION	16-QAM
4	OVER SAMPLING FACTOR (L)	4
5	PHASE SEQUENCES (U)	8
6	SUBBLOCKS (V)	2
7	PHASE FACTORS (W)	[1 -1 J -J]
8	μ LAW	255
9	A LAW	87.6

For U = 8 sequences and V = 2 disjoint subblocks at CCDF = 10^{-2} in Fig. 2.a, the PAPR of PTS with μ-law is reduced to 3.5 dB and PTS with A-law to ~5.0 dB than the conventional PTS. Hence, the performance of the OFDM system is improved with less hardware complexity.

From Fig. 2.b, compared to conventional SLM, the PAPR of SLM with μ-law is ~ 4.0 dB and with A-law is 5.6 dB.

Therefore, the performance is improved with less computational complexity. From the Fig.2.c and Fig. 2.d, the hybrid method produced an optimum PAPR than a hybrid with A-law and μ-law. By this, the OFDM design complexity is reduced.

III. MOTIVATION

A. THE GAIN OF OFDM SYSTEM

The gain of the OFDM system is considered to compare the PAPR methods. Under Additive White Gaussian Noise (AWGN) or other channel conditions, the gain is defined as the best approach function [39] for PAPR reduction.

$$A = -10log_{10}\left(\frac{PAPR\ after\ reduction}{PAPR\ before\ reduction}\right) \quad (5)$$

From Table 2, the net gain of the proposed PAPR methods are analyzed by considering the PAPR value at CCDF = 10^{-2}. The gain of PTS is twice the SLM method since the hardware complexity is less in PTS. Hence PTS method accomplishes better PAPR reduction. Since the companding techniques are less complex, coalescing these with SLM and PTS methods doesn't craft the OFDM system to be complex. Since the dynamic range of μ-law is larger than A-law in the speech signal, the PTS with μ-law, SLM with μ-law and hybrid technique can be appreciated as the useful techniques with reliable PAPR reduction performance with low complexity and high gain.

B. POWER EFFICIENCY

The power of the signal can be saved in wireless communication systems by reducing the PAPR of the signal. Because of the restraint of the battery life at the uplink, saving the power becomes more pertinent. As mentioned, [40], class A power

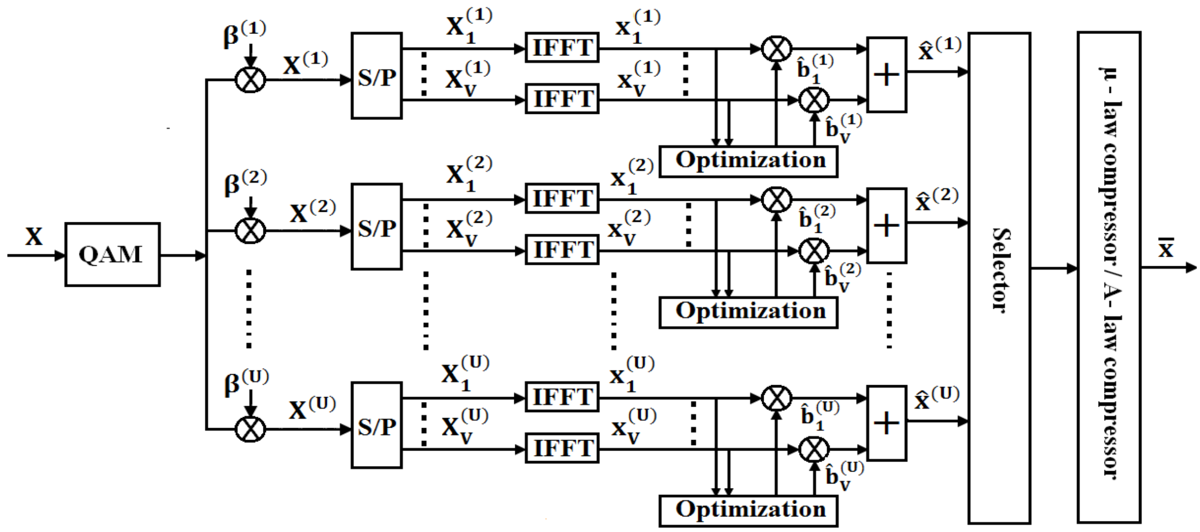
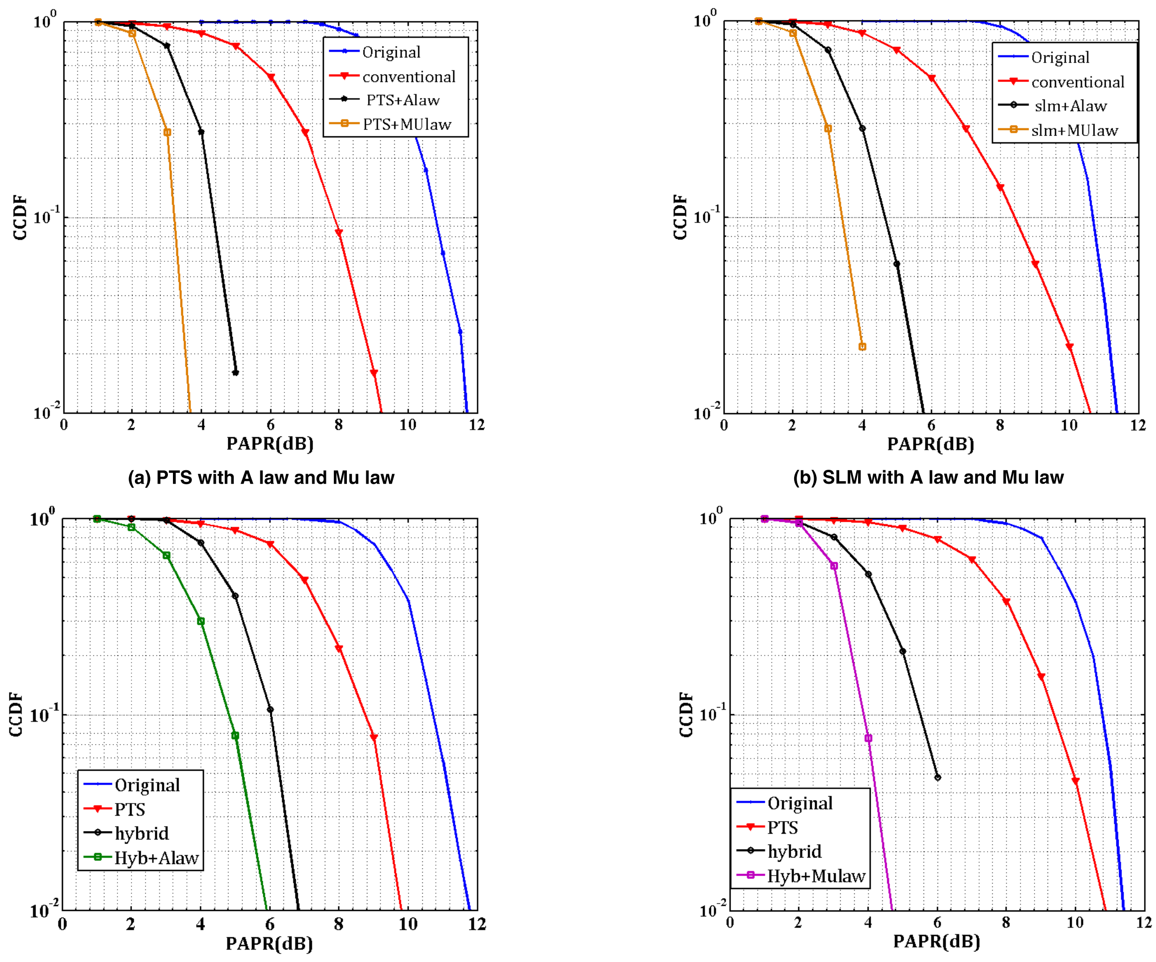


FIGURE 1. New hybrid method.



(a) PTS with A law and Mu law

(b) SLM with A law and Mu law

(c) Hybrid with A law

(d) Hybrid with Mu law

FIGURE 2. PAPR Analysis of hybrid method.

amplifiers working mostly in a linear region, the maximum HPA efficiency 50%. Therefore, the HPAs maximum efficiency is defined as with a maximum efficiency cutoff of class A amplifier:

$$\eta = \frac{\max \textit{efficiency}}{PAPR} = \frac{0.5}{PAPR} \tag{6}$$

TABLE 2. Net gains of hybrid methods.

S No	PAPR Reduction Method	GAIN (Y) (dB)
1	OFDM WITH SLM	0.5
2	OFDM WITH SLM AND A-LAW	3.1
3	OFDM WITH SLM AND μ-LAW	4.5
4	OFDM WITH PTS	1.0
5	OFDM WITH PTS AND A-LAW	3.6
6	OFDM WITH PTS AND μ-LAW	5.1
7	OFDM WITH HYBRID	2.1
8	OFDM WITH HYBRID AND A-LAW	2.9

TABLE 3. Power efficiency of hybrid methods.

S No	PAPR reduction Method	PAPR (dB)	PAPR (linear)	η (%)
1	OFDM	11.5	14.1	3.54
2	OFDM with SLM	10.2	10.4	4.77
3	OFDM with SLM and A-law	5.6	3.6	13.77
4	OFDM with SLM and μ-law	4.0	2.5	19.9
5	OFDM with PTS	9.0	7.9	6.32
6	OFDM with PTS and A-law	5.0	3.1	15.8
7	OFDM with PTS and μ-law	3.5	2.2	22.72
8	OFDM with Hybrid	7.0	5.0	10.0
9	OFDM with Hybrid and A-law	5.8	3.8	13.1
10	OFDM with Hybrid and μ-law	4.5	2.8	17.8

The PAPR is uttered in linear units. The PAPR of each reduction technique is taken at a probability of 10^{-2} in dB and converted into linear values of OFDM signal with 64 subcarriers,16-QAM, 500 symbols for U = 8, V = 2, A = 87.6 and $\mu = 255$ with oversampling factor L = 4.

Table 3 analyses the efficiency of power amplifiers in terms of linear PAPR values. The active range of μ-law is larger than A-law and μ-law realms, the encoded information at lower amplitudes which can be befuddled by using linear methods, the power efficiency of OFDM system can be increased by using PTS with μ-law, SLM with μ-law and Hybrid with μ-law methods. Therefore, accomplishing low power efficiency is the strong inspiration for using a PAPR reduction techniques.

IV. HPA

A. IBO AND OBO

The characteristics of an amplifier saturation region depend on the nonlinear distortion of the signal by HPA is measured using power back-off of an amplifier as Input Back-Off (IBO) and Output Back-Off (OBO) [41]. The IBO and OBO are defined as:

$$IBO = 10log\left(\frac{A_s^2}{P_{avg,input}}\right) \tag{7}$$

$$OBO = 10log\left(\frac{A_0^2}{P_{avg,output}}\right) \tag{8}$$

where A_s^2 is the saturated input voltage applied , A_0^2 is the maximum voltage output of HPA, while $P_{avg,input}$ and $P_{avg,output}$ are the input and output power of the signals.

B. HPA MODELS

High power amplifiers parade various magnitudes of non-linearity. The amplitude and phase transfer characteristics are usually described by these amplifiers which are stated as Amplitude Modulation/Amplitude Modulation (AM/AM) conversion and Amplitude Modulation /Phase Modulation (AM/PM) conversion. Fig.3 shows the power spectral density of the OFDM signal along with PAPR reduction techniques before HPA.

In this, the PSD of the Hybrid method is stronger than PTS, SLM, PTS with companding, SLM with companding and Hybrid with companding method.

1) SALEH MODEL

It is a two-parameter frequency-independent model that has been adopted for nonlinear amplifiers. It is developed for modelling Travelling-Wave Tube Amplifiers (TWTA's) [42]. Appropriate selections for the amplitude and phase coefficients (α's and β's) provide a suitable model for solid-state amplifiers as well. The two-parameter amplitude and phase $r(t)$ are represented by:

$$A(r(t)) = \frac{\alpha_a r(t)}{1+\beta_a r(t)^2} \tag{9}$$

$$\Phi(r(t)) = \frac{\alpha_\Phi r(t)}{1+\beta_\Phi r(t)^2} \tag{10}$$

Here, the amplitude coefficients $\alpha_a = 2.1587$; $\beta_a = 1.1517$ and phase cofficients $\alpha_\Phi = 4.033$; $\beta_\Phi = 9.1040$ are considered as the RMS error is less [43] for input signal r(t).

PSDs of input and output signals of HPA with the Saleh model are compared. The PSD (dB/MHz) of the OFDM signal has been increased from -18 to 18 using Saleh model. From Figs. 3 and 4, the PSD (dB/MHz) of PTS and PTS with companding is increased from 18 to 20, SLM and SLM with companding from $\sim$ 8 to 12 and hybrid with companding are same since the hardware and computational complexity has been reduced (U = 8 and V = 2). Therefore, PSD is strengthened by reducing PAPR and from this hybrid with companding performs better than others.

From Table 4, it is observed that the Saleh HPA works almost in the linear region with high IBO and OBO which is OFDM with the hybrid method.

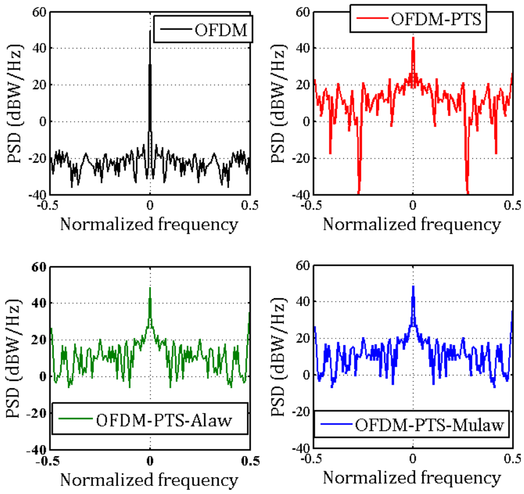
2) SSPA MODEL

The Solid-State Power Amplifier (SSPA) output signal is modelled as [43]:

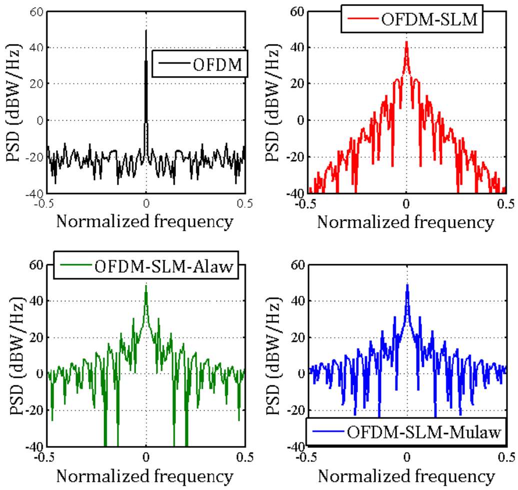
$$A(r(t)) = \frac{\alpha r(t)}{\left[1+\left(\frac{\alpha r(t)}{A_0}\right)^{2p}\right]^{\frac{1}{2p}}}; \quad \Phi[r] \approx 0 \tag{11}$$

where $\alpha = 1$, $A_0 = \alpha A_s$ is saturating amplitude with α small gain and the linearity of the AM/AM curve depends on integer p. As p increases, the curve comes close to the nonlinear transformation.

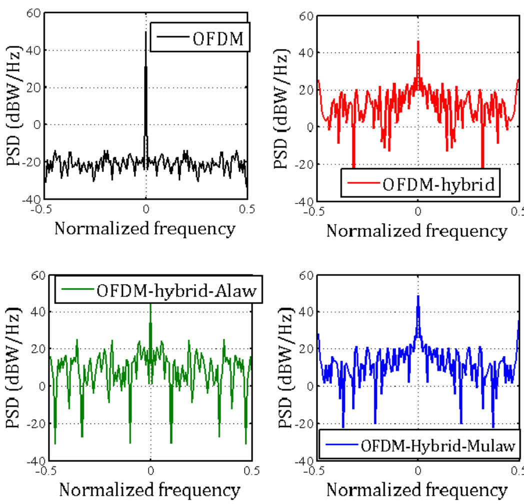
It is also observed that from Table 5 the SSPA HPA works almost in the linear region with high IBO and OBO for



(a) OFDM, PTS, PTS with A law and Mu law

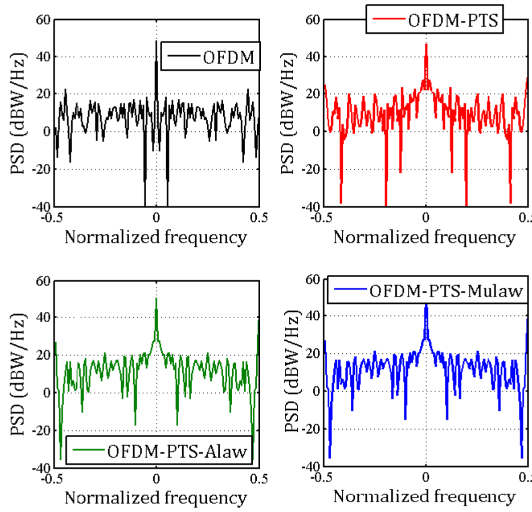


(b) OFDM, SLM, SLM with A law and Mu law

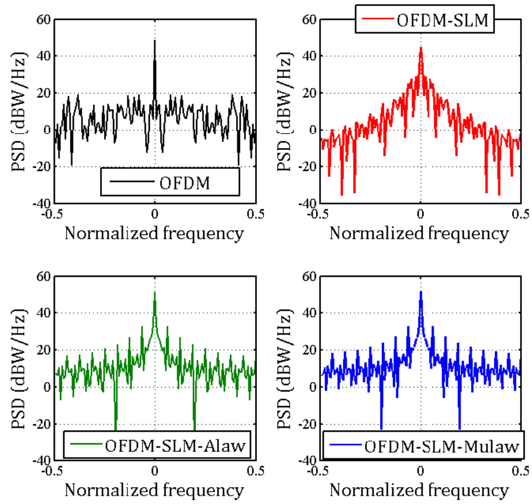


(c) OFDM, Hybrid with A law and Mu law

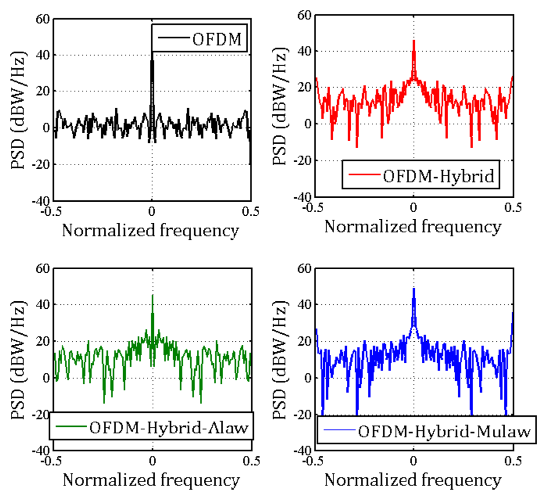
FIGURE 3. The spectrum of OFDM signal before HPA.



(a) OFDM, PTS, PTS with A law and Mu law



(b) OFDM, SLM, SLM with A law and Mu law



(c) OFDM, Hybrid with A law and Mu law

FIGURE 4. Spectrum after HPA with Saleh model.

OFDM with hybrid.The PSD of the SSPA amplifier model is generated for all PAPR reduction methods for p = 2. The characteristics of the SSPA model are almost the same as Saleh model. The SSPA model can work continuously even

TABLE 4. IBO and OBO of Saleh model.

S No	PAPR REDUCTION METHOD	IBO (dB)	OBO (dB)
1	OFDM	21.55	59.87
2	OFDM WITH PTS	6.01	8.34
3	OFDM WITH PTS AND A-LAW	2.32	6.34
4	OFDM WITH PTS AND MU LAW	2.20	6.34
5	OFDM WITH SLM	6.58	8.52
6	OFDM WITH SLM AND A-LAW	4.10	6.96
7	OFDM WITH SLM AND MU LAW	3.99	6.91
8	OFDM WITH HYBRID	13.03	13.60
9	OFDM WITH HYBRID AND A-LAW	10.69	11.17
10	OFDM WITH HYBRID AND MU LAW	10.29	11.08

TABLE 5. IBO and OBO of SSPA model.

S No	PAPR REDUCTION METHOD	IBO (dB)	OBO (dB)
1	OFDM	21.55	31.97
2	OFDM WITH PTS	13.03	14.08
3	OFDM WITH PTS AND A-LAW	9.35	11.18
4	OFDM WITH PTS AND MU LAW	9.177	11.06
5	OFDM WITH SLM	12.70	13.82
6	OFDM WITH SLM AND A-LAW	10.33	11.83
7	OFDM WITH SLM AND MU LAW	10.21	11.73
8	OFDM WITH HYBRID	12.61	13.73
9	OFDM WITH HYBRID AND A-LAW	10.00	10.18
10	OFDM WITH HYBRID AND MU LAW	8.65	10.76

a failure occurs and requires only low supply voltages. From Figs.4 and 5, Saleh model is more stable than SSPA.

3) GHORBANI MODEL

The characteristics of the Saleh model which was accessible for modelling TWTA amplifiers are not suitable for the SSPA model because SSPA does not have larger roll-off at saturation and low phase distortion as TWTAs. The Ghorbani model [44] was designed for the SSPA model with a similar style of Saleh model having a four-parameter equation of amplitude and phase.

$$A\left(r\left(t\right)\right) = \frac{a_0 r(t)^{a_1}}{1 + a_2 r(t)^{a_1}} + a_3 r(t) \tag{12}$$

$$\Phi\left(r\left(t\right)\right) = \frac{b_0 r(t)^{b_1}}{1 + b_2 r(t)^{b_1}} + b_3 r(t) \tag{13}$$

The four parameters are obtained from [43] of signal $r\left(t\right)$ are:$a_0 = 8.1081, a_1 = 1.5413, a_2 = 6.5202, a_3 = -0.0718, b_0 = 4.6645, b_1 = 2.0965, b_2 = 10.88, b_3 = -0.003$ which has a smaller amount of roll-off at saturation and the small-signal amplification is exponential instead of linear as in Saleh model. Also, for high input amplitude values the phase shift is almost constant as in Saleh model.

In the Ghorbani model, the strength of the signal is poor which implies this amplifier is working in a high non-linear mode. From Fig.3 and Fig.6, it can be observed that the PSD strength of OFDM signal is less than the above mentioned HPAs but the PSD is obstinate as the PAPR of the OFDM signal is reduced. Therefore, this amplifier works in linear mode by reducing PAPR.

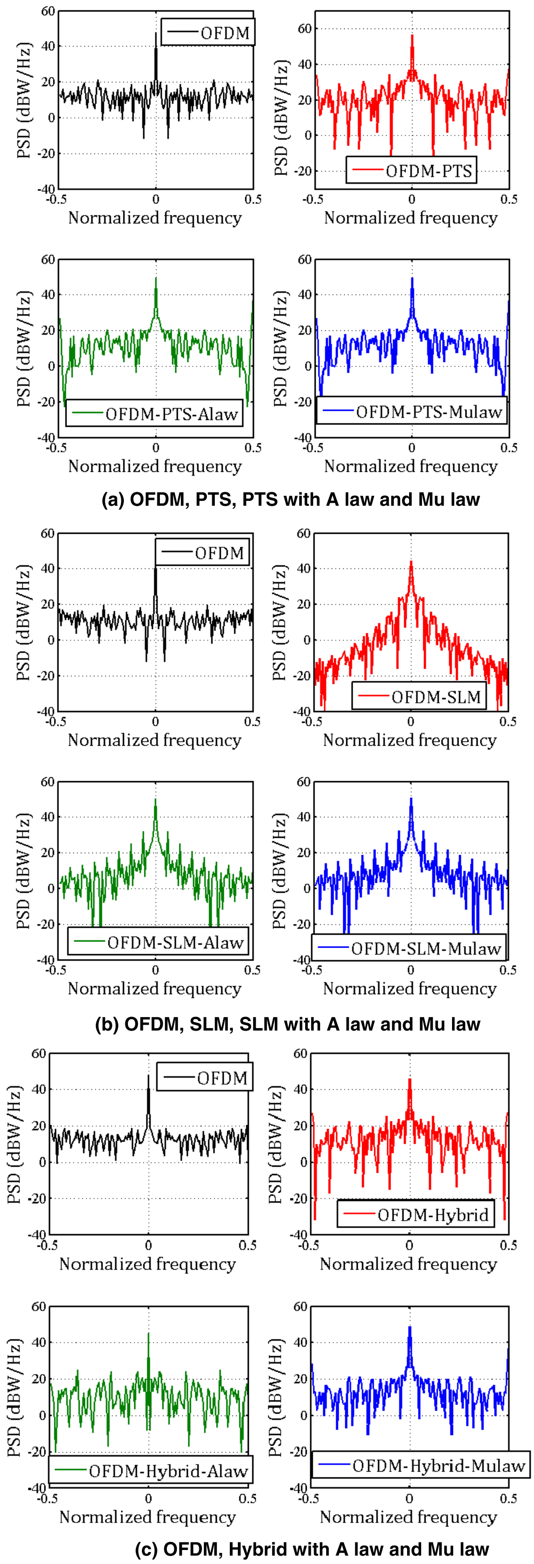
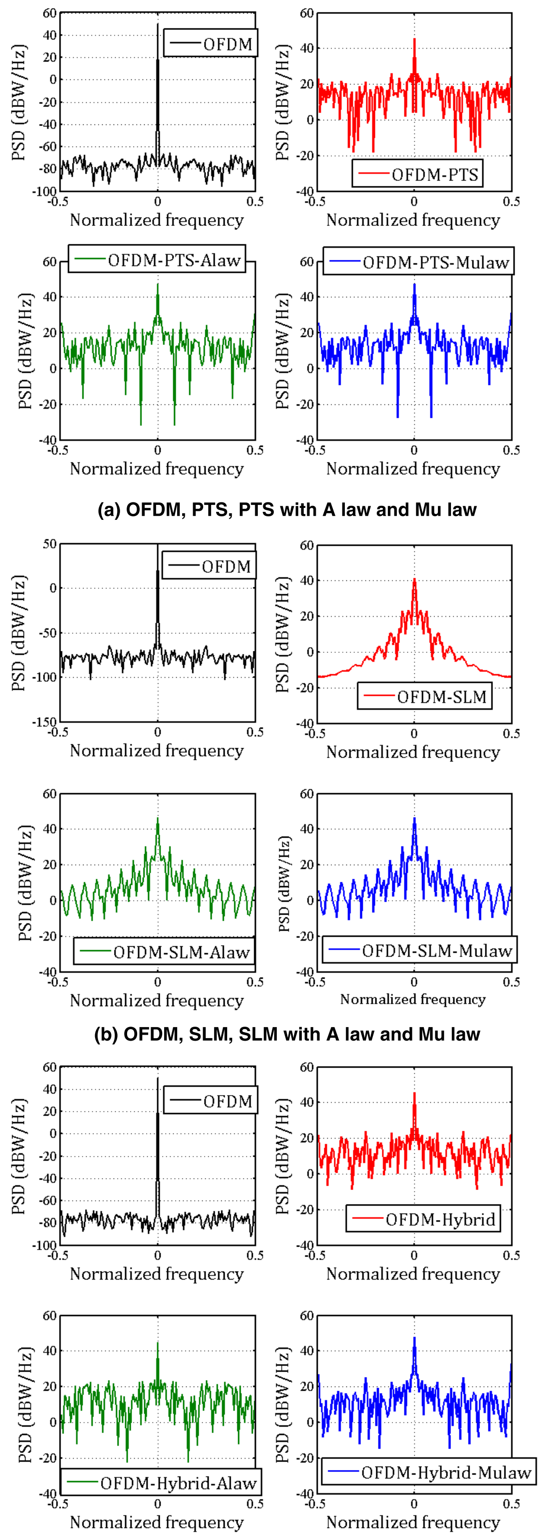


FIGURE 5. Spectrum after SSPA LNA.

Since the OBO of the hybrid method is less than all other techniques from Table 6, the characteristics of Ghorbani model can be operated in linear mode by using hybrid methods.



(a) OFDM, PTS, PTS with A law and Mu law

(b) OFDM, SLM, SLM with A law and Mu law

(c) OFDM, Hybrid with A law and Mu law

FIGURE 6. Spectrum after Ghorbani PA (LNA/HPA).

4) RAPP MODEL

The Rapp model was published by Christopher Rapp [45] yields a flat transition from a modified envelope to saturation level which pretends the SSPA model. The analytical expression is different from the above models.

$$A\left(r\left(t\right)\right)=v\frac{r(t)}{\left[1+\left(\frac{vr(t)}{y_0}\right)^{2p}\right]^{\frac{1}{2p}}};\quad \Phi\left[x(t)\right]=0 \qquad (14)$$

Here $v=1$ is a small signal gain, $y_0=1$ is limiting output amplitude and $p=3$ is a rolling factor that reins the evenness of the conversion from linear to saturation mode.

From Fig.7, it can be observed that the strength of PSD of OFDM signal and OFDM PAPR reduction methods are almost equal i.e., though the PAPR of OFDM signal is high or low using reduction methods, this Rapp HPA is working in a linear region. This is because of the rolling factor (p >0 [45]) and from Table 7. the input back-off (IBO) and output back-off (OBO) are almost equal.

TABLE 6. IBO and OBO of Ghorbani model.

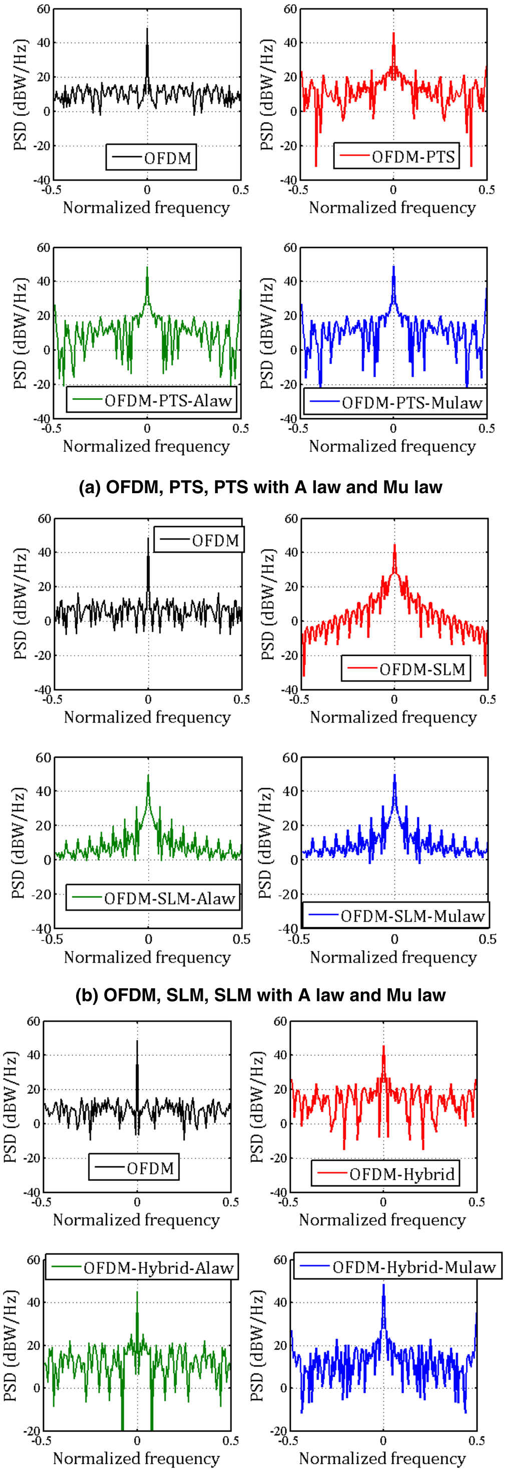
S No	PAPR reduction Method	IBO (dB)	OBO (dB)
1	OFDM	21.55	55.91
2	OFDM with PTS	12.65	3.01
3	OFDM with PTS and A-law	8.95	8.90
4	OFDM with PTS and Mu law	8.77	9.25
5	OFDM with SLM	12.38	4.38
6	OFDM with SLM and A-law	8.84	9.15
7	OFDM with SLM and Mu law	8.67	9.50
8	OFDM with Hybrid	12.66	2.86
9	OFDM with Hybrid and A-law	10.01	6.66
10	OFDM with Hybrid and Mu law	8.51	9.91

TABLE 7. IBO and OBO of Rapp model.

S No	PAPR reduction Method	IBO (dB)	OBO (dB)
1	OFDM	22.52	30.97
2	OFDM with PTS	13.82	13.88
3	OFDM with PTS and A-law	10.09	10.27
4	OFDM with PTS and Mu law	9.92	10.10
5	OFDM with SLM	15.32	15.34
6	OFDM with SLM and A-law	12.44	12.48
7	OFDM with SLM and Mu law	12.30	12.34
8	OFDM with Hybrid	13.47	13.53
9	OFDM with Hybrid and A-law	17.17	17.24
10	OFDM with Hybrid and Mu law	17.17	17.24

TABLE 8. IBO and OBO of white model.

S No	PAPR reduction Method	IBO (dB)	OBO (dB)
1	OFDM	22.51	6.79
2	OFDM with PTS	13.50	8.42
3	OFDM with PTS and A-law	9.76	6.95
4	OFDM with PTS and Mu law	9.58	6.89
5	OFDM with SLM	13.73	8.53
6	OFDM with SLM and A-law	11.26	7.43
7	OFDM with SLM and Mu law	11.13	7.39
8	OFDM with Hybrid	13.47	8.40
9	OFDM with Hybrid and A-law	17.73	10.57
10	OFDM with Hybrid and Mu law	10.81	7.28

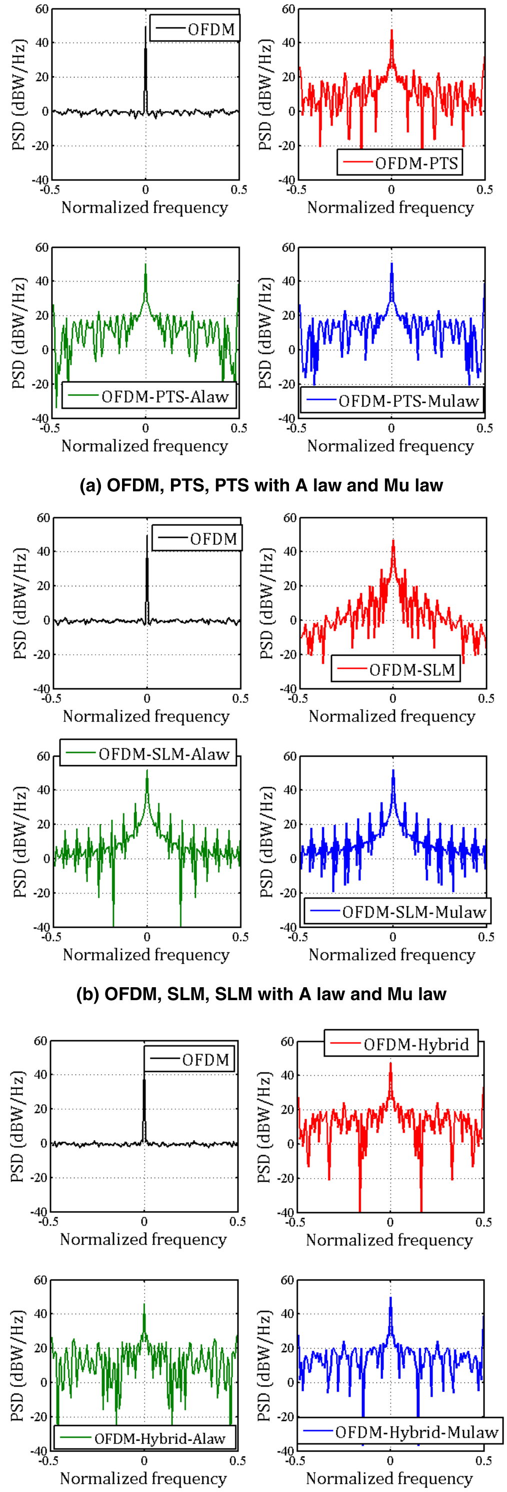


(a) OFDM, PTS, PTS with A law and Mu law

(b) OFDM, SLM, SLM with A law and Mu law

(c) OFDM, Hybrid with A law and Mu law

FIGURE 7. Spectrum after Rapp HPA.



(a) OFDM, PTS, PTS with A law and Mu law

(b) OFDM, SLM, SLM with A law and Mu law

(c) OFDM, Hybrid with A law and Mu law

FIGURE 8. Spectrum after White HPA.

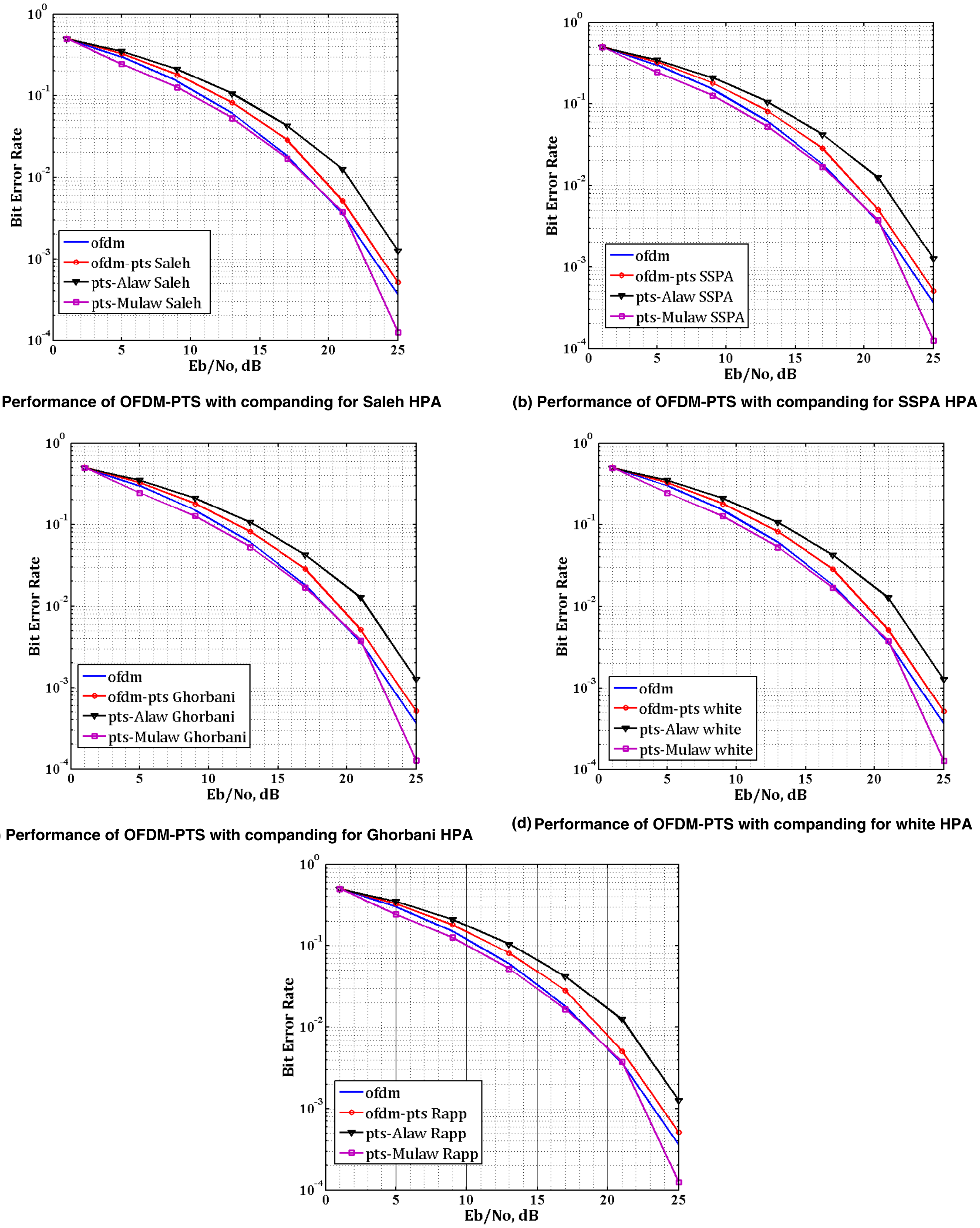
5) WHITE MODEL

The accurate modelling of Ka-band (26-40GHz) SSPAs [46] published by George White is the White model. The amplitude and phase conversions are represented with four-parameter are given by:

$$A\left(r\left(t\right)\right) = a_0\left(1 - e^{-a_1 r(t)}\right) + a_2 r(t) e^{-a_3 r(t)^2} \tag{15}$$

$$\Phi\left[r\left(t\right)\right] = \begin{cases} b_0\left(1 - e^{-b_1(r(t)-b_2}\right) & , r\left(t\right) \geq b_2 \\ 0, r(t) < b_2 & \end{cases} \tag{16}$$

The four-parameter of signal r(t) is amplitude saturation $a_0 = 1$, linear region gain $a_1 = 1$, parameters $a_2 = 0.45$ and



(a) Performance of OFDM-PTS with companding for Saleh HPA

(b) Performance of OFDM-PTS with companding for SSPA HPA

(c) Performance of OFDM-PTS with companding for Ghorbani HPA

(d) Performance of OFDM-PTS with companding for white HPA

(e) Performance of OFDM-PTS with companding for Rapp HPA

FIGURE 9. BER performance of OFDM-PTS with μ-law and A-law for different HPA's.

$a_3 = 0.5$ are recycled to contest non-linearity conversation. The phase shift of three-parameter $b_0 = 0.5$ for controlling amplification, $b_1 = 0.6$ and $b_2 = 0.3$ controls the shift along the axis.

In this model (Fig. 8), the power of the OFDM signal is neutralized to 0 dBW/Hz from ~ -15 dBW/Hz. The low OBO from Table 8 indicates the saturation region is transformed into a linear region based on the two parameters a_2 and a_3. Hence, for high frequency signal, the PSD strengthens based on parameters and further, the amplifier can be operated more in a linear region by proposed hybrid PAPR reduction methods as shown in Fig.8.

V. PERFORMANCE OF HYBRID TECHNIQUE

As OFDM suffers from high PAPR, the proposed hybrid PAPR reduction methods have been implemented for reducing the system complexity and increasing the BER performance. The PAPR of each reduction technique is taken at a probability of 10^{-2} in dB and converted into linear values of OFDM signal with 64 subcarriers,16-QAM, 500 symbols for $\mathrm{U} = 8$, $\mathrm{V} = 2$, $\mathrm{A} = 87.6$ and $\mu = 255$ with oversampling factor $\mathrm{L} = 4$.

From the above PAPR reduction methods for all amplifier models the PTS ($\mathrm{V} = 2$) with companding, SLM ($\mathrm{U} = 8$) with companding and hybrid ($\mathrm{U} = 8$ and $\mathrm{V} = 2$) technique presentation is virtuous than others. Out of these methods, the most efficient and less complex PAPR reduction method is PTS with companding as the PAPR is reduced almost equal to other best methods only with two iterations($\mathrm{V} = 2$).

Fig. 9 shows the BER performance after transmitting the OFDM, OFDM with PTS and OFDM-PTS with companding through different HPA models. The curves in each figure are labelled as 'ofdm', 'ofdm-pts', 'pts-Alaw', 'Mulaw' with different HPA names.

In summary, the PTS with companding offers almost the same BER performance as that of conventional PTS. The PTS with companding technique with low complexity has better BER performance without expansion of bandwidth, offering better low PAPR. Therefore, the PTS with companding method can be applied to more scenarios.

VI. CONCLUSION

OFDM plays an important role in 4G and 5G wireless communications systems. As OFDM suffers from high PAPR, the proposed hybrid PAPR reduction methods have been implemented for reducing the system complexity and increasing the BER performance.

This work analyzes the gain and power efficiency of the proposed methods. PTS with companding, SLM with companding and hybrid technique presentation is virtuous than others. Out of these, the BER performance in PTS with companding technique is better without the expansion of bandwidth and less complex. Various frequency-independent HPA models and calculated IBO and OBO for all PAPR reduction methods and are assessed. The results show that Ghorbani model presents poor performance and Rapp models outperform than others with minimum distortion.

Finally, it is concluded that the linear amplification can be achieved with hybrid PAPR reduction methods for various frequency-independent amplifier models, and PTS with companding reduces OFDM system hardware and computational complexities among the other proposed techniques. Hence these methods can be used in future generation wireless communications like 5G and beyond.

REFERENCES

[1] F. Liu, Z. Pan, and L. Chen, "HARQ method and system," U.S. Patent 7 760 812, Jul. 20, 2010.

[2] Y. Wang, J. Xu, and L. Jiang, "Challenges of system-level simulations and performance evaluation for 5G wireless networks," *IEEE Access*, vol. 2, pp. 1553–1561, 2014.

[3] H. Yang, "A road to future broadband wireless access: MIMO-OFDM-based air interface," *IEEE Commun. Mag.*, vol. 43, no. 1, pp. 53–60, Jan. 2005.

[4] S.-Y. Lien, S.-L. Shieh, Y. Huang, B. Su, Y.-L. Hsu, and H.-Y. Wei, "5G new radio: Waveform, frame structure, multiple access, and initial access," *IEEE Commun. Mag.*, vol. 55, no. 6, pp. 64–71, Jun. 2017.

[5] K. Anoh, C. Tanriover, and B. Adebisi, "On the optimization of iterative clipping and filtering for PAPR reduction in OFDM systems," *IEEE Access*, vol. 5, pp. 12004–12013, 2017.

[6] F. Khan, *LTE for 4G Mobile Broadband: Air Interface Technologies and Performance*. Cambridge, U.K.: Cambridge Univ. Press, 2009, ch. 5, pp. 88–108.

[7] Y. Huo, X. Dong, and W. Xu, "5G cellular user equipment: From theory to practical hardware design," *IEEE Access*, vol. 5, pp. 13992–14010, 2017.

[8] T. Jiang, W. Xiang, H.-H. Chen, and Q. Ni, "Multicast broadcast services support in OFDMA-based WiMAX systems," *IEEE Communication Mag.*, vol. 45, no. 8, pp. 78–86, Aug. 2007.

[9] B. Bougard, "Cross-layer energy management in broadband wireless transceivers," Ph.D. dissertation, Dept. Elect. Eng., Katholieke Univ. Leuven, Louvain, Belgium, Mar. 2006.

[10] Y. Rahmatallah and S. Mohan, "Peak-to-average power ratio reduction in OFDM systems: A survey and taxonomy," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 4, pp. 1567–1592, 4th Quart., 2013.

[11] X. Wang, T. Tjhung, and C. Ng, "Reduction of peak-to-average power ratio of OFDM system using a companding technique," *IEEE Trans. Broadcast.*, vol. 45, no. 3, pp. 303–307, Sep. 1999.

[12] T. Pratt, N. Jones, L. Smee, and M. Torrey, "OFDM link performance with companding for PAPR reduction in the presence of non-linear amplification," *IEEE Trans. Broadcast.*, vol. 52, no. 2, pp. 261–267, Jun. 2006.

[13] S. H. Müller and J. B. Huber, "A comparison of peak power reduction schemes for OFDM," in *Proc. IEEE Global Telecommun. Conf. (GLOBECOM)*, Phoenix, AZ, USA, Nov. 1997, pp. 1–5.

[14] R. Bäuml, R. Fischer, and J. Huber, "Reducing the peak-to-average power ratio of multicarrier modulation by selected mapping," *Electron. Lett.*, vol. 32, no. 22, pp. 2056–2057, Oct. 1996.

[15] S. Müller and J. Huber, "OFDM with reduced peak-to-average power ratio by optimum combination of partial transmit sequences," *Electron. Lett.*, vol. 33, no. 5, pp. 368–369, 1997.

[16] C. Tellambura, "Improved phase factor computation for the PAR reduction of an OFDM signal using PTS," *IEEE Commun. Lett.*, vol. 5, no. 4, pp. 135–137, Apr. 2001.

[17] T. Sravanti, Y. Kamatham, and C. S. Paidimarry, "Reduced complexity hybrid PAPR reduction schemes for future broadcasting systems," in *Advances in Decision Sciences, Image Processing, Security and Computer Vision* (Learning and Analytics in Intelligent Systems), vol. 4, S. C. Satapathy, Ed. Cham, Switzerland: Springer, 2019, pp. 69–76.

[18] H.-J. Chou, P.-Y. Lin, and J.-S. Lin, "PAPR reduction techniques with hybrid SLM-PTS schemes for OFDM systems," in *Proc. IEEE 75th Veh. Technol. Conf. (VTC Spring)*, Yokohama, Japan, May 2012, pp. 1–5.

[19] S. Weinstein and P. Ebert, "Data transmission by frequency-division multiplexing using the discrete Fourier transform," *IEEE Trans. Commun. Technol.*, vol. COM-19, no. 5, pp. 628–634, Oct. 1971.

[20] S. H. Han and J. H. Lee, "An overview of peak-to-average power ratio reduction techniques for multicarrier transmission," *IEEE Wireless Commun.*, vol. 12, no. 2, pp. 56–65, Apr. 2005.

[21] X. Wang, T. Tjhung, and C. Ng, "Reduction of peak-to-average power ratio of OFDM system using a companding technique," *IEEE Trans. Broadcast.*, vol. 45, no. 3, pp. 303–307, Sep. 1999.

[22] X. Huang, J. Lu, J. Zheng, K. Letaief, and J. Gu, "Companding transform for reduction in peak-to-average power ratio of OFDM signals," *IEEE Trans. Wireless Commun.*, vol. 3, no. 6, pp. 2030–2039, Nov. 2004.

[23] T. Jiang, Y. Yang, and Y.-H. Song, "Exponential companding technique for PAPR reduction in OFDM systems," *IEEE Trans. Broadcast.*, vol. 51, no. 2, pp. 244–248, Jun. 2005.

[24] Y. Jiang, "New companding transform for PAPR reduction in OFDM," *IEEE Commun. Lett.*, vol. 14, no. 4, pp. 282–284, Apr. 2010.

[25] J. Hou, J. Ge, D. Zhai, and J. Li, "Peak-to-average power ratio reduction of OFDM signals with nonlinear companding scheme," *IEEE Trans. Broadcast.*, vol. 56, no. 2, pp. 258–262, Jun. 2010.

[26] A. Vallavaraj, B. G. Stewart, and D. K. Harrison, "An evaluation of modified μ-Law companding to reduce the PAPR of OFDM systems," *AEU-Int. J. Electron. Commun.*, vol. 64, no. 9, pp. 844–857, Sep. 2010.

[27] M. Breiling, S. Miiller-Weinfurtner, and J. Huber, "Distortionless reduction of peak power without explicit side information," in *Proc. IEEE Global Telecommun. Conf.*, vol. 3, Nov. 2002, pp. 1494–1498.
[28] A. Jayalath and C. Tellambura, "A blind SLM receiver for PAR-reduced OFDM," in *Proc. IEEE 56th Veh. Technol. Conf.*, vol. 1, Jun. 2003, pp. 219–222.
[29] D.-W. Lim, J.-S. No, C.-W. Lim, and H. Chung, "A new SLM OFDM scheme with low complexity for PAPR reduction," *IEEE Signal Process. Lett.*, vol. 12, no. 2, pp. 93–96, Feb. 2005.
[30] S. Le Goff, S. Al-Samahi, B. Khoo, C. Tsimenidis, and B. Sharif, "Selected mapping without side information for PAPR reduction in OFDM," *IEEE Trans. Wireless Commun.*, vol. 8, no. 7, pp. 3320–3325, Jul. 2009.
[31] S.-J. Heo, H.-S. Noh, J.-S. No, and D.-J. Shin, "A modified SLM scheme with low complexity for PAPR reduction of OFDM systems," in *Proc. IEEE 18th Int. Symp. Pers., Indoor Mobile Radio Commun.*, Sep. 2007, pp. 1–5.
[32] S. Müller and J. Huber, "OFDM with reduced peak-to-average power ratio by optimum combination of partial transmit sequences," *Electron. Lett.*, vol. 33, no. 5, pp. 368–369, Feb. 1997.
[33] A. Jayalath and C. Tellambura, "The use of interleaving to reduce the peak-to-average power ratio of an OFDM signal," in *Proc. IEEE. Global Telecommun. Conf.*, vol. 1, Nov. 2002, pp. 82–86.
[34] A. Joshi and D. S. Saini, "Performance analysis and peak-to-average power ratio reduction of concatenated LDPC coded OFDM system using low complexity PTS," in *Proc. Int. Conf. Signal Process. Commun. (ICSC)*, Mar. 2015, pp. 195–200.
[35] A. A. Abouda, "PAPR reduction of OFDM signal using turbo coding and selective mapping," in *Proc. 6th Nordic Signal Process. Symp. (NORSIG)*, Jun. 2004, pp. 248–251.
[36] H. Breiling, S. Müller-Weinfurtner, and J. Huber, "SLM peak-power reduction without explicit side information," *IEEE Commun. Lett.*, vol. 5, no. 6, pp. 239–241, Jun. 2001.
[37] G. Yue and X. Wang, "A hybrid PAPR reduction scheme for coded OFDM," *IEEE Trans. Wireless Commun.*, vol. 5, no. 10, pp. 2712–2722, Oct. 2006.
[38] S. Thota, Y. Kamatham, and C. S. Paidimarry, "Performance analysis of hybrid companding PAPR reduction method in OFDM systems for 5G communications," in *Proc. 9th Int. Conf. Comput., Commun. Netw. Technol. (ICCCNT)*, Bangalore, India , pp. 1–5, Jul. 2018.
[39] R. Rajbanshi, "OFDM-based cognitive radio for DSA networks," Ph.D. dissertation, Dept. Elect. Eng. Comput. Sci., Inf. Telecommun. Technol. Center, Univ. Kansas, Lawrence, KS, USA, 2007.
[40] R. Baxley and G. Zhou, "Power savings analysis of peak-to-average power ratio reduction in OFDM," *IEEE Trans. Consum. Electron.*, vol. 50, no. 3, pp. 792–798, Aug. 2004.
[41] E. Costa and S. Pupolin, "M-QAM-OFDM system performance in the presence of a nonlinear amplifier and phase noise," *IEEE Trans. Commun.*, vol. 50, no. 3, pp. 462–472, Mar. 2002.
[42] A. Saleh, "Frequency-independent and frequency-dependent nonlinear models of TWT amplifiers," *IEEE Trans. Commun.*, vol. 29, no. 11, pp. 1715–1720, Nov. 1981.
[43] E. Costa, M. Midrio, and S. Pupolin, "Impact of amplifier nonlinearities on OFDM transmission system performance," *IEEE Commun. Lett.*, vol. 3, no. 2, pp. 37–39, Feb. 1999.
[44] A. Ghorbani and M. Sheikhan, "The effect of solid-state power amplifiers (SSPAs) nonlinearities on MPSK and M-QAM signal transmission," in *Proc. 6th Int. Conf. Digital Process. Signals Commun.*, Sep. 1991, pp. 193–197.
[45] C. Rapp, "Effects of HPA-nonlinearity on a 4-DPSK/OFDM-signal for a digital sound broadcasting signal," in *Proc. 2nd Eur. Conf. Satell. Commun.*, Liège, Belgium, Oct. 1991, pp. 179–184.
[46] G. White, A. Burr, and T. Javornik, "Modelling of nonlinear distortion in broadband fixed wireless access systems," *Electron. Lett.*, vol. 39, no. 8, pp. 686–687, Apr. 2003.

SRAVANTI THOTA received the B.Tech. degree in electronics and communication engineering and the M.Tech. degree in digital electronics and communication systems from JNTU Hyderabad (JNTUH), Hyderabad, India. She is currently pursuing the Ph.D. degree with the Department of Electronics and Communication Engineering, University College of Engineering, Osmania University, Hyderabad, India. She has 11 research publications. Her research interests include digital communications, signal processing, wireless, cellular and mobile networks, and wireless MIMO multicarrier techniques.

YEDUKONDALU KAMATHAM (Senior Member, IEEE) was born in Biradawada, India, in July 1976. He received the B.Tech. degree in electronics and communication engineering from Nagarjuna University, Guntur, India, in 1998, the M.Tech. degree in opto electronics and laser technology from the Cochin University of Science and Technology, Thrikkakara, India, in 2001, and the Ph.D. degree from the ECE Department, University College of Engineering (autonomous), Osmania University, Hyderabad, India, in 2013. He is currently a Professor with the Electronics and Communication Engineering Department, CVR College Engineering, Hyderabad, India. His areas of interest include GNSS signal processing, adaptive/biomedical signal processing, optical, and wireless communications. He is supervising four research scholars and several B.Tech. and M.Tech. students in these areas. He has 54 research publications to his credit.

Dr. Yedukondalu is a Fellow of IETE, India, and a Life Member of ISTE.

CHANDRA SEKHAR PAIDIMARRY (Member, IEEE) received the B.E. degree from Nagpur University, in 1991, the M.Tech. degree from JNTU Hyderabad, in 1999, and the Ph.D. degree from Osmania University, in 2009. He had been awarded with Postdoctoral Fellowship by Shizuoka University, Japan, for one year. Prior to joining in teaching, he has eight years of industrial experience of design and development of Embedded Systems. He has been working with the Department of Electronics and Communication Engineering, University College of Engineering, Osmania University, Hyderabad, since 2001. He has been elevated as Professor of ECE, in 2015. He is currently serving as the Head of the Department of ECE, Osmania University. He served as the Head and Chairman BOS with the ECE Department for two years. He is actively involved in establishing the state of art laboratories in the department. He has more than 50 research publications to his credit. He delivered more than 15 invited talks and guest lecturers in various conference and events. UGC sanctioned a Major Research Project on GNSS Receiver: Baseband algorithms in FPGA. He received a consultancy projects from DLRL and RCI. His research interests include development of high performance computational electro-magnetic and efficient FPGA-based signal processing algorithms and design automation. He is currently a Principal Investigator for CSIR SRF scheme. He is currently serving as a Peer Review Committee Member of DLRL projects and member of system engineering with BDL. He is a member of Board of Studies in several Engineering colleges.

Prof. Paidimarry is a Chair of the CAS Society Hyderabad Section.