Implementation of a Weighted Memory Polynomial model for high non-linear RF-PA behavior

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Resumen

Este artículo propone la implementación de un Modelo Polinomial con Memoria Ponderado (WMPM) para el modelado para un amplificador de potencia de radiofrecuencia (RF-PA). El modelo desarrollado introduce una dependencia directa del valor medido de la señal de entrada-salida; en este caso, el punto de compresión de 1 dB (P1dB) se tiene en cuenta en el algoritmo de cálculo. Como primera etapa del experimento, el modelado se realizó basado en las mediciones de entrada-salida de un RF-PA NXP 10W@2.5 GHz. La validación experimental mostró una precisión adecuada durante la etapa de modelado de -23.20 dB NMSE en relación a las curvas de conversión. En una segunda etapa, se desarrolla la implementación del WMPM en una placa Cyclone V FPGA. Los resultados de la compilación del FPGA reportan un bajo uso de recursos de menos del 1% de las unidades lógicas disponibles. Además, el proceso de extracción de coeficientes se reduce en comparación con el método tradicional Modelo Polinomial con Memoria (MPM). De lo obtenido, se concluye que el WMPM se muestra como una alternativa de modelado no lineal para RF-PA de banda única. Se demostró que el WMPM se puede utilizar para la caracterización y linealización de RF-PA en una etapa posterior de predistorsión digital (DPD) donde se requieren modelos de alta precisión.

Palabras clave— *Amplificador de potencia, FPGA, P1dB, RF, WMPM.*

Abstract

This paper proposes the implementation of a Weighted Memory Polynomial Model (WMPM) as a proposal of modeling stage for a radiofrequency (RF) power amplifier (PA). The developed model introduces a direct dependence on the measured value of the input-output signal; in this case the compression point of 1 dB (P1dB) is taken into account in the calculation algorithm. As a first stage of the experiment, modeling was carried out based on an input-output measurement database of a RF-PA NXP 10W@2.5 GHz. Experimental validation shows a proper accuracy during the modeling stage of -23.20 dB NMSE for the conversion curves. In a second stage, the implementation of the WMPM on a Cyclone V FPGA board is developed. FPGA compilation results report low resource usage less than 1% of the available adaptive logic module. Furthermore, the coefficient extraction process is reduced compared to the traditional MPM method. From the obtained, it is concluded that the WMPM is shown as a non-linear modeling alternative for single-band RF-PA. It was shown that the WMPM can be used for the characterization and linearization of RF-PA at a later stage of digital predistortion (DPD) where high precision models are required.

Keywords— *FPGA, P1dB, Power Amplifier, RF, WMPM.*

1. INTRODUCTION

The explosive growth of cellular transmission and wide bandwidth force to the telecommunications companies to emigrate to a bigger digital multiplexing schemes as Wide Code Division Multiple Access (WCDMA) and Long Term Evolution (LTE) as the standard for efficient transition towards increase the capacity of the mobile networks. Nowadays technologies like LTE-Advanced are able to extend the maximum data rate up to 3 Gbps [1]. Additionally, 5G is not yet widely available, but it is coming, it is estimated that for 2020 this infrastructure will change the way we live supporting faster mobile connections including the requirements of users for the Internet of Things (IoT) at less in North America.

In order to properly address this high wide bandwidth and network handling is required to propose an efficient technique to reduce the undesirable effect of the spectral regrowth and spurious signals. Since 1990s the cellular communication change from analog to digital and was adopted the digital predistortion (DPD) as the technique to linearize satisfactory the power amplifier (PA) as the main device in the transmitter chain as can be found in [2-4]. Despite its relative simplicity, this digital implementation technique can be applied with very good results and cost effectiveness in telecommunications applications [5].

The RF-PA is the device which involves more of the memory effect in short term in the transmitter chain and is the device in charge of increase the power before pass the signal to the antenna. In the process the intermodulation products (IMD) are added to the carrier and message signals, due that it is required to have a very accurate modeling stage coupled to a DPD algorithm, in this case the reduced order polynomial models are a proper alternative when a DPD chain must be coupled in the same development board.

Models derived from Volterra series are a proved technique in the current research, and they are applied in the telecommunications field to model any nonlinear system with memory effects. Memory Polynomial Model (MPM) and Generalized Memory Polynomial Model (MGMP) are some of these derived methods as seen in [6] and [7]. In this work is implemented a WMPM as an interesting alternative due that is considered the P1dB as reference in its design. WMPM is another variant of the MPM and can be used for the mathematical modeling of radiofrequency power amplifier (RF-PA) behavior. This modeling method has already been applied with good results in [8] and [9] as a viable modeling option. In the case, it is decided to apply it to obtain a behavioral model from the data set of input - output measurements of a RF-PA NXP 10W@2.5 GHz. It is desired at a later stage of the study to apply DPD to the model obtained as the final phase of a linearization process. The authors agree that this type of model allow thinking in an adaptive modeling stage if the RF-PA as device under test (DUT) change due to the aging process.

The remainder of this paper is organized as follows. Section II introduces the MPM and WMPM and depicts all the involved stage used for the coefficient extraction process. Section III introduces the hardware implementation of the WMPM used for the modeling stage of the RF-PA. Section IV shows the main results. Finally, Section V are discussed the conclusions.

2. MODEL DESCRIPTION

2.1 Traditional Memory Polynomial Model

The state of the art involved for RF-PA reports the MPM as a traditionally technique derived from Volterra series as shown in [10] and [11]. The MPM does not have all the elements of the original series, to model the memory effects and RF-PA nonlinearities it is necessary to perform truncations in order to optimize calculation resources and estimation times. The MPM consists of several delay phases and only contemplates the diagonal terms of the Volterra series, this model offers a considerable reduction compared to the original series. The MPM can be expressed by the equation (1).

$$y(n) = \sum_{k=1}^{K} \sum_{m=0}^{M} a_{k,m} x(n-m)|x(n-m)|^k, \quad [1]$$

where $x(n)$ is the input complex base-band signal, $y(n)$ is the output complex base-band signal, $a_{k,m}$ are the complex polynomial coefficients, M is the memory depth, and K is the polynomial order. In this work is probed an additional technique little explorer by the research community related to telecommunication devices, in this case the WMPM [8], where the 1 dB compression point (P1dB) is considered.

2.2 Weighted Memory Polynomial Model

In the case of high bandwidth and variable amplitude signals, the power amplifier behaves like a non-linear dynamic system that exhibits static (non-linearity) and dynamic distortion (memory effects). To better address these nonlinearities, the WMPM incorporates in its model weight functions to deal with static and dynamic distortion depending on the voltage levels in the input data. These weight functions are inserted to the static and dynamic terms of the classic polynomial model. This analysis is based on the fact that due to low levels of input voltage the effect of memory caused is greater compared to the non-linearity that occurs, the opposite occurs when the levels of the input voltage are increased [8-9]. The WMPM is described in equation (2):

$$y_{WMPM}(n) = \sum_{k=1}^{K_S} \alpha_k W_S(|x(n)|)\, x(n)|x(n)|^k + \sum_{k=1}^{K_D} \sum_{m=0}^{M} \beta_{k,m} W_D(|x(n-m)|) x(n-m)|x(n-m)|^k \quad [2]$$

where α_k are the coefficient of the static part of the model, $\beta_{k,m}$ are the coefficients of the dynamic part of the model. In this case $W_s(|x(n)|)$ and $W_D(|x(n)|)$ represent the weighted functions involved in the dynamics of the model, in both cases the P1dB is the crucial parameter of the calculus. Then, $y_{WMPM}(n)$ is the output complex base-band signal.

3. WMPM SIMULATION

As previously described in equation (2), the entire WMPM contains dynamic and static part. The high level of dispersion and nonlinearity observed in the measurement data for all voltage levels of the input signal can only suggest the use of the dynamic part of the WMPM to perform the modeling. However, it is decided to model both static and dynamic part of the WMPM in order to reduce the number of coefficients in the model.

Then, the weighting function for the dynamic part of the model is formulated in equation (3) as:

$$W_D(|x(n)|, k, m) = \frac{1}{2}\left(\tanh\left(G(k,m) * \left(1 - \frac{|x(n-m)|}{|x|_{th}}\right)\right) + 1\right) [3]$$

As described in [12], tanh refers to the hyperbolic tangent function, and $|x|_{th}$ is the threshold value given by equation (4):

$$|x|_{th} = x_{th\_n} * |x|_{max} \quad [4]$$

The value of x_{th_n} should be selected near the 1dB compression point as a criterion for modeling for each RF-PA. On the other hand, $|x|_{max}$ is the maximum voltage value of the data set of input measurements. The $G(k,m)$ function is given by equation (5):

$$G(k,m) = \frac{1}{k * m^2} \quad [5]$$

Similarly, the weight function of the static model is described below in equation (6):

$$W_S(|x(n)|,k) = \frac{1}{2}\left(\tanh\left(-F(k) * \left(1 - \frac{|x(n)|}{|x|_{th}}\right)\right) + 1\right) \qquad [6]$$

The $F(k)$ function is described as in (7):

$$K(k) = k \qquad [7]$$

After having developed the mathematical modeling of the RF-PA according to the WMPM from the input-output data, it was found that obtained results were satisfactory and was established the Normalized Mean Square Error (NMSE) as a metric to estimate the general deviations between the predicted and measured values. The calculation methods and functions used were programmed in Matlab and include the three variants of extraction of coefficients for modeling (all, even and odd). The results that we show in this paper apply to the use of only even coefficients in the model due to a better NMSE value obtained for the case at hand.

Figure 1 and 2 show the AM/AM and AM/PM distortion curves of the DUT, as can be seen containing high orders of nonlinearity due to the dispersion of the data in a small voltage range. In the same figures, the simulation result can also be observed after using the WMPM as a modeling strategy.

Fig. 1. Curva de distorsión AM/AM del RF-PA NXP 10W@2.5 GHz.

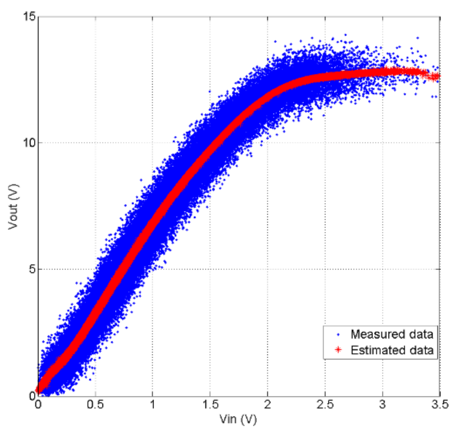


Fig. 2. Curva de distorsión AM/PM del RF-PA NXP 10W@2.5 GHz.

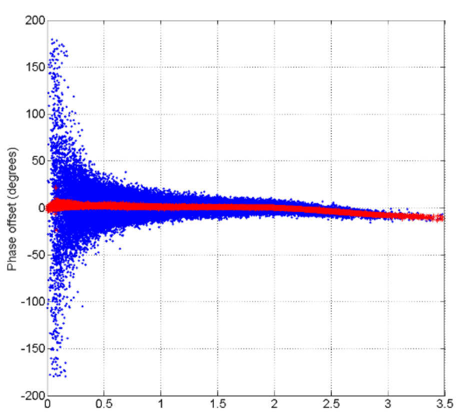
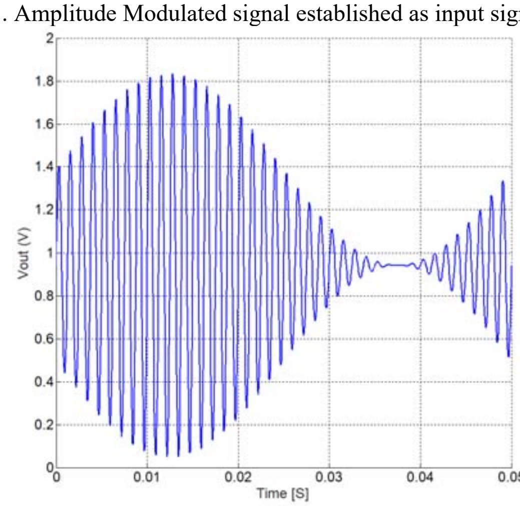


Figure 3 shows the amplitude modulated signal established as input signal, the amplitude of the signal must be related with the range of the input voltage defined by the AM/AM conversion curve, in this case is defined a maximum voltage of 1.82 V in order to test the RF-PA model in the linear region, before the P1dB compression point.

Fig. 3. Amplitude Modulated signal established as input signal.



4. HARDWARE IMPLEMENTATION

To carry out the hardware implementation, the WMPM modeling is first performed in Simulink/Matlab. Once the simulation has been carried out, it is then implemented in the Altera Cyclone V FPGA board. For the modeling process in Simulink, the same nonlinearity and memory depth values reported in the previous section were taken into account. For the modeling process in Simulink, the same nonlinearity and memory depth values reported in the previous section were taken into account. For this, a generic scheme was designed with architecture that covers several modeling cases, up to order $N = 15$ of nonlinearity and memory depth $M = 7$. A general design like the one mentioned above was preferred so that it can be used to model systems from low to high complexity without having to modify the design blocks for each case.

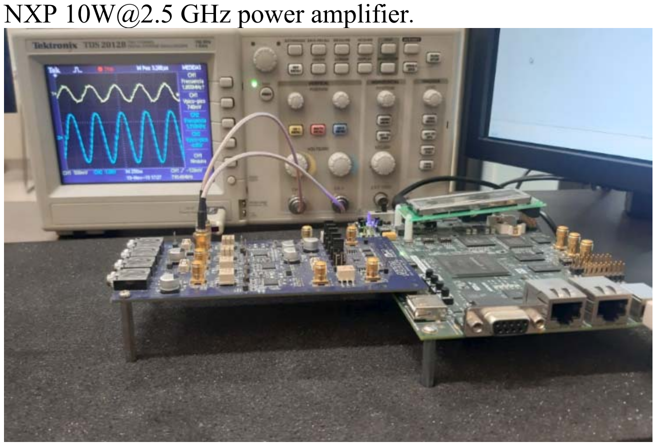
The next step was to generate the modulated amplitude signal that will be entered into the model designed in Simulink in order to amplify it and then check the result of the implementation. To generate this signal, the information provided by the AM/AM amplitude conversion curve was taken into account. The Figure 4 shows the Simulink oscilloscope readings for the modulated signal, AM / AM distortion and the resulting amplified complex signal to the effects of both AM / AM and AM / PM compression that the amplifier introduces to the input signal. Once these results are obtained through the simulation, they are implemented in the FPGA card.

Table 1. Comparative results for both models.

Model	N		M	No. of Coefficients	NMSE
MPM	11		6	77	-22.89
WMPM	7	13	6	62	-23.20

Figure 4 shows the implementation in which the system uses the 14-bit resolution of the data acquisition card, in this case the digital-analog converters (DAC) as output points, however, the input signal It is linked to a generator via analog-digital converters (ADC), the data is stored in a 1024-way look-up table (LUT). The DSP Builder tool was used for the use of HDL language in algorithms developed in a Matlab/Simulink environment in FPGA development board.

Fig. 4. Hardware implementation of the modeling stage for a NXP 10W@2.5 GHz power amplifier.

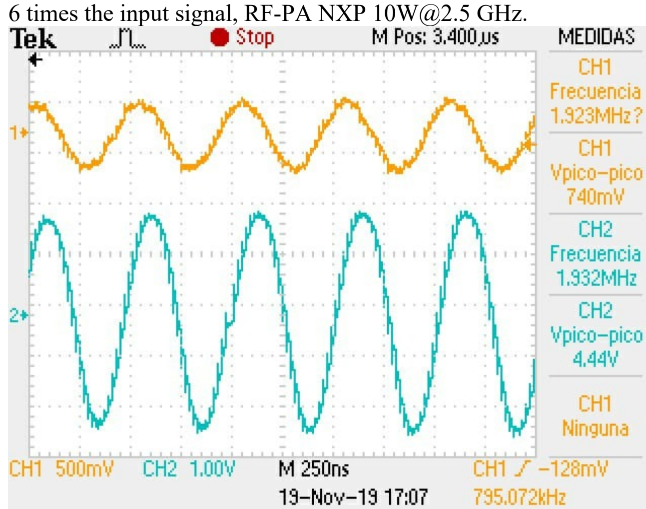


The results are stored as a data array in the form of LUT with a maximum amplitude of 2^{14} bits, that is, that both the digital input and output of the DUT. The signals obtained are converted to a ratio of 0 to 16,383 based on the characteristic of the HSMC acquisition card. In this system, the signal modeled by the power amplifier passes through the DAC2 and the original signal through the DAC1 of the HSMC card. In the process of data management at the input stage, 10 bits of resolution were handled for the address, that is, the data were stored in 1024 data LUTs for each simulation event, it should be noted that the system based on the DSP Builder design tool has a resolution of up to 16,384 data.

The final result obtained is checked by means of the Tektronix TDS2012B oscilloscope and is shown in Figure 5, the amplification rate of approximately 6 times the amplitude of the input signal of the DUT is achieved, the AMAM conversion curve is properly addressed by the developed modeling stage.

Table 2 shows the developed implementation, the use of resources in this system is shown. In this case, the FPGA of the Cyclone V development card used is 5CEFA7F31/7. The 369 logical units used of the 56,480 represent less of the 1% of those available in the system. This point is crucial since it is projected as future work to add an adaptive DPD process as a correction process for various RF-PAs. Another important point is the analysis of 43,008 memory blocks, which represent less than 1% of the total card capacity.

Fig. 5. Oscilloscope view of the amplification achieved in a ratio of 6 times the input signal, RF-PA NXP 10W@2.5 GHz.



The system is adaptable for an adaptive DPD process based on development cards for amplifiers with high nonlinearity rates and variable memory levels. The -23.20 dB NMSE error obtained is considered an acceptable value since it was obtained from an input-output dataset with such a high degree of dispersion.

Table 2. Hardware resources summary.

Family	Cyclone V
Logic Utilization	369/56,480 (<1%)
Total Registers	784
Total pins	40/480 (8%)
Total virtual pins	0
Total block memory bits	43,008/7,024,640(<1%)
Total PLLs	1/7 (14%)

5. CONCLUSIONS AND RECOMMENDATIONS

An alternative method was applied for the behavioral modeling of the non-linear dynamic distortions of RF-PA, a method that incorporates an adaptive weight function to the traditional MPM coefficients. This weight function is dependent on input samples based on their power levels and the compression point of P1dB, the -23.20 dB NMSE for the conversion curves allow us to think in an accurate modeling stage in order to apply a further DPD stage. The implementation reports less than 1% of the available adaptive logic module. The implemented WMPM in this work represents the first approach of an adaptive modeling stage the proposal is to take into account the electrical characteristic of a RF-PA where the aging process is affecting the normal amplification process of the device due to the use.

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