A Methodology for Analysis of mm-Wave Transmitter Linearization Trade-offs Under Spectrum Constraints

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***Abstract*—This paper presents a simple method to estimate the efficiency and modulated RF performance for pre-distortion linearized PAs. The method is based on AM/AM and AM/PM and DC power data obtained from single tone measurements or simulations. This method allows us to investigate the tradeoffs between efficiency, output power, and predistortion complexity in PAs, under spectrum mask requirements. This is particularly important for in mm-wave applications. For demonstration, a 29 GHz GaAs PA has been modeled and used to study how biasing and pre-distortion complexity shape the output in terms of power and efficiency.**

***Keywords*—Predistortion, linearization, power amplifier (PA), complexity**

I. INTRODUCTION

Power amplifiers (PA) are inherently nonlinear components that are used in all communication systems. In mm-wave bands, they are usually biased for class A operation, which have a very linear response but in turn their efficiency drops very quickly at back-off. Higher efficiency can be achieved with other PA classes or advanced architectures like Doherty, however typically to the price of increased nonlinearities. The resulting spectral regrowth may cause the output signal to violate the emission mask when pushing for higher efficiencies [1]. Hence, linearization techniques such as digital predistortion (DPD) or analog predistortion (APD) are important to improve efficiency of mm-wave PAs. In mm-wave communication, such as the planned 5G system, linearizer implementation is limited by complexity in both digital and analog domains. For DPD, the need for excessive oversampling causes high energy consumption and complexity. For APD, circuit complexity causes overall efficiency to drop. Moreover, broadband modulated mm-wave measurements are complicated. Thus, to summarize, there is a need to determine a suitable tradeoff between efficiency, linearity, and design complexity, as early as possible in the product development phase. This leads to a need to co-design the pre-distorter and the PA in order to maximize their combined performance so that the trade-offs between each section is addressed better.

Different techniques have been researched in literature to compensate the nonlinear effects for mm-wave PAs in satellite or 5G communication systems [2-5]. Some of these works target high bandwidth linearization at the expense of complexity [2], while other studies seek either linearization for low bandwidth communication channels [3,4] or do not consider different amplifier classes [5] for additional efficiency improvement. None of these report co-optimization of the PA with linearization under realistic spectrum mask constraints.

In this work, our aim is to identify the level of complexity needed for a PA to perform at an acceptable linearity level when a spectrum emission mask is in place. To investigate the trade-offs, a general analysis framework is presented based on an AM/AM/PM and power dissipation representation of the PA. Here we ignore memory effects. Although they can be important, a quasi-static approximation usually represents most dominant nonlinearities. The use of this framework is later exemplified using a PA working around 29 GHz. The method is therefore useful to provide accurate enough predictions for evaluation of simple analog and digital pre-distortion schemes relevant for mm-wave applications. In turn we investigate, given a modulated input signal, how average efficiency and output power (P_{out}) can be improved for different bias points, i.e. PA classes.

II. METHODOLOGY

Figure 1 presents a block diagram of the proposed framework, consisting of a pre-distorter, a PA and accompanying signal processing blocks. A signal consisting of random bits is modulated to create a complex baseband representation of a wireless communication signal. This signal is fed as the input to the non-linear PA model, represented by its amplitude to amplitude (AM/AM) and amplitude to phase (AM/PM) conversion characteristics. The response of the PA is linearized using a pre-distorter where the complexity is controlled through its polynomial order. Pre-distorter parameters are found for different power levels. The power of the modulated signal is scaled to control the average power level of the input of the PA and to compare the output to a spectral emission mask. This procedure is repeated for different bias points and different polynomial orders. Using the DC power characteristics of the PA and post processing, it is possible to calculate output parameters such as average output power ($P_{out,av}$), average power added efficiency (PAE_{av}) and error vector magnitude (EVM).

A. *Non-linear PA Model*

Measurement or simulation data can be used to create a non-linear PA model. For this purpose, (AM/AM) and (AM/PM data have been used. Such measurements are usually performed by a vector network analyzer (VNA). In this work we create a quasi-static PA model by using the measured data at a single frequency. It assumes that the PA characteristics stay the same in the signal bandwidth while still including the dominant nonlinear effects. In order to analyze the effect of PA classes, these measurements need to be done for different bias points. DC power consumption is also measured at each power level for these bias points to enable calculation of parameters like efficiency.

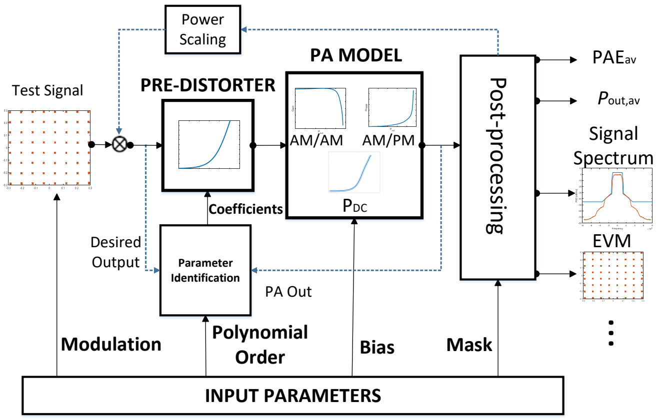

Figure 1. Block diagram of the proposed framework for prediction of linearity and efficiency in a pre-distortion linearized transmitter.

B. *Linearization*

As shown in Fig. 1, a pre-distorter is often placed before the PA to counter its nonlinear characteristics. There are several techniques to counter the nonlinear behavior of a PA. The implementation can either be in digital and/or analog domain [6]. Pre-distorters are commonly polynomial. In this work, a memoryless polynomial model of P^{th} order is used. The complexity is controlled by the number of coefficients [7]. Indirect learning architecture (ILA) based parameter identification is used. This procedure starts with post-distortion of the PA to find the initial values of the pre-distorter coefficients. A normalization gain is used to create a desired output signal [8]. These coefficients are typically found using a least square method due to its high accuracy and fast convergence. In this work, the coefficients values in the pre-distorter model converged after a few iterations, which are then used along with the nonlinear model of the PA for linearization.

C. *Test Signals, Modulation and Post-processing*

The block diagram in Figure 1 shows how a modulated signal is used to predict efficiency and RF-spectrum using the proposed framework. The modulated signal is filtered using a raised cosine filter with specific filter length and roll-off factor. The output of the filter should satisfy spectrum mask requirements which depend on modulation type. The filter parameters and the mask requirements vary based on the communication channel.

Both the PA itself and the linearized PA are tested by comparing their output spectrums to the spectrum emission mask. This is done by gradually increasing the average power by scaling it up until the output spectrum reaches the mask limit. At this point post processing is performed by calculating average PAE, average P_{out}, EVM, etc. These parameters allow us to investigate relevant performance trade-offs at the mask limit for transmitters with and without pre-distortion linearization.

III. Results

This part exemplifies the methodology presented in the previous section. A PA has been tested at 29 GHz. The process is repeated for multiple bias points to observe this improvement for different PA classes. Our aim is to predict the trade-off options between linearization, efficiency, PA classes and complexity.

A. *PA Design and Characteristics*

The class AB PA used in this paper is reported in [9] and operates between 26.5-31.5 GHz. The MMIC circuit was fabricated by Win Semiconductor using their pp1010 pHEMT process. The pinch-off voltage is given approximately at -0.95+/-0.2V by the foundry.

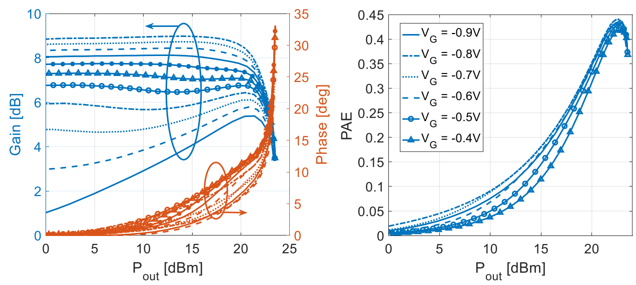

Figure 2. a) Measured AM-AM and AM-PM characteristics of the PA at 29 GHz. b) Power added efficiency (PAE) versus output power. In both figures, results are reported for different bias points from V_{GS}=-0.9V to -0.4V

The PA uses a single 6x50 transistor and was optimized to operate as a class AB amplifier with a small signal gain of 8 dB with V_{DS} = 3.3V. In-band measurements performed included AM-AM and AM-PM characterization at V_{GS} from -0.9V to -0.4V. In Figure 2-a, the measured large signal gain and phase for these bias points at 29 GHz are shown. The phase is plotted relative to its small signal value for each V_{GS}. At this frequency, the AM-AM and AM-PM profiles change considerably for different bias points. The saturation level of the P_{out} is around 23.5 dBm. Figure 2-b shows the PAE curves for different gate bias points from V_{GS} = -0.9V to -0.4V. As seen in the figure, back-off efficiency drops faster when the gate bias increases towards V_{GS} = -0.4V. The data from Figure 2 is stored and used to model the PA, as described in Section 2.

B. *Trade-off Between Complexity and Linearity*

A software infrastructure was prepared based on the methodology in Section II and the block diagram in Figure 1 using MATLAB. The input used for testing was a 192 Msymbol/s 64 QAM signal with 10000 symbols. The roll-off factor of the raised cosine filter is set to 0.3. This signal is first tested without any predistortion. To exemplify its use, a mask for E-band with 250 MHz bandwidth has been implemented. For each gate bias voltage, $P_{out,av}$ and PAE_{av} are found at the spectrum mask limit. This process is repeated for a linearized case by finding the coefficients using ILA which converges after 3 iterations. Spectrum mask limit is again tested with the PA using polynomials of 3rd, 5th and 7th order. The results are shown in Figure 3.

Figure 3 (top) presents average output power at the mask limit for different gate biases when a 3rd, 5th and 7th order pre-

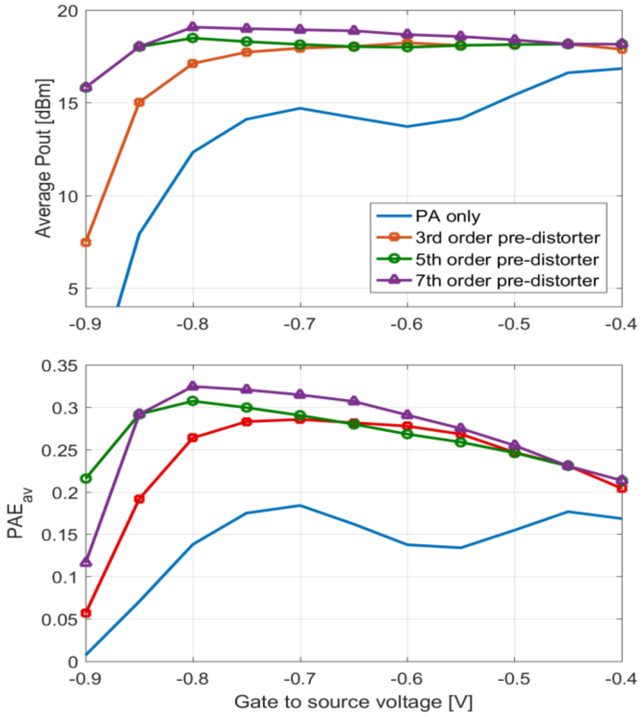

Figure 3. (top) $P_{out,av}$ and (bottom) PAE_{av} for different bias points and different number of pre-distorter coefficients at the spectrum mask.

distorter is applied. These results are compared to the case where no pre-distorter is used. Here we can see that $P_{out,av}$ is improved to some extent for all bias levels when linearization is applied. In the low bias region, where the nonlinearity is higher, the improvement increases for higher order polynomials. The gap between 3rd and higher order polynomials decrease when the V_{GS} is set to -0.4V. At this bias point, the effect of predistortion is also minimal when compared to other classes, around 1dB vs >6dB improvement at V_{GS} = -0.8V. Another result is that the power level after linearization stays relatively constant between these two bias points.

Figure 3 (bottom) presents average PAE at the mask limit for different gate biases when 3rd, 5th and 7th order pre-distorters are used. These results are compared to the case where no linearization is used. The average PAE has a peak value close to pinch-off at V_{GS} = -0.8V, where it also shows the largest improvement. At this point there is a 3dB $P_{out,av}$ improvement between 3rd and 7th order pre-distorters, which translates to 12% improvement in PAE. At this bias, higher order pre-distortion gives better improvement. If we look at the curve when V_{GS} = -0.4V instead, the 3rd order pre-distorter gives nearly the same result as higher order DPDs.

Figure 4 presents power spectral density (PSD) of the resulting output signal of the PA with and without linearization. V_{GS} is chosen to be -0.7V and $P_{out,av}$ is set to 17.8 dBm, which is the power level where 3rd order pre-distorter is used. Here we can clearly see how the margin between the output signal and spectrum mask increases with higher order linearization in the spectrum band.

IV. Conclusions

We have proposed a framework to quantify the trade-offs between the linearity, output power, efficiency and complexity.

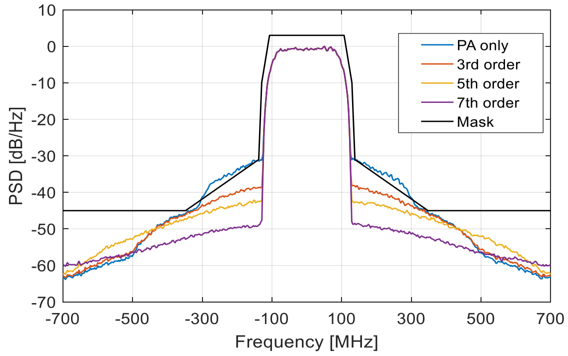

Figure 4. Power spectral density of output signal when 3rd, 5th and 7th order pre-distorter is applied.

The framework has been used with nonlinear model of a PA operating at 29 GHz to investigate these trade-offs by changing the gate bias and pre-distorter order. It is shown how much improvement is achieved in average efficiency and P_{out} for different PA classes, when a modulated input signal is given. The results show that even a 3rd order pre-distorter can give significant efficiency improvement for certain PA classes under spectrum mask constraints. Hence, the proposed methodology can be used to co-design the pre-distorter and the PA to maximize their combined performance for better addressing the trade-offs between each section. This methodology can be an important tool for mm-wave PA and transmitter development.

Acknowledgment

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