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Simulation of nonlinear distortion in W-CDMA communication circuits

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ABSTRACT

Different circuit-level approaches to study the effects of nonlinear distortion on coded division multiple access (CDMA) wireless communication systems are analyzed. These techniques are used to predict spectral regrowth and baseband signal vector constellation at the output of a nonlinear device. To demonstrate and verify their capability, a simple MESFET amplifier has been tested with a W-CDMA waveform. The active device was widely characterized including the extraction of large-signal model parameters. Measurements were satisfactorily compared with the simulated results.

Keywords: Nonlinear distortion, microwave amplifiers, digital communications

1. INTRODUCTION

The interest on a precise approach to analyze the effects of nonlinear distortion in modern mobile and wireless communication systems is still generating a great effort in the development of simulation techniques.[1] Nonlinear devices generate co-channel and adjacent-channel interference due to intermodulation and spectral regrowth.

In mobile communications the bandwidth of each RF channel is much smaller than the carrier frequency and therefore the RF signal $s(t)$ can be represented as a narrowband passband signal as:

$$s(t) = \mathrm{Re}\,[\tilde{s}(t)\exp(j\omega_c t)]\ , \tag{1}$$

where $\tilde{s}$ is the complex envelope $\tilde{s}(t) = r(t)\exp(j\psi(t))$. When the narrowband signal is applied to a LTI system which impulse response is expressed in terms of its complex envelope $\tilde{h}(t)$, the output signal $y(t)$ yields:

$$y(t) = \mathrm{Re}\,[\tilde{s}(t)\exp(j\omega_c t)]\ ,\ \tilde{y}(t) = \tilde{s}(t) * \tilde{h}(t)\,. \tag{2}$$

This paper is aimed at the simulation of communications signals in presence of a channel with mild nonlinearities, where (2) is inaccurate enough to be considered even a rough approximation. A number of models have been reported during the last years to account for the effects of nonlinear distortion. Starting with the most simple representation, behavioral modeling allows a quick estimation of nonlinear performance. As an example we can cite Saleh's model[2]:

$$A(r) = \frac{\alpha_a r}{1+\beta_a r^2}\ ,\ \Phi(r) = \frac{\alpha_\phi r}{1+\beta_\phi r^2}\ , \tag{3}$$

which stands for AM-AM and AM-PM conversions of a TWT amplifier, $A(r)$ and $\Phi(r)$, respectively. Due to its memoryless formulation, retaining the components around f_c, the output signal can be expressed as[3]:

$$y(t) = \mathrm{Re}\,[\tilde{s}(t)\exp(j\omega_c t)]\ ,\ \tilde{y}(t) = r(t)A\,[r(t)]\exp\{j\,[\psi(t) + \Phi[r(t)]]\}\ . \tag{4}$$

On the other hand, circuit level approaches present more accurate results at the cost of longer simulation times. Another technique, the Envelop Transient Analysis[4] decouples RF and baseband spectra gaining in computational efficiency but retaining much of the simulation time. The Method of the Envelop Currents[5] is an alternative solution that exploits the weakly nonlinear characteristics of communication circuits to achieve a great improvement in simulation speed, although this method presents a limited dynamic range.

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2. SIMULATION APPROACHES

Overriding the memoryless assumption, circuit level simulation provides a better insight of the nonlinear performance. One of the most popular techniques for nonlinear circuit analysis is the method of nonlinear currents (NC), which is based on a Volterra-series description of the incremental node voltages. Components of order n satisfy the following linear equation system:

$$\boldsymbol{L}\,[v_n] = \boldsymbol{i}_n\,, \tag{5}$$

where $\boldsymbol{i}_1$ is a vector with the original driving excitations and $\boldsymbol{i}_n$ are the nonlinear currents expressed in terms of voltage components of order $m < n$. The method takes advantage of the recursive structure of the procedure to obtain $\boldsymbol{i}_n$, although closed-form expressions for the nonlinear currents are rather cumbersome for $n > 3$, limiting thus the practical dynamic range of the algorithm.

The NC method is straightforward to obtain the output response for a single-tone input, when the differential operator $\hat{p} = d/dt$ can be exchanged by the complex frequency $j\omega$, and even with a discrete multitone excitation in terms of nonlinear transfer functions. However, when the driving sources are narrowband communication signals, solving (5) requires a large simulation time. Borich *et al*[5] have proposed the Method of Envelop Currents (MEC) as a simple approach to the efficient computation of (5) in case of narrowband modulated excitations. Two fundamental assumptions are behind the MEC: a quasiperiodic treatment for the complex envelopes around each harmonic of f_c and a first-order Taylor series expansion of the admittance matrix $\mathbf{Y}(\hat{p}) \simeq \mathbf{Y}_c + \mathbf{Y}_d \cdot \hat{p}$. When this expansion is applied to (5) the following expression results: $[\mathbf{Y}_c + j\boldsymbol{\Omega} + \mathbf{Y}_d \cdot \hat{p}]\,\hat{v}_n(t,m) = \hat{\boldsymbol{i}}_n(t,m)$, where $\hat{v}_n(t,m)$ is the vector with the waveforms of the voltage complex envelopes around mf_c and $\boldsymbol{\Omega}$ is a diagonal matrix accounting for the time derivatives of the terms $\exp(jm\omega_c t)$. This differential equation can be solved with a Backward-Euler discretization method.

A different approach presented in[6] differs with the MEC in the way how the nonlinear currents are calculated. The basic idea behind this method is to express the variables of the circuit as a sum of incremental voltages: $v = v_0 + \ldots + v_n = \bar{v}_{n-1} + v_n$, each of one being the solution of a time-varying circuit excited by a nonlinear current. The time dependence of this changeless circuit and its exciting nonlinear currents are updated at each iteration. The fact that a time-varying linear circuit has to be analyzed is the main difference with respect to the NC method, and the search for the solution in case of narrowband modulated signal excitation is based on formulation similar to conversion matrices followed by a Backward-Euler discretization method.

2.1. Modeling a MESFET device

The methods discussed in the previous section have been tested with a simple amplifier at 2 GHz based on a CFB0301 (Celeritek) MESFET. The active device was biased under $V_{DS} = 2$ V and $I_D = 25$ mA and the elements of the small-signal circuit were obtained from S-parameter measurements using Fukui method for extraction of access resistors and Dambrine-Cappy method for the elements of the intrinsic circuit, following an overall optimization with Libra Series IV HP EESOF simulator for parameters R_i and τ.

With regard to the large-signal performance, only the nonlinear current source has been taken into consideration. Its parameters have been fitted to an Angelov model (6 coefficients), using the test bench shown in Fig. 1. Two signals at incommensurate VHF frequencies are injected into the source and drain ports and the different intermodulation products are measured with a spectrum analyzer. Extraction of the large-signal parameters is accomplished through a double Volterra-series approach[7] comparing measurements of each product with the predicted IMD in terms of nonlinear transfer functions of order $n + m$. The accuracy of the achieved adjustment is depicted in Fig. 2, showing a good agreement.

3. RESULTS

In order to check the accuracy of the methods shown in Section 2, we have implemented a MESFET amplifier using a single device. Its performance has been widely characterized at 2 GHz and measurements have been compared with predictions using the large-signal model described previously. Fig. 3 shows the first, second and third harmonics at the output in a wide range of input power levels. Simulations have been accomplished with the second method using the adjusted Angelov model to obtain the time-varying derivatives of the nonlinear

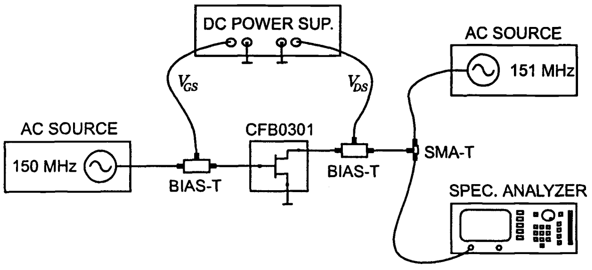

Figure 1. Test-bench configuration for MESFET large-signal characterization.

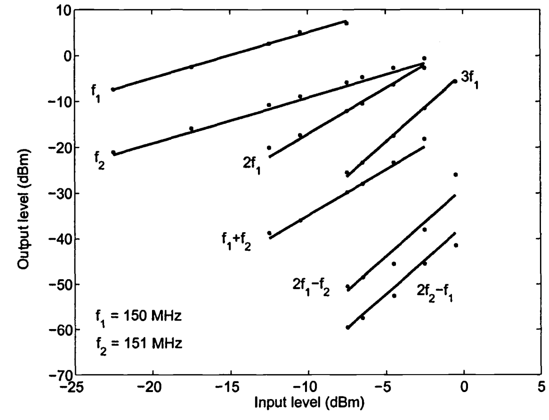

Figure 2. Level of IM products at the input of the spectrum analyzer: dots, measurements; solid line, predictions with Angelov model.

current source. The transducer power gain is depicted in Fig. 4, demonstrating also a good correspondence between measurements and the NC method.

The amplifier has also been tested with a 2 GHz W-CDMA 3GPP QPSK signal at a rate of 3.84 Mcps using raised and root-raised cosine filters. To perform the simulations 256 symbols of a QPSK sequence have been generated taking 8 samples/symbol and using conforming filters with a length equivalent to 6 symbols and a 0.22 roll-off factor. Fig. 5 compares the measured spectrum at the output ports with the simulated PSD following the MEC in the case of a raised-cosine filter. For the sake of comparison, Fig. 6 presents the same information using a root-raised cosine filter, with predictions obtained with the alternative method. It is clearly noticeable a greater spectral regrowth in the second case because of the conforming filter applied. While in both cases simulations agree with measurements, it is important to emphasize that the MEC method needs three iterations to yield the results (one per each nonlinear current), whereas in Fig. 6 only one iteration has been calculated.

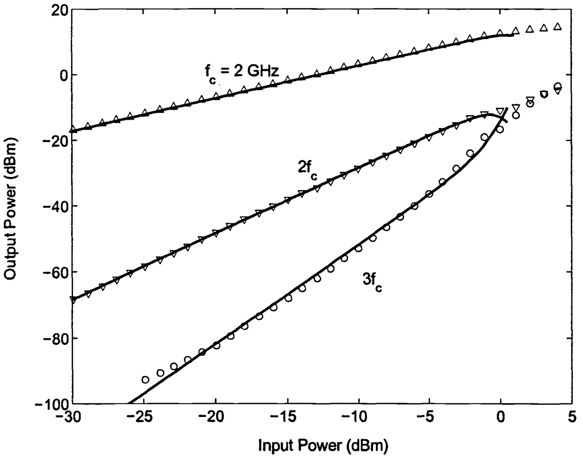

Figure 3. Power levels at the output of the MESFET amplifier for the first, second and third harmonics. Dots, measurements; solid line, simulation.

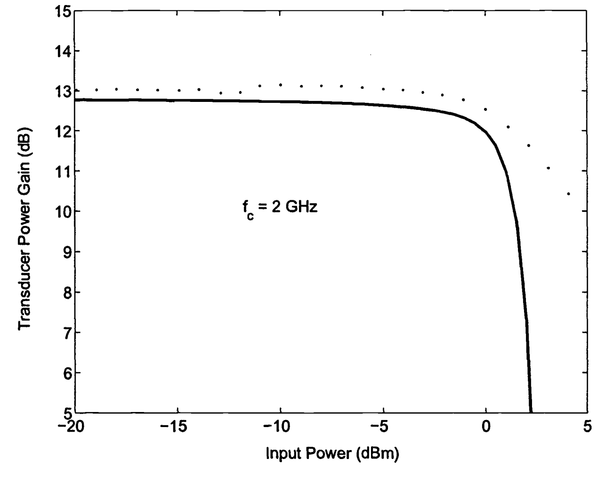

Figure 4. Transducer power gain at 2 GHz. Dots, measurements; solid line, simulation.

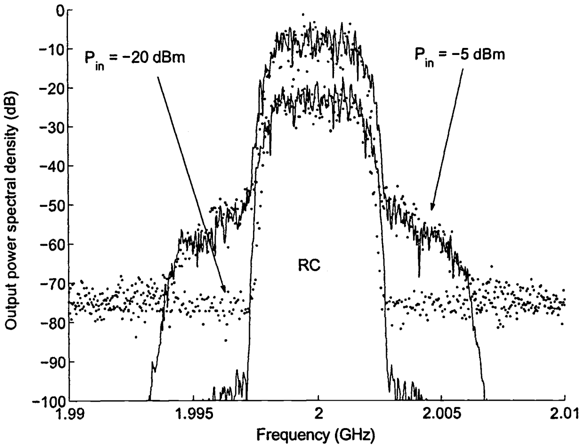

Figure 5. Output power spectral density at two different input levels using a raised cosine filter. Dots, measurements; solid lines, prediction with MEC.

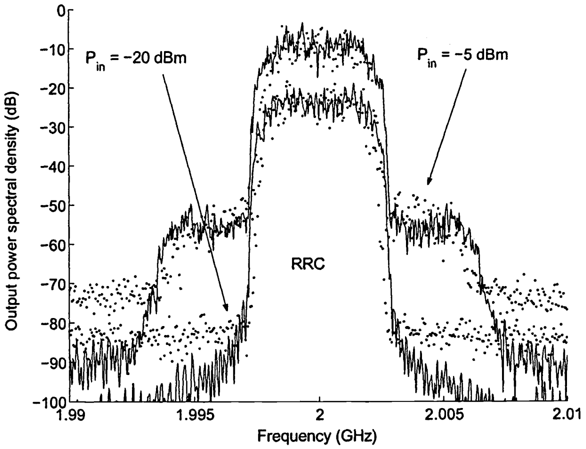

Figure 6. Output power spectral density at two different input levels using a root-raised cosine filter. Dots, measurements; solid lines, prediction with our approach.

4. CONCLUSION

In this paper different circuit-level simulation approaches have been applied to the analysis of distortion due to nonlinear channels excited by W-CDMA communication signals. An amplifier at 2 GHz was constructed using a CFB0301 (Celeritek) MESFET with $V_{DS} = 2$ V and $I_D = 25$ mA to test the methods. Model parameters for the nonlinear current source of the transistor large-signal equivalent circuit were extracted and used to predict output at fundamental, second and third harmonics. After that, a 2 GHz W-CDMA signal modulated at 3.84 Mcps using raised and root-raised cosine pulses was generated from a vector signal generator and applied to the input of a spectrum analyzer and compared with results obtained using the different techniques, showing a good agreement.

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