

Understanding P2D Nonlinear Models

Power-dependent S-parameter models can be used in ADS and other high-frequency simulation tools to model the nonlinear behavior of RF power amplifiers.

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Measurement-based nonlinear amplifier models ideally predict the performance of a high-frequency amplifier as accurately as possible. A usable nonlinear behavioral model can project the performance of a design under different operating conditions, saving the time and expense of building an amplifier circuit for experimentation. Of course, detailed circuit models often require a transistor model, a package model, and models for the transmission lines, passive elements, and other devices found in the matching and bias networks. Alternately, it is possible to treat a packaged transistor as a "black box" as part of a measurement-based circuit behavioral model, to speed and simplify the large-signal amplifier modeling and simulation process.

The nonlinear Microwave Data Interchange Format (MDIF) power-dependent S-parameter (P2D) files available in the Advanced Design System (ADS) simulation suite of tools from Agilent Technologies (www.agilent.com) serve as a simple behavioral model format for nonlinear microwave devices.¹ Because high-frequency power amplifiers tend to exhibit power-dependent transducer gain, where the output signal level is no longer a linear relationship of the input signal level, their behavior can be recreated through the use of a P2D file-based model. The P2D format is essentially measurement based, using vector-network-analyzer (VNA) test results for a device under test (DUT) to fashion a device model that can be integrated into an amplifier model.

The P2D modeling approach is simple and convenient, since these models are readily available in the ADS software site, although it also has limitations. A good review of alternative behavioral models emerging from the extensive research being conducted worldwide in this area can be found in ref. 2. In terms of limitations, a P2D model, for example, is not the best choice when predicting device/amplifier load-pull contours or load-dependent power behavior. More advanced behavioral models are becoming available for these and other more complex simulations.³

Since the P2D model is based on measurement data, the type of measurement and the amount of data both play a large role in defining the amount of data that can be reliably extracted from simulating the model within a system. Since the P2D file is rather versatile, the amount of data needed to reliably represent a device's behavior depends largely on the application for which the model is being developed. However, the MDIF P2D file's sole requirement for operation in Agilent ADS is that large-signal S-parameters for the device are available and are inserted into the file in the proper format. Additionally, data blocks for small-signal S-parameters, intermodulation-distortion (IMD) information, and noise-figure data offer the potential for relatively versatile small-signal and large-signal models.

To demonstrate the P2D modeling approach, a 2.45-GHz WLAN amplifier was measured in order to create a P2D model for simulation and comparison with the measured results. For the purpose of creating an accurate, nonlinear amplifier model, measured data was required for 1-dB compression, amplitude-modulation-to-amplitude-modulation (AM-to-AM) conversion, AM-to-phase-modulation (AM-to-PM) conversion, small- and large-signal (power-dependent) S-parameters, and the input-power-versus-output-power response. A P2D model was developed, simulated, and compared with the measured data in order to demonstrate the reliability of the model, resulting in eventual integration into a communication system design for system-level analysis.

Careful attention to detail is needed in creating a P2D file in the suitable format. While it is true that a device model is being extracted by means of the measurements, this is a file-based model format, so the programming and/or creation of functional MDIF files is a critical step in the model creation. The procedures detailed in this article have been developed for the Agilent Citifile format associated with the company's (now obsolete or discontinued) Agilent HP 8719C and Agilent HP 8753D VNAs. The procedures deal with the creation of the P2D file rather than the specific measurement techniques performed to collect the data for the P2D file. The file format for this example, which accommodates frequency-swept and power-swept S-parameter data as well as noise-parameter data, can be viewed on the long version of this article available on the *Microwaves & RF* website at www.mwrf.com.

The test configuration used to build the example P2D-file-based amplifier model featured in this article is shown in [Fig. 1](#). The test setup features an HP 8753 RF/microwave VNA, DC power supply, broadband bias tee, 6-dB attenuator, and a microwave power meter. In order to collect data for the model, a commercial power amplifier operating at the nominal wireless-local-area-network (WLAN) frequency of 2.45 GHz was tested. Measurements were set for a frequency sweep of 2 to 3 GHz while the input power sweep range was set between -20 and 0 dBm, with device S-parameters measured on the HP 8753 VNA.

The measurement-based nonlinear P2D model was constructed in order to perform analysis of the amplifier model's AM-to-AM compression, AM-to-PM compression, and output power versus input power behavior within the Agilent ADS simulator. The 6-dB fixed attenuator was added to the power amplifier (PA) under test in order to improve the load impedance match with the test equipment at fundamental as well as harmonic frequencies.

The ADS test bench for the 2.45GHz example amplifier is shown in [Fig. 2](#). This particular file only contains frequency-dependent small-signal and large-signal S-parameters at specific frequencies. The file format is fairly versatile, since it does not require extensive software debugging that is inherent in many programmable data formats. Although a File/Instrument server is available in ADS, experience has shown that software conflicts can exist among the various file formats used with different commercial VNAs. Thus, careful attention must be paid to measured data implementation within the file itself. Although the instrument server, when properly used, makes the task significantly easier, it is important to note that the data can be manually programmed into the nonlinear data file, thus not requiring the use of file server software. For the example amplifier, the P2D file was created manually using Microsoft Excel to organize the swept-frequency and swept-power Sparameter data.

Agilent offers an automatic solution for the generation of P2D file-based behavioral models based on measurement data sets that is called the Connection Manager. It has a built-in module that can perform swept-power S-parameter measurements on nonlinear devices and amplifiers. Once the measurements are completed, this tool can process the measured data into the appropriate P2D file format that can be used directly by the behavioral model component "AmplifierP2D" in ADS. This automatic approach can significantly reduce the time required to create a similar model manually.⁴

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The ADS schematic for the example amplifier for large-signal S-parameters, gain compression, and phase compression employs the P2D file called "2.45GHz_PA.p2d." The file was simulated for the nominal operating frequency of the amplifier (a CW frequency of 2.45 GHz), with the output of the amplifier terminated in 50 ohms, thereby facilitating Sparameter simulations. The large-signal S-parameter simulation block was inserted (LSSP) and the powers set to the measured input power to the device.

[Figures 3](#) and [4](#) show plots of the simulated AM-to-AM compression and AM-to-PM compression, respectively, based on the use of P2D files in ADS based on measurements of the Intersil 2.45-GHz PA. Although the P2D file is effective in providing large-signal amplifier simulations, the basic large-signal measurement setup can also be used for small-signal measurements and modeling with only very minor adjustments. [Figure 5](#) shows the setup for small-signal Sparameter analysis using the

P2D file approach. Using the P2D file, the simulated small-signal S-parameter data for amplitude (gain) and phase shown in [Fig. 6](#) resulted.

In addition to traditional one-tone or two-tone simulations, a P2D amplifier model can also be used to predict performance with the complex digitally modulated signals found in modern communications systems. Communications system performance parameters such as adjacent-channel power ratio (ACPR) and error vector magnitude (EVM), which are used to evaluate amplifier spectrum spreading outside of the desired channel(s) and the amplifier's effects on modulation quality, respectively, can be evaluated by means of a P2D amplifier model.

[Figure 7](#) shows an example simulation schematic in which a WLAN signal is used at the amplifier input. [Figure 8](#) shows the results of an envelope-domain simulation using a P2D model. Nonlinear spectral-regrowth behavior is apparent, predicted by the nonlinear model integrated into the P2D amplifier model. [Figure 9](#) shows the ACPR performance of the amplifier at various input power levels. The P2D amplifier model helps identify high levels of ACPR at large input power levels, as expected.

Although this example is based on the Agilent ADS software, the P2D file modeling approach can be used with other software tools. For example, The MathWorks (www.mathworks.com) is adding support for P2D file-based behavioral models in the latest release of its popular MATLAB mathematical analysis and modeling software.

A schematic diagram for a MATLAB simulation setup is shown in [Fig. 10](#). [Figure 11](#) shows simulated gain-compression and phase-compression curves generated by using P2D-based behavioral models in MATLAB, with the results closely matching those of the ADS simulations in [Figs. 3](#) and [4](#).

In short, the P2D-file-based behavioral model format available in simulators such as ADS from Agilent Technologies and MATLAB from The MathWorks allows users to conveniently represent a number of important nonlinear device effects in a compact format. The simulations shown in this article demonstrate how the P2D models can be used to go well beyond S-parameters in providing predictions of power-dependent device behavior such as AM-to-AM conversion and AM-to-PM conversion effects. The P2D models can also be used for more advanced simulations with complex digitally modulated test signals in the envelope domain, including simulations and analysis of ACPR and EVM performance.

Editor's Note: A slightly longer version of this article, complete with an example of the P2D file format that was adapted from an example provided by Agilent Technologies in the ADS software suite, can be found on the Microwaves & RF website at: www.mwrf.com. The ADS files used for the example simulations shown in this paper will be made available for download from the following

Modelithics web area: www.modelithics.com/free-models.asp. Further information is available by e-mailing info@modelithics.com.

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FOOTNOTE

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