Solutions for

Memory Effects in Microwave Components

Using X-Parameters to Characterize and Model Long-Term Memory Effects of Wideband Modulated Signals

Application Note

Overview

Designers of power amplifiers (PAs) used in wireless communication infrastructure today face many unique challenges, not the least of which is characterizing and modeling the component's linear and nonlinear behavior. Complicating this task are long-term memory effects that make describing the PA characteristics, and therefore designing products with the PA, much more difficult.

What is a memory effect? Consider that a "memoryless" system is defined as $y(t) = f(x(t))$, where $y(t)$ is the output signal, $x(t)$ is the input signal and f is a linear or nonlinear function. Here, the output at any time depends only on the input signal value at that particular instant. In a system that has memory, this does not hold true. The output at a given time can depend not only on the present input value, but also previous output and input values. Common symptoms that let the designer know a system has memory are when the amplifier's measured intermodulation distortion (e.g., TOI or IM3) changes as a function of the frequency difference between the two stimulus tones, its IM3 upper and lower sidebands exhibit asymmetry, or it produces hysteretic/multi-valued AM-AM and AM-PM amplifier responses in response to modulated signals.

Particularly difficult to deal with are long-term memory effects, where the memory persists for timescales that are many orders of magnitude longer the timescales associated with the carrier frequency or even the frequency at which the carrier is being modulated. Long-term memory effects are caused by a number of factors, including time-varying operating conditions such as dynamic self-heating, bias-line modulation and semiconductor trapping phenomena that are induced by the input signal and vary at a relatively slow rate compared to the modulation speed.

Problem

Modeling the memory effects of microwave components like PAs is a difficult and challenging task. Memory effects make quantifying distortion (nonlinearity) much more complicated. They also make designing for linearity for arbitrary signals much more difficult, since pre-distortion of components with memory is much harder. The first step in dealing with memory effects is the ability to characterize and model them, systematically. Only then is it possible to eliminate or even exploit memory effects in design. Doing so would enable the designer to correct for distortion, design better instruments, and correct parts that would otherwise be more useful were it not for long-term memory. For example, the desirable high frequency and high-power capabilities of a promising technology like GaN HFETs is somewhat less attractive given that the devices often exhibit significant long-term memory effects due to trapping phenomena which adversely impacts linearity. Unfortunately, until recently, no unified approach yet exists to accurately characterize, model and simulate long-term memory effects for wide bandwidth communication signals.

Solution

X-parameters*, a new category of nonlinear network parameters for deterministic, high-frequency design, can be used to characterize both a components' linear and nonlinear behavior, but dealing with long-term memory effects demands an extension of this technology to support these effects. This extension must provide a unique method of quantifying a component's memory effects, along with development of a mathematical model that would enable designers to design with nonlinear components exhibiting significant memory effects. Methods for counteracting (pre-distorting) or mitigating, or exploiting memory can then be built upon such a foundation.

Today, X-parameters are able to capture some memory effects, in particular, the quasi-static memory effects caused by such things as bias and temperature modulation at low frequencies. Here, generated or measured X-parameters are characterized over a range of static independent variable values, but used for design in circumstances where these values are allowed to vary slowly. This is accomplished by embedding the model port corresponding to the static parameter (e.g., bias) into a network which passes signals, at low frequency, that will be generated by the component model in response to modulated input signals at the RF ports. As a result, memory effects are induced with respect to the RF ports (including as indicated above). The model that describes this behavior is accurate, provided that the time variation of the voltage is sufficiently slow.

The X-parameters can be generated from a circuit-level design in Agilent Technologies' Advanced Design System (ADS) software or measured using the Nonlinear Vector Network Analyzer (NVNA) software running inside the Agilent Technologies' PNA-X microwave network analyzer. Whether created or measured, these X-parameters can be easily imported into ADS and then dropped into a component or system to start the design process or for use with ADS linear, harmonic balance or circuit envelope simulation.

An example of how to use one-tone X-parameters to predict quasi-static memory effects is shown in Figure 1. Here, the output port on the right supplies a bias to the IC. The bias is supplied from a 3-volt battery through the resistor and the inductor and into port 2. The inductor was chosen as the ideal choke to provide the ideal bias. The component is characterized over a range of static biases and an X-parameter model generated (based on an infinite inductor) that is valid over a whole range of biases on port 2. The model is then used to estimate the memory effects that the realistic bias line (with a finite inductor value) might induce if a modulated signal was input into the component. In this case, a two-tone signal is input in the model. By putting two narrowly spaced tones into the device, the spectral component generated at the difference frequency starts propagating through the bias network with the finite inductor. Because the model incorporated the effect of the voltage at port 2 on the RF properties at ports 1 and 2, the model effectively modulates how the RF gets treated.

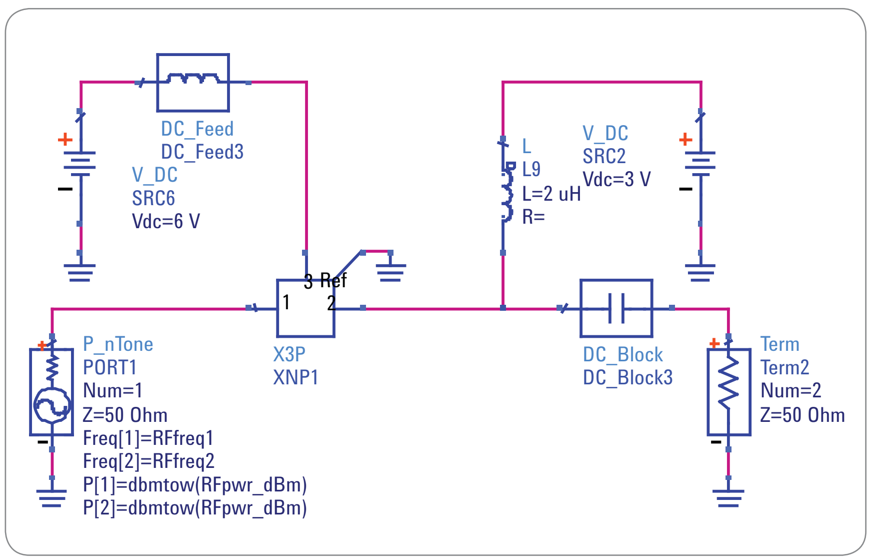

FIGURE 1: *An X-parameter model, extracted under true static bias conditions, can be used to model a component's quasi-static memory effects with respect to bias modulation.*

Figure 2 depicts the different outputs at the fundamental frequency that result from allowing bias modulation. Both the X-parameter model and the actual simulation model show that if the bias line interaction is allowed, very different characteristics from those produced by the flat lines (e.g., where there are no memory effects) result. Moreover, the quasi-static X-parameter model is in excellent agreement with the detailed circuit-level model from which it was generated, in both the ideal and memory application cases.

Two-Tone X-Parameters

X-parameters have been extended to handle one of the common signatures of underlying memory effects—offset-frequency dependence of intermodulation. This capability is currently available in ADS. In fact, ADS can extract two or even multi-tone X-parameters from a schematic. In the near future, designers will also be able to make two-tone X-parameter measurements with the NVNA. The ability to not only extract X-parameters from detailed models in the simulator, but measure them independently on real DUTs with the NVNA instrument, is of great potential value to designers who want to know what the magnitude and phase of the distortion (as measured by the IM3 figure of merit) looks like as a function of a signal's tone separation, power and frequency.

Two-tone X-parameters capture the frequency dependence and asymmetry of the intermodulations. These X-parameters can be used to create a simulatable model for design with frequency-dependent distortion.

Figure 3 depicts an example of a two-tone X-parameter measurement. It shows the extreme case of a commercial component with a great deal of memory. The figure shows the difference and the accuracy compared to the measured actual characterization of the device.

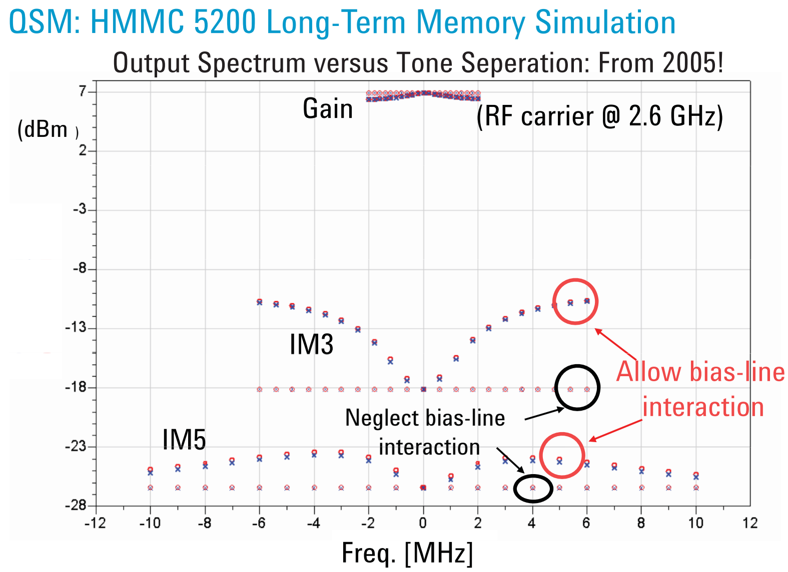

FIGURE 2: *When bias-line interaction is allowed, the offset frequency dependence and the absolute value of the distortion (as measured by IM3) can change dramatically.*

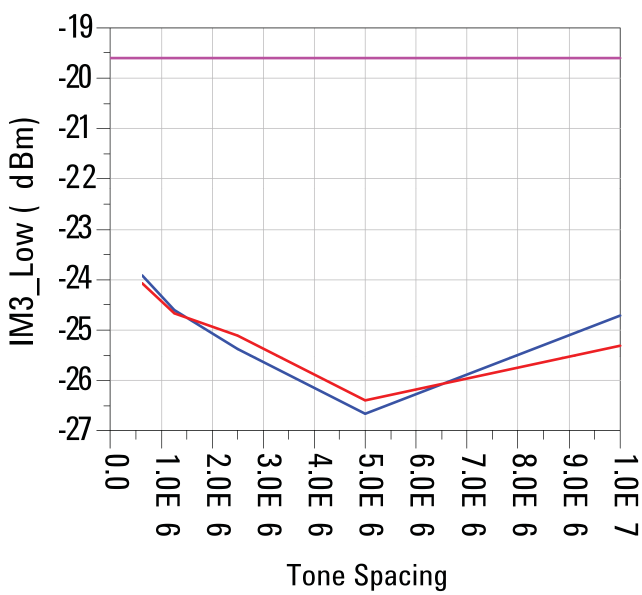

FIGURE 3: *Shown here are memory effects exhibited by two-tone X-parameters. The two-tone X-parameters' prediction of intermodulations in ADS is shown in red, while the independently measured data is shown in blue. One-tone X-parameter predicted IM3 is depicted in magenta.*

Dynamic X-Parameters

While designers of PAs can today deal with some memory effects quasi-statically (e.g., bias and temperature) using X-parameters, recent work has led to a significant step beyond the quasi-static application of X-parameters into full dynamic X-parameters (Figures 4 and 5).

Summary of Results

PA designers often consider memory effects an unwanted and difficult problem of working with new wireless communication technologies. It is vitally important, therefore, that they be aware of memory and its symptoms. This is the only way they can stay away from or try to eliminate the effects of memory. More sophisticated designers may even try to exploit these memory effects.

To do so, designers need to be able to characterize, model and design for memory. Today, X-parameters support quasi-static memory effects. Two-tone X-parameters, a capability that is currently present in ADS will soon be available in measured X-parameters via Agilent's NVNA. In the future, dynamic X-parameters will take X-parameters beyond quasi steady state to help designer's robustly design systems and components where memory effects are important.

The Power of X

The Agilent X-Parameters and PNA-X Microwave Network Analyzer with the NVNA software are key products in Agilent's comprehensive Power of X suite of products. These products grant engineers the power to gain greater design insight, speed manufacturing processes, solve tough measurement problems, and get to market ahead of the competition.

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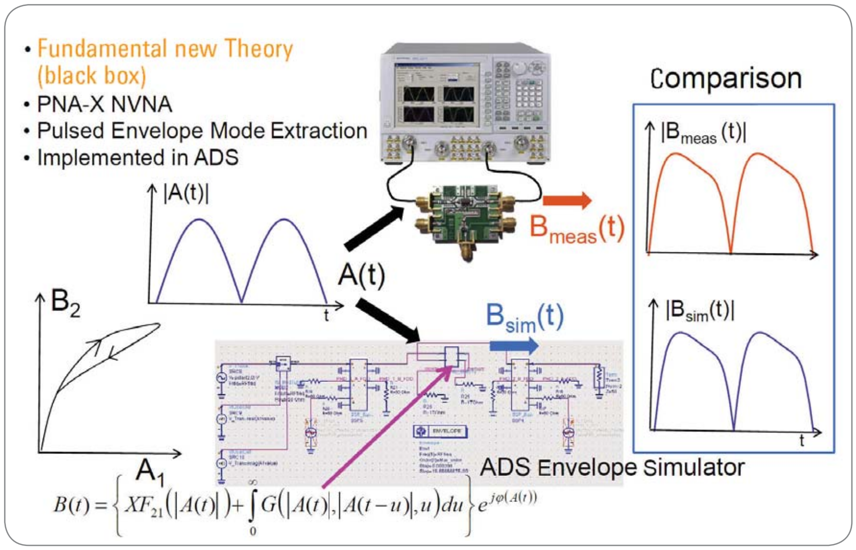

FIGURE 4: *Dynamic X-parameters extends the application of X-parameters to memory effects beyond the quasi steady state.*

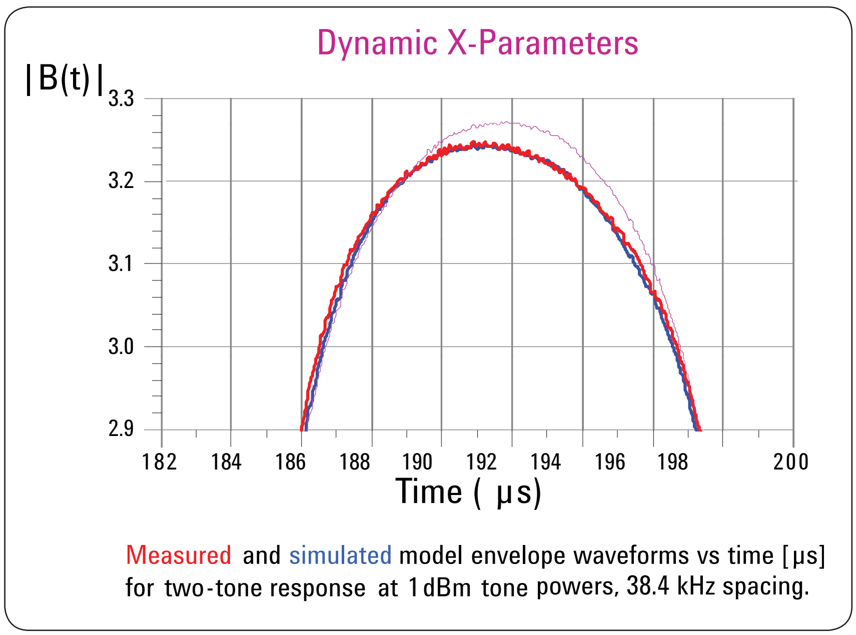

FIGURE 5: *Measured (red) and simulated (blue) dynamic X-parameter model envelope waveforms versus time for a two-tone response of an amplifier. The magenta waveform is the result of using a one-tone static X-parameter model.*

For More Information:

- J. Verspecht, J. Horn, L. Betts, D. Gunyan, R. Pollard, C. Gillease, and D. E. Root, *"Extension of X-parameters to include longterm dynamic memory effects,"* IEEE MTT-S International Microwave Symposium Digest, 2009. pp 741-744, June, 2009.
- J. Verspecht, J. Horn, and D. E. Root, *"A Simplified Extension of X-parameters to Describe Memory Effects for Wideband Modulated Signals,"* IEEE ARFTG Conference Proceedings, May, 2010.

These documents can be found at **www.agilent.com**

Related Applications

- Semiconductor IC design and validation of active components
- Handset PA design and validation
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- Military active component design and validation

Related Agilent Products

- W2305 X-Parameter Generator
- W2200 ADS Core
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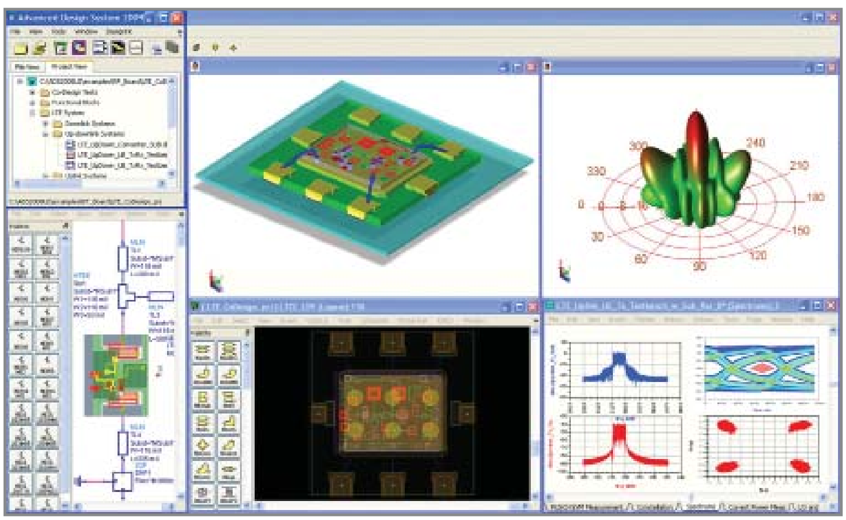

W2200 ADS Core

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Revised: October 1, 2009

Printed in USA, May 13, 2010
5990-5799EN

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