

# DPD with PAPR Suppression for F-OFDM Systems

Xiao Liao

Hunan University

Zhinian Luo (✉ [zhinianluo@hnu.edu.cn](mailto:zhinianluo@hnu.edu.cn))

Hunan University

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## Research Article

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# DPD with PAPR Suppression for F-OFDM Systems

Xiao Liao · Zhinian Luo

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**Abstract** A combined digital pre-distortion (DPD) and peak to average power ratio (PAPR) reduction for Filtered Orthogonal Frequency Division Multiplexing (F-OFDM) systems is proposed where F-OFDM is one of the candidates for 5G waveform technology. In the system, the power amplifier (PA) will produce nonlinear distortion because it works in the saturation region and the high PAPR. DPD based on PAPR reduction structure may be adopted to compensate the nonlinear resulting from PAs. Firstly, in order to reduce the PAPR, a low complexity iterative partial transmission sequence (IPTS) algorithm combined with iterative clipping revision (ICR) is introduced. And then, the joint structure of DPD and IPTS-ICR is proposed. Simulation results show that the proposed structure can improve the PAPR suppression performance of F-OFDM system compared to low complexity IPTS algorithm or ICR algorithm alone. The proposed structure can also effectively improve the nonlinear distortion of the F-OFDM system.

**Keywords** Digital pre-distortion · Iterative clipping revision · PAPR · Iterative partial transmission sequence

## 1 Introduction

In modern wireless communication systems, F-OFDM is a flexible multicarrier waveform developed on the basics of OFDM and exhibits low Out-of-Band (OOB) radiation [1]. However, high PAPR value will also generated in the F-OFDM system as in the OFDM system. The high PAPR leads the peak value signal to enter the nonlinear range of the PA which can generate nonlinear

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Xiao Liao  
Institute of Information Science and Engineering, Hunan University, Changsha 410082, China

Zhinian Luo  
E-mail: zhinianluo@hnu.edu.cn

distortion and harmonics, resulting in spectral broadening and in-band distortion. Meanwhile, the high PAPR will increase the complexity of digital to analog converter (DAC) and analog to digital converter (ADC), and then, the accuracy of DAC and ADC will be reduced [2]. Therefore, the high PAPR reduces the efficiency of PA and results in the performance degradation of the system.

PAPR reduction has been widely studied by various researchers for OFDM systems in this context. In [3], Leonard J. Cimini proposed a suboptimal PTS algorithm to reduce the PAPR in OFDM systems and lower the computational complexity. In [4], K. Anoh and C. Tanriover proposed an adaptively optimized ICF of OFDM signals, and the performance of proposed methods is compared from the aspects of bit error rate (BER), power efficiency and computational complexity with the simplified optimized iterative clipping and filtering (SOICF). J. Zhao and S. Ni proposed an improved bilayer partial transmit sequence and ICF (IBPTS-ICF) structure to reduce the PAPR of the FBMC/OQAM system [5], compared with only use PTS or TC, the PAPR suppression performance has been improved. Furthermore, PA is an indispensable component of the F-OFDM system. To improve its power efficiency, DPD technology has been widely adopted.

Recently, indirect learning structure (ILA) and direct learning structure (DLA) are commonly used in the field of DPD technology. In [6], Chao Yu presented a new DPD system based on Volterra series that can significantly improve the system performance and reduce the implementation costs. M. Tanio used a structured pruning technique to reduce the computational complexity and presented an efficient neural-network-based DPD in [7]. However, DPD cannot compensate for the signals whose amplitude exceeds PA input saturation voltage. Meanwhile, PAPR reduction technology will bring nonlinear distortion in the process of PAPR reduction. Therefore, some papers combine PAPR reduction technology with DPD technology. In [8], R. N. Braithwaite combined the DPD and CFR for the system, and the proposed CFR is structured like DPD. In [9], O. B. Usman proposed signal clipping for PAPR reduction and combined with the DPD to improve the performance of PA. To sum up, signal clipping is a nonlinear PAPR suppression algorithm which is easy to implement and has low computational complexity. However, it reduces the bit error rate performance of system [10]. Although the signal can be pre-distortion compensated by using DPD structure only, the operating point is far away from saturation point, which will lead to low efficiency. As a result, based on the research in the past, we combined the ICR and IPTS in the system, and joint the DPD structure. The proposed structure can make the working region of PA close to the saturation region and improve its linearity at the same time.

The remaining structure of this paper is: Section 2 introduces the F-OFDM system and PAPR reduction technology. The technology of PAPR reduction and DPD are combined in the Section 3. Section 4 presents the simulation results. Finally, Section 5 gives the conclusions.

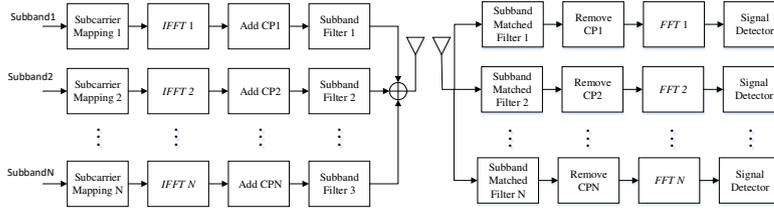


Fig. 1: F-OFDM system block diagram

## 2 System Model and PAPR

### 2.1 F-OFDM System

As one of 5G candidate waveforms, F-OFDM has great development space and can be used for 5G subsequent versions. As showed in Fig.1. The process of F-OFDM system is as follows, compared with OFDM, each subband can add a different filter. Firstly, the transmitter generates the F-OFDM signals from the  $M$  continuous subcarrier blocks assigned to F-OFDM symbols [11]. Then, the symbols pass the  $N$ -point inverse fast Fourier transform (IFFT) and finally, adding a cyclic prefix (CP) and filter. The obtained data symbols is given by

$$x(n) = \sum_{t=0}^{L-1} x_k(n - k(N + N_g)) \quad (1)$$

Where  $L$  is the data length, the symbols length after adding the CP length is  $N + N_g$  and the  $x_k(n)$  in equ.(1) can be defined as

$$x_k(n) = \sum_{m=m'}^{m'+M-1} d_{k,m} e^{j2\pi mn/N}, \quad -N_g \leq n < N \quad (2)$$

Where  $d_{k,m}$  denotes the data symbols of the F-OFDM symbol  $k$  with the subcarriers serial number  $m$  and the assigned subcarriers are from  $m'$  to  $m' + M - 1$ . After filtering, we can get the F-OFDM signal

$$\tilde{x}(n) = x(n) * h(n) \quad (3)$$

Where the  $h(n)$  is the spectrum shaping filter and the bandwidth of the subband filter is the sum of the bandwidth of the assigned subcarriers.

### 2.2 PAPR Reduction

PAPR reduction is useful to improve the performance of the PA. As discussed in the section Introduction, the ICR have a lower complexity while reducing the

BER and the IPTS is distortion-free. The PAPR reduction methods including IPTS and ICR are used in this paper, which will be discussed in the following section.

### 2.2.1 PTS Technical

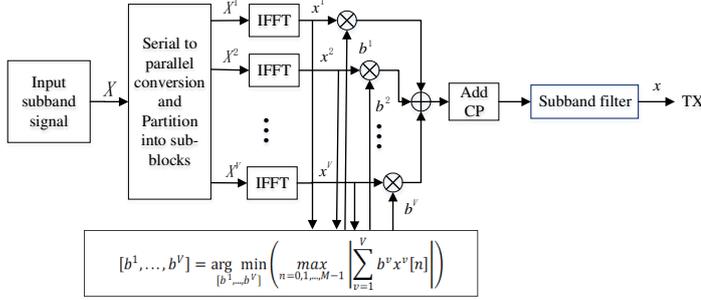


Fig. 2: PTS block diagram

PTS is a distortion-free method and a weighting factor is added to each sub-block to make the combined signal have a lower PAPR. Fig.2 shows the block diagram of the transmitter structure which based on PTS algorithm. The input subband signal  $X$  is divided into  $V$  sub-blocks [12], each sub-block has no intersecting parts and can be written as

$$X = [X^1, X^2, \dots, X^V]^T \quad (4)$$

Where  $X^i$  are continuously distributed and of the same size. And then, multiplying a phase factor to each sub-block

$$x = IFFT \left\{ \sum_{v=1}^V b^v X^v \right\} = \sum_{v=1}^V b^v x^v \quad (5)$$

Choose the optimal phase factor to minimize PAPR and the process can be defined as

$$[b^1, \dots, b^V] = \operatorname{argmin} \left( \max_{n=0,1,\dots,M-1} \left| \sum_{v=1}^V b^v x^v[n] \right| \right) \quad (6)$$

Therefore, the signal of the minimize PAPR value is given by

$$x = \sum_{v=1}^V b^v x^v \quad (7)$$

To reduce the complexity, an iterative PTS is used in this paper. We consider binary (i.e.,  $\pm 1$ ) weighting factors. The phase factors search method is shown below

1. Assume that  $b^v = 1$ ,  $v = 1, 2, \dots, V$ , compute the PAPR of signals in (7) and set it as  $PAPR(min)$ . Set  $v = 1$ .
2. Set  $b^v = -1$  and recompute the resulting PAPR. If the new PAPR is higher than  $PAPR(min)$ ,  $b^v = 1$ . Otherwise,  $PAPR(min) = PAPR$ .
3. If  $v < V$ , set  $v = v + 1$ , and repeat the step 2). Otherwise, the optimal weighting factor is the renew  $b^v$ ,  $v = 1, 2, \dots, V$  and end the algorithm.

### 2.2.2 Clipping Technical

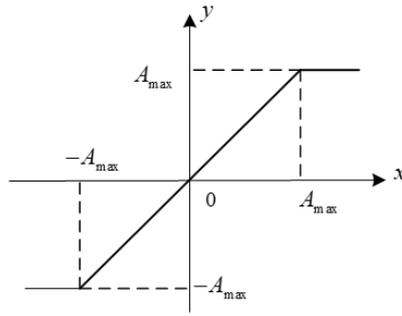


Fig. 3: Schematic diagram of clipping

The traditional clipping (TC) technique is a very effective nonlinear technique to suppress the PAPR of signals, and it can be used to reduce the PAPR of signals to the threshold amplitude of F-OFDM signals. The Schematic diagram of traditional clipping is shown in Fig. 3. Suppose the time domain signal is  $x_k = |x_k| e^{j\phi(x_n)}$ ,  $n = 1, 2, \dots, L$ , the signal throughout TC can be written as

$$x_k = \begin{cases} A e^{j\phi(x_n)}, & |x_k| > A \\ x_k, & |x_k| \leq A \end{cases} \quad (8)$$

Where  $A$  represents the threshold limit value of the signals amplitude given by the system,  $L$  is the length of the signal, and  $\phi(x_n)$  is the phase of the signal which remains constant during the clipping operation. The threshold limit value  $A$  depends on a clipping ratio (CR)  $\gamma$  that can be described as

$$\gamma = \frac{A}{\sqrt{\sigma}} \quad (9)$$

where  $\sigma$  is the root mean square (RMS) power of the signals [5]. Notice that the CR is a fixed parameter. Based on the TC technical, we proposed an iterative clipping revision (ICR) algorithm. First, the signal pass through the TC part, and then, the value of  $\sigma$  will change and thus the value of  $A$  changed to  $A_1$ . Finally, the signal limited by the threshold value  $A_1$  according to Equation (10).

### 2.3 PAPR reduction in F-OFDM System

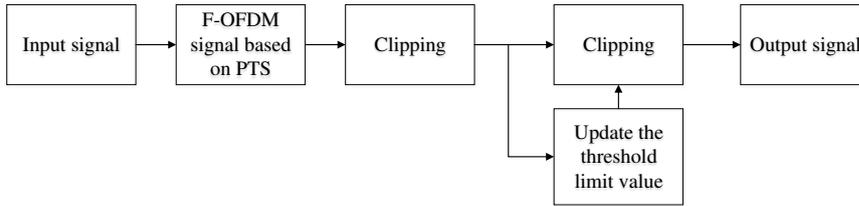


Fig. 4: F-OFDM system based on IPTS-ICR algorithm

IPTS-ICR algorithm is used in this paper to reduce the PAPR in F-OFDM system. Fig.4 shows the F-OFDM system based on IPTS-ICR algorithm, and the PAPR reduction based on IPTS and ICR are included in the block diagram.

## 3 Combining the DPD and PAPR reduction

### 3.1 Adaptive Pre-distorter

The DPD is an effective method to improve the PA linearity [13]. And the PAPR reduction technical can reduce the nonlinear distortion in PA. This paper is adopted an adaptive pre-distorter based on polynomial after PAPR reduction to optimize the non-linear distortion of PA and improve the efficiency. While modeling the system with DPD, the parameters of the pre-distorter behavior model need to be determined precisely, and the key to accurately determine the parameters is the adaptive estimation algorithm. In order to ensure good linearization effect, after the model parameters are extracted for the first time, adaptive estimation algorithm is still needed to continuously adjust the model parameters. The least mean square (LMS) algorithm is a classical algorithm in the adaptive filtering algorithm, and it can better adapt to adjust parameters in the predistortion system [14], as shown in Fig.5, which is the adaptive identification system of the pre-distorter.

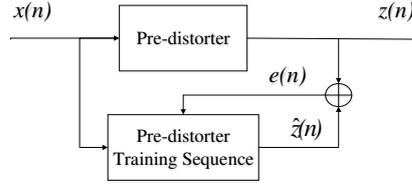


Fig. 5: Block diagram of an adaptive identification system

$x(n)$  are the input signals,  $z(n)$  are the actual output signals,  $\hat{z}(n)$  are the expected output signals and  $e(n)$  are the error signals [12]. The error signals are defined such that

$$e(n) = z(n) - \hat{z}(n) \quad (10)$$

In order to make the actual output signal as close as possible to the expected output signal, thus minimizing the value of  $e(n)$ , the mean square error (MSE) is the most commonly used objective characteristic function in evaluation criteria.

$$\varepsilon(n) = E\{e^2(n)\} = E\{[z(n) - W_N(n) X_N^T(n)]^2\} \quad (11)$$

Where the  $E\{e^2(n)\}$  is the mathematical expectation of  $e^2(n)$ ,  $\varepsilon(n)$  is a function of  $n$ , and if  $\varepsilon(n)$  does not change, the system will reach a relatively stable state. Assume that when  $n = 0$ , the initial value of the filtering coefficient is  $W_N(0)$ , and the iterative formula is expressed as follows

$$W_N(n+1) = W_N(n) - \frac{1}{2}\mu\nabla[\varepsilon(n)] \quad (12)$$

Where the weight coefficients  $[W]$  gradient  $\nabla[\varepsilon(n)]$  can be expressed as

$$\nabla[\varepsilon(n)] = -2E\{e(n)X(n)\} \quad (13)$$

The statistical average value is replaced by the instantaneous value in equation (15)

$$\nabla[\varepsilon(n)] = -2E\{e(n)X(n)\} = -2e(n)X_N(n) \quad (14)$$

And then, the iterative formula can be expressed as

$$W_N(n+1) = W_N(n) + \mu e(n)X_N(n) \quad (15)$$

Where  $\mu$  is the iterative steps. In summary, the adaptive estimation algorithm based on LMS algorithm uses the instantaneous value to replace the average value, which greatly reduces the computational complexity.

### 3.2 PA Model

In this paper, the PA model is using a Saleh model that requires only four parameters, and the  $AM - AM$  and  $AM - PM$  expressions of the PA are given by

$$\begin{aligned} y_{AM}(r) &= \frac{\alpha_a r}{1 + \beta_a r^2} \\ y_{PM}(r) &= \frac{\alpha_\varphi r^2}{1 + \beta_\varphi r^2} \end{aligned} \quad (16)$$

Where  $r$  is the envelope of the input signal,  $\alpha_a$  and  $\beta_a$  are the AM/AM parameters,  $\alpha_\varphi$  and  $\beta_\varphi$  are the AM/PM parameters of the Saleh model [15]. The degree of the nonlinear distortion is determined by all these parameters.

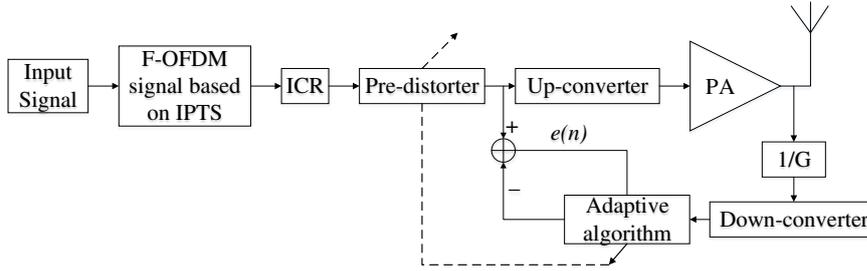


Fig. 6: F-OFDM with DPD and IPTS-ICR

### 3.3 Combining DPD and PAPR reduction in F-OFDM System

A combined design of DPD based on polynomial predistortion and IPTS-ICR algorithm is proposed in this section and is showed in fig.6 can be described as follows:

1. Signals pass through the F-OFDM system based on IPTS algorithm, and using the 64 QAM modulation and coding mapping. The high-rate data flow is converted into low-speed parallel data flow through the serial-to-parallel convention so that it can be transmitted in the communication channel, and the baseband modulation of the signal is realized by using IFFT. The parallel data flow is converted into serial data and then output from the F-OFDM system.
2. The output signals of the IPTS-F-OFDM system are modified with ICR method to further reduce the PAPR.
3. After the signals pass through the DPD, it enters the D/A conversion and the up-converter module, and then the processed signals enter the PA for amplification. Because of the PA produces nonlinear distortion, the output signals will produce nonlinear distortion.

4. The signals amplified by the PA are attenuated and transmitted to the down-converter and A/D conversion module. After processing, the adaptive estimation algorithm is used to estimate the parameters of the appropriate polynomial pre-distorter.
5. Finally, the step 4 is iterated and the parameters are updated adaptively, so that the digital pre-distorter reaches a convergent state, indicating that the parameters are ideal and the input and output signals in this system is linear.

#### 4 Simulation Results

In this section, MATLAB is used for simulation to study the performance of the proposed PAPR reduction and DPD joint scheme in the F-OFDM system. System parameters in this paper can be defined as follows: the IFFT size of the F-OFDM signals is 2048-point, the signal is divided into 1200 subcarriers, subcarrier interval adopts 15KHZ and each subcarrier is modulated by 64QAM.

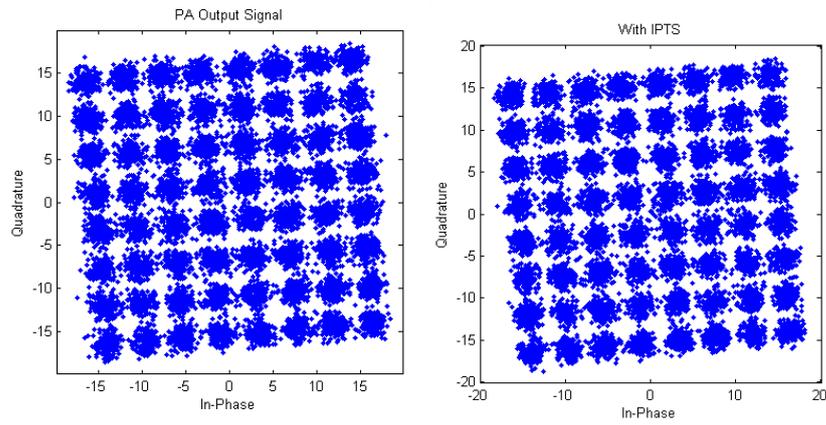
Table 1: The EVM, NMSE and PAPR of different structure

	EVM/%	NMSE/dB	PAPR/dB
PA Output	19.6540	-7.0655	7.3048
DPD	3.8631	-14.1306	8.4585
DPD+IPTS	3.4127	-14.6690	8.1954
DPD+ICR	2.8292	-15.4988	6.4000
DPD+ICR+IPTS	2.8277	-15.4856	6.2761

In this paper, we use the Saleh model for the PA and the coefficients of the model are  $\{\alpha_a = 1.3, \beta_a = 1.7, \alpha_\varphi = 1.2, \beta_\varphi = 2\}$ . For the digital pre-distorter, we adopt polynomial predistortion method and divide the polynomial predistortion into amplitude predistortion and phase predistortion.

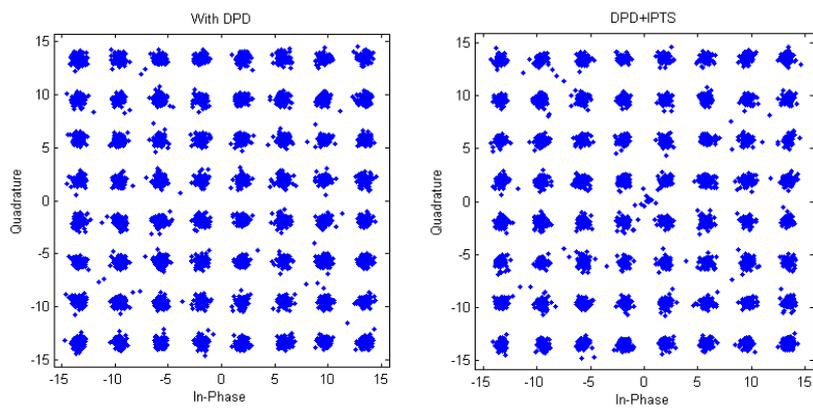
The constellation comparison of the signal is shown in Fig.7. It can be noticed that the PA output signal generates significant nonlinear distortions, including phase rotation and dispersion in Fig.7(a). The signal constellation with IPTS algorithm is shown in Fig.7(b), the dispersion has been improved compared with Fig.7(a). The output signal constellation which joint IPTS and DPD structures that is shown in Fig.7(d), compared with the signal constellation with DPD structure in Fig.7(c), the phase rotation in Fig.7(d) has been greatly corrected. Fig.7(e) is the signal constellation joint ICR and DPD structures. It is obvious that increase the ICR structure will generate dispersion and Fig.7(f) shows the signal constellation joint IPTS-ICR and DPD structures, while increasing the IPTS structure, the BER can be reduce and the dispersion have been clearly concentrated.

Fig.8 shows the  $AM - AM$  and  $AM - PM$  characteristics respectively represent the signal with or without DPD, where the blue curve shows the signal



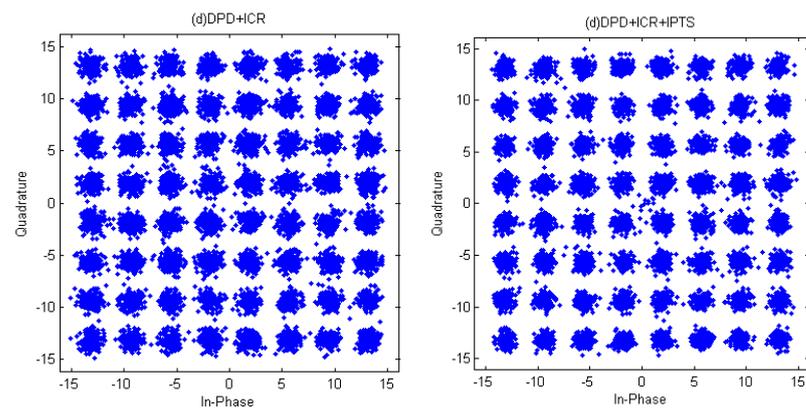
(a) The PA output signal

(b) The PA output signal with IPTS



(c) The PA output signal with DPD

(d) DPD+IPTS



(e) DPD+ICR

(f) DPD+IPTS-ICR

Fig. 7: The signal constellation diagram

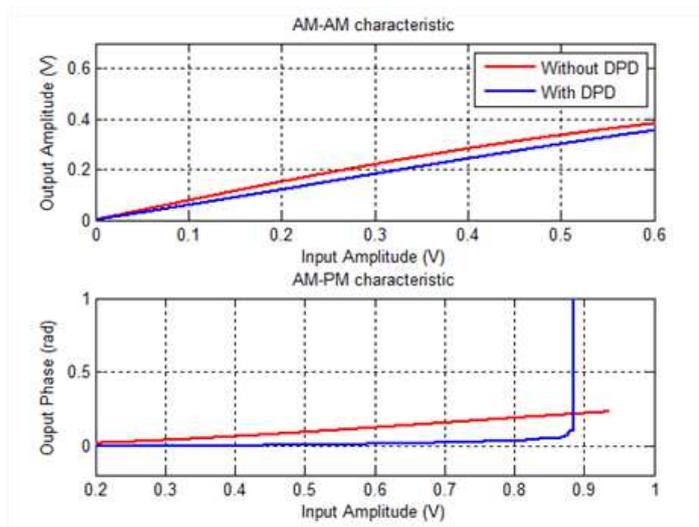
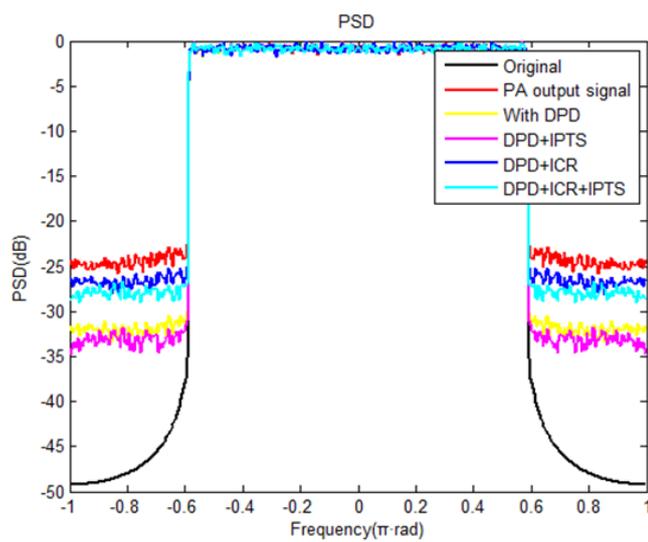
Fig. 8:  $AM - AM$  and  $AM - PM$  characteristic

Fig. 9: The PSD of different structure

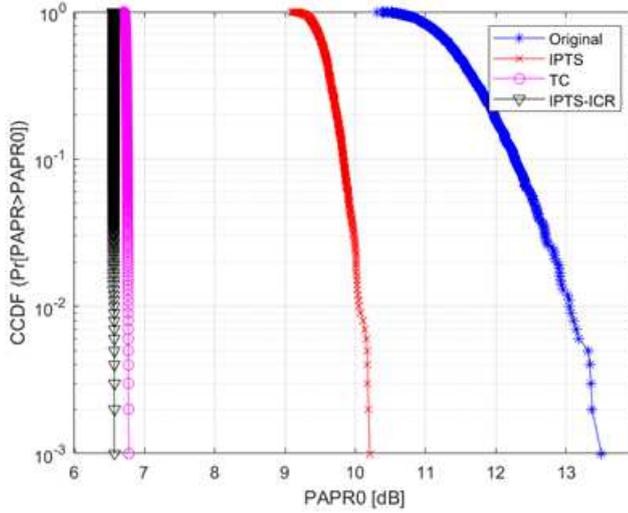


Fig. 10: The CCDF of different methods

with DPD and the red curve shows the signal without DPD. The simulation results indicate that, compared with the signal without DPD, the performance of the  $AM/AM$  and  $AM/PM$  characteristics in this system with the proposed structure have been greatly corrected.

Fig.9 is the power spectral density(PSD), the signals with DPD and IPTS show the best performance, compared with the signal only with DPD, it improved about 3dB. The proposed structure IPTS-ICR with DPD compared with the ICR with DPD also achieved improvements. It can be concluded that IPTS algorithm can improve the PSD performance of the signal.

Fig.10 is the complementary cumulative distribution function (CCDF) for the PA output signals, the PA output signals based on IPTS structure, based on TR structure and based on IPTS-ICR structure. It shows that the IPTS-ICR structure in this system can improve the PAPR performance compared with the other three curves.

Finally, Table 1 shows the error vector magnitude (EVM), normalized mean square error (NMSE) and PAPR of the signals. The NMSE and PAPR of the original PA output signal are well, but the EVM is 19.6540% and should be further improved. When the signals are processed only by DPD, the EVM and NMSE are well, but it has high PAPR. And then, compared with the DPD based on IPTS or the DPD based on ICR, the IPTS-ICR approach is better and the PAPR has been reduced. The proposed structure is valuable within a certain range.

## 5 Conclusion

In this paper, we presented an IPTS-ICR algorithm to reduce the PAPR and combined an DPD structure to maximum the PA efficiency. The Simulation results reveal that the DPD technique can reduce the AM-AM and AM-PM distortion, and IPTS-ICR algorithm can improve the performance of EVM and PAPR while other performances decreasing within the acceptable range. Thus, the proposed method is effective due to low computational complexity and simple design implement. Meanwhile, The IPTS-ICR algorithm can reduce the BER of the system compared with use ICR algorithm only. As a result, the proposed jointed DPD and IPTS-ICR structure in this paper have the best performance.

## Declarations

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All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

## References

1. X. Yang, S. Yan, X. Li and F. Li, A Unified Spectrum Formulation for OFDM, FBMC, and F-OFDM, *Electronics*, 9(8), 1285 (2020)
2. Pooria, Varahram, Borhanuddin and M. A., Low complexity partial transmit sequence with complex gain memory predistortion in OFDM systems, *Wireless Personal Communications*, 68(4), 1435-1448(2013).
3. L. J. Cimini and N. R. Sollenberger, Peak-to-average power ratio reduction of an ofdm signal using partial transmit sequences, *IEEE Communications Letters* 4(3), 86-88 (2000). DOI 10.1109/4234.831033
4. K. Anoh, C.Tanriover and B. Adebisi, On the optimization of iterative clipping and ltering for papr reduction in ofdm systems, *IEEE Access* 5, 12004-12013 (2017). DOI 10.1109/ACCESS.2017.2711533
5. J. Zhao, S. Ni and Y. Gong, Peak-to-Average Power Ratio Reduction of FBMC/OQAM Signal Using a Joint Optimization Scheme, *IEEE Access* 5, 15810-15819 (2017). DOI 10.1109/ACCESS.2017.2700078
6. C. Yu, L. Guan, E. Zhu and A. Zhu, Band-Limited Volterra Series-Based Digital Predistortion for Wideband RF Power Amplifiers, *IEEE Transactions on Microwave Theory and Techniques*, 60(12), 4198-4208 (2012). DOI 10.1109/TMTT.2012.2222658
7. M. Tanio, N. Ishii and N. Kamiya, Efficient Digital Predistortion Using Sparse Neural Network, *IEEE Access*, 8, 117841-117852 (2020). DOI 10.1109/ACCESS.2020.3005146
8. R. N. Braithwaite, Implementing crest factor reduction (CFR) by offsetting digital predistortion (DPD) coefficients, 2012 Workshop on Integrated Nonlinear Microwave and Millimetre-wave Circuits, 1-3 (2012). DOI 10.1109/INMMIC.2012.6331928
9. O.B. Usman, A. Knopp and S. Dimitrov, Onboard PAPR Reduction and Digital Predistortion for 5G waveforms in High Throughput Satellites, 2020 IEEE 3rd 5G World Forum (5GWF), pp. 174-179(2020). DOI 10.1109/5GWF49715.2020.9221426

10. M. Qing, Z. Luo, A Combined Approach of DPD and CFR in F-OFDM System, *Wireless Personal Communications* (10), 2681-2691 (2020). DOI 10.1007/s11277-020-07497-7
11. A. Javad, M. Jia, and J. Ma, Filtered ofdm: A new waveform for future wireless systems, 2015 IEEE 16th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC) (2015)
12. Lei Guo, Hui Li, Yejun Liu, Xiaoxue Gong and Yufang Zhou, Twofold peak-to-average power ratio reduction technique in direct-detection optical orthogonal frequency division multiplexing system, *Optical Engineering*, (2015).
13. P. Gilabert, G. Montoro and E. Bertran, On the Wiener and Hammerstein models for power amplifier predistortion, 2005 Asia-Pacific Microwave Conference Proceedings, vol. 2 (2005). DOI 10.1109/APMC.2005.1606491
14. Z. Li, D. Yang, J. Kuang and H. Wang, A New Joint Memory Polynomial and Look-Up-Table Predistorter Algorithm Design, 2011 7th International Conference on Wireless Communications, Networking and Mobile Computing, pp. 1-4 (2011). DOI 10.1109/wicom.2011.6040188
15. A. A. M. Saleh, Frequency-Independent and Frequency-Dependent Nonlinear Models of TWT Amplifiers, *IEEE Transactions on Communications* 29(11), 1715-1720 (1981). DOI 10.1109/TCOM.1981.1094911

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