

# Evaluating X-parameter\*, P2D and S2D Models for Characterizing Nonlinear Behavior in Active Devices

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Accurate modeling of a power amp using circuit-level or behavioral models is critical

Power amplifiers (PAs) play an important role in RF and microwave communication systems. To successfully design such systems, accurate modeling of the PA using circuit-level or behavioral models is critical. For system simulation, behavioral models are preferable. One simple behavioral model that can be used for the PA is small-signal *S*-parameters. They can be used to predict small-signal gain and typical linear budget analysis, but they do not provide complete information on the device-under-test (DUT), such as inherent nonlinear behavior. To characterize the nonlinear transfer between the PA input and output, behavioral models are often supplemented with nonlinear mathematical expressions.

Most commercial CAE software packages (e.g., Agilent's Advanced Design System (ADS) software) provide built-in behavioral amplifier models, with small-signal *S*-parameters and P1dB/IP3 being required to capture the PA's large-signal behavior. To capture the frequency-related nonlinearities of the PA in the behavioral model, file-based S2D and P2D models can be used. Both of these models are currently accessible in commercially available microwave circuit and system simulators.

A more recent option for measuring and characterizing nonlinear PA behavior is the

X-parameter model. This sophisticated behavioral model describes the relationship between different frequency spectra on a multi-port device for a given large-signal operation condition. The availability of measurement instrumentation and design simulation software to support this technology now makes X-parameters an excellent solution to nonlinear device modeling. To better understand the value of this approach, let's take a closer look at the use of X-parameter, P2D and S2D models for characterizing nonlinear behavior in active devices.

## Understanding X-parameter Modeling

To compare the various modeling techniques, it's important to first understand X-parameters and how they are used for nonlinear device modeling. X-parameters are a mathematically correct superset of *S*-parameters that are valid for nonlinear and linear components under both large-signal and small-signal conditions. Like *S*-parameters, X-parameters deal with incident and scattered traveling voltage waves, as defined by:

$$\begin{aligned} A &= \frac{V + I * Z_c}{2} \\ B &= \frac{V - I * Z_c}{2} \end{aligned} \quad (1)$$

where *V* and *I* are the voltage and current at a given port, and *Z<sub>c</sub>* is the characteristic impedance.

## Modeling-Power Amps

For comparison, note that 2-port  $S$ -parameters are defined as:

$$\begin{aligned} b_1 &= S_{11}a_1 + S_{12}a_2 \\ b_2 &= S_{21}a_1 + S_{22}a_2 \end{aligned} \quad (2)$$

where  $a_i$  and  $b_i$  are the incident and scattered traveling waves at port  $i$  ( $i = 1, 2$ ). The X-parameter model can be defined as:

$$b_{ij} = X_{ij}^F(A_{11})P_j + \sum_{k,l \neq (1,1)} (X_{ij,kl}^{(S)}(A_{11})P^{j-l}a_{kl} + X_{ij,kl}^{(T)}(A_{11})P^{j+l}a_{kl}^*) \quad (3)$$

where  $A_{11}$  is the large signal driven into port 1 at the fundamental frequency. Index  $i$  is the output port,  $j$  is the output frequency index,  $k$  is the input port, and  $l$  is the input frequency index.

Comparing  $b_{ij}$  from Equation 3 to  $b_i$  in Equation 2, it's obvious that the X-parameter model provides not only the fundamental tone frequency mapping, but harmonic frequency mapping as well. Granted Equation 3 looks complex, but in a simulator the actual X-parameter model is very easy to understand and closely correlates to the equation.

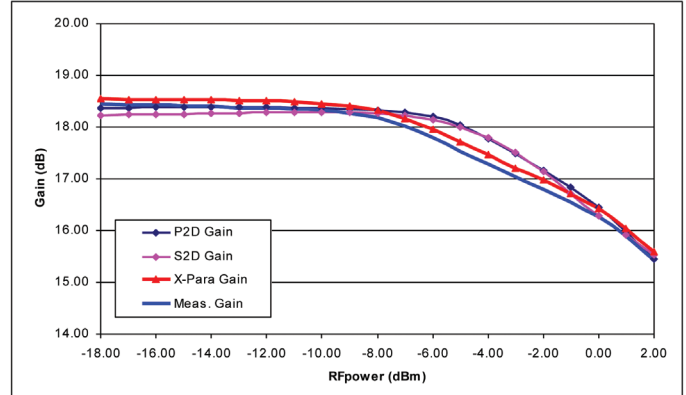
X-parameters can be generated in one of two ways—either from a nonlinear simulation of a circuit-level design using ADS software or through actual measurement using Agilent's Nonlinear Vector Network Analyzer (NVNA) running on the PNA-X network analyzer. Whether created or measured, X-parameters can 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.

### Comparing Modeling Techniques

To compare the S2D and P2D models with the X-parameter model, consider the example of a surface mount RFIC amplifier. In this case, the device used as the DUT is the RFMD RF2878 LNA/PA driver, which operates between 150 MHz to 2.5 GHz, with a typical gain of around 20 dB and typical bias at  $V_{cc}$  and  $V_{pd}$  of 3 and 2.8 V, respectively. Both the small-signal and power-swept  $S$ -parameter data was obtained using a traditional vector network analyzer (HP 8753D). All model setups and simulations were performed using Agilent's ADS simulation environment.

X-parameters were measured using the PNA-X NVNA under a 50 ohm condition (no impedance tuners) with a one-tone large stimulus at the input ( $A_{11}$ ). One-tone and two-tone large signal load-pull measurements were taken using a Maury ATS system combined with conventional spectrum analyzer, power meter and signal source equipment. The resulting measurements yielded an independent nonlinear verification dataset.

The P2D and S2D models were created based on the small-signal  $S$ -parameter data files and the 50 ohm power-



**Figure 1 • A comparison of the simulated and measured gain compression results, with the frequency at 715 MHz. The source and load reflection coefficients up to the 3rd harmonics are given.**

Var	VAR
Eqn	VARG2
	$\Gamma_{S1} = 0.02156 + j*0.00175$
	$\Gamma_{S2} = 0.05182 + j*0.02025$
	$\Gamma_{S3} = 0.07053 + j*0.04224$
	$\Gamma_{L1} = 0.01866 + j*0.00666$
	$\Gamma_{L2} = 0.03099 - j*0.01277$
	$\Gamma_{L3} = 0.06066 + j*0.11841$

swept  $S$ -parameter measurement dataset. These two models, as well as the X-parameter model, were then exercised against the load-pull one-tone and two-tone measurement datasets to predict 50 ohm gain compression, harmonics, source/load tuned gain compression and IP3.

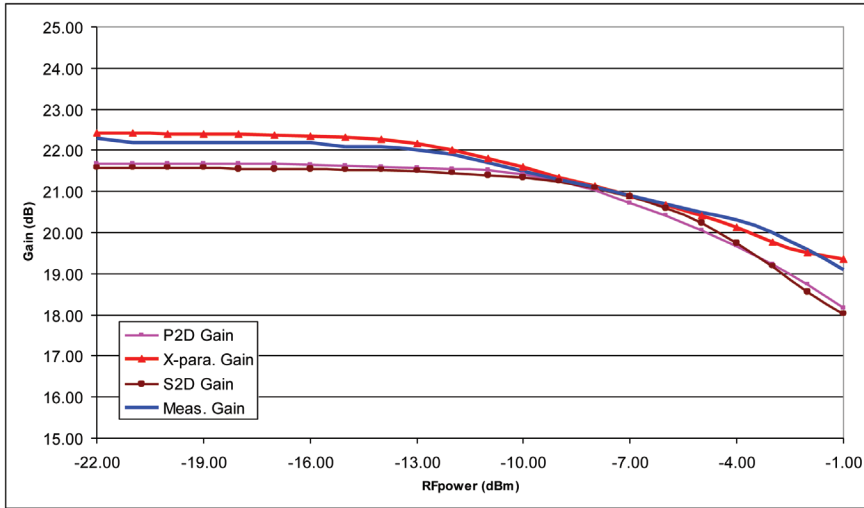
### Evaluating the Results

The near 50 ohm gain compression result for the P2D, S2D and X-parameter models, along with the measured dataset, is shown in Figure 1. Overall, the X-parameter model predicted the measured gain better, especially over the -8 to 0 dBm input power range.

The gain compression and output power results simulated by all three models, with the source and load impedances tuned for maximum output power, are shown in Figures 2a – 2c. Figure 2a shows that the P2D and S2D models provide similar results. The X-parameter model shows gain expansion behavior after -7 dBm, providing a much better match to the measured load-pull result. It also demonstrates excellent ability to predict the 2nd and 3rd order harmonics (Figure 2b). In fact, this specific measured X-parameter model was set up to capture up to the 5th harmonic order.

By comparison, the P2D model doesn't predict harmonics in the ADS Harmonic Balance simulator. Instead, an envelope domain simulator must be used. The S2D model does predict the 3rd harmonic, however, only odd-order harmonics are predicted (Figure 2c). Moreover, the predicted 3rd order harmonic does not match the measurement well under this tuned source/load impedance condition.

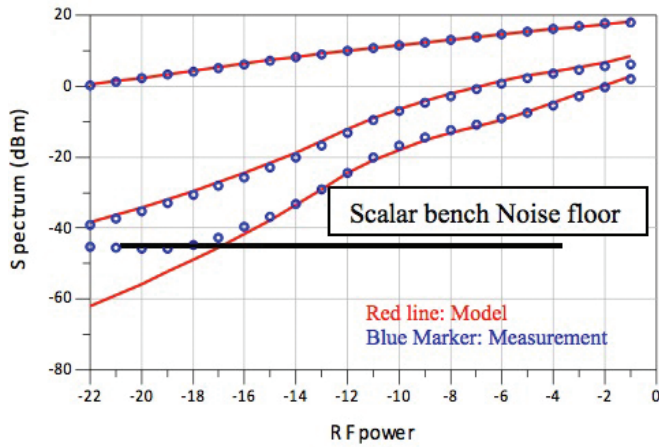
Modeling-Power Amps



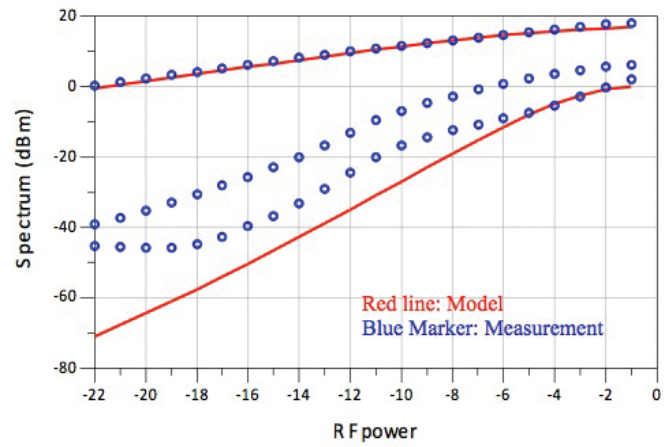
Var  
Eqn

**VAR**  
**VAR67**  
GammaS=0.43967+ j\*0.12716  
GammaS2=0.10354+ j\*0.19389  
GammaS3=0.12105+ j\*0.32442  
GammaL= -0.02317+ j\*0.32563  
GammaL2=0.19514 - j\*0.17270  
GammaL3=0.17070 - j\*0.13224

(a) Comparison of the gain compression and Pout simulated by the P2D, S2D and X-parameter models.



(b) X-parameter model simulated output spectrum compared to measured results



(c) S2D simulated output spectrum. The 2nd (or even-order) harmonics are suppressed.

**Figure 2 •** Shown here is a comparison of the gain compression and  $P_{out}$  simulated by the three models under source- and load-tuned conditions, with the frequency at 470 MHz.

Lastly, the P2D and X-parameter models can be exercised using an envelope domain simulation to simulate the two-tone intermodulation products. Since both P2D and X-parameter models used were frequency domain mapping, an envelope simulator is required to simulate the IM3. The setup for this exercise is shown in Figure 3.

A comparison of the simulated and measured results is shown in Figure 4. As before, the X-parameters were measured in a 50 ohm environment with no tuners using the NVNA with a one-tone large signal stimulus. The independent measured results were taken using the Maury ATS system as previously described, with a center frequency at 960 MHz and a spacing of 1 MHz. The input power sweeps from -18 to 3 dBm. Both source and load impedances are tuned for optimal IP3.

Overall, the X-parameter model provided better agreement to the measured IM3 compared to the P2D model. The resulting impedances used to maximize IP3 are at varying gammas away from the 50 ohms. This illustrates the mobility of the X-parameter model to accurately predict behavior outside the impedance environment (beyond 50 ohm) used during measurements of the model. The one-tone X-parameter model also accurately predicted the two-tone IM3 results for this particular device. The discrepancy at low power levels is due to the noise floor limit in the measurement system. The P2D model shows a convergence issue after -3 dBm, therefore, the given result is limited in the input RF power. Still, the IM3 in the limited range shows a worse comparison to the measured results.

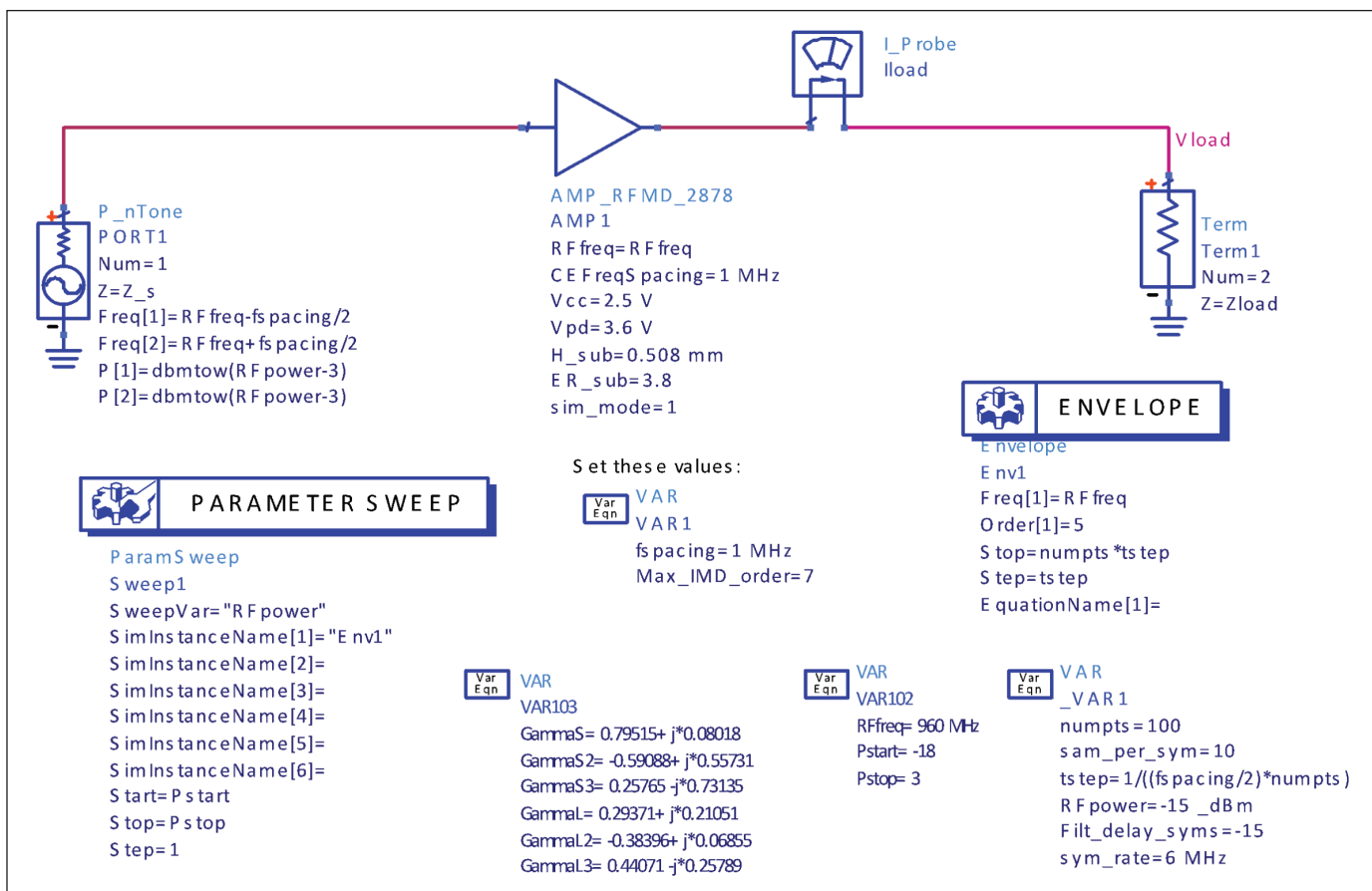


Figure 3 • Depicted here is an example envelope simulation schematic using the X-parameter mode (sim\_mode of 1) of the AMP\_RFMD\_2878 model.

**Conclusion**

The X-parameter, S2D and P2D models all provide a viable way for engineers to capture a PA’s nonlinear behavior. The X-parameter modeling technique provides a more accurate way to measure and characterize the nonlinear PA behavior through the capture of the fundamental and harmonic components at different drive levels. This complete view is invaluable when it comes to predicting the harmonics and IM3. When only the fundamental tone is of interest, the P2D and S2D modeling techniques may be more convenient to construct since they are based on the small-signal and power swept S-parameter measurements using conventional VNAs. However, when more accurate prediction of device behavior is required, X-parameters clearly offer the better choice.

For more information, go to: [www.agilent.com/find/nvna](http://www.agilent.com/find/nvna). To download free PNA-X application notes on nonlinear power amplifier design, go to: [www.agilent.com/find/pnaxapps](http://www.agilent.com/find/pnaxapps).

\*X-parameters is a trademark of Agilent Technologies. The X-parameter format and underlying equations are

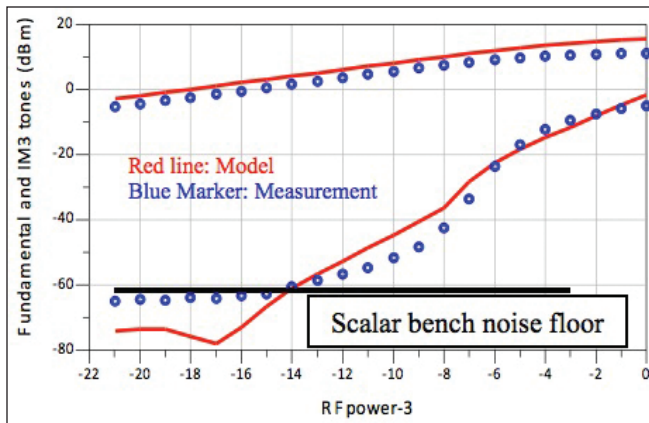
open and documented. For more information, visit [www.agilent.com/find/eesof-x-parameters-info](http://www.agilent.com/find/eesof-x-parameters-info).

**About the Authors**

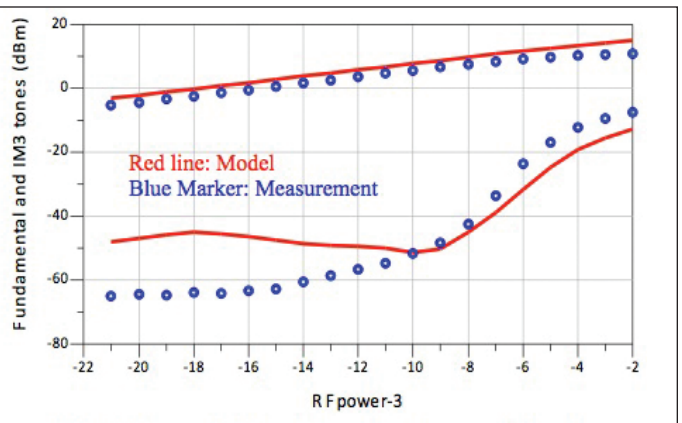
Dr. Jiang Liu joined Modelithics in 2006, and works as a modeling engineer with expertise in device, circuit and system characterization, and modeling. He received his B.S.E.E from Nanjing University of Telecom and Posts in 1996, and M.S.E.E and Ph.D. degrees in 2002 and 2005, respectively, from the University of South Florida.

Hugo I. Morales has worked as an engineering project leader with Modelithics, Inc. Tampa, FL since 2006. He has expertise in complex RF and microwave transistor characterization, passive component and diode modeling. Mr. Morales received his B.S.E.E. degree in 2002 from the University of South Florida and is presently working on his M.S.E.E. degree with emphasis in material characterization.

Lawrence P. Dunleavy co-founded Modelithics, Inc. in 2001 and currently serves as its president & CEO. He also maintains a part-time position as a tenured Professor within the University of San Francisco’s Department of Electrical Engineering. Dr. Dunleavy received his B.S.E.E.



(a) X-parameter model simulated fundamental and IM3 tones compared to measured results.



(b) P2D model simulated fundamental and IM3 tones compared to measured results.

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Var
Eqn  VAR
VAR103
GammaS= 0.79515+ j*0.08018
GammaS2= -0.59088+ j*0.55731
GammaS3= 0.25765 -j*0.73135
GammaL= 0.29371+ j*0.21051
GammaL2= -0.38396+ j*0.06855
GammaL3= 0.44071 -j*0.25789

Var
Eqn  VAR
VAR104
RFfreq= 960 MHz
Pstart= -18
Pstop= 3
  
```

Figure 4 • A comparison of the simulated fundamental and IM3 tones from both X-parameter and P2D models to measured results.

degree from Michigan Technological University in 1982 and his M.S.E.E. and Ph.D. degrees in 1984 and 1988, respectively, from the University of Michigan. He is a Senior Member of IEEE, and is active in the IEEE MTT Society and the Automatic RF Techniques Group.

Loren Betts is a research scientist and senior engineer at Agilent Technologies focusing on complex stimulus/response measurements and modeling of nonlinear components utilizing vector network analyzers. He co-developed the pulse measurement detection algorithms utilized in Agilent's PNA and PNA-X vector network analyzers. Loren holds a B.Sc. degree in computer engineering and M.Sc. and Ph.D. degrees in electrical engineering. His Ph.D. research focused on the PNA-X Nonlinear Vector Network Analyzer.