Nonlinear Analog Behavioral Modeling of Microwave Devices and Circuits

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IEEE MTT-S DML Lecture #1
Bergen, Norway
May 7, 2010
Acknowledgement

Norway IEEE MTT/AP Chapter
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Karl-Martin Gjertsen
Marius Ubostad
Jonny Langmyren
Peter Myhrberg
Bjorn Birkeland
Riccardo Giacometti
Giovanni Damore

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Nick Tufillaro
Jan Verspecht
Jianjun Xu
John Wood
Agilent Management
Many others
Integrated Diodes

Hyperabrupt Diodes

MEMS

Liquid metal switches

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

HFTC Model & Measurement IP
analytical empirical behavioral

Agilent Measurement HW & SW IP

Agilent ADS Momentum

HFTC Fabrication & Access

Characterize (measure)

Model (predict)

Simulate (design)

Fabricate (make)

Measurement and Modeling Sciences

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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

Circuit

Device

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

Equivalent Circuit Model
“Compact Model”

Multivariate functions for \( i_1, i_2 \)

Embedding Variables

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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

Detailed Circuit Model (SPICE/ADS) of IC

Simple for Linear Ckts: S-parameters
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

**S-parameters**

\[
\begin{align*}
  b_1 &= S_{11}a_1 + S_{12}a_2 \\
  b_2 &= S_{21}a_1 + S_{22}a_2
\end{align*}
\]

### Measure with linear VNA: Small amplitude sinusoids

\[
\begin{align*}
  S_{11} & \quad \text{(Reflected)} \\
  S_{12} & \quad \text{(S 12)} \\
  S_{21} & \quad \text{(Transmitted)} \\
  S_{22} & \quad \text{(Reflected)}
\end{align*}
\]

### Model Parameters: Simple algebra

\[
S_{ij} = \frac{b_i}{a_j} \quad \text{for} \quad k \neq j
\]
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

\[ \sin(2\pi f_0 t) \]

Predict signal and harmonics (magnitude and phase) through chains of \textit{cascaded} nonlinear components under drive

- Inter-stage mismatch is important to final results
  - Can not infer these effects from VNA measurements (even “Hot S\textsubscript{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

- \( A_{1k} \)
- \( B_{1k} \)
- \( A_{2k} \)
- \( B_{2k} \)

Port Index
Harmonic Index

\[ I_1 \]

- Time

\[ I_2 \]

- Time
Nonlinear Vector Network Analyzer (NVNA) [14]:


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
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

\[ \dot{\mathbf{u}}(t) = \mathbf{f}(\mathbf{u}(t), \mathbf{x}(t)) \]

Vector of State Equations

\[ y(t) = h(\mathbf{u}(t), \mathbf{x}(t)) \]

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, \( u(t) \), 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.
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’**
  - Used for models
  - Symbols: $f_1$, $f_1 + \Delta f$

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

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

- **‘Modulation’ (CDMA)**
  - Symbols: $f_1 + \Delta f$
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)

\[ X(t) \rightarrow Y(t) \]

Stimulate / Excite System
Sufficiently complex stimulus

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

Embed:
Create auxiliary variables (represent waveform)

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

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

Fit:
Nonlinear function \( f \)
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 naïve 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

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

“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])

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

\[ v_1 = y \]

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

\[ \vdots \]

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

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

1. **Choose DUT**
2. Define range of operation
3. **Excitation Design**
   - ADS Simulation
   - NVNA Measurement
4. Read data into MATLAB
5. Choose model variables
6. **Embedding Dimension**
8. **Model Verification**
9. Create Model in ADS

**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**

**Circuit model data**

**Fundamental Gain**

\[
I_i(t) = f_i(I_i, V_1(t), V_2(t), \dot{V}_1(t), \dot{V}_2(t), V_1^{(2)}(t), V_2^{(2)}(t))
\]

19 neurons

1 - 19 GHz

229.68 seconds

11315.67 seconds

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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. NL TSA Behavioral Model Results vs. Measured 3GPP WCDMA (lower) ACLR

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

3GHz simulated
2.4GHz meas

Model is also *cascadable*
Model works in TA, HB, Envelope
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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 \[\rightarrow\] 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)

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

Concept: simplify general nonlinear spectral mapping by spectral linearization

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

Perfectly matched response

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

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

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

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

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

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

**NLTSA**
- Works in TA, HB, Envelope
- Excellent for strongly nonlinear, but lumped (low order ODE) systems
- Training non-algorithmic
- Experiment design not fully solved
- Not as robust for convergence
- Scales well with complexity
- Great gains in simulation speed

**X-Parameters**
- Frequency Domain natural for highly linear, distributed, broad-band cchts
- Experiment Design completely solved
- Highly automated Model Identification
- Works in HB & Envelope
- Very robust for convergence
- Always accurate if sampled densely
- Complexity increases rapidly for multiple tones
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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

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

\[ B_2(t) \]

\[ X_h(t) \] 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 

\[ B_{pk} = X_{pk}^{(F)} (A_{11}, A_{12}, \ldots, A_{21}, A_{22}, \ldots) \]

→ 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:

\[ \hat{B}_{21} (t) = f_{21} (\hat{B}_{20} (t), \hat{A}_{11} (t)) \]

\[ \frac{d\hat{B}_{20} (t)}{dt} = g (\left\langle \left| \hat{A}_{11} (t) \right|^2 \right\rangle , \hat{B}_{21} (t)) \]
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


