X-parameters*: A new paradigm for measurement, modeling, and design of nonlinear microwave & RF components

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Outline

- Introduction: X-parameter Basics
- Survey of X-parameter benefits and applications
- Summary
- References and Links
X-Parameters: Mainstream Nonlinear Interoperable Technology

\[ B_{pm} = X^p_m \left( A_{11} \right) + X^s_{pm,qn} \left( A_{11} \right)^P m+n A_{qn} + X^p_{pm,qn} \left( A_{11} \right)^P m+n A_{qn} \]
S-parameters Solve All Small-Signal Problems

But devices must operate linearly

**Measure**

Agilent Vector Network Analyzer

**Model**

Reflected

Transmitted

Incident

B₁ = S₁₁A₁ + S₁₂A₂

B₂ = S₂₁A₁ + S₂₂A₂

**Design**

What about large-signal nonlinear problems?
X-parameters Solve Nonlinear Problems
Same use model as S-parameters, but much more powerful

\[ B_{pm} = X^F_{pm} \left( A_{11} \right) P^m + X^S_{pm, qn} \left( A_{11} \right) P^{m-n} A_{qn} + X^T_{pm, qn} \left( A_{11} \right) P^{m+n} A_{qn}^* \]
Capturing the imagination of the industry

Solves real-world problems now

Interoperable characterization, modeling, and design solutions

Potential to do for nonlinear components and systems what S-parameters do for linear components and systems

Changing the way the industry works

Continuous wave of innovations and award-winning research
**X-parameters: Hierarchical Design and Validation**

Top-Down Design Specifications (not yet available)

Bottom-up Measurement-based Verification

Electronic System Level Design

System Integrators

Component vendors

NVNA 50 GHz

X-par generator

X-par analysis

Simulator

XnP component

XnP: native simulation component

load-dep X-pars

high power X-pars

X-parameter DML lecture Norway #2

D. E. Root

May 7, 2010
Introduction: NVNA measurements
complex spectra and waveforms

Port Index
Harmonic Index

$A_{1k}$ $B_{1k}$

$A_{2k}$ $B_{2k}$

$I_1$ $I_2$

$A_{pk}$ $B_{pk}$
Measurement-Based Modeling & Design Flow

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

NVNA
Nonlinear Measurements

ADS
Simulation and Design

X-parameter blocks

X-parameters enable accurate nonlinear simulation under small to moderate mismatch. (See later for large mismatch)

allowing prediction of component behavior in complicated nonlinear circuits.
IMD / ACPR exact in narrow-band limit

“X-parameters: the same use model as S-parameters but much more powerful”
X-parameter Concept: Linearized Spectral Map around a Large-Signal Operating Point (LSOP)

Incident Port 1

\[ B_{2k} (D, C, A_{11}, A_{12}, A_{13}, \ldots A_{21}, A_{22}, A_{23}, \ldots) \]

Scattered Port 2

Multi-variate NL map

\[ \approx \]

Simpler NL map

\[ X_{2k}^{(F)} (D, C, A_{11}, 0, 0, 0, \ldots) \]

Linear non-analytic map

\[ \sum [ X_{2k, p_j}^{(S)} (D, C, A_{11}) A_{p_j} + X_{2k, p_j}^{(T)} (D, C, A_{11}) A_{p_j}^* ] \]

X-pars include exact nonlinear mapping to totally linear (S-pars) & everything in between

Trade simplicity for accuracy.
X-parameters: What they are & where they come from

- Scattering of multiple incident large-amplitude waves.
- Can be simplified according to linear or nonlinear dependence on inputs (simplicity vs accuracy)

- Measured on NVNA or generated in simulator

- Rules for computing the response to general signals given extracted X-parameters

\[
B_{e,f} = X_{ef}^{(F)}(\|A_{11}\|)P^f + \sum_{g,h} X_{ef,gh}^{(S)}(\|A_{11}\|)P^{f-h} \cdot a_{gh} + \sum_{g,h} X_{ef,gh}^{(T)}(\|A_{11}\|)P^{f+h} \cdot a_{gh}^* \\
P = e^{j\varphi(A_{11})}
\]
Simplest X-parameters for a Power Amplifier

\[ B_{11}(|A_{11}|) = X^{(F)}_{11}(|A_{11}|) P + X^{(S)}_{11,21}(|A_{11}|) A_{21} + X^{(T)}_{11,21}(|A_{11}|) P^2 A_{21}^* \]

\[ B_{21}(|A_{11}|) = X^{(F)}_{21}(|A_{11}|) P + X^{(S)}_{21,21}(|A_{11}|) A_{21} + X^{(T)}_{21,21}(|A_{11}|) P^2 A_{21}^* \]

X-parameters reduce to (linear) S-parameters in the appropriate limit

\[ X^{(F)}_{11} \bigg/ |A_{11}| \xrightarrow{|A_{11}| \to 0} S_{11} \]
\[ X^{(F)}_{21} \bigg/ |A_{11}| \xrightarrow{|A_{11}| \to 0} S_{21} \]
\[ X^{(S)}_{11,21} \bigg/ |A_{11}| \xrightarrow{|A_{11}| \to 0} S_{12} \]
\[ X^{(S)}_{21,21} \bigg/ |A_{11}| \xrightarrow{|A_{11}| \to 0} S_{22} \]
\[ X^{(T)}_{11,21} \bigg/ |A_{11}| \xrightarrow{|A_{11}| \to 0} 0 \]
\[ X^{(T)}_{21,21} \bigg/ |A_{11}| \xrightarrow{|A_{11}| \to 0} 0 \]

X-parameters are a superset of S-parameters
Stimulate port 1 with large tone at freq. $f$
Stimulate port 2 with small tone at freq. $f + \Delta$
Measure response at three different frequencies
Take limit as $\Delta$ goes to zero

\[
X^{(F)}_{21} = B_{21}(f, |A_{11}|) P^{-1}
\]

\[
X^{(S)}_{21,21} = \frac{B_{21}(f + \Delta, |A_{11}|)}{A_{21}(f + \Delta)}
\]

\[
X^{(T)}_{21,21} = \frac{B_{21}(f - \Delta, |A_{11}|)}{A_{21}(f + \Delta)} e^{2j\phi(A_{11} - A_{21})}
\]

Similarly for harmonics

Optimal and orthogonal experiment design and model identification
**X-Parameters and the Harmonic Jacobian [1]**

X-parameters are the “modeling analog” of HB analysis

Write model equations in language native to simulator algorithms

From 1-tone HB analysis

\[ X_{pm}^{(F)} (|A_{11}|) = B_{pm} P^{-m} \]

\[ X_{pm,qn}^{(S)} (|A_{11}|) = P^{-m+n} \frac{\partial B_{pm}}{\partial A_{qn}} \bigg|_{A_{11},A_{12}=0,...,A_{21}=0,...} \]

\[ X_{pm,qn}^{(T)} (|A_{11}|) = P^{-m-n} \frac{\partial B_{pm}}{\partial A_{qn}^*} \bigg|_{A_{11},A_{12}=0,...,A_{21}=0,...} \]

from *known Jacobian of 1-tone HB analysis*.

Jacobian comes from I-V and \( G_{ij}, C_{ij} \) from element constitutive relations

Never need 2-tone HB analysis. Faster, guaranteed spectrally linear

Most of the terms in the required Jacobian *are know ahead of time*

\[ B_{e,f} = X_{ef}^{(F)} (|A_{11}|) P^f + \sum_{g,h} X_{ef,gh}^{(S)} (|A_{11}|) P^{f-h} A_{gh} + \sum_{g,h} X_{ef,gh}^{(T)} (|A_{11}|) P^{f+h} A_{gh}^* \]
X-Parameter: How they are measured:

Experiment Design & Identification (2): Ideal Case

E.g. functions for $B_{pm}$ (port p, harmonic m) given small extraction tones $A_{qn}$ (port q, harmonic n)

$$B_{pm} = X_{pm}^{(F)}\left(\left|A_{11}\right|\right)P^m + X_{pm,qn}^{(S)}\left(\left|A_{11}\right|\right)P^{m-n}A_{qn} + X_{pm,qn}^{(T)}\left(\left|A_{11}\right|\right)P^{m+n}A_{qn}^*$$

Perform 3 independent experiments with fixed $A_{11}$

input $A_{qn}$  
output $B_{pm}$
X-parameter properties and benefits

Static nonlinearity (AM-AM) at any/all CW frequencies
High-frequency memory (AM-PM)
Large-signal output match (correct “Hot S22”)
Harmonics (even and odd) at input and output ports
PAE and DC currents / voltages at supply ports

**Cascadable:** distortion through chains of components
Does for *driven nonlinear systems* what S-parameters do for linear systems

**Hierarchical:** apply to one component or multiple (e.g. multi-stage amp)

**Transportable:** mismatch at fundamental and harmonics taken into account

Can be used to simulate some *long-term memory* affects
Can be *generated from Simulation and Measurement*

*Highly automated* experiment design & model identification
Outline

• Introduction: X-parameter Basics

• Survey of X-parameter benefits and applications
  – Cascading nonlinear blocks
  – Integrating handset amplifier into cell phone (customer example)
  – Load-dependent X-parameters and their harmonic tuning capability
  – High power X-parameter measurements
  – X-parameter generation from detailed schematics in ADS
  – X-parameter simulation component (XNP) built-in to ADS
  – Dynamic X-parameters: Long-term memory research

• Summary

• References and Links
Measurement-based nonlinear design with X-parameters

| Source | ZFL-AD11+ 11dB gain, 3dBm max output power | Connector 80 ps delay | ZX60-2522M-S+ 23.5dB gain, 18dBm max output power | Load |

Amplifier Component Models from individual X-parameter measurements
Results
Cascaded Simulation vs. Measurement

Red: Cascade Measurement
Blue: Cascaded X-parameter Simulation
Light Green: Cascaded Simulation, No $X^{(T)}$ terms
Dark Green: Cascaded Models, No $X^{(S)}$ or $X^{(T)}$ terms

Fundamental Gain

Fundamental Phase
Results

Cascaded Simulation vs. Measurement

Red: Cascade Measurement
Blue: Cascaded X-parameter Simulation
Light Green: Cascaded Simulation, No $X^{(T)}$ terms
Dark Green: Cascaded Models, No $X^{(S)}$ or $X^{(T)}$ terms

Fundamental % Error

Second Harmonic % Error

“X-parameters enable predictive nonlinear design from NL data”
X-parameters solve key, real customer problems
Example: GSM amp. and cell phone integration

Horn et al IEEE European Microwave Conference, Amsterdam, October 2008

Skyworks amp

 Measurements small colored crosses

Blue circular shape Hot $S_{22}$ prediction
Red Elliptical shape: X-parameter prediction

“X-parameters predict output match under large input drive Hot $S_{22}$ does not”

Allowed Sony-Ericsson to take into account second-harmonic mismatch on amp in system integration
Complete X-parameter Model of GSM Amplifier

“We didn’t think this was possible”
– Sony-Ericsson engineer
Joakim Eriksson, Ph.D
Unprecedented capability
Data acquisition 30x faster

“X-parameters provide a nonlinear electronic interactive datasheet based on data”

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Load-dependence of another GSM commercial Amp from X-parameters measured at only 50 ohms
900 MHz Vbatt=3.7, Vapc = 1.4

System Integrator wants to use X-parameters to compare performance among vendor parts within their system

Pout, 1dBm contour spacing

Red: LoadPull measurements
Blue: Simulations using X-parameters extracted in 50 ohms

50 ohm X-parameters, predict performance well over a wide range of impedance

But what if we want even more accuracy?
X-parameters with load-dependence

X-parameters allow us to **simplify** the general B(A) relations:

Trade efficiency, practicality, for generality & accuracy

**Powerful, correct, and practical**

\[
B_{e,f} = X_{ef}^{(F)}(DC, |A_{11}|)P^f + \sum_{g,h} X_{ef,gh}^{(S)}(DC, |A_{11}|)P^{f-h} \cdot A_{gh} + \sum_{g,h} X_{ef,gh}^{(T)}(DC, |A_{11}|) \cdot P^{f+h} \cdot A_{gh}^* \\
B_{e,f} = X_{ef}^{(F)}(DC, |A_{11}|, |A_{21}|, \theta)P^f + \sum_{g,h} X_{ef,gh}^{(S)}(DC, |A_{11}|, |A_{21}|, \theta)P^{f-h} \cdot A_{gh} + \sum_{g,h} X_{ef,gh}^{(T)}(DC, |A_{11}|, |A_{21}|, \theta) \cdot P^{f+h} \cdot A_{gh}^* \\
B_{e,f} = X_{ef}^{(F)}(DC, |A_{11}|, \Gamma_2)P^f + \sum_{g,h} X_{ef,gh}^{(S)}(DC, |A_{11}|, \Gamma_2)P^{f-h} \cdot A_{gh} + \sum_{g,h} X_{ef,gh}^{(T)}(DC, |A_{11}|, \Gamma_2) \cdot P^{f+h} \cdot A_{gh}^* \\
\]

"**X-parameters unify S-parameters and Load-Pull**"
NVNA+Load-Pull = Instant Large-Signal Model

- Drag and drop measured X-parameters for immediate ADS simulation “This is a breakthrough for the industry.”

  – Gary Simpson Maury Microwave
Load-Dependent X-Parameters of a FET


Measurements X-par Simulation

WJ FP2189 1W HFET

P<sub>out</sub> Contour (dBm)

Measured and Simulated Voltage and Current Waveforms

Experimental Harmonic Balance  X-parameters unify S-parameters and load-pull
Harmonic Load-Tuning Predictions from X-parameters

**Key Agilent IP** calibrates out uncontrolled harmonic impedances presented by tuner & re-grids impedance data for accuracy and interpolation in ADS

*Harmonic load-pull may be unnecessary! Simpler, cheaper, faster alternatives exist*
Simple Setup
Fast, automated measurements
Time-domain waveforms

Load-dependent X-parameters as a measurement-based device model
“The data is the model”

Useful for:
• High-power device characterization
• X-parameter transistor models
• multi-stage amps w. large mismatch

Control power, frequency, bias and load
at fundamental frequency: faster, fewer data, simpler setup than harmonic L-P

• Get sensitivity to harmonic loads at output and input ports without having to control harmonic impedances

• Estimate the effects of source-pull on device performance in ADS without having to control source impedance
Load-dependent X-parameters versus harmonic load-pull

Root et al INMMiC Conference, April, 2010
Horn et al submitted to IEEE CSICS2010

Load-dependent X-pars

- One output tuner to vary load at fundamental frequency. At each load inject small tones at 2\textsuperscript{nd} and 3\textsuperscript{rd} harmonic freqs (9x(1+2x2) = 45 measurements, actually ~99 measurements)

- Measured DC – 4\textsuperscript{th} harmonic

- Take into ADS. Present 729 independent loads to model

Harmonic load-pull validation

- Three output tuners to vary loads at fundamental, second, and third harmonics independently (9x9x9 = 729 measurements)

- Measured DC - 4\textsuperscript{th} harmonic

Compare waveforms, PAE, dynamic load-lines, etc.
Load-dependent X-parameter model for GaN HEMT:

Cree CGH40010 GaN HEMT 10 W packaged transistor

- 900 MHz
- Measure Load-dependent X-parameters vs power at 9 impedances
- 4 harmonics measured
- probe tones at 2nd and 3rd harmonics
- harmonic impedances uncontrolled

X-parameter file taken into ADS for independent validation.
Harmonic Load-pull Setup: For Validation Only

J. Horn et al *Submitted to CSICS2010*

- Waveforms measured versus power at each set of 729 harmonic loads as controlled independently by the tuners.
- Fundamental, second, and third complex impedances set independently

Diagram:

- DC Supply
- Bias Tees
- GPIB
- PNA-X
- Maury Software
- NVNA Firmware
- Maury Tuner
- DUT
- Maury Tuner Z1
- Maury Tuner Z2
- Maury Tuner Z2
- 9 states
- 9 states
- 9 states
Load-dependent X-parameters versus harmonic load-pull

Load-dependent X-pars
- *One output tuner* to vary load at fundamental frequency. At each load inject small tones at 2\textsuperscript{nd} and 3\textsuperscript{rd} harmonic freqs (9x(1+2x2) = 45 measurements, actually \sim 125 measurements)
- Measured DC – 4\textsuperscript{th} harmonic
- Take into ADS. Present 729 independent loads to model

Harmonic load-pull validation
- *Three output tuners* to vary loads at fundamental, second, and third harmonics independently (9x9x9 = 729 measurements)
- Measured DC - 4\textsuperscript{th} harmonic

Compare waveforms, PAE, dynamic load-lines, etc.
Prediction of GaN HEMT harmonic-load dependence from fundamental-only load-dependent X-pars

Courtesy of J. Horn

Harmonic loads

Cree CGH40010 GaN HEMT

X-parameter model
Harmonic time-domain load-pull measurements
Prediction of GaN HEMT harmonic-load dependence from fundamental-only load-dependent X-pars

Harmonic loads

Cree CGH40010 GaN HEMT

Pin (available)

PAE

Vd [V]

Id [A]

Vd

Id

Time (nanoseconds)
Prediction of GaN HEMT harmonic-load dependence from fundamental-only load-dependent X-pars
Prediction of GaN HEMT harmonic-load dependence from fundamental-only load-dependent X-pars
Summary:
Fundamental-only load-dependent X-parameters

- Full two-port nonlinear functional block model for simulation
  - *Accounts for load-tuning dependence of device performance* without the requirement of independently controlling harmonic loads
  - Use to design matching networks, multi-stage amps, Doherty amps., ...

- Large data / time reduction compared to harmonic load-pull
  - X-parameter model scales linearly in number of loads N
  - Harmonic L-P scales as $N^H$, $H =$ no. of controlled harmonic loads

- Harmonic load-pull may be unnecessary
  - Validates “principle of harmonic superposition” (Verspecht et al 1997)
  - Source-pull unnecessary (Horn et al submitted to CSISC 2010)] except for power transfer
## X-parameters at 100W
(courtesy K. Anderson)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part Number</td>
<td>ZHL-100W-52</td>
</tr>
<tr>
<td>Pout max (@1dB compression)</td>
<td>45dBm (min, 50M-500MHz)</td>
</tr>
<tr>
<td></td>
<td>47dBm (typ, 50M-500MHz)</td>
</tr>
<tr>
<td>Pout max (@3dB compression)</td>
<td>46.5dBm (min, 50M-500MHz)</td>
</tr>
<tr>
<td></td>
<td>48.5dBm (typ, 50M-500MHz)</td>
</tr>
<tr>
<td>Pin max (no damage)</td>
<td>+3dBm</td>
</tr>
<tr>
<td>Gain</td>
<td>48dB (min)</td>
</tr>
<tr>
<td></td>
<td>50dB (typ)</td>
</tr>
<tr>
<td>Input VSWR</td>
<td>1.45:1 (typ)</td>
</tr>
<tr>
<td>Output VSWR</td>
<td>2.5:1 (typ)</td>
</tr>
</tbody>
</table>

![Graph showing Gain Compression at fundamental frequency](image)

X-parameters have been measured at 250 W
X-parameters at 100W

5 harmonics, magnitude and phase: fund=150 MHz
Generate an IP-Protected X-parameter model

Slide courtesy of J. Sifri

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Single Tone Amp model with 50 ohm load

IP-protected model; Fast X-parameter simulation component (20x faster)

X-pars Vs ckt-level PA Results

Test the PA circuit
Soon: Two-tone X-parameter NVNA measurements

- Magnitude and Phase of intermod products and sensitivity to mismatch
- Measure and simulate freq-dependence & asymmetry of complex intermods
- Design nonlinear circuits that cancel distortion
- ADS X-parameter generator and XnP component can do this already

Red = 2-Tone X-parameters prediction
Blue = Independent measured data

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3-Port X-parameter Measurements

For characterization and measurement-based simulation of three-port components (mixers, converters, switches)

Note: ADS can already generate and simulate with multi-port, multi-tone X-parameters

Here A and B waves include *multiple spectral components*
Multi-tone, Multi-port X-parameters: Two large signals at different frequencies at different ports

Less restrictive approximation to the general theory:
Linearization around the multi-tone nonlinear responses

$$B_{i,kl} = X^{(F)}_{i,kl}(A_{1,10}, A_{2,01}, 0, 0, \ldots) + \text{Terms linear in the remaining components}$$
Mixers: X-parameters extracted from an Agilent DC-50 GHz InP-based Mixer 1GC1-8068: Mismatched (10 Ohms) at IF

Accurate, fast, IP-protected

Down Conversion

Gain (dB)

Phase (deg)

Up Conversion

Simulation-based

LO: 45 GHz  RF: 45.1 GHz  LO power = 3.5 dBm

Circuit Model (solid blue)  X-parameter Model (red points)
Mixers: X-parameters extracted from an Agilent DC-50 GHz InP-based Mixer 1GC1-8068: Mismatched (10 Ohms) at IF

Accurate, fast, IP-protected

Gain (dB)

Phase (deg)

Down Conversion

Up Conversion

Simulation-based LO: 45 GHz RF: 45.1 GHz

Circuit Model (solid blue) X-parameters (red points)

LO power = 3.5 dBm
Two Fundamentals: 50 GHz Integrated Mixer
Mismatched load (10 Ohms) at IF

LO Leakage

RF Leakage

Gain (dB)

Phase (deg)

LO: 45 GHz RF: 45.1 GHz LO power = 3.5 dBm

Simulation-based Circuit Model (solid blue) X-parameter Model (red points)
Agilent MMICs: Available for purchase

50 GHz InP-based Mixer
Part number: 1GC1-8068

See: http://www.agilent.com/find/mmic

X-parameters available
Design Nonlinear RF Systems

Simulation speedup of 20x to 100x
X-Parameter technology available in commercial EDA SW

Advanced Design System (ADS)
Premier RF & Microwave Design Platform

Available Today

Genesys
Affordable, High Performance HF/Microwave Board Design Software

Available Soon

SystemVue
Electronic System-Level Design (ESL) Software

Available Soon
Extending X-parameters to long-term memory

Original X-parameters are Static Spectral Mappings

Slides courtesy J. Verspecht

Static transmission

X-parameter: $XF_{21}$

Can be measured under True CW, pulsed DC or Pulsed RF conditions

Frequency Domain:

$$B_2 = XF_{21} \left( |A_1| \right) e^{j \varphi(A_1)}$$
Modulation Simulated in Envelope Domain:

\[ B_2(t) = X_{F_{21}} \left( |A_1(t)| \right) e^{j \varphi(A_1(t))} \]

- X-parameters determine Quasi-Static Response
- No “BW” effects
- Symmetric intermods independent of envelope rate (or history)
Memory Effects: Beyond Static X-parameters

Memory Effects:
When output depends not only in instantaneous input but also on past input values

• Response to fast input envelope variations may violate quasi-static assumption for use in envelope domain for estimation of response to modulated signals

• Physical causes of memory: Dynamic self-heating, bias-line interaction, trapping effects caused by *additional dynamic variables* – multiple time-scale problem

  IM3 products asymmetric
  Depend on tone spacing

HBT IM3 [dBm] versus tone separation [Hz]

Hysteresis in compression plot

Gain-compression

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Dynamic X-parameters: Long-Term Memory

Fundamental “hidden variable” theory

\[
B(t) = \left\{ X F_{21}(|A(t)|) + \int_{0}^{\infty} G(|A(t)|, |A(t-u)|, u) du \right\} e^{j \phi(A(t))}
\]

Measured Data: Red
Memory model prediction: Blue
Static X-parameter prediction: Magenta
Dynamic X-parameters Beyond Quasi-Static

- Pulsed Envelope NVNA extraction
- Prototyped in ADS
- Not yet commercialized

\[ B(t) = \left\{ X F_{21} \left( |A(t)| \right) + \int_{0}^{\infty} G \left( |A(t)|, |A(t-u)|, u \right) du \right\} e^{j \phi(A(t))} \]

Comparison

\[ |B_{\text{meas}}(t)| \quad \text{vs} \quad |B_{\text{sim}}(t)| \]
Dynamic X-parameters Predict Memory Effects

See Latest Research Results on Dynamic X-parameters
J. Verspecht, J. Horn, D. E. Root “A Simplified Extension of X-parameters to Describe Memory Effects for Wideband Modulated Signals”
ARFTG Conference Session 2-1 Friday, May 28, 2010 10:20AM (Hilton)
Summary: X-parameter universe is expanding rapidly

Powerful, practical interoperable solutions for nonlinear characterization, modeling, and design of microwave and RF

X-parameters: “doing for nonlinear components and systems what S-parameters do for linear components and systems”

Applications

• X-parameters for GSM amp.
• Load-dependent X-parameters
• 50 GHz Agilent NVNA
• High-Power X-parameter meas.
• X-parameter generator in ADS
• XnP component in ADS
• Two-tone measured X-pars
• Three-port measured X-pars
• Memory: Dynamic X-params
• Device modeling
• Education, training, app. notes
• Industry is adopting paradigm
X-Parameters: Agilent Completes the Nonlinear Puzzle!

Agilent Nonlinear Vector Network Analyzer

Electronic design automation software

Nonlinear Measurements

Nonlinear Simulation & Design

Nonlinear Modeling

Customer Applications

\[ B_{pm} = X^T_{pm}(A_{11}) + X^S_{pm,qu}(A_{11})P_{m-qm}A_{qu} + X^T_{pm,qu}(A_{11})P_{m+q}A_{qu}^* \]
Selected References and Links