Nonlinear Analog Behavioral Modeling of Microwave Devices and Circuits

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Measurement and Modeling Sciences

Integrated Diodes

Liquid metal switches

Hyperabrupt Diodes

MEMS

Internal and external technology

GaN

GaAs

InP

Diodes

Thin Film

Collaborative Innovation

packaging / subsystem

digital & mixed signal IC

Tech Access

microwave IC

Modeling and Measurement Science

microwave nano / microfabrication / MEMS

semiconductor material

HBT ICs

pHEMT & FET ICs

Thin Film

Ferromagnetics

Semiconductor switches

Agilent Measurement HW & SW IP

Agilent ADS Momentum

HFTC Fabrication & Access

HFTC Model & Measurement IP

analytical  empirical  behavioral
Outline

Introduction: Behavioral Models and NVNA

Functional Block Models

• Nonlinear Time Series
• X-parameters (PHD Model) in the Frequency Domain
• Mixed Time-Frequency Methods

Summary and Conclusions
Introduction: Behavioral Modeling and Design Hierarchy

Top-down: system design and specifications
Increasing model complexity

System

Multivariate functions for $i_1, i_2$,

Behavioral Model:
Accurate model of lower level component
for simulation at next highest level

Increasing circuit/system complexity
Bottom up: verification

Device

Circuit

Multivariate functions for $i_1, i_2$.

Embedding Variables

Equivalent Circuit Model
“Compact Model”
Measurement-Based and Simulation-Based Models

Actual Circuit

Measurement-Based Model
- Ckt. model may not exist
- Ckt. models may be inaccurate
- Completely protect design IP

Simulation-Based Model
- Simulation speedup
- Design system before building/buying IC
- Completely protect design IP

Design of Module or Instrument Front End

Amplifier or Mixer IC
DC-20 GHz HBT Agilent HMMC 5200 amp [2]

Generate Behavioral Model

Simple for Linear Ckts: S-parameters

Detailed Circuit Model (SPICE/ADS) of IC
S-parameters as simplest behavioral model

- 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

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

Measure with linear VNA:
Small amplitude sinusoids

- Incident: \( a_1 \) → \( b_1 \)
- Reflected: \( a_1 \) → \( b_2 \)
- Transmitted: \( a_2 \) → \( b_2 \)

Model Parameters:
Simple algebra

\[
S_{ij} = \frac{b_i}{a_j} \quad \text{for} \quad a_k = 0 \quad \text{if} \quad k \neq j
\]
Three Components of Behavioral Modeling

1. Model Formulation
   - Nonlinear ODEs in Time Domain (e.g. Transient Analysis; all others)
   - NL Spectral Map in Freq. Domain (e.g. Harmonic Balance) X-params
   - Mixed Domains (e.g. ODE-Coupled Envelopes in Circuit Env. Analysis)

2. Experiment Design
   - Stimulus needed to excite relevant dynamics

3. Model Identification
   - Procedure to determine model “parameters”
Model Formulation: Time & Freq. Domains [1,6]

\[ I(t) = F(V(t), \dot{V}(t), \ddot{V}(t), \ldots, \dot{I}(t), \ldots) \]

Natural for strongly nonlinear low-order (lumped) systems

\[ B_k = F_k(A_1, A_2, A_3, \ldots) \]

Freq. Domain natural for low-distortion, high-freq. ICs

Formulate model eqs. in language native to appropriate simulator
Wanted: Cascadability of **Nonlinear Components**

Predict signal and harmonics (magnitude and phase) through chains of *cascaded* nonlinear components under drive

- Inter-stage mismatch is important to final results
  - Can not infer these effects from VNA measurements (even “Hot S_{22}”)
- Required for communication circuits and module design
- **Linear S-parameter theory doesn’t apply!**
  Most previous attempts to generalize S-parameters to nonlinear case are wrong!
Wanted: Hierarchical Modeling

Model the cascade directly

A cascade of many models reduced to one
Experiment Design: Simulation

Detailed Circuit Model Goes here
Experiment Design: Measurement

Nonlinear Vector Network Analyzer [9,14] (NVNA)

Calibrated magnitude & phase of harmonics/IMD
Measures under realistic large-signal conditions
Based on Standard Agilent PNA Hardware
And custom reference generator
Introduction: NVNA measurements
complex spectra and waveforms

\[ I_1 \quad I_2 \]

Port Index
Harmonic Index

IEEE DML Norway talk #1    David E. Root
May 7, 2010
Nonlinear Vector Network Analyzer (NVNA) [14]:

\[ \text{Network Analyzer} + \text{Phase Reference} + \text{Meas. Science Algorithms \\& Software} = \text{NVNA} \]

NVNA = PNA-X + Phase Reference (custom InP IC) + Application SW and calibration (mag and phase)
two internal sources, internal switches, and an internal broadband combiner

NVNA measures Magnitude and Phase of all relevant frequency components (cross-frequency coherence) necessary to measure X-parameters!
Nonlinear Vector Network Analyzer (NVNA) [14]

- Vector (amplitude/phase) corrected nonlinear measurements from 10 MHz to 50 GHz
  - Calibrated absolute amplitude and relative phase (cross-frequency relative phase) of measured spectra traceable to standards lab
  - 50 GHz of vector corrected bandwidth for time domain waveforms of voltages and currents of DUT
  - Multi-Envelope domain measurements for measurement and analysis of memory effects
  - X-parameters: Extension of Scattering parameters into the nonlinear region providing unique insight into nonlinear DUT behavior. Efficient measurements with phase control. External instrument control, pulsed, triggered measurements
  - X-parameter MDIF file read by ADS XnP component or nonlinear simulation and design.
  - X-parameter generation from detailed schematics within ADS simulator.

- Standard VNA HW with Nonlinear features & capability
Outline

Introduction: Behavioral Models and NVNA

Functional Block Models

• Nonlinear Time Series
• X-parameters (PHD model) in the Frequency Domain
• Mixed Time-Frequency

Summary and Conclusions
Nonlinear Time Series method of Behavioral Modeling [1,6]
Dynamical Systems & State Space

The dynamics of the nonlinear system can be assumed to be described by a system of nonlinear ODEs

\[ y^{(n)}(t) = f(y^{(n-1)}, \ldots, y, x, \dot{x}, \ldots x^{(m)}) \]

Order of time derivative

\[ \dot{\mathbf{u}}(t) = f(\mathbf{u}(t), \mathbf{x}(t)) \quad \text{Vector of State Equations} \]

\[ y(t) = h(\mathbf{u}(t), \mathbf{x}(t)) \quad \text{Scalar output } y(t) \]

The sampled solution of the ODE, \( y(t) \), is a time-series

The solution of the dynamical equations for state variables, \( \mathbf{u}(t) \), is a time-parameterized trajectory in Phase Space
Phase Space and Time Series

The multi-dimensional space spanned by the state variables is known as phase space.

Any measurable output is a projection of this trajectory versus time: a Time Series.

Lorenz system
Nonlinear Time Series (NLTS) Phase Space Reconstruction by Embedding

NLTS Behavioral Modeling is “inverse” of solving known ODEs
Start from input & output time series and discover dynamics

Stimulate System with drive \( x(t) \)
Record Time Series output \( y(t) \)
Embed drive \( x(t) \) & response \( y(t) \)
Stop when trajectory single valued
This results in the Nonlinear ODE:
\[
f(y(t), \dot{y}(t), x(t), ...) = 0
\]
Approximate \( f \) with smooth function
Attach ODE Model to Circuit Simulator
Excitation Designs

Goal: stimulate all *relevant* (observable) dynamics

Sweep Power and Frequency to “cover phase space”

- **‘Two-tone’**
  - $f_1$
  - $f_1 + \Delta f$

- **‘Three-tone’**
  - $f_1$
  - $f_1 + \Delta f$
  - $f_1 + \Delta f$

- **‘Multi-tone’ or ‘Multi-sine’**
  - $f_1$
  - $f_2$
  - $f_n$
  - $f_1 + \Delta f$

- **‘Modulation’ (CDMA)**
  - $f_1$
  - $f_1 + \Delta f$
Embedding: Building up phase space to define ODE

\[ i(t) \neq i(v(t)) \]

\[ i(t) = i(v(t), \dot{v}(t)) \]
Model Identification: Nonlinear Time Series (NLTS)

```
X(t)   Y(t)
```

Stimulate / Excite System
Sufficiently complex stimulus

Embed:
Create auxiliary variables
(represent waveform)

Sample data:
at high frequency
(or envelope;
hard if multiple timescales)

```
x(t) \rightarrow [x(t), \dot{x}(t), ..., x^{(m)}(t)]
y(t) \rightarrow [y(t), \dot{y}(t), ..., y^{(n)}(t)]
```

```
x(t_1) \dot{x}(t_1) ... x^{(m)}(t_1) y(t_1) \dot{y}(t_1) ... y^{(n)}(t_1)
x(t_2) \dot{x}(t_2) ... x^{(m)}(t_2) y(t_2) \dot{y}(t_2) ... y^{(n)}(t_2)
... ... ... ... ...
x(t_p) \dot{x}(t_p) ... x^{(m)}(t_p) y(t_p) \dot{y}(t_p) ... y^{(n)}(t_p)
```

```
y^{(n)} = f(y^{(n-1)}, ..., y, x, \dot{x}, ..., x^{(m)})
```
**Function approximation Artificial Neural Networks**

An ANN is a parallel processor made up of simple, interconnected processing units, called *neurons*, with weighted connections.

\[ F(x_1, \ldots, x_K) = \sum_{i=1}^{I} v_i s \left( \sum_{k=1}^{K} w_{ki} x_k + a_i \right) + b \]

- Universal Approximation Theorem: Fit “any” nonlinear function of any # of variables
- Infinitely differentiable: *better for distortion than naive splines or low-order polynomials.*
- Easy to train (fit) using standard third-party tools (MATLAB)
- Easy to train on scattered data
Function approximation: Artificial Neural Networks

\[ y^{(n)}(t) = f_{ANN}(y^{(n-1)}(t), y^{(n-2)}(t), \ldots, y(t), u^{(n)}(t), u^{(n-1)}(t), \ldots, u(t)) \]

“Dynamic Neural Network”

\[ \{ w_{ki}, a_k \} \quad \text{Obtained by Training} \]

Can also define \( f \) by polynomials, radial basis functions, lookup tables etc.
Model Implementation: ODE in circuit simulator
(after Zhang and Xu in [6])

\[ y^{(n)} = f(y^{(n-1)}, \ldots, y, x, \dot{x}, \ldots x^{(m)}) \]

\[ v_1 = y \]

\[ \dot{v}_1 = v_2 \]

\[ \vdots \]

\[ \dot{v}_{n-1} = v_n \]

\[ \dot{v}_n = f(v_{n-1}, v_{n-2}, \ldots, v, x, \dot{x}, \ldots, x^{(m)}) \]
**NLTSA modeling flow**

- **MATLAB Toolbox**, plus 3rd-party software
- ‘NLTSAfile’ structure
- ADS/NVNA-MATLAB interfaces
- ADS templates for
  - simulation
  - data display
  - model verification
- Model as SDD in ADS
Example: GaAs HBT MMIC

Actual Circuit

DC-20 GHz GaAs HBT
(Agilent HMMC 5200 Amp)
Series-Shunt Amplifier
Gain: 9.5 dB @ 1.5GHz

Detailed ckt model
Results: NLTS Accuracy and Speed $[1,6]$

**NLTS Behavioral model**

**Fundamental Gain**

\[ I_i(t) = f_i(I_i, V_1(t), V_2(t), V_1'(t), V_2'(t), V_1^{(2)}(t), V_2^{(2)}(t)) \]

19 neurons

**Circuit model data**

**Fundamental Phase**

1 - 19 GHz

Time Domain Waveforms

- 229.68 seconds
- 11315.67 seconds
Circuit Co-Simulation vs. NLTSA Model

Results 3GPP WCDMA (lower) ACLR

3GHz WCDMA
Model generated from only sinusoidal signals

294 sec/pt NLTS
1532 sec/pt Ckt.

40 neuron model

Courtesy Greg Jue
Circuit Co-Simulation vs. NLTSA Behavioral Model
Results vs. Measured 3GPP WCDMA (lower) ACLR

WCDMA Lower ACLR Comparison:
Circuit Co-Sim vs. NLTSA Model vs. Measured

Model is also cascadable
Model works in TA, HB, Envelope
Outline

Introduction: Behavioral Models and NVNA

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• X-parameters (PHD Model) in the Frequency Domain
• Mixed Time-Frequency Methods

Summary and Conclusions
X-parameters (PHD model): a *nonlinear* paradigm

“Is there an analogue with linear S-parameters to help with the nonlinear problem?”

Frequency Domain description is natural for high-frequency, distributed systems
Natural for Harmonic Balance Algorithms and NVNA data

*Arbitrarily Nonlinear,* Not limited to Volterra Theory
X-Parameters: The Nonlinear Paradigm

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 X-params**

**X-parameter block**

**ADS: Simulate with X-params**

Interoperable Nonlinear Measurement, Modeling & Simulation with X-params

“X-parameters have the potential to do for characterization, modeling, and design of nonlinear components and systems what linear S-parameters do for linear components & systems”
X-Parameters: Why They are Important:

Predict performance of cascaded NL components

Cascaded Nonlinear Amplifiers:
X-parameters enable nonlinear simulation from measured data in the presence of mismatch

• Unambiguously identifiable from a simple set of measurements
• Extremely accurate for high-frequency, distributed nonlinear systems
• Fully nonlinear vector quantities (Magnitude and phase of all harmonics)
• Cascadable (correct behavior in mismatched environment)
X-parameters come from the **Poly-Harmonic Distortion (PHD) Framework** [3-6,12]

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

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

Port Index \hspace{1cm} Harmonic (or carrier) Index

Spectral map of complex *large* input phasors to *large* complex output phasors

Black-Box description holds for transistors, amplifiers, RF systems, etc.
X-parameters: Simplest Case - driven with single large tone at port 1 [1] (derivation in lecture 2)

\[ B_{e,f} = F_{e,f}(D, C, A_{11}, A_{12}, \ldots, A_{21}, A_{22}, \ldots) \]

Concept: simplify general nonlinear spectral mapping by spectral linearization

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

Perfectly matched response

Mismatch terms:
- linear in \( A_{gh} \)
- linear in \( A_{gh}^* \)

Not both \( g \) and \( h = 1 \) in sums

\[ P = e^{j\varphi(A_{11})} \]

Phase terms come from time-invariance:

“Output of delayed input is just the delayed output”
X-parameter Results: Cascadability of Nonlinear Blocks

Compression

2nd Harmonic Amplitude

2nd Harmonic Phase

3rd Harmonic Amplitude

3rd Harmonic Phase

Sin(2\pi f_0 t)

Pout

f_0 2f_0 3f_0

Cascaded PHD models
Cascaded Ckt. Models

0.6GHz – 6.0GHz

Does for distortion of nonlinear components
what S-parameters do for linear components
Improved Asymptotic Behavior

Volterra Theory Constraints Added for Improved asymptotic behavior at low power
X-parameters: HMMC 5200 Response to Digital Modulation

Circuit Model

X-parameters generated from ckt model

Excellent Results from Simple Excitations
X-parameter Results: Transportability
27 Ohm validation measurement-based model 50 Ohm data

Measurement-Based X-parameter Model

Independent NVNA Data
## Rough Comparison of Methods and Applicability

<table>
<thead>
<tr>
<th><strong>NL TSA</strong></th>
<th><strong>X-Parameters</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Works in TA, HB, Envelope</td>
<td>Frequency Domain natural for highly linear, distributed, broad-band cks</td>
</tr>
<tr>
<td>Excellent for strongly nonlinear, but lumped (low order ODE) systems</td>
<td>Experiment Design completely solved</td>
</tr>
<tr>
<td>Training non-algorithmic</td>
<td>Highly automated Model Identification</td>
</tr>
<tr>
<td>Experiment design not fully solved</td>
<td>Works in HB &amp; Envelope</td>
</tr>
<tr>
<td>Not as robust for convergence</td>
<td>Very robust for convergence</td>
</tr>
<tr>
<td>Scales well with complexity</td>
<td>Always accurate if sampled densely</td>
</tr>
<tr>
<td>Great gains in simulation speed</td>
<td>Complexity increases rapidly for multiple tones</td>
</tr>
</tbody>
</table>
Outline

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Summary and Conclusions
Envelope Domain for Long-Term Memory [7,8]
Applies to systems under large-signal modulated drives
Time-varying spectra for all inputs, outputs, & state variables
Perfectly suited for Circuit Envelope Analysis
Well-matched for data from Nonlinear Vector Network Analyzer

Time-varying spectrum

\[ x(t) = \text{Re} \left( \sum_{h=0}^{H} X_h(t) e^{j 2\pi h f_0 t} \right) \]

\( X_h(t) \) set of complex (amplitude and phase) waveforms at each harmonic index \( h \)
Modeling problem: map input envelopes to output envelopes
Envelope Domain for Long-Term Memory [7,8]

**Merge Frequency and Time Domains**

Spectral mapping $B_{pk} = X^{(F)}_{pk}(A_{11}, A_{12}, \ldots, A_{21}, A_{22}, \ldots)$

→ a differential equation *in the envelope domain*

\[ \hat{B}_k = f_k(\hat{B}_k^{(1)}(t), \ldots, \hat{B}_k^{(n)}(t), \hat{A}_l(t), \hat{A}_l^{(1)}(t), \ldots, \hat{A}_k(t), \ldots, \hat{A}_k^{(m)}(t)) \]

Order of time derivative
Envelope or carrier index

Example:
\[ \hat{B}_{21}(t) = f_{21}(\hat{B}_{20}(t), \hat{A}_{11}(t)) \]
\[ \frac{d\hat{B}_{20}(t)}{dt} = g(\left\langle |\hat{A}_{11}(t)|^2 \right\rangle, \hat{B}_{21}(t)) \]
Envelope Model: Amplifier with Self-Heating [8]

Fundamental Input

Fundamental Output

Gain Reduces as device heats up

Third Harmonic Output Mag & Phase

Pulsed RF signal at 1GHz:
Thermal Time Const. 10usec

Systematic approach to identifying “hidden” state variables for long-term memory IMS2007 [13]
Dynamic Long-Term Memory PHD Models
Envelope Differential Equations in ADS [7,8,13]

Verspecht et al in 2007 *International Microwave Symposium Digest* [13]

X-parameters with dynamic memory (red) compared to circuit-level model (blue)
Conclusions

Powerful nonlinear device & behavioral modeling approaches in time, frequency, and mixed domains have been presented

• X-parameters are mature. Commercial solutions to measure, model, and simulate are available, supported, and expanding (see lecture 2).
• Time-domain (NLTSA) techniques could become practical soon.
• Envelope domain (dynamic X-parameters) is attractive for memory.

Emergence of commercially available Large-Signal HW & SW

• e.g. NVNA on modern PNA-X platform [9,14]
• e.g. nonlinear simulators with built-in XnP components & X-param analysis

Great opportunity for applications

• Specification of active components by X-parameters
• Device and behavioral modeling applications of NVNA measurements
• Stability analysis and matching power amplifiers under drive
• Active Signal Integrity
References


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

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* X-parameters is a trademark of Agilent Technologies, Inc.
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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

Nonlinear Measurements

Nonlinear Simulation & Design

Nonlinear Modeling

Customer Applications

\[ B_{pm} = X_p^P \left( A_{11} \right) + X_p^{q_n} \left( A_{11} \right) P_{pm}^{m-n} A_{qn} + X_{pm}^{q_m} \left( A_{11} \right) P_{m-n}^{m+n} A_{qn} \]
S-parameters Solve All Small-Signal Problems
But devices must operate linearly

Measure

Agilent Vector Network Analyzer

Model

B1 = S_{11}A_1 + S_{12}A_2
B2 = S_{21}A_1 + S_{22}A_2

Design

S-Parameters

What about large-signal nonlinear problems?
**X-parameters Solve Nonlinear Problems**

Same use model as S-parameters, *but much more powerful*

\[
B_{pm} = X^F_{pm} (|A_{11}|) P^m + X^S_{pm,qn} (|A_{11}|) P^{m-n} A_{qn} + X^T_{pm,qn} (|A_{11}|) P^{m+n} A^*_{qn}
\]

**Measure**

Nonlinear Vector Network Analyzer

**Design**

EDA Software
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
- Bottom-up Simulation-based Verification

Electronic System Level Design

X-parameter Specs

X-par generator
X-par analysis

Simulator

Component vendors

NVNA 50 GHz
X-par meas

X-nP: native simulation component

X-nP component

load-dep X-pars
high power X-pars
Introduction: NVNA measurements
complex spectra and waveforms

Port Index
Harmonic Index
Measurement-Based Modeling & Design Flow

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

NVNA
Nonlinear Measurements

ADS
Simulation and Design

Data File
Drag and drop

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

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

Scattered Port 2

Multi-variate NL map

\[ \approx \]

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

Simpler NL map

\[ + \]

Linear non-analytic map

\[ \sum [X^{(S)}_{2k, pj}(DC, A_{11}) A_{pj} + X^{(T)}_{2k, pj}(DC, A_{11}) A_{pj}^*] \]

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

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

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

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

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

\[ X_{11}^F (|A_{11}|) \rightarrow S_{11} \]
\[ X_{21}^F (|A_{11}|) \rightarrow S_{21} \]
\[ X_{11,21}^S (|A_{11}|) \rightarrow S_{12} \]
\[ X_{21,21}^S (|A_{11}|) \rightarrow S_{22} \]
\[ X_{11,21}^{(T)} (|A_{11}|) \rightarrow 0 \]
\[ X_{21,21}^{(T)} (|A_{11}|) \rightarrow 0 \]

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

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

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

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

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

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

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

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

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

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

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

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

input $A_{qn}$  
output $B_{pm}$

$$B_{pm}^{(0)} = X^{(F)}_{pm} \left| A_{11} \right| P^n$$

$$B_{pm}^{(1)} = X^{(F)}_{pm} \left| A_{11} \right| P^n + X^{(S)}_{pm,qn} \left| A_{11} \right| P^{m-n} A_{qn} + X^{(T)}_{pm,qn} \left| A_{11} \right| P^{m+n} A_{qn}^*$$

$$B_{pm}^{(2)} = X^{(F)}_{pm} \left| A_{11} \right| P^n + X^{(S)}_{pm,qn} \left| A_{11} \right| P^{m-n} A_{qn}^{(2)} + X^{(T)}_{pm,qn} \left| A_{11} \right| P^{m+n} A_{qn}^{(2)*}$$
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

Amplifier Component Models from individual X-parameter measurements

<table>
<thead>
<tr>
<th>Source</th>
<th>ZFL-AD11+ 11dB gain, 3dBm max output power</th>
<th>Connector 80 ps delay</th>
<th>ZX60-2522M-S+ 23.5dB gain, 18dBm max output power</th>
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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

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

Measurements small colored crosses

Skyworks amp

“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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Page 23
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

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

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

X-parameters allow us to simplify the general B(A) relations:
Trade efficiency, practicality, for generality & accuracy
Powerful, correct, and practical

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

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

\[
B_{e,f} = X_{ef}^{(F)} (DC, |A_{11}|, |A_{22}|, \Gamma_2) P^f + \sum_{g,h} X_{ef,gh}^{(S)} (DC, |A_{11}|, \Gamma_2) P^{f-h} \cdot A_{gh} + \sum_{g,h} X_{ef,gh}^{(T)} (DC, |A_{11}|, \Gamma_2) P^{f+h} \cdot A_{gh}^*
\]

"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

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Page 26
Load-Dependent X-Parameters of a FET


Measurements X-par Simulation

WJ FP2189 1W HFET

P_out Contour (dBm)

Measured and Simulated Voltage and Current Waveforms

Measured and Simulated Dynamic Load Line

Experimental Harmonic Balance X-parameters unify S-parameters and load-pull
Harmonic Load-Tuning Predictions from X-parameters
Horn et al, IEEE Power Amplifier Symposium, September, 2009

Fundamental Output Magnitude  Second Harmonic Output Magnitude

Cree CGH40010 10 W RF Power GaN HEMT
Contours vs. 2nd Harmonic Load (Fixed input power and fundamental load)

X-Parameter Prediction: Blue
Measured with Harmonic LP System: Red

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

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 \textasciitilde 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 showing the setup with labels for PNA-X, DC Supply, Bias Tees, Maury Software, Maury Tuner, DUT, Maury Tuner Z1, Maury Tuner Z2, and connections via GPIB and USB]
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 ~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

J. Horn et al, submitted to CSICS2010

Harmonic loads

Cree CGH40010 GaN HEMT

Id [A] vs. Vd [V]

Vd vs. Time (nanoseconds)

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**

- Z₁
- Z₂
- Z₃

**Cree CGH40010 GaN HEMT**

**PAE**

**Pin (available)**

**Vd [V]**

**Id [A]**

**Time (nanoseconds)**

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Page 35
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>

Gain Compression at fundamental

Mini-Circuits ZHL-100W-52

X-parameters have been measured at 250 W

X-parameter DML lecture Norway #2
D. E. Root
May 7, 2010
X-parameters at 100W

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

Slide courtesy of J. Sifri
Single Tone Amp model with 50 ohm load

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

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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X-parameter DML lecture Norway #2
D. E. Root
May 7, 2010
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):**
  - LO: 45 GHz  RF: 45.1 GHz  LO power = 3.5 dBm
- **Phase (deg):**
  - Circuit Model (solid blue)  X-parameter Model (red points)

---

**Up Conversion**

- **Gain (dB):**
  - LO: 45 GHz  RF: 45.1 GHz  LO power = 3.5 dBm
- **Phase (deg):**
  - 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  LO power = 3.5 dBm

Circuit Model (solid blue)  X-parameters (red points)
Two Fundamentals: 50 GHz Integrated Mixer Mismatched load (10 Ohms) at IF

Gain (dB)

Phase (deg)

LO Leakage

RF Leakage

Simulation-based Circuit Model (solid blue) X-parameter Model (red points)

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

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X-parameter DML lecture Norway #2
D. E. Root
May 7, 2010
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
Extending X-parameters to long-term memory

Original X-parameters are Static Spectral Mappings

Static transmission
X-parameter: $XF_{21}$

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

Frequency Domain:

$$B_2 = XF_{21}(\|A_1\|)e^{j\varphi(A_1)}$$
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

**Graphs:**
- HBT IM3 [dBm] versus tone separation [Hz]
- Gain-compression with hysteresis in compression plot
Dynamic X-parameters: Long-Term Memory

Fundamental “hidden variable” theory

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

Anadigics AWT6282

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

\[ B(t) = \left\{ X F_{21}(|A(t)|) + \int_0^\infty G(|A(t)|, |A(t-u)|, u) du \right\} e^{i \phi(A(t))} \]
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

\[ B_{pm} = X^{T}_{pm}(A_{11}) + X^{S}_{pm,qn}(A_{11})P^{m+n}_{qn} A_{qn} + X^{F}_{pm,qn}(A_{11})P^{m+n}_{qn} A_{qn}^* \]
Selected References and Links

   http://www.nxtbook.com/nxtbooks/cmp/mwee1208/#/16
Survey and Trends in Nonlinear Transistor Modeling Methodologies

Dr. David E. Root
Principal R&D Scientist
High Frequency Technology Center
Santa Rosa, CA USA

IEEE MTT-S Lecture #3
Bergen, Norway
May 7, 2010
Key Contributors

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- Jason Horn
- Masaya Iwamoto
- Alexander Pekker
- Dominique Schreurs
- Jonathan Scott
- Gary Simpson
- Franz Sischka
- Paul Tasker
- John Wood
- Jianjun Xu
Presentation Outline

• Introduction
• I-V modeling
• Nonlinear Charge Modeling
• Non Quasi-Static Effects & Dispersion Modeling
• Electro-Thermal Modeling
• Advanced Measurements
• NVNA data and advanced dynamical FET modeling
• Symmetry Considerations
• Summary & Conclusions
Introduction

All models are wrong, but some are useful.“

- statistician George Box

“All models are approximations. Some models are useful.”

- attributed to Mike Golio and others
Compact Transistor Models (AgilentHBT model)

[48, 49, 10]

I_{CE} = \frac{\left( \frac{I_c}{q^3} \right) - I_{cr}}{d}

I_{crit1} = IKDC3\left(1 - \frac{V_{BC1} - VJC}{VKDC} \right)

q3 = \sqrt{\frac{1}{IKDC2} (Icf - I_{crit1})^2 + \left( \frac{IKDC1}{IKDC2} \right)^2 \left( \frac{1}{IKDC2} (Icf - I_{crit1}) - \left( \frac{IKDC1}{IKDC2} \right) \right) + 1 - q3_o}

Coupled nonlinear ordinary differential equations in the time domain

Equivalent Circuit with nonlinear elements

Thermal Subcircuit (Two-Poles)
Agilent HBT Model Parameters (over 100)

Resistances: 5
DC Currents: 26
Depletion Charge: 14
Delay Charge: 25
Parasitics: 6
Temp., DC & R’s: 22
Temp., Charges: 12
Noise: 6
Transistor Modeling

• Compact Models: Equivalent circuit models for IC design formulated in the time-domain. Examples are BSIM models for MOSFET, Angelov model for GaAs FETs, Gummel-Poon models for bipolars, AgilentHBT model for III-V HBTs

• “Compact” models can be complex (> 100 parameter values)

• Parameters typically extracted from DC and S-pars
  Ironic for a nonlinear model

  – Some devices may not be able to be characterized under DC and static operating conditions (power, temperature)
  – Advanced models may not be identifiable from only DC and S-parameter data.
  – No direct evidence that these nonlinear models will reproduce large-signal behavior
Device Requirements and Modeling Implications

- **Linearity:** Harmonic & Intermod. Distortion; ACPR; AM-AM; AM-PM
- **Efficiency:** PAE; Fundamental Output Power; Self-biasing
- **Memory:** Slow thermal effects, slow trapping phenomena
- **Modeling Challenges from**
  - Device physics (III-V transport, trapping dynamics)
  - Complex signals, multiple time-scale dynamics
  - Amplifier, switch, and mixer applications
  - Wide variety of device designs in many material systems
- **Accuracy required over**
  - Bias, frequency, and temperature; power;
- **Different types of models may be required at different stages in the development of a technology**
Physical Models to Circuit (compact) Models [16,17]

**Shockley:** Physical PDEs and approximations such as field-independent mobility, gradual channel approximation, etc.

Derive terminal dynamics and constitutive relations:

\[ I_D(t) = I_D^{DC}(V_{GS}(t), V_{DS}(t)) - \frac{dQ(V_{GD}(t))}{dt} \]

\[ I_G(t) = \frac{dQ(V_{GS}(t))}{dt} + \frac{dQ(V_{GD}(t))}{dt} \]

\[ I_D^{DC}(V_{GS}, V_{DS}) = \frac{W \mu q N_D a}{\varepsilon L} \left( V_{DS} - \frac{2}{3} \sqrt{2 \varepsilon} q N_D a^2 \left( (V_{DS} + \phi - V_{GS})^{3/2} - (\phi - V_{GS})^{3/2} \right) \right) \]

\[ Q(V) = -WL \sqrt{2q \varepsilon N_D (\phi - V)} \quad \text{(up to a constant)} \]
Typical characteristics of real devices not ideal

Typical Features of real device often not captured by simple physics-based models

Non-zero, and sometimes negative, output conductance
Drain-voltage dependent “pinch-off voltage”
Higher drain current at lower ambient temperature (near Vp)
Measurement-Based (Empirical) Modeling
“The Device Knows Best”
Electrons know where to go, even if the modelers don’t!

*Use device data as much as possible in the model*
Useful for circuit design when good measurements are available, and when no good (fast, robust, extractable) physical models are available
• Empirical models (fitting closed-form functions to data)
• Table-based models with spline interpolation
• Neural-network based models

Experiment Design:
  • measure the device I-V (and Q-V)

Model Identification
  • fit the empirical expressions to data (parameter extraction)
  or store data and interpolate
Empirical Models

The same dynamics (equivalent circuit topology)

\[ I_D(t) = I_D^{DC}(V_{GS}(t), V_{DS}(t)) - \frac{dQ_{GD}(V_{GD}(t))}{dt} \]

\[ I_G(t) = \frac{dQ_{GS}(V_{GS}(t))}{dt} + \frac{dQ_{GD}(V_{GD}(t))}{dt} \]

Modified Constitutive Relations for easy fitting (Curtice Cubic[7])

\[ I_D^{DC}(V_{GS}, V_{DS}) = \left( A_0 + A_1V_1 + A_2V_1^2 + A_3V_1^3 \right) \tanh(\gamma V_{DS}) \]

\[ Q_{GS}(V) = -\frac{C_{j0}\phi}{\eta + 1} \left( 1 - \frac{V}{\phi} \right)^{\eta+1} \]

\[ Q_{GD}(V) = C_{GD0}V \]
Experiment Design: Measure DC I-V curves

Model Identification (1): minimize error

\[ I^\text{DC}_{D}(V_{gs}, V_{ds}) = (A_0 + A_1 V_1 + A_2 V_1^2 + A_3 V_1^3) \cdot \tanh(\gamma V_{ds}) \]

Guess Initial Coefficient Values in Fixed Constitutive Relations

\[ \downarrow \]

Simulate Circuit

\[ \downarrow \]

Compare Simulation with Measurements

\[ \downarrow \]

Good Fit?

\[ \downarrow \]

Yes

Done

\[ \downarrow \]

No

Modify Coefficient Values

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Page 13

Norway #3 Transistor Modeling
D. E. Root
May 7, 2010
Issues with parameter extraction

Optimization-based parameter extraction can be:

- Slow (simulate circuit and update parameters hundreds of times)
- Sensitive to initial parameter values
- Non-repeatable
- Can get stuck in local minima of optimizer cost function
- Require user interaction
- Good parameter values depend on good data

- May never achieve good fit
  (constitutive relations may not be flexible enough)
Changes to constitutive relations -> changes to extraction routines
Parameter Extraction: What can go wrong

(Curtice Cubic example also see [30])

\[ I_{DC}^D(V_1, V_2) = \left( A_0 + A_1 V_1 + A_2 V_1^2 + A_3 V_1^3 \right) \tanh(\gamma V_2) \]
Table-Based Models: Accurate and General [3,17,21]

Measure, transform data, tabulate, interpolate, scale

Vertical Power Si MOSFET

<table>
<thead>
<tr>
<th>V_DS (V)</th>
<th>I_D (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>10.0</td>
<td>0.3</td>
</tr>
</tbody>
</table>

GaAs pHEMT

<table>
<thead>
<tr>
<th>V_DS (V)</th>
<th>I_D (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>5.0</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Process and Technology Independent
## Table Models

Constitutive Relations are interpolated from data

### Table 1

<table>
<thead>
<tr>
<th>$V_{gs}$</th>
<th>$V_{ds}$</th>
<th>$I_{d_DC}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5</td>
<td>-0.3</td>
<td>7.14E-08</td>
</tr>
<tr>
<td>-5</td>
<td>-0.2</td>
<td>7.55E-08</td>
</tr>
<tr>
<td>-5</td>
<td>-0.1</td>
<td>7.98E-08</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>$V_{gs}$</th>
<th>$V_{ds}$</th>
<th>$Q_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5</td>
<td>-0.3</td>
<td>-1.20E-13</td>
</tr>
<tr>
<td>-5</td>
<td>-0.2</td>
<td>-1.13E-13</td>
</tr>
<tr>
<td>-5</td>
<td>-0.1</td>
<td>-1.08E-13</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

$$I_d(t) = \text{Interpolate}\{\text{Table1, } [V_{gs}(t), V_{ds}(t), I_{d\_dc}]\}$$

$$+ \frac{d}{dt} \text{Interpolate}\{\text{Table2, } [V_{gs}(t), V_{ds}(t), Q_d]\}$$

Works well for dc, S versus bias & freq., med-high power signals
Warning: Interpolation algorithms may limit table models! [43]

Two-tone Intermodulation

Original HPFET Model with ADS splines vs Measured

Input Power (dBm)

Output Power (dBm)

Rough and unphysical behavior

Spline-based Root Model

Measured

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Page 18

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Naïve Splines Limit Distortion Accuracy [17, 8]

2-tones @ 100MHz (+1MHz) Si NJFET Table Model

(a) Vg=-1V Power=-10dBm

(b) Vg=-1V Power=-20dBm

Simple Cubic Splines
• Third order derivative vanishes at symmetry points
• Low order polynomial can’t predict high-order distortion at low amplitudes interpolation model is better when signal size ~ data spacing
Spline Alternatives: Artificial Neural Networks

\[ y_i = F_i(x_1, x_1, x_3) \]

\[ y_1 \]
\[ y_2 \]

\[ y_j = \sum_k V_{jk} Z_k \]

\[ Z_k = \tanh(\sum W_{ki} x_i) \]

Parameters \( w = [W_{ki}, V_{jk}] \)

- Universal Approx. Thm: Can fit any nonlinear function of many variables
- Infinitely differentiable: better for distortion than naïve splines
- Easy to train (identify) using standard third-party tools (MATLAB)
NeuroFET: FET Model using ANNs [43]

Constitutive Relations are ANNs!

ANN-based FET model (—) measured device test data (○)

$V_{gs} = 1.4\, \text{V}$

$V_{gs} = -1.2\, \text{V}$

$V_{gs} = -1.6\, \text{V}$

$V_{gs} = -2.0\, \text{V}$

$I_d$ (mA)

$V_{ds}$ (V)
NeuroFET Distortion Validation (2-tone) [43]

ANN-Based FET vs Measured

Alternatives to ANNs are “Smoothing Splines” [5] but they don’t have all the advantages
Global Domains for Measurement-based Models

Enables nonlinear simulation from discrete, bounded, measured data

ANNs inside, Intelligent Extrapolation outside [44]

Two orders of continuity at boundary
Asymptotically \( \sim \) exponential

Required for robust convergence

+ simpler algorithm
x robust algorithm
Guided Extrapolation Algorithm Compiled into Model

Improves DC convergence, HB, TA range of use [45]
Presentation Outline

• Introduction
• I-V modeling
• Nonlinear Charge Modeling and Related Issues
• Non Quasi-Static Effects & Dispersion Modeling
• Electro-Thermal Modeling
• Advanced Measurements for Experiment Design & Model Identification
• Symmetry Considerations
• Summary & Conclusions

Artificial Neural Network applications given throughout
Charge Modeling: Key to Distortion at high frequencies [4]

Model A = Shockley  Model B = Statz[32]  Model C = HP/AgilentFET [33]

All three models use the same DC analytical equations

Good Charge Model Required to Predict ACPR

Model A = Shockley junction capacitances

Model B = Statz/Raytheon gate terminal charge conserving but not terminal charge conserving at drain

Model C = HPFET (Root model) terminal charge conserving model at both gate and drain by direct integration of measured admittances and spline interpolation
Adjoint Neural Network Training for Qg

Train Adjoint network on \textit{partial derivative data} derived from S (Y) parameters

\[ Q_g = f_{ANN}^g (V_{gs}, V_{ds}, w) \]

\[ I_g(t) = \frac{dQ_g}{dt} \]

\textbf{Jianjun Xu,} M.C.E. Yagoub, Runtao Ding and Q.J. Zhang,
“Exact adjoint sensitivity analysis for neural based microwave modeling and design,”
Adjoint Neural Network Approach to Charge Modeling

Charge $Q_g$ obtained by Adjoint Training Methods [27,43]
(Generate an ANN function given partial derivative data)

\[(F)_{x10^{-12}} \quad Im(Y_{11})/\omega \text{ and } \partial Qg/\partial Vgs\]

Another experimental validation of \textit{terminal charge conservation} at the gate for GaAs pHEMT
Advantages of Adjoint ANN over contour Integration

- More uniform approximation of terminal charges than implementations of contour integration
- Applies to scattered data. No gridding necessary.
- Results in infinitely differentiable charge function rather than finite-order spline representation
- More easily deals with complicated boundary of data domain
- More easily generalizes to higher number of terminals
Artificial Neural Network applications given throughout
Dynamic electro-thermal (self-heating) model

\[
I_d(t) = I_d(V_{ds}(t), V_{gs}(t), T(t)) \\
Q_g(t) = Q_g(V_{ds}(t), V_{gs}(t), T(t))
\]

Temperature evolution equation based on dissipated power

\[
\tau \frac{dT}{dt} + \Delta T = R_{TH} (I_D(t)V_{DS}(t) + I_G(t)V_{GS}(t))
\]

This example is a simplified to 1\textsuperscript{st} order ODE

Heat propagates via diffusion Eqn. (PDE)

. Alternatively estimate T(t) as linear filter in frequency domain [34]

Trade off “fractional pole” response for nonlinearity
Dynamic electro-thermal (self-heating) model

Currents, Voltages, and Temperature calculated by the simulator self-consistently using coupled electrical and thermal equivalent circuits

\[ T = T_{amb} + \Delta T \]

Can approximate distributed nature of heat propagation by many sections

External node allows coupling to other heat sources

\[ Q_G(V_{GS}(t), V_{DS}(t), T(t)) \quad Q_D(V_{GS}(t), V_{DS}(t), T(t)) \]

\[ I_G(V_{GS}(t), V_{DS}(t), T(t)) \quad I_D(V_{GS}(t), V_{DS}(t), T(t)) \]

Electrical Equivalent Circuit

\[ T = \text{device junction temperature} \]

\[ T_{amb} = \text{device ambient (backside) temperature} \]
ANN T-dependent constitutive relations

Given measured non-isothermal ambient temp. \( (T_0 - \text{dependence}) \), one constructs isothermal \( (T - \text{dependent}) \) constitutive relations.

NeuroFET

T-dependent

dc I-V curves

Blue: \( T_0 = 25 \) constant ambient temp
Red: \( T = 70 \) constant junction temp
NeuroFET dynamic self-heating results

Fixed Vg

Vd

Ig

Id

T, V

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Page 35

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NeuroFET static self-heating

pHEMT

O : Data    — : Model

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Artificial Neural Network applications given throughout
Need for Advanced Characterization for empirical Modeling [21]

Dynamic Operating Trajectory of Table-based model constructed from
dc + S-parameter data:

True for neural network model too if built from dc + S-param data
GaN Devices

1 mm 10 fingers
GaN on Si
$\text{f}_T \sim 30\text{GHz}$
Pulse width 2us

Slide courtesy J. Scott

Pulsed measurements provide much more data than can be measured under static (DC) conditions.
Pulsed I-V characteristics at different quiescent points vs DC [1,21]

pHEMT device
Nonlinear Vector Network Analyzer (NVNA) Measurements for Transistor Modeling:

- These measurements will compliment and eventually totally replace small-signal measurements for large-signal device model experiment design and model identification [36-38]. Such systems are also useful for model validation.

  - Stimulates device with more realistic signals
  - Reduce degradation of device characteristics from static measurements
  - Less reliance on inferring large-signal dynamic behavior from linear small-signal measurements
  - Some device properties may very different (breakdown, Ig, …)
  - Use to identify parametric (empirical) models or even train (generate) data-based models directly
(1a) NVNA data for compact model validation

- Parameters extracted from DC and S-parameters (or CV)
- BSIM3 model simulated in Harmonic balance (HB) analysis
- Results compared with NVNA data

Slide courtesy of Franz Sischka, data from [51]
(1b) Model parameter extraction from NVNA Data [51]

NVNA data vs HB simulation using initial parameter values extracted from DC + CV

Modify parameter values (optimize) to better fit large-signal NVNA data

- Get optimal parameter set for given model
- trade-off DC, SP, for nonlinear performance
- App-dependent tuning
- Explore model limits
Parameter extraction from NVNA data

Slide courtesy Franz Sischka
Examples of measured dynamic load-lines using NVNA for advanced FET model construction

- Entire operating range covered
- Can measure into limiting operating regions
- Get data under realistic operating conditions

Root et al INMMiC2010 [52]
Xu et al IMS2010 [53]
Model I-V characteristics at different trap-states

\[ I_D(V_{gs}(t), V_{ds}(t), T_j, \varphi_1, \varphi_2) \]

Xu et al IMS2010 [53]

Corresponds to *drain-lag* (knee walk-out) (intrinsic)
Trap state \( \varphi_1 = -2, \varphi_2 = 8 \)

Static “Iso-thermal” intrinsic I-V
\( \varphi_1 = V_{gs}, \varphi_2 = V_{ds}, T_j = 65 \)

Measured and simulated extrinsic DC - IV

Bias-dependent small-signal admittances fit better everywhere
Nonlinear validation of advanced GaAs FET model (using NVNA data)

Xu et al IMS2010 [53]

Simulated (— )
Measured data (symbols)

With NVNA, Nonlinear validation **comes for free**
Tradeoffs

- Physical Insight
  - Physical TCAD Device Model
- Ability to Generalize
  - Physics-based Circuit Model
  - Table Model
  - X-parameter Behavioral

Ease of Use / extraction
Accuracy
Conclusions

• Physical, Empirical, Table-based, and Behavioral models (e.g. X-parameters) of transistors all have their place in device modeling

• Advanced characterization techniques and instruments (e.g. NVNA) will change the paradigm for nonlinear device modeling and validation. This is a key industry trend.

• Modeling is a rigorous and complex process. Good results take time, expertise, good measurements, and care.
References


[6] HP NMDG Group


[10] Agilent ADS manual


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[38] Martin-Guerrero et al, "Frequency domain-based approach for nonlinear quasi-static FET model extraction from large-signal waveform measurements," EuMICC Conf. 2006


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