# Novel Approach for Static Nonlinear Behavior Identification in RF Power Amplifiers Exhibiting Memory Effects

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***Abstract* — In this paper, an experimental approach is proposed to accurately identify, under a modulated signal drive, the memoryless nonlinearity of power amplifiers exhibiting memory effects. It is experimentally demonstrated that, when they are present, memory effects bias the extracted static nonlinearity. Accordingly, the sampling rate of the WCDMA test signal waveform is varied to reduce the signal's bandwidth. It is shown that this approach minimizes the memory effects contribution to the amplifier's nonlinear behavior and leads to accurate characterization of the "true" static nonlinearity. The performance of the proposed approach is then assessed through experimental memoryless digital predistortion.**

***Index Terms* — digital predistortion, memory effect, power amplifier, static nonlinearity, WCDMA.**

## I. INTRODUCTION

Radio frequency (RF) power amplifiers (PAs) are being driven by wideband / multi-carrier envelope varying signals, such as wideband code division multiple access (WCDMA) and orthogonal frequency division multiplexing (OFDM). Under such conditions, the assumption of the PA's memoryless behavior is no longer valid, and memory effects need to be taken into account, in order to effectively model power amplifiers and compensate for their nonlinear behavior. Recently, several research activities focused on the identification and compensation of memory effects in RF power amplifiers [1]-[8]. The reported forward and reverse models can be divided into two different types. The first type, which encompasses Volterra series [1] and memory polynomials [2] as well as multi-dimensional look-up tables [3], does not require the decoupling of the PA's static nonlinearity and memory effects. On the other hand, two- and three-box based models, including Hammerstein and Wiener types [4][5], call for the de-embedding of the static nonlinearity and the accurate identification of the residual memory effects' components. In addition, the decoupling of the static (memoryless) and dynamic (memory effects) components of the PA's nonlinearity is useful for the evaluation of memory effects intensity and the PA's linearizability using memoryless predistorters, or linearizers in a more general sense.

Two-tone, as well as multi-tone, signals have been used extensively to identify the memory effects in RF power amplifiers and to quantify their contributions to the PAs' nonlinear behavior [4][6]. These approaches have provided valuable results that quantify the memory effects intensity under the above-mentioned excitation signals. However, there is no straightforward relation that links these results to the behavior of power amplifiers driven by realistic modulated signals, such as WCDMA and OFDM types of signals. A first attempt to quantify the memory effects intensity for PAs driven by modulated signals was described in [7]. In this work, the memory effects intensity was defined as the ratio between the channel power and the residual adjacent channel power for a PA linearized using a memoryless predistorter / linearizer. Hence, it is obvious that the precision of this method depends on the accuracy of the PA's memoryless behavior identification.

Low-frequency ramp signals (having a 1ms period) were proposed in [8] for quasi-static nonlinearity extraction. However, similar to continuous wave measurements, this technique stimulates a different PA behavior, mainly due to heating effects [9]. Conversely, the use of real-time input and output complex waveforms measurements excites a more realistic behavior of the amplifier. The static behavior of the PA is then extracted from the raw measured gain using an averaging technique [10]. In this paper, the limitation of the latter approach, which is mainly due to the biasing of the averaged data by the memory effects, is shown. Then, a new experimental procedure for static nonlinearity and memory effects decoupling is proposed and validated. In section II, the novel static nonlinearity extraction approach is presented and compared to conventional techniques. The effectiveness of this approach is validated through memoryless digital predistortion in section III. The conclusions are presented in section IV.

## II. MEMORYLESS NONLINEARITY EXTRACTION

Figure 1 presents a typical measurement setup for transmitter / power amplifier characterization using instantaneous input and output waveforms. The baseband complex waveform at the input of the device under test was compared to the demodulated output baseband complex waveform, in order to extract the nonlinear behavior of the device under test. In this work, the digital modulation, digital-to-analog conversion (DAC) and frequency up-conversion of the input signal were performed within an arbitrary waveform generator. A vector signal analyzer was used as a receiver to down-convert, digitize and demodulate the RF output signal.

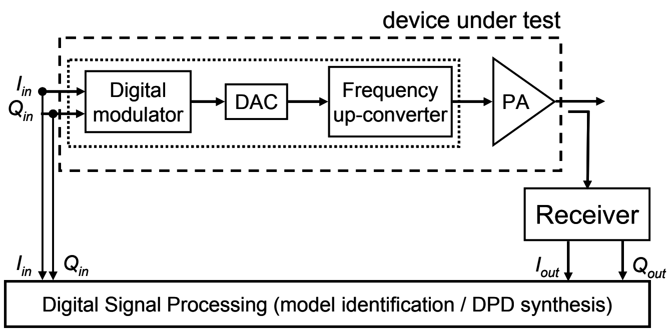


Fig. 1. Experimental setup for PA characterization.

The experimental setup presented in Figure 1 was used to characterize a 300-Watt peak power amplifier operating in the 2110-2170 MHz frequency band. The device under test was driven by a single-carrier WCDMA signal around 2140 MHz. The measured PA's nonlinearity included both the static and the dynamic components, and primarily depended on the signal's statistics (mainly the complementary cumulative distribution function and the peak-to-average power ratio), bandwidth and average power. These signal characteristics affect the PA's static and dynamic nonlinearities in different ways. In fact, while the signal's statistics and average power influence the static nonlinearity, the signal's bandwidth is the key factor that dominates the memory effects. At this point, it is worth mentioning that the signal's statistics and average power are directly related to the digital samples / waveform, and that the signal's bandwidth is defined by the sampling rate. Accordingly, it is possible to independently control the amplifier's static or dynamic nonlinearities by acting on the signal's waveform or its sampling rate, respectively. Since the memory effects intensity decreases as the signal bandwidth decreases, the reduction of the signal's sampling rate minimizes and ideally cancels the memory effects' contributions to the PA's nonlinearity. Under such conditions, it is possible to accurately extract the "true" PA's memoryless nonlinearity.

To validate this approach experimentally, a WCDMA signal waveform was generated according to Test Model 1 (TM1). The sampling rate of this digital waveform was varied over a wide range. The sampling rate scaling factor ($\alpha$), defined as the ratio between the waveform's actual sampling rate ($f_s'$) and the waveform's original sampling rate ($f_s$), was swept from 1 to 0.2 in steps of 0.1.

$$\alpha = \frac{f_s'}{f_s} \tag{1}$$

Accordingly, the bandwidth of the signal applied to the device under test was varied from that of the original WCDMA signal (3.84 MHz) to 20% of the original WCDMA signal's bandwidth (0.77 MHz). For each testing signal, the static nonlinearity of the device under test was extracted from the measured AM/AM and AM/PM characteristics using a standard averaging algorithm similar to that proposed in [10]. Figure 2 presents the static nonlinear AM/AM curves extracted from different sets of measurements. For clarity purposes, curves corresponding to only three values of the sampling rate scaling factor are plotted. As one can observe, the extracted static nonlinear curves depend on the bandwidth of the driving signal and consequently on the memory effects. This corroborates the biasing phenomenon of the extracted static nonlinear characteristic by the memory effects when wideband signals are used. Thus, the "true" static nonlinear characteristic of the device under test is the one that is extracted with the narrow bandwidth signal that does not stimulate the PA's memory effects. To further assess this statement, memoryless digital predistortion was applied to linearize the device under test driven by different test signals. The results are reported in section III.

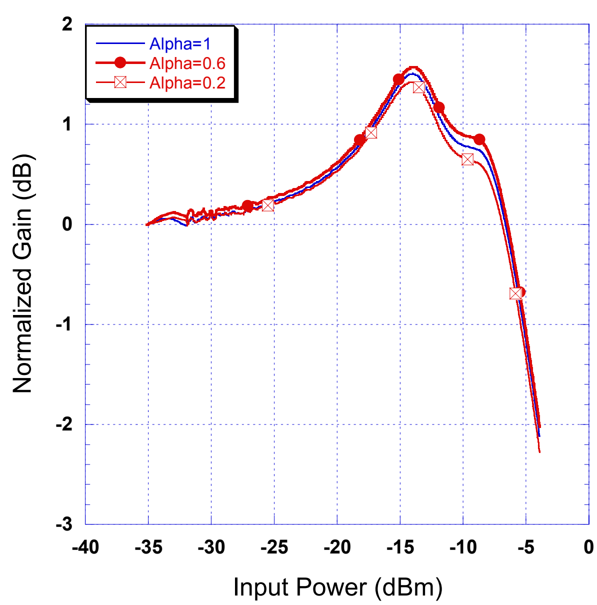


Fig. 2. Extracted static AM/AM characteristics vs. sampling rate scaling factor.

## III. Accuracy Assessment Through Memoryless Digital Predistortion

Digital predistortion is undeniably the ultimate test that can be used to assess the accuracy and performance of PA's forward and reverse modeling. Here, digital memoryless predistortion was applied to the device under test to evaluate the residual nonlinearity at the output of the linearized PA. This residual nonlinearity is attributed to the memory effects. First, the device under test was driven by the original single-carrier WCDMA signal (3.84 MHz bandwidth) and linearized using a memoryless look-up table based digital predistorter. The results are presented in Figure 3, which reports the measured spectra at the output of the power amplifier before and after linearization. These results illustrate the efficiency of the predistorter in improving the linearity of the device under test, since an improvement of around 30 dBc in the adjacent channel power ratio (ACPR) is observed. They also highlight the memory effects exhibited by the device under test. In fact, these memory effects can be noticed in the spectral asymmetry, as well as in the residual nonlinearities in the measured spectra after memoryless digital predistortion.

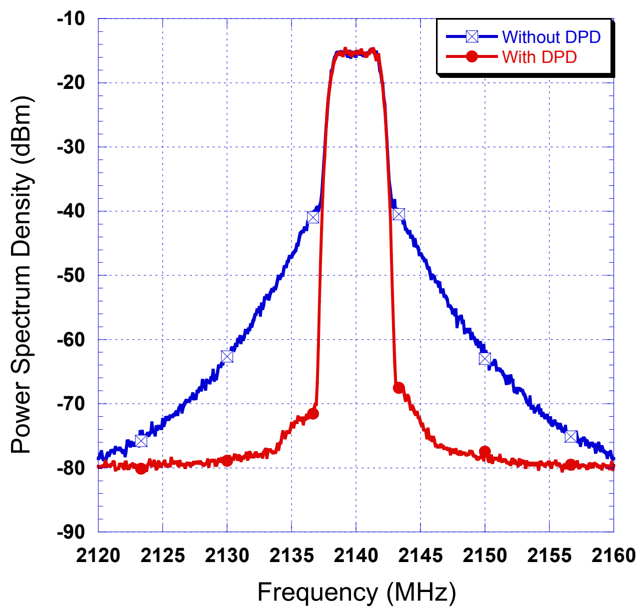


Fig. 3. Measured spectra at the output of the PA before and after linearization. ( $\alpha = 1$ )

The previous test was repeated with the PA driven by the same WCDMA waveform, for which the sampling rate was varied. The measured spectra at the output of the linearized PA under these conditions (variable values of the sampling rate scaling factor) are reported in Figure 4. In order to objectively compare the linearity performance of the linearized device under test, the output spectra were plotted versus the normalized frequency ( $f_n$ ):

$$f_n = \frac{f - f_c}{BW(\alpha)} \qquad (2)$$

where $f_c$ is the carrier frequency, and $BW(\alpha)$ is the actual signal bandwidth, which depends on the sampling rate scaling factor.

Accordingly, the spectra were centered around zero, and the signals' bandwidths were normalized to unity. Figure 4 shows that the performance of memoryless digital predistortion improved as the signal's bandwidth narrowed. In fact, the residual nonlinearity was significantly reduced, and the spectrum asymmetry was cancelled.

Figure 5 illustrates the spectrum imbalance cancellation when the signals bandwidths were reduced. The spectrum imbalance is associated with memory effects and is an indication of their intensity. In this figure, the left and right hand sides of the measured spectra are overlaid. This clearly demonstrates that the linearized spectra for $\alpha = 0.2$ does not present any spectrum imbalance. The residual nonlinearity, 60 dBc below the carrier power, is attributed to the measurements noise and the setup's accuracy. Thus, the PA behavior measured under these conditions is free from memory effects. Accordingly, the use of this sampling rate scaling factor ( $\alpha = 0.2$ ) leads to the extraction of the "true" static nonlinearity that is independent from memory effects.

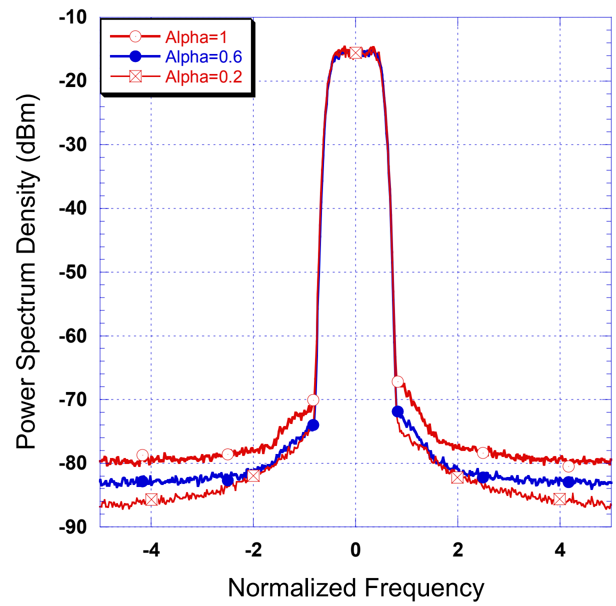


Fig. 4. Measured spectra at the output of the linearized PA vs. re-sampling factor.

## IV. Conclusion

In this paper, a novel approach for the accurate extraction of static nonlinearity in RF transmitters / power amplifiers exhibiting memory effects was presented. It was shown that, in the conventional approaches used for static nonlinearity extraction under a modulated drive signal, the results are biased by memory effects. Consequently, a waveform re-sampling technique that reduces the signal's bandwidth, while keeping its statistics unchanged, has been proposed to extract the "true" static nonlinearity. Experimental validation, including characterization and memoryless predistortion, was carried out on a high-power third-generation RF power amplifier. Measurement results demonstrated the accuracy of the proposed approach. The outcome of this work is useful for accurate estimation of memory effects intensity and for linearizability study.


## ACKNOWLEDGEMENTS

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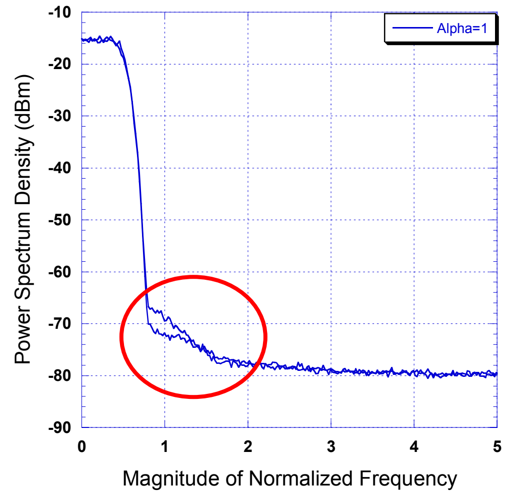
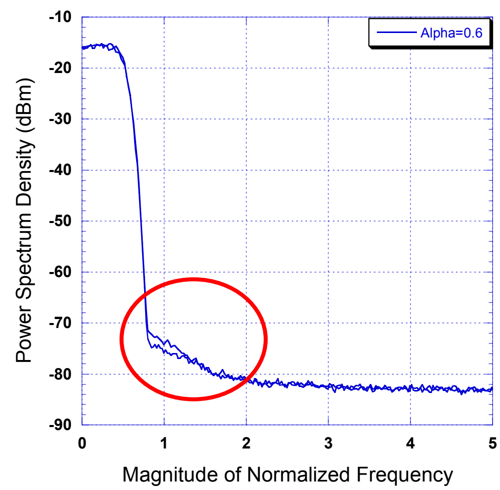
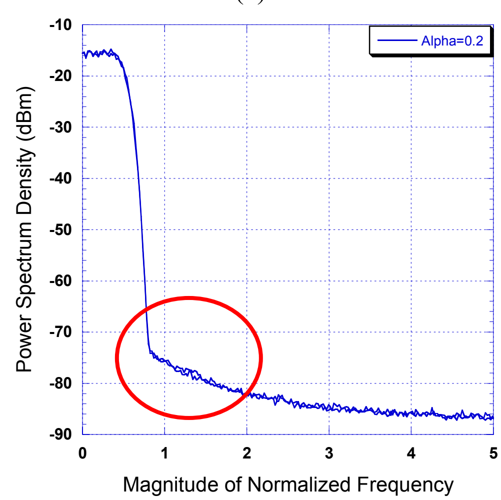



(a)




(b)




(c)

Fig. 5. Linearized spectra symmetry vs. re-sampling factor. (a) $\alpha = 1$, (b) $\alpha = 0.6$, (c) $\alpha = 0.2$.