Agilent NVNA & X-Parameters

The new paradigm for nonlinear measurements, modeling, and simulation with ADS of nonlinear components
Measuring nonlinearities for use directly in design

Wouldn’t it be nice if you could measure and display the full amplitude and phase information of each spectral component? Wouldn’t it be even nicer to then use it directly in ADS harmonic balance or circuit envelope simulation?
Nonlinear Vector Network Analyzer (NVNA): The new industry standard for nonlinear measurements

Fast, Accurate, and Easy to Use!

Network Analyzer + Phase Reference + Software = NVNA

The most innovative HP/Agilent instrument in 25 years!
Co-developed by CTD and HFTC

NVNA = PNA-X + Phase Ref. ckt.
+ Application SW and calibration (mag and phase)
+ ADS-simulation application with X-parameter measurement option

NVNA measures Magnitude and Phase of all relevant frequency components (cross-frequency coherence) necessary to measure X-parameters!
S-parameters: linear measurement, modeling, & simulation

- Easy to measure at high frequencies
  - measure voltage traveling waves with a (linear) vector network analyzer (VNA)
  - don't need shorts/opens which can cause devices to oscillate or self-destruct
- Relate to familiar measurements (gain, loss, reflection coefficient ...)
- Can cascade S-parameters of multiple devices to predict system performance
- Can import and use S-parameter files in electronic-simulation tools (e.g. ADS)
- BUT: No harmonics, No distortion, No nonlinearities, ...
  Invalid for nonlinear devices excited by large signals, despite ad hoc attempts

**Linear Simulation:** Matrix Multiplication

\[
\begin{align*}
S_{11} & = S_{11}a_1 + S_{12}a_2 \\
S_{21} & = S_{21}a_1 + S_{22}a_2 \\
S_{22} & = S_{22}a_2 + S_{21}a_1 \\
\end{align*}
\]

**Measure with linear VNA:** Small amplitude sinusoids

\[
S_{ij} = \frac{b_i}{a_j}\lvert_{a_k \neq 0}
\]

**Model Parameters:** Simple algebra
What are X-Parameters?

X-parameters are the mathematically correct superset of S-parameters, applicable to both large-signal and small-signal conditions, for linear and nonlinear components. *The math exists!*

We can measure, model, & simulate with X-parameters. Each part of the puzzle has been created. The pieces now fit together seamlessly.

**NVNA:** Measure device X-parameters

**ADS:** Simulate using X-parameters

**ADS:** Design using X-parameters
X-parameters come from the Poly-Harmonic Distortion (PHD) Framework

\[
B_{1k} = F_{1k} \left( DC, A_{11}, A_{12}, \ldots, A_{21}, A_{22}, \ldots \right) \\
B_{2k} = F_{2k} \left( DC, A_{11}, A_{12}, \ldots, A_{21}, A_{22}, \ldots \right)
\]

Port Index  \quad Harmonic (or carrier) Index

Spectral map of complex \textit{large} input phasors to \textit{large} complex output phasors
Black-Box description holds for transistors, amplifiers, RF systems, etc.

\[
B_{e,f} = X^{(F)}_{ef} (\left| A_{11} \right|) P^{f} + \sum_{g,h} X^{(S)}_{ef,gh} (\left| A_{11} \right|) P^{f-h} \cdot A_{gh} + \sum_{g,h} X^{(T)}_{ef,gh} (\left| A_{11} \right|) P^{f+h} \cdot A_{gh}^{*}
\]

Simplest X-parameters \quad g,h \quad approximate general \quad g,h \quad mapping
X-parameter Concept: Approxs. to NL Mapping

Incident

\[ B_k(DC, A_1, A_2, A_3, \ldots) \]

Multi-variate NL map

\[ \approx \]

\[ X_k^{(F)}(DC, A_1, 0, 0, 0, \ldots) \]

Simpler NL map

+ 

Linear non-analytic map

\[ \sum \left[ X_k^{(S)}(DC, A_1)A_j + X_k^{(T)}(DC, A_1)A_j^* \right] \]

Scattered
X-Parameters: Why They are Critical:

\[ B_{e,f} = X_{ef}^{(F)} (|A_{11}|) P^f + \sum_{g,h} X_{ef,gh}^{(S)} (|A_{11}|) P^{f-h} \cdot A_{gh} + \sum_{g,h} X_{ef,gh}^{(T)} (|A_{11}|) P^{f+h} \cdot A_{gh}^* \]

Cascaded Nonlinear Amplifiers: Nonlinear effects of mismatch versus drive

- Unambiguously identifiable (simple, automated extraction) from automated set of measurements
- Fully nonlinear vector quantities (Magnitude and phase of all harmonics)
- Extremely accurate for high-frequency, distributed nonlinear circuits
- Cascadable (correct behavior in mismatched environment)
Results: Design of Cascade vs. Measurement of Cascade

Objective: Design nonlinear circuits in ADS from NVNA-measured X-parameter component data

X-parameters are superior to Hot S22

Cascaded Measurement
Cascaded Design with X-parameters
Cascaded Design with “Hot S-parameters” but No $X^{(T)}$ terms

Similar results hold at harmonics

“X-parameters enable predictive nonlinear design from NL data”
NVNA System Configuration

X-Parameter extraction/multi-tone source

Amplitude Calibration

Vector Calibration

Phase Calibration

Phase Reference

Standard PNA-X Network Analyzer

New!! Agilent NVNA

New!! Agilent Calibrated Phase Reference
Black-Box Characterization & Behavioral Modeling

Actual Amp Circuit

Measurement-Based Model
- Circuit models don’t exist
- Completely protect design IP

Generate Behavioral Model

Design of Module or Instrument Front End

Detailed Circuit Model (SPICE/ADS) of IC
PHD Framework: Simulating with Measured Data

Once measured, the X-parameters can be immediately used for design in ADS.

NVNA
- Measure X-Parameters
- Take X-parameter measurements
- Export model file

DUT

Agilent PHD Code
- Extract X-parameters

MDIF File
- Script generates PHD model component

ADS
- Harmonic Balance: Captures magnitude and phase of harmonics, frequency dependence, and mismatch effects
- Envelope: Accurately simulate narrowband multi-tone or complex stimulus

Works in HB and Envelope, Not in Transient
Example: X-Parameters Verification

Amplifier component models from individual measured X-parameters
Results Cascaded Simulation vs. Measurement

Red: Cascade Measurement
Blue: Simulation of Cascaded Models

“X-parameters enable predictive nonlinear design from NL data”
Third Order Intercept Simulation

VAR
VAR1
Fmod=5 MHz
z0=50
NoFFTpts=500
NofModPer=10
fundamental=2.0 GHz
A11N= 0

Envelope
Env1
Freq[1]=fundamental
Order[1]=8
Slope=NofModPer*1/Fmod
Step=NofModPer*1/Fmod/NoFFTpts

Fundamental vs IM3
TOI vs Power
Pin
Input / Output Spectrums & ACPR

Transmitted Spectrum

Spectral Re-growth

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PA Linearization using X-Parameters in ADS Digital Pre-Distortion Linearization Design Guide

![Diagram showing PA linearization using X-Parameters](image)

Before Digital Predistortion
After Digital Predistortion

PA Output

Corrected PA Output

Power (dBm)

Frequency (MHz)
Summary

- X-parameters are a mathematically correct superset of S-parameters for nonlinear devices under large-signal conditions.
- X-parameters (for two-port devices under large-signal excitation from a single large input tone in this offering) can be accurately measured by automated set of experiments on the new Agilent NVNA instrument.
- Together with the PHD Framework, measured X-parameters can be used in ADS to design nonlinear circuits.
- All pieces of the puzzle are available and they fit together!