Power Amplifier Optimization for M2M Node using DPD and Hybrid DFT-s-OFDM with CFR

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ABSTRACT

Power Amplifiers (PAs) play a vital role in mobile communication. However, their inherent nonlinearity can lead to issues such as unwanted radiation, interference with neighboring channels, and distortion within the desired frequency range. To address these problems, PAs are typically operated at a lower power level than their saturation point, sacrificing power efficiency to improve Error Vector Magnitude (EVM) performance. Consequently, more than 70-80% of the DC power is wasted as heat. This inefficiency necessitates the exploration of techniques to enhance PA efficiency while maintaining acceptable linearity and performance. Digital Pre-Distortion (DPD) is a useful technique to linearize PAs. DPD allows affordable nonlinear PAs to function with minimal distortion in their nonlinear operating regions. This results in amplified signals with increased power output and improved power efficiency. Using nonlinear functions, the output signal of the PA can be linearized, mitigate distortions, and be effectively optimized. When using various operating channels and varying time, temperature, and PA nonlinearity, the DPD must adjust. In order to increase the power efficiency of 5G systems, DPD-enabled systems are inculcating with adaptive DFT-s-OFDM employed 5G physical layer along with the Crest Factor Reduction (CFR) algorithm.

Keywords-CFR; DPD; PA; PAPR; DFT-s-OFDM; mMTC; 5G (NR)

I. INTRODUCTION

Efficient power utilization is a crucial consideration in any communication system, particularly in machine-to-machine communication scenarios. Among various techniques, Digital Pre-Distortion (DPD) offers easier implementation compared to alternatives like feedforward linearization, which operate in the RF domain and affect the digital baseband domain. By employing DPD, power efficiency can be enhanced by enabling low-cost nonlinear Power Amplifiers (PAs) to operate with reduced distortion at higher output levels, even within their nonlinear regions [1]. Figure 1 illustrates the similarity between DPD and a nonlinear circuit. DPD counteracts the power amplifier's phase rotation (AM/PM) by introducing a phase rotation in the opposite direction. Likewise, DPD also addresses the issue of gain suppression (AM/AM) in PA by incorporating a gain expansion response. Adapting to changes in PA nonlinearity is a crucial requirement for DPD. As the signal bandwidth increases, these memory effects become more pronounced and need to be addressed alongside PA nonlinearity. While most adaptive DPD blocks effectively handle progressive modifications in PA characteristics, they often overlook fast fluctuations. DPD techniques could be implemented through Volterra series memory polynomials and generalized memory polynomials are more suitable in these scenarios [2]. To apply nonlinear correction to complex baseband signals, various digital signal processing techniques can be utilized. These techniques enable the application of DPD and help mitigate the impact of memory effects [3]. For efficient processing of the extended bandwidth's high sample rate, it is beneficial to employ a parallel processing architecture that can simultaneously handle multiple samples. This parallel processing approach is ideal for executing nonlinear correction in the DPD system. Figure 2 shows the DPD integration in the transmission chain of a typical communication system, situated between the DAC and ADC functions and the crest-factor reduction (CFR) block [4]. The DPD subsystem comprises various components, including a look-up table (LUT) for the DPD model and an adaptation block [5].

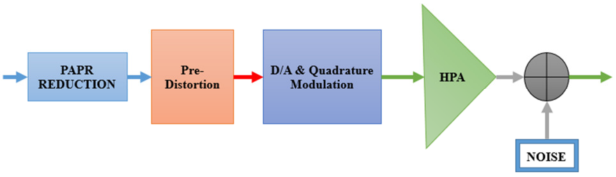

Fig. 1. DPD integration.

Enhancing PA efficiency is a critical aspect of communication systems, as it directly contributes to extending battery life and reducing overall system expenses [6]. PA typically account for a significant portion of the total power consumption, often reaching up to 80% of the overall power budget [7]. The operating class of the power transistor and the selected input or output back-off play a crucial role in determining the efficiency of a PA [8]. Different PA classes exhibit varying trade-offs between linearity and efficiency. For instance, a Class A amplifier offers excellent linearity and is characterized by low efficiency, since it operates with a high biasing current even when there is no input signal. On the other hand, a Class AB amplifier design is a compromise between linearity and efficiency to achieve better efficiency by allowing the power transistor to operate in a more efficient region when there is no input signal [9]. However, in modern base stations, Doherty amplifiers are commonly used. Doherty PAs combine elements from both Class AB and Class C [10]. This design offers superior linearity and improved efficiency compared to other PA classes. By utilizing a combination of a main amplifier operating in Class AB mode and an auxiliary amplifier operating in Class C mode, Doherty PAs achieve higher efficiency without compromising linearity.

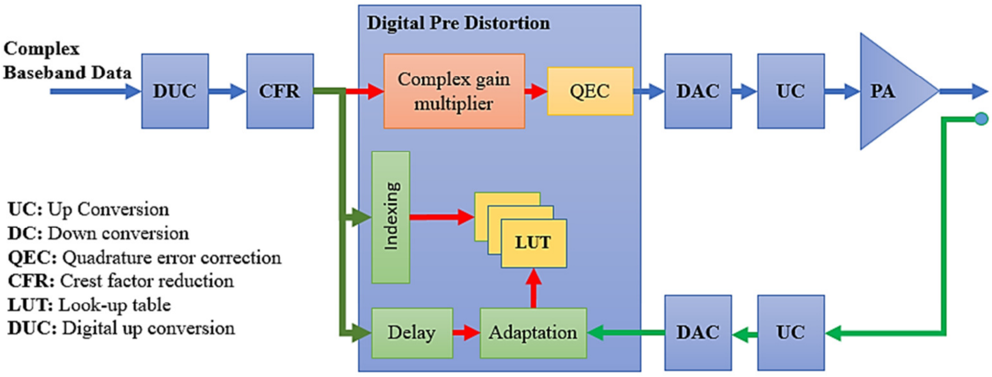

Fig. 2. Simulation scenario.

In our definition, the capacity to convert DC energy into RF signal is referred to as PA efficiency. Using the following criteria, the PA's efficacy is evaluated as:

- **Drain Efficiency:** It is the ratio of the RF output power to the DC power consumed by the PA. This parameter measures how efficiently the PA converts the supplied DC power into RF power. Higher drain efficiency indicates better utilization of the power supply.
- **Power Added Efficiency (PAE):** PAE represents the proportion of the DC power utilized by the PA. It quantifies the efficiency of power addition by PA.

Drain efficiency and PAE are crucial attributed for assessing the efficiency PA and provide insights into the PA's power conversion capabilities. PAE accounting for input RF signal is described as:

$$PAE = \frac{P_{out}-P_{in}}{P_{DC}}\% \quad (1)$$

In an ideal situation of a perfect PA there would be no power consumption in the PA. However, in veracity, no PA can function in a linear fashion completely, so achieving zero power consumption is not feasible. When considering the ideal conditions for a linear response, a typical PA exhibits a characteristic graph depicting the relationship between input power and output power. This graph, shown in Figure 3 illustrates how the PA's response gets increasingly nonlinear as the power input rises. This implies that the PA requires less input power compared to when it operates in the nonlinear region. By operating within the linear range, the PA can achieve the necessary linearity and minimize the negative effects on the transmitted signal. This point is commonly used to determine the extent of back-off required for maintaining linearity. In Figure 3, the operational range of the PA is shown in blue without DPD and the input power is reduced to preserve linearity. Green indicates the DPD-enabled functioning area in Figure 3, enhances the PAE of the device, thus improving its efficiency.

Efforts to enhance the efficiency of reducing PAPR in wireless communication systems have led to the development of various schemes on the channel modeling side, including FBMC, DFT-s-OFDM, iterative clipping, and numerous others. However, an important aspect that has often been overlooked is compensating for the non-linearity of the power amplifier in conjunction with these channel modeling techniques. In our approach, for the very first time, we address device-level optimization by simulating DPD before the PA in conjunction with DFT-s-OFDM. This novel combination aims to achieve a significant level of PAPR reduction, by integrating DPD into the system before the PA, the non-linearity can be compensated by its source, effectively mitigating distortions that could otherwise compromise signal quality. This holistic approach not only focuses on improving the signal characteristics through channel modeling but also ensures that the transmitted signals are better suited to the capabilities of the power amplifier.

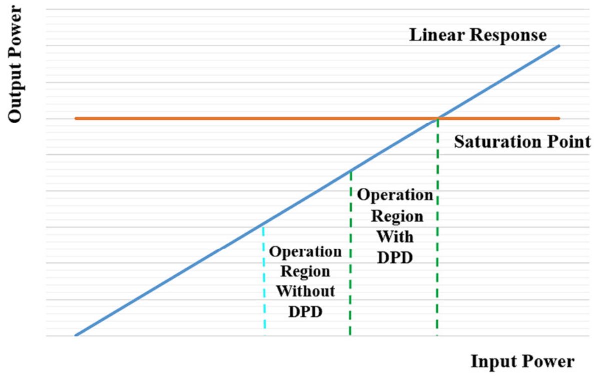

Fig. 3. DPD on the operational zone of a PA.

II. EASE POWER AMPLIFIER MODEL AND CHARACTERISTIC

The non-linearity of High Power Amplifiers (HPAs) can cause two types of distortion: out-of-band distortion and in-band distortion. These distortions can have detrimental effects on the performance of wireless communication systems, specifically in terms of Adjacent Channel Interference (ACI) and Bit Error Rate (BER). An alternative solution is HPA linearization, which involves employing various algorithms to counteract the non-linear effects. The Look-Up Table (LUT) technique is utilized for digital adaptive pre-distortion, enabling the correction of non-linear effects in the HPA.

A. Traveling-Wave Tube Amplifier Model

The frequently utilized Traveling Wave Tube Amplifier (TWTA) is employed in this study [11]. This model is commonly employed in literature for analyzing the performance of HPAs. The input signal's complex envelope is denoted by:

$$y(\tau) = \chi(\tau).\exp[\gamma\ \rho(\tau)] \qquad (2)$$

The HPA's output signal might be represented as follows:

$$x(\tau) = \alpha[\chi(\tau)].\exp[i(\gamma\ \rho(\tau) + \kappa\ [\chi(\tau)])\ ] \qquad (3)$$

In the context of the non-linear amplifier, $\alpha(\chi)$ refers to AM-AM and $\kappa(\chi)$ states AM-PM distortion. The distortion property of TWTA can be represented as:

$$\alpha[\chi(\tau)] = \alpha^2\ \frac{\chi(\tau)}{\chi^2(\tau)+\alpha^2} \qquad (4)$$

$$\kappa\ [\chi(\tau)] = \frac{\Pi}{3}\ \frac{\chi^2(\tau)}{\chi^2(\tau)+\alpha^2} \qquad (5)$$

where α represents the input voltage for the PA.

B. An Ineffective Predisorter

There are two scenarios in which an HPA predistorter may lose its effectiveness. In such situations, the predistorter is unable to adequately correct the nonlinearities caused by the high signal amplitudes. As described by (4), the behavior of the TWTA exhibits specific nonlinearity patterns outlined in Saleh's model.

$$\alpha[\chi] = \frac{\alpha^2{}_{sat}}{\chi+\frac{\alpha^2{}_{sat}}{\chi}} \leq \frac{\alpha^2{}_{sat}}{2.\alpha_{sat}} = \frac{\alpha_{sat}}{2} \qquad (6)$$

The maximum outcome of the HPA is α_{sat}, as may be seen from (6). Any signals greater than α_{sat} would be clipped. Based on this observation, the following conclusions can be made:

- Limitation of Predistortion: The predistorter's ability to compensate for distortion is constrained when the input signals have amplitudes exceeding $\alpha_{sat}/2$. The predistortion technique becomes less effective in correcting nonlinearities caused by these high-amplitude signals.
- Clipping Distortion: Signals with amplitudes exceeding $\alpha_{sat}/2$ will experience clipping distortion in the HPA output. This distortion arises due to the HPA's saturation limit, where the signal is cut off or flattened at $\alpha_{sat}/2$.
- Signal Integrity: In OFDM modulated data streams, it is crucial to ensure that the signal amplitudes remain below $\alpha_{sat}/2$ to maintain signal integrity and avoid significant distortion.

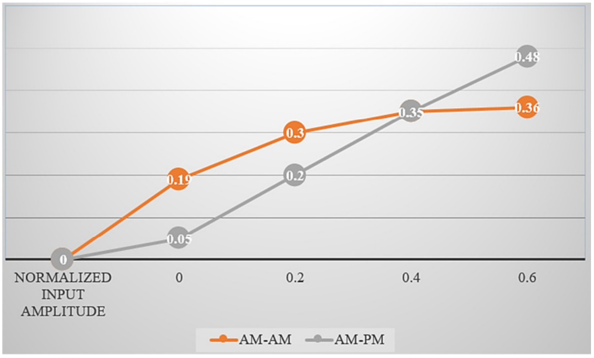

Fig. 4. Transfer curve of AM-AM and AM-PM.

These conclusions highlight the importance of considering the saturation limit of the HPA and its impact on signal amplitudes in the design and optimization of communication systems using predistortion techniques. When the HPA operates in linear region, which is away from the saturation region, where α_{sat} (saturation point) is much larger than α_{sat} (maximum signal amplitude) in the modulated data streams, it becomes possible to effectively predistort all amplitude distortions using a predistorter. Consequently, this leads to significant degradation in Power Spectral Density (PSD) and BER performance.

III. PAPR REDUCTION TECHNIQUE

According to the literature, there are three main categories of methods for Peak-to-Average Power Ratio (PAPR) reduction:

1. Signal distortion techniques: These methods involve introducing signal distortions, such as clipping and filtering, to reduce the PAPR [12].
2. Signal scrambling techniques: These methods, such as Selective Mapping (SLM) [13] and Partial Transmit Sequences (PTS) [14], involve modifying the signal through specific scrambling algorithms to reduce the PAPR.
3. Coding techniques: These methods utilize coding schemes, as described in [15], to reduce the PAPR. However, the improved PAPR performance comes at the expense of reduced bandwidth efficiency.

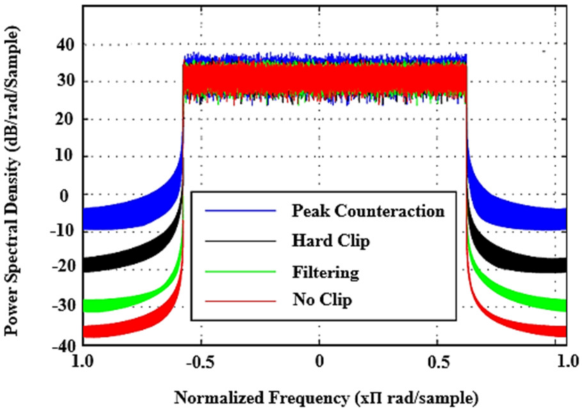

Fig. 5. PSD comparison of various PAPR reduction techniques.

Each PAPR reduction technique has its own advantages and disadvantages. Scrambling techniques like SLM and PTS involve complex optimization procedures, resulting in higher system complexity and computational burden [16]. Coding techniques offer PAPR reduction benefits but may impact bandwidth efficiency. When considering the effects of PAPR reduction on HPA linearization, it is important to focus on the impact on out-of-band and in-band noises.

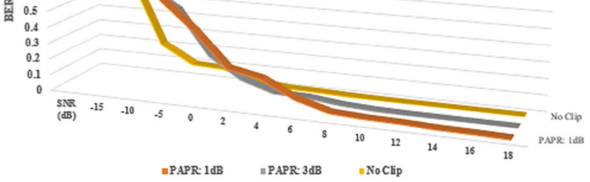

Fig. 6. Performance of BER at 256-QAM modulation.

Figure 5 illustrates the PSDs after applying PAPR reduction from 10.34 dB to 4.2 dB. It is apparent that the filtering method effectively mitigates out-of-band noises [17] successfully suppresses out-of-band distortion. However, in-band noises can be introduced during the clipping process. Figure 6 displays the BER performance versus Signal-to-Noise Ratio (SNR) with hard clipping. The observation shows that bit error rate significantly deteriorates with reduced PAPR. These results demonstrate the trade-off between PAPR reduction and BER performance when the Clipping Ratio (CR) is 4 dB (specified in (6)), using 256-QAM modulation and N=1024. While PAPR reduction techniques can mitigate out-of-band noises, they may introduce in-band noises and degrade the BER performance. However, the application of methods like Decision-Aided Reconstruction can help mitigate the impact on BER, reducing the additional SNR required to achieve a desired BER level.

$$\mathrm{CR} = 20\log\frac{\alpha}{\delta}\ \mathrm{dB} \tag{7}$$

where δ represents the rms value input signal power. The study also presents the Bayesian inference technique [19] as a way for reconstructing clipped signals with better BER performance. To reduce out-of-band distortion, this approach is used in conjunction with others like peak counteraction. The Bayesian inference method offers improved BER performance by employing probabilistic inference techniques to reconstruct the distorted signals. By leveraging statistical information and prior knowledge, the aim of this method is to mitigate the negative effects of signal clipping and enhance the overall performance of the communication system.

IV. IMPACT OF PAPR REDUCTION ON LINEARIZATION

In this section, we will evaluate the effects of PAPR lessening on HPA linearization by analyzing the PSD and BER. Figure 7 illustrates a simplified diagram that depicts the process of PAPR lessening and linearization.

A. PSD Analysis

Out-Of-Band *(OOB)* radiation can have a significant impact on communication systems, particularly in multi-user and RF wireless applications. The PSD performance provides a means to evaluate the ACI effects [20]. Figure 7 illustrates the improvements in PSD performance with and without the implementation of PAPR reduction techniques. The PSD performance analysis provides insights into the ACI effects caused by out-of-band radiation. It highlights the importance of managing and reducing ACI through techniques such as PAPR reduction [21]. While operating the HPA in the linear region allows for complete compensation without PAPR reduction, it comes at the cost of lower power efficiency.

B. Bit Error Rate Analysis

PAPR lessening techniques can be present in-band clipping noises, which have a detrimental effect on the system's BER. This is due to the fact that distortion may be efficiently reduced by utilizing a predistorter to account for the input signal to the HPA. In contrast, an OBO of 4.6421 dB is produced when the HPA runs close to the saturation area with better power efficiency, such as when the saturation point (α_{max}) is equal to the maximum signal amplitude ($\alpha_{\max}$).

- The predistorter's input signal is "clipped-off" in the clipping operation to a maximum value of 1.5 $\alpha_{max}/2$. As a result of the HPA's 1.5 $\alpha_{max}/2$ output power limitation, any information with amplitudes that fall in this range will be clipped or removed. As a consequence, any information whose amplitudes exceed $\alpha_{max}/2$ will be clipped or removed or modified to $\alpha_{max}/2$'s maximum value.
- Data that travel between the predistorter to HPA is $\alpha_{max}/2$ if the clipping procedure is not used. However, they cannot be completely erased or reversed by further processing.

C. OBO (Output Backoff) Performance

Output Backoff is a parameter commonly used to assess the performance characteristic of an HPA. It can be characterized as:

$$OBO = 10.\log_{10}\left(\frac{W_{max}}{W_{avg}}\right) \qquad (8)$$

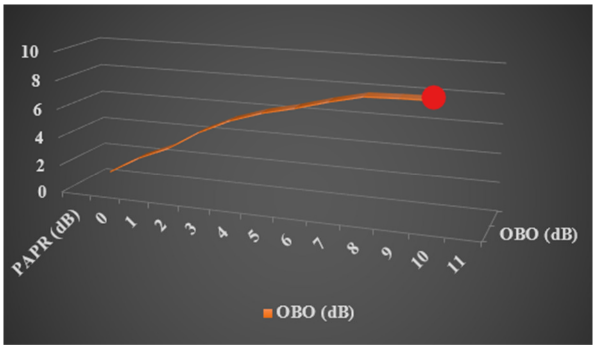

Fig. 7. PAPR performance for the OBO model.

To achieve superior outcomes using predistorter (without a clipping), the α_{max} should satisfy the condition $\alpha_{sat} \geq 2\alpha_{max}$. This is illustrated by the highlighted circle in Figure 7. With this configuration, a good predistortion can be achieved. In case clipping procedure is employed, significant improvement in HPA power efficiency can be achieved, albeit with some permitted degradation in BER. The clipping process allows for higher power efficiency by operating the HPA near its saturation region, leading to improved power performance [22]. However, this comes with the trade-off of potential BER degradation due to the clipping process. By incorporating the clipping process, significant enhancements in HPA power efficiency can be attained. This trade-off allows for improved power performance, as illustrated by the solid line in Figure-7, while accepting a certain level of BER degradation with superior predistortion outcome.

V. CONCLUSION AND FUTURE SCOPE

Evaluation of PAPR lessening with High Power Amplifier linearization, combined with the use of (DPD), provides valuable insights. DPD can able to enhance the overall efficiency by making linear PA. In the absence of DPD, the PA would need to work with significant back-off to comply with the spectral emission mask. PAPR reduction mitigates out-of-band radiation but introduces in-band clipping noises and degrades BER. Operating the HPA in the linear region with a predistorter yields good BER performance but low power efficiency. Employing a clipping process with DPD improves power efficiency, but careful consideration must be given to the trade-off between power efficiency, BER degradation, and the effectiveness of DPD in achieving desired linearity.

In the future, DPD-based hardware followed by the CFR algorithm will be designed as a prototype to compensate for the non-linearity of power amplifiers and also inculcate the smart algorithm for MIMO antennas for power optimization to enhance the overall system power efficiency.

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