Gaussian Pulse Characterization of RF Power Amplifiers

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Abstract—This work presents a new RF power amplifier characterization technique based on a Gaussian pulse, which is shown to approximate the envelope of a multi-carrier signal with 0.5% error around the peaks. The standard deviation of the Gaussian pulses is inversely proportional to the I/Q signal bandwidth. This test signal is shown to accurately capture nonlinear memory effects that result in gain dispersion after the peak power is reached. As an example, it is shown that the gain amplitude and phase can vary up to 2.3 dB and 6° for a 10-W 3.75-GHz GaN power-amplifier evaluation board, depending on the I/Q signal bandwidth and peak power level.

Index Terms—gallium nitride, memory effects, nonlinear characterization, power amplifier, RF measurements, trapping effects.

I. INTRODUCTION

BEHAVIORAL MODELING of RF power amplifiers (PAs) relies on characterization with test signals capable of exciting nonlinear memory effects accounted by the model [1]. These effects are mainly caused by matching and biasing circuits, transistor parasitics, temperature, and in some technologies (e.g. GaAs or GaN) by charge-trapping phenomena [2]–[5]. Memory time constants are in the ns to s range, affecting a wide spectrum response of the PA, from a few Hz to GHz from the carrier frequency [6]. Nonlinear memory effects are more detrimental when amplifying signals with large peak-to-average power ratios (PAPRs), such as in multcarrier signals. A (local) maximum of the envelope temporarily changes the PA behavior, and if the envelope remains below this value, the PA can recover to a certain degree [5]. This is illustrated in Fig. 1 with the coloured arrows.

Test signals used in PA behavioral modeling include: 1) the application signal itself (e.g. LTE); 2) single-, two- or multi-tone sinusoidal signals [7]–[9]; and 3) single, double or multiple pulses [10]–[12]. The first approach leads to signal-dependent PA gain characterization; when the signal changes, the characterization data is no longer representative of the PA behavior. The other two approaches are more general and the main differentiator is their time-frequency resolution: multi-tone test signals enable the study of precisely-located effects in time but they require a large number of tones to capture both slow and fast effects [9]. Rectangular pulses allow instead the study of precisely located effects in time domain if a fast rise and fall time is used, but they result in a unnecessarily broadband PA excitation (with possible ringing).

In this work, we propose a new characterization technique using a Gaussian pulse which optimizes the time-frequency resolution of the characterization based on the signal application: the rise and fall times of the Gaussian waveform closely match those of the multi-carrier test signal, or equivalently the spectral response of a Gaussian pulse approximates the bandwidth of the application signal. This technique also simplifies the PA characterization by avoiding the use of a high number of rectangular pulses or sinusoidal tones as only a single Gaussian pulse is required to extract the PA characteristic. This approach is similar to other hybrid time-frequency analysis techniques such as Wavelet transform. However, Gaussian pulses are appropriate due to the stationary nature of the signal [13] and the sensitivity of a RF-PA to voltage peaks.

II. GAUSSIAN CHARACTERIZATION

Multi-carrier signals (e.g. downlink LTE [14]) are commonly used in high-capacity wireless links. A bit stream is split into \( N \) lower-rate symbol streams \( x_n \), which are modulated by \( N \) sub-carriers with frequency spacing \( 1/T \):

\[
x(t) = i(t) + jq(t) = \sum_{n=1}^{N} x_n e^{j2\pi nt/T}.
\]

Here \( T \) is the signal period, and symbols \( x_n \) belong to an independent identically distributed random variable \( X \) [15]. For large \( N \), because of the central limit theorem (CLT) [16], the real and imaginary parts of \( X \) tend to a Gaussian distribution with zero mean and standard deviation \( \sigma \), namely

\[
I \sim \frac{1}{\sqrt{2\pi \sigma^2}} \exp\left(-\frac{I^2}{2\sigma^2}\right), \quad Q \sim \frac{1}{\sqrt{2\pi \sigma^2}} \exp\left(-\frac{Q^2}{2\sigma^2}\right).
\]
It is widely accepted that the PA nonlinear memory effects are caused by signal amplitude as described by AM-AM and AM-PM model, therefore $X$ is expressed in polar form,

$$R \sim \frac{r}{\sigma^2} \exp \left( -\frac{r^2}{2\sigma^2} \right), \quad \Theta \sim \begin{cases} 1/2\pi, & -\pi \leq \theta < \pi \\ 0, & \text{otherwise} \end{cases}$$

A numerical representation of random variable $R$ is given in Fig. 1 where it is seen that its shape tends to a Rayleigh PDF (note the logarithmic scale). Eq. (3), however, does not provide information on amplitude distribution, or if a recurring shape is present in the envelope.

In this work, we aim to extract the most likely repetitive shape in a multi-carrier signal envelope, and to this purpose we average the multi-carrier envelope pulses to find a recurring shape in a multi-carrier signal envelope, and to this purpose we provide a numerical demonstration that a bell-shaped waveform. A rigorous proof is outside the scope of this paper, we average the multi-carrier envelope pulses to find a recurring shape in a multi-carrier signal envelope, and to this purpose we provide a numerical demonstration that a bell-shaped pulse gives the desired approximation of the envelope.

The minima-maxima decomposition algorithm can be summarized as follows:

1) The envelope is partitioned based on consecutive minima. The $m$-th partition is delimited by two consecutive minima $\tilde{t}_m$ and $\tilde{t}_{m+1}$, namely

$$P_m = [r(\tilde{t}_m), \ldots, r(\tilde{t}_m), \ldots, r(\tilde{t}_{m+1})].$$

As seen in Fig. 2a, if the envelope partitions include more than one maximum (or more than two minima), their average presents a second peak (dashed lines). When instead the partition is defined by two nearest minima, the average tends to a Gaussian pulse with 99.5% R-square confidence.

2) From Rolle’s theorem, a maximum $r'(\tilde{t}_m)$ is present between two consecutive minima, so the maximum $\tilde{t}_m$ can be aligned to $t = 0$ as also qualitatively depicted in Fig. 2b.

3) The average of a large-enough number $M$ of partitions tends to a bell-shaped curve (Fig. 2c) which can be approximated by a Gaussian waveform with standard deviation $\tau$ and maximum value $\bar{r}(0)$, namely

$$P_{avg} = \frac{1}{M} \sum_{m=1}^{M} P_m \approx G(0) = \bar{r}(0) \exp \left( -\frac{t^2}{2\tau^2} \right).$$

It is interesting to note the similarity between (5) obtained by minima-maxima analysis in the time domain and the original I/Q amplitude PDF of (2). The full-width at half-maximum (FWHM) of a Gaussian pulse in time domain is

$$\text{FWHM} = \sqrt{8 \ln 2} \cdot \tau \approx 2.355 \cdot \tau.$$  

The FWHM is also inversely proportional to the I/Q signal bandwidth $BW_{-3dB}$ as verified in Table 3. Therefore

$$\text{FWHM} \approx \frac{1}{BW_{-3dB}} \Rightarrow \tau \approx \frac{1}{2.355 \cdot BW_{-3dB}}.$$  

In summary, this last property can be used to investigate the PA behavior in response to an arbitrary I/Q signal with $-3$ dB bandwidth equal to $1/\text{FWHM}$.

III. EXPERIMENTAL RESULTS

This characterization technique is validated with an evaluation board of a Wolfspeed CG2H40010F GaN-on-SiC transistor. The PA input and output signals are sensed with couplers connected to a 200-MHz vector signal generator and analyzer (NI PXIe-5646R VST) as shown in Fig. 4. Power calibration is performed at 3.75 GHz (PA central frequency). Six LTE signals with channel bandwidths of 1.4, 3, 5, 10, 15, and 20 MHz are generated according to the E-UTRA FDD test model (v1.1) and are used as a benchmark for the validation of the technique. We note that the -3 dB bandwidths of these LTE signals is obtained by removing the guard bands and results in the values in the second column of the table in Fig. 3.

The Gaussian characterization technique is validated against partitions of the original LTE signal with the aim of showing...
the equivalence between the two waveforms in capturing the PA gain. Fig. 5a reports the gain resulting from four random partitions at increasing amplitudes of the 1.4-MHz LTE signal, extracted with the algorithm of Section II, which are compared to the PA gain in response to a Gaussian pulse with FWHM = 930 ns. The two techniques provide very similar results both in gain amplitude and phase. Similarly, the gain resulting from a 20-MHz LTE signal excitation is compared to a Gaussian pulse with FWHM = 60 ns showing good agreement, Fig. 5b.

Next, the flexibility of the characterization technique is demonstrated by measuring the gain of the PA for all the LTE signal bandwidths, Fig. 6. The gain amplitude and phase is approximately the same until it reaches the peak output power (→ direction). For $r(0) = [1/\sqrt{10}, 1]$, the gain after the maxima is degraded to a lower amplitude and phase value (← direction). For lower LTE bandwidths, this dispersion is larger, possibly because of a longer pulse duration (higher self-heating) and permanence at higher voltage levels (more charge trapping). Note that this gain and phase dispersion occurs for envelope amplitudes well below 10 dB which represent 71-77% of the entire signal duration (see PDF on Fig. 1), and this justifies the need for a flexible signal representation capable of capturing these effects within the signal evolution.

**Conclusion**

In this paper, we present a novel characterization technique based on a Gaussian waveform suitable for studying the nonlinear memory effects in RF power amplifiers. A minima-maxima algorithm is used to extract the most-likely pulse shape within a multi-carrier signal, which can be approximated by a Gaussian pulse, with full-width at half-maximum inversely proportional to the I/Q signal bandwidth. The Gaussian pulse and the original “LTE pulse” are demonstrated to be equivalent in extracting the PA characteristics. This technique is then applied to characterize the gain of the PA with a Gaussian-pulse instead of a 1.4-20 MHz LTE signal, which results in a gain and phase deviations of up to 2.3 dB and 6° respectively.

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