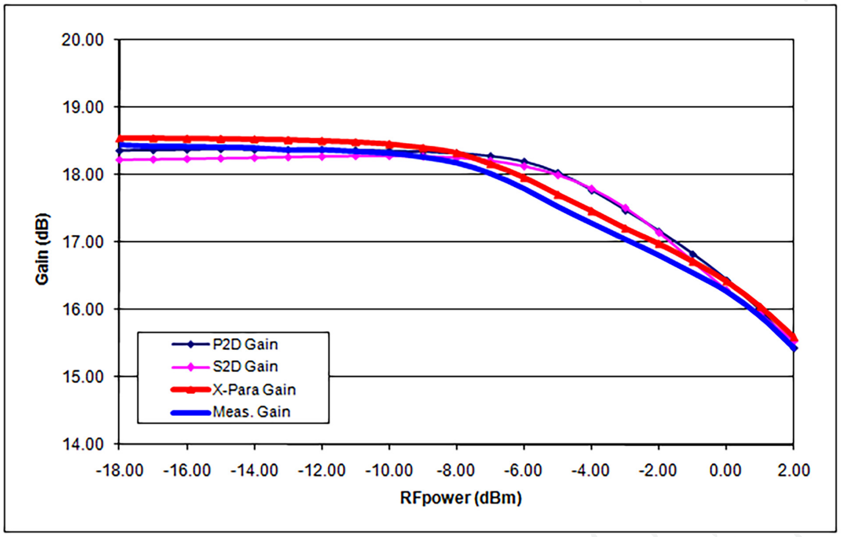
APPLICATION NOTE

An Evaluation of X-parameter*, P2D and S2D Models for Characterizing Nonlinear Behavior in Active Devices



KEYSIGHT TECHNOLOGIES

Introduction

All active devices exhibit nonlinear behavior to varying degrees. When researching and designing high-performance, active RF devices, it is critical to characterize this behavior so that it can be utilized and used in the design process. A prime example of one such active device is the power amplifier (PA), often considered an indispensible component in RF and microwave communication systems.

This application note examines three different modeling techniques that can be used to capture nonlinear behavior in a PA: the more conventional S2D and P2D models, and the more recently commercialized X-parameter model. For evaluation purposes, individual models will be developed based on the measurement results of a surface mounted RFIC amplifier using each of the three techniques. Simulation results will then be compared to identify the different model's capabilities.

Linear and Nonlinear Behavioral Models

Successfully designing today's RF and microwave communication systems requires accurate modeling of the PA. This can be accomplished using either circuit-level or behavioral models, although for system simulation, behavioral models are preferable. [1-4] Behavioral models can be used as building blocks for receivers and transmitters and allow a fast and accurate system-level simulation.

One simple behavioral model that can be used for the PA is a small-signal S-parameter file. [5] S-parameters were developed as a method to analyze and model the linear behavior of RF devices and can be used to predict small-signal gain and perform budget analysis, but they do have limitations. They are defined only for small-signal linear systems and fail to capture harmonic, distortion or other nonlinear effects. As a result, they serve only as a starting point for further analysis incorporating more complete information.

Measuring the nonlinear behavior of the PA therefore, requires an alternate model. Typically, to characterize the nonlinear transfer between the PA input and output, behavioral models are supplemented with nonlinear mathematical expressions. Three popular approaches for describing this nonlinear transfer relationship include: polynomial functions, rational functions and hyperbolic tangent functions. [6-7]

Today, most commercial CAE software packages (e.g., the Keysight Technologies, Inc. Advanced Design System (ADS) software) provide built-in behavioral amplifier models, with small-signal S-parameters and P1dB/IP3 serving as required input to capture the PA's large-signal behavior [8]. To capture the frequency-related nonlinearities of the PA in the behavioral model, file-based S2D and P2D models can be used. [8, 9] Both of these nonlinear behavioral 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, a sophisticated behavioral model that models a nonlinear device by describing the relationship between different frequency spectra on a multi-port device for a given large-signal operation condition. The implementation of this approach is available inside Keysight's Nonlinear Vector Network Analyzer (NVNA) running on the PNA-X network analyzer. The availability of measurement instrumentation and design simulation software to support this technology now makes X-parameters an excellent solution to nonlinear device modeling. [5, 11-13]

X-Parameter Theory

X-parameters represent a new category of nonlinear network scattering parameters for high-frequency design. Unlike S-parameters, they represent the linear and nonlinear behavior of RF components. As an extension of S-parameters under large-signal operating conditions, X-parameters are measured over the linear and nonlinear regions of the device. When making this measurement, no knowledge is used or required concerning the internal circuitry of the device-under-test (DUT). Rather, the measurement is a stimulus/response model of the voltage waves. In other words, the absolute amplitude and cross frequency relative phase of the fundamental, and all related frequency spectra, are accurately measured and represented by X-parameters.

In effect, 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 [5], as defined by.

$$A = \frac{V + I * Zc}{2} \qquad (1)$$

$$B = \frac{V - I * Zc}{2}$$

where V and I are the voltage and current at a given port, and Zc is the characteristic impedance.

For comparison, note that a 2-port S-parameter is defined as:

$$b_1 = S_{11}a_1 + S_{12}a_2 \qquad (2)$$
$$b_2 = S_{21}a_1 + S_{22}a_2$$

where a_i and b_i are the incident and scattered traveling waves at port i (i = 1, 2).

As shown in Figure 1, the X-parameter model can be defined as:

$$b_{ij} = X^F_{ij}\,(|A_{11}|)P_j + \sum_{k,l\neq(1,1)} (X^{(S)}_{ij,kl}\,(|A_{11}|)P^{j-l}a_{kl} + X^{(T)}_{ij,kl}\,(|A_{11}|)P^{j+l}a^*_{kl}) \qquad (3)$$

where A_{11} is the large signal driven into port 1 at 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.

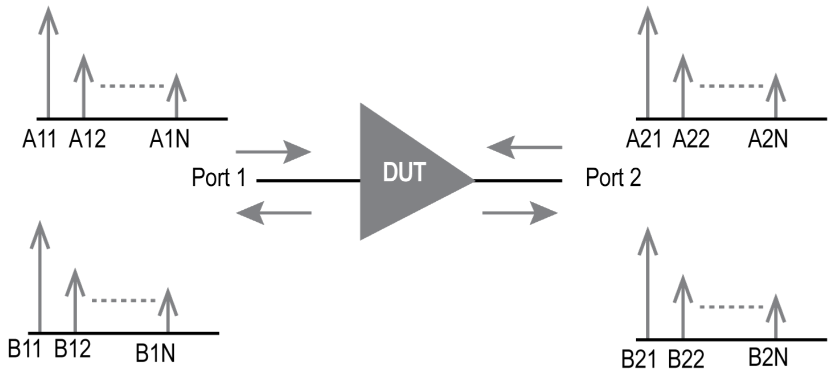


Figure 1. The input and output variables for a two-port network used in the large-signal scattering function are composed of fundamental tones and harmonics for both the incident and scattered waves.

Comparing b_{ij} from Equation 3 to b_i in Equation 2, it becomes obvious that the X-parameter model provides not only the fundamental tone frequency mapping, but harmonic frequency mapping as well.

While Equation 3 looks complex, the actual X-parameter model is very easy to understand in a simulator and, in fact, closely correlates to the equation. A typical two-port X-parameter file header will contain a VAR variable for fundamental frequency. Since the X-parameter measurements usually sweep the input fundamental tone power levels, this power information is stored in an "AN_1_1" variable and is used as an index in simulation to retrieve all other coefficients applied in the X-parameter model.

For each individual "AN_1_1" power level, there is a set of coefficients denoted "FB_1_1," "S_1_2_1_1" or "T_2_5_1_2," etc. The "FB_#_#" relates to the X^F_{ij} term, "S_#_#_#_#" relates to $X^S_{ij,kl}$ term and "T_#_#_#_#" relates to the $X^T_{ij,kl}$ term. As an example, the S_2_5_1_2 coefficient represents the influence of the 2nd harmonic at port 1 on the 5th order harmonic at port 2.

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 the PNA-X NVNA (Figure 2). 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.

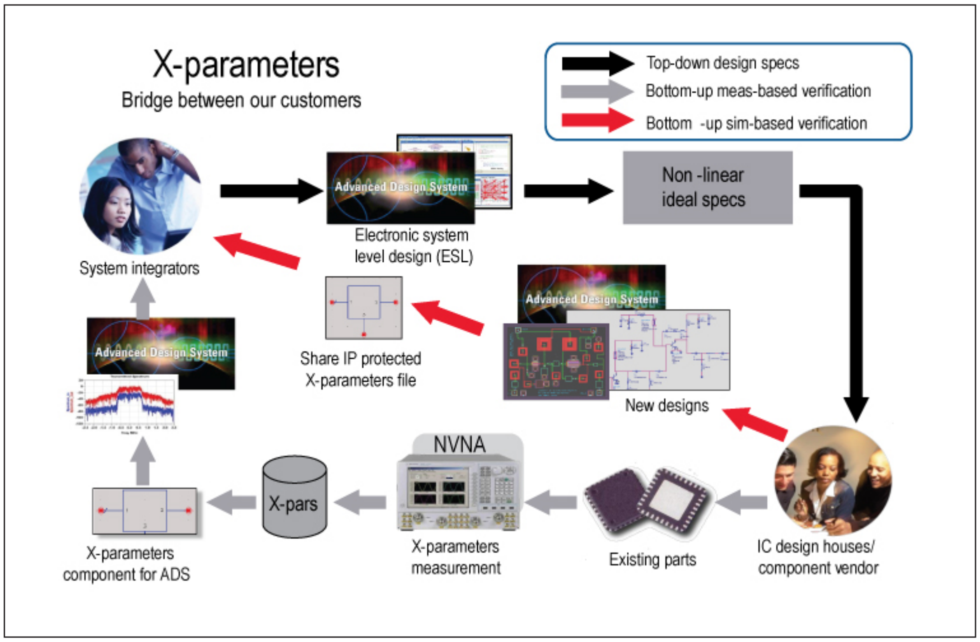


Figure 2. X-parameters can be created from measurement or ADS simulation with the same speed and convenience as the well-known linear S-parameters.

An example of a typical setup interface from the NVNA is shown in Figure 3. The X-parameter model generated from this configuration contains 10 frequency points. For each frequency point, there are 15 power levels recorded in "AN_1_1." For each power level, there will be 10 "FB_#_#" coefficients (2 port, 5 harmonics), 100 "S_#_#_#_#" and "T_#_#_#_#" coefficients (2 ports, 5 harmonics). The generated X-parameter model captures the magnitude and phase information of the fundamental, as well as harmonics at both ports, and can reproduce the nonlinear behavior in the simulator.

File Response Analysis Stimulus Utility Help

Measure : Single

Measurement Configuration

Start Frequency	Stop Frequency	Frequency Points	Start Power	Stop Power	Power Points	Power Sweep Linearity	Maximum Harmonics	IFBW
400.000000 MHz	600.000000 MHz	3	-20.00 dBm	0.00 dBm	15	dBm	5	30 Hz
470.000000 MHz	470.000000 MHz	1	-20.00 dBm	0.00 dBm	15	dBm	5	30 Hz
700.000000 MHz	800.000000 MHz	2	-20.00 dBm	3.00 dBm	15	dBm	5	30 Hz
715.000000 MHz	715.000000 MHz	1	-20.00 dBm	3.00 dBm	15	dBm	5	30 Hz
900.000000 MHz	1.000000 GHz	2	-20.00 dBm	5.00 dBm	15	dBm	5	30 Hz
960.000000 MHz	960.000000 MHz	1	-20.00 dBm	5.00 dBm	15	dBm	5	30 Hz

Figure 3. Shown here is an example measurement setup using Keysight's PNA-X running the NVNA. The measurement is split into 6 frequency bands. At 470 MHz, the input power sweeps from –20 dBm to 0 dBm. The maximum harmonic to record is the 5^{th}.

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 Keysight'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-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.

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 4. Overall, the X-parameter model predicts the measured gain better, especially over the –8 to 0 dBm input power range.

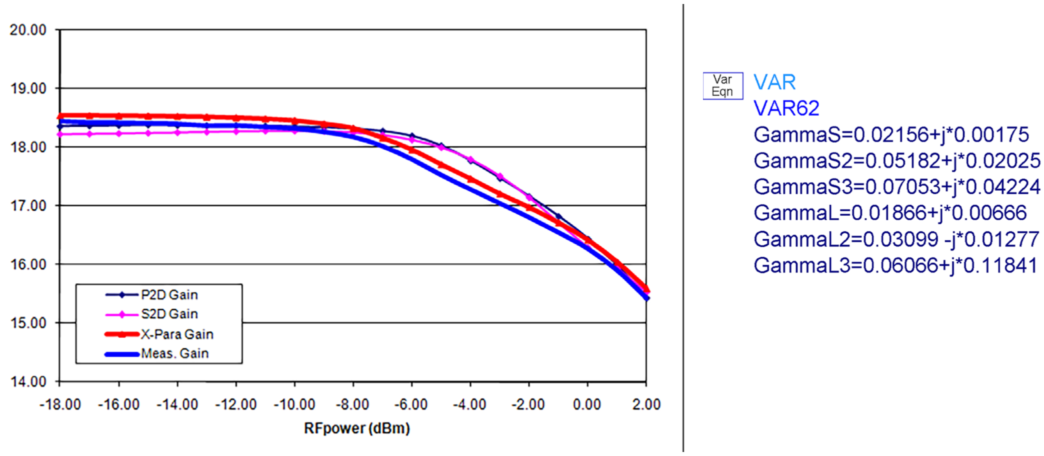
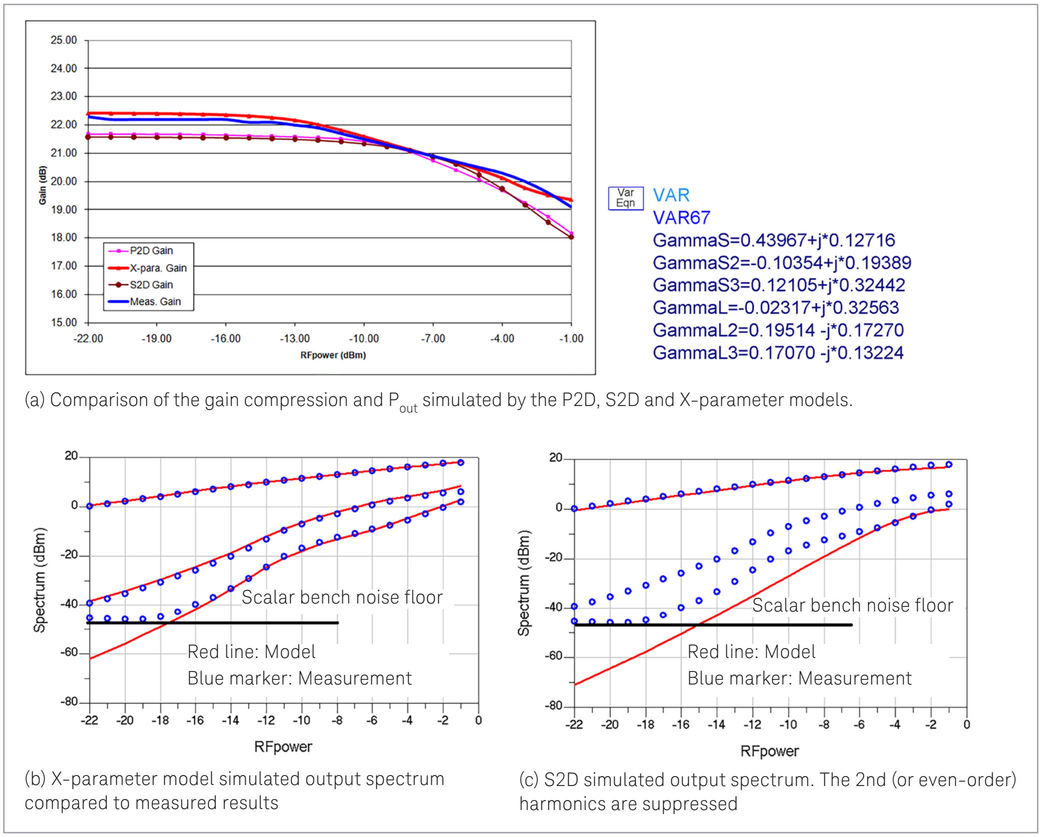


Figure 4. A comparison of the simulated and measured gain compression results, with the frequency at 715 MHz. The source and load reflection coefficients up to the 3rd harmonics are given.

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 5(a) – 5(c). Figure 5(a) 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 5b). In fact, as previously pointed out, 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 the harmonics in the ADS Harmonic Balance simulator because it provides only the fundamental tone mapping in its implementation (the frequency-domain-defined device component is used in the P2D implementation). To obtain the harmonics, an envelope domain simulator must be used. The S2D model does predict the 3rd harmonics, however, only odd-order harmonics are predicted (Figure 5(c)). Moreover, the predicted 3rd order harmonic does not match the measurement very well under this tuned source/load impedance condition.



(a) Comparison of the gain compression and P_{out} 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 5. 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 are frequency domain mapping, an envelope simulator is required to simulate the IM3. The setup for this exercise is shown in Figure 6.

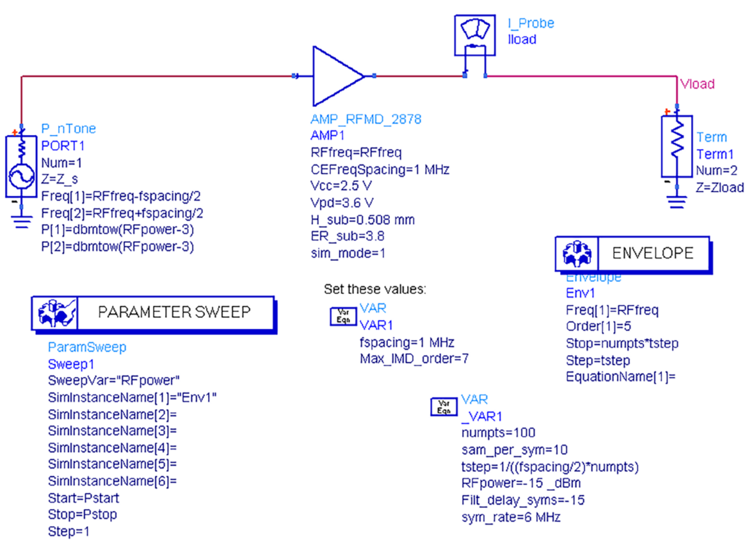
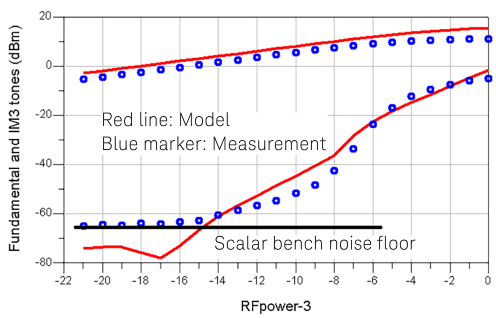


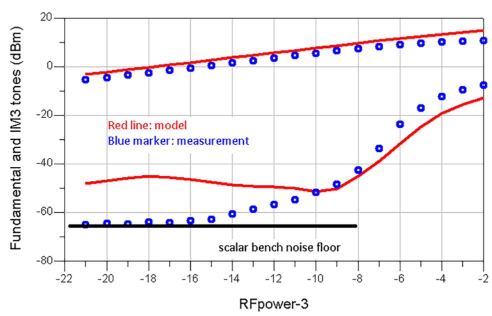
Figure 6. Depicted here is an example envelope simulation schematic using the X-parameter mode (sim_mode of 1) of the AMP_RFMD_2878 model.

A comparison of the simulated and measured results is shown in Figure 7. 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. Figure 7 also shows the actual impedances.

Overall, the X-parameter model provides 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 predicts the two-tone IM3 results for this particular device. Note that the discrepancy shown 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.



(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.

Var Eqn
VAR
VAR99
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
VAR100
RFfreq=960 MHz
Pstart=-18
Pstop=3

Figure 7. A comparison of the simulated fundamental and IM3 tones from both X-parameter and P2D models to measured results.

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 vector network analyzers. However, when more accurate prediction of device behavior is required, X-parameters clearly offer the better choice.

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