Automated Macromodel Generation for (Electronic) Systems

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Bluetooth mixed-signal RFIC

Cambridge Silicon

 OSX: Cheap ☜ Low margins ☜ Must work first time
MEMS Sensor System

- MEMS
- Analog
- Mixed-Signal
- Digital/VLSI
- RFIC/RFMEMS

- Sensor
- ADC
- Microprocessor
- Clock
- Baseband Modem
- Wireless Interface
- Antenna
- Actuator
- DAC

FE Tools
AHDL Custom IC Tools
MS-HDL Custom IC Tools
VHDL Synthesis Tools
AHDL Custom RFIC Tools

McCorquodale et al, U of Michigan

- Multiple physical domains to model
Verification Challenges

- Large entire (multi-physics) systems to verify
- Interactions between blocks, “second-order effects”
- Interconnect, coupling, noise
- Speed with SPICE-like accuracy becoming necessity
- **Impossible at SPICE level**
Today’s bottom-up design

- 3-5 spins = cutting edge; >10 at Lucent
“The primary problem hindering the change to analog top-down design and bottom-up verification has been the lack of tool support for the design process between system-level specification and transistor-level implementation, as well as between transistor implementation and chip fabrication. These missing tools are commonly referred to as The Gap.” - EE Times, 2001
Solution: **good bottom-up macromodels**
Generating Macromodels

- **Today:** *manually*

- Highly skilled activity
  - what if designer leaves?

- Mistakes (esp “second-order”)

- Time-consuming

- **Tomorrow:** myriad new technologies
  - Carbon nanotubes, spintronics, ballistic nanotransistors, photonic crystals, ...
Carbon Nanotubes
Carbon Nanotube FETs

Poor device characteristics: manual abstraction hard
Photonic Nanocrystals

Blaze Photonics

Silica (250nm)
Semiconductor Nanocrystals (4nm)

NEC

Cross Section
Pallab Bhattacharjee, UMich

Blaze Photonics

MIT

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Photonic Crystal Applications

- Optical interconnect, nano-lasers, electro-optic modulators, freq multipliers...

Joannopoulos group, MIT
More domains to macromodel at system level

Manual expertise scarce: \textcolor{red}{\textbf{general automated capability}}?
Top-down Design

McCorquodale et al, U of Michigan
Automated Macromodelling

- The dream: **push-button bottom-up model generation**
  - prescribed accuracy guaranteed
  - trade-off speed vs accuracy
- **Needed** for design sustainability
  - complexity exceeds manual ability to keep up
"At this point, you may wonder why you should bother with behavioral libraries and calibration. Why not just submit the transistor-level design to some smart software and let it come up with a model? Unfortunately, despite some claims to the contrary, practical model synthesis is still a long way off. Attempts at this technology rely on pre-existing templates, which are unlikely to exist for leading-edge or proprietary designs. There’s no pushbutton approach to analog modeling, and from all indications, this will remain the case for some time to come.” - EE Times, 2001

- Perhaps not quite so bleak!

- Automated macromodel generation is difficult
Why Difficult?

Dynamic system complexity ---->

System size ---->

Interconnect

Linear Time-Invariant (LTI)

NONLINEAR

Logic circuits

Comparators

Switching filters

Linear Time-Varying (LTV)

Mixers

DC-DC converters

PLLs, Sigma-Deltas

Oscillators

AUTONOMOUS

"Linear" amps

Passive filters

"Linear" amps

Passive filters

Dynamic system complexity ----->
Approaches to Macromodelling

- **Black-box** problems
  - samples of input-output pairs
  - measurement and/or simulation
  - paucity of information

- **Extraction (bottom-up reduction)** problems
  - Detailed circuit/system info available
  - eg, SPICE netlist: **differential equations**
  - surfeit of information
  - potential for better macromodels
Automated MM Approaches

Input–output description (eg, measurements)

Structural description (eg, SPICE netlist)

BLACK BOX APPROACHES

Multidimensional Tables

Neural networks

Genetic algorithms

Regression

Support–vector machines

EXTRACTION APPROACHES

LTI approaches

LTV approaches

Weakly nonlinear methods

Piecewise methods

Kernel–based methods

Topology morphing

Symbolic methods

Verilog/VHDL/Matlab/SPICE macromodel
Macromodelling Languages

- Output of macromodelling process
- AHDL Languages - eg, Verilog-A, VHDL-AMS
  - the EDA choice
- Matlab/Simulink
  - widely used by designers
- SPICE(?)
- Fundamentally: (integro-)differential-algebraic equations
Macromodelling Languages

Multiplicity of languages, should inter-operate
“Algorithmic” MM Approaches

- Mathematical algorithms based on theory
-Provably preserve some useful property
  - eg, moments of transfer function

- **AWE**: first prominent method (LTI)
- PVL, PRIMA, TBR methods (all LTI)
- Variety of nonlinear, LTV methods

- **Generally applicable** (eg, multi-physics)
Linear Time Invariant Systems

- **What is LTI?**
  - Scale input waveform $\Rightarrow$ scale output waveform
  - Time-shift input $\Rightarrow$ time-shift output

- **Interconnect**, “linear” circuit elements

- Well understood: 50 years of theory
  - Laplace transforms, LTI ODEs, controllability/observability,
    ...
  - Powers hand analysis by most designers
Asymptotic Waveform Evaluation

- **AWE (Pillage/Rohrer ~1990)**
- **Preserve moments** of LTI transfer function
  - frequency-domain xfer-fn derivatives
  - time-domain rise/fall time interpretations
- **Explicit moment matching**
  - calculate moments of original system
  - solve (linear matrix) equations to get small rational-function macromodel
LTI MM Accuracy/Scalability

- Increasing size does not increase accuracy
  - Explicit moment generation, Hankel-matrix-based calculation numerically ill-conditioned

- **Implicit moment matching**: Krylov-subspace methods
  - don’t calculate moments: generate related Krylov subspaces robustly (Lanczos/Arnoldi methods)
  - generate macromodels directly - moments matched implicitly

- Pade-via-Lanczos (**PVL**, Feldmann/Freund ~1994/5)
Original Linear Space

\[ E \frac{dx}{dt} = Ax + Bu(t) \]

Reduced Linear Space

\[ \hat{E} \frac{dz}{dt} = \hat{A}z + \hat{B}u(t) \]

\[ H(s) = C(sE - A)^{-1}B \]

\[ y = Cx \]

\[ \hat{H}(s) = \hat{C}(s\hat{E} - \hat{A})^{-1}\hat{B} \]

\[ x = Vz, x \in \mathbb{R}^n, z \in \mathbb{R}^q \]
LTI MM Stability/Passivity

- Interconnect: basically R, L, C elements
  - Passive: can’t generate energy

- But macromodels can!
  - small inaccuracies in MM parameters ⇒ qualitative stability problems ⇒ useless MM!
  - must preserve passivity

- Passivity for RC, RLC circuits
  - Congruence transformations (Kerns/Yang 95)
  - PRIMA (Odabasioglu/Celik/Pileggi, 97)
  - Others: PVL extensions, beyond RLC ...
LTI MM Optimality/Compactness

- **Truncated Balanced Realizations (TBR)**
  - Silveira/White et al
  - Trim internal states that are not controllable/observable
  - Provably optimal: minimizes I/O norm error for given MM size

- **But: computationally expensive**
  - cubic in original size

- **Mix and match: Krylov + TBR (Phillips et al 02)**
  - First create big (~100s) MM via Krylov
  - Use TBR to make compact MM
LTI MM Summary

- Important features
  - Accuracy vs size tradeoff
  - MM scalability
  - MM passivity

- Computational properties
  - AWE, Krylov methods linear with original size
  - TBR methods cubic (but **new results from Joel**)!

- Relatively mature and practically usable

- Basis for nonlinear approaches
Nonlinear Macromodelling

Original Nonlinear Space

\[ E \frac{dx}{dt} = f(x) + Bu(t) \]

Reduced Nonlinear Space

\[ \hat{E} \frac{dz}{dt} = \hat{f}(z) + \hat{B}u(t) \]

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Weakly Nonlinear Systems

- Distortion, IM important!
- Must capture small distortion/IM
Strong Nonlinearities

Comparators, switching mixers

- Large signal clipping
- Must capture strong nonlinearities
Polynomial Reduction

\[ E \frac{dx}{dt} = f(x_i) + A_1(x - x_i) + A_2(x - x_i)^2 + Bu(t) \]

\[ \hat{E} \frac{dz}{dt} = \hat{f}(z_i) + \hat{A}_1(z - z_i) + \hat{A}_2(z - z_i)^2 + \hat{B}u(t) \]

- Good for small distortion, Poor for large swing

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Piecewise Linear MM

\[ f(x) = f(x_1) + A_1x + f(x_2) + A_2x + f(x_3) + A_3x \]

Region: I  Region: II  Region: III

\[ E \frac{dx}{dt} = \sum w_i(x)(f(x_i) + A_ix + Bu(t)) \]
Good for small distortion, also good for large swing
Nonlinear MM Results

Transient simulation of 1s, measured on Linux/Matlab

Transmission Line (27 regions): \( u(t) = 2\sin(2\pi t) + \sin(10\pi t) \)

<table>
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<tr>
<th>Model Type</th>
<th>Model Size</th>
<th>Gen. Time [s]</th>
<th>Runtime [s]</th>
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<tr>
<td>Reduced PWL</td>
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<tr>
<td>Reduced PWP</td>
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<td>10.91</td>
</tr>
</tbody>
</table>

Cascade Amplifier (17 regions): \( u(t) = 3 + 10^{-3}(\sin(4\pi t) + \sin(10\pi t)) \)

<table>
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<tr>
<th>Model Type</th>
<th>Model Size</th>
<th>Gen. Time [s]</th>
<th>Runtime [s]</th>
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</table>
Linear Time Varying MM

- Useful abstraction for some nonlinear systems
  - mixers, switching filters, samplers, DC/DC converters, ...
  - Leverage LTI methods (Krylov, TBR, ...)
  - frequency translation/TD nonlinear sampling captured
  - signal-path nonlinearities not captured

- Input-output relationship linear
  - but not time-invariant
LTV MM on RF Mixer

- I-channel mixer and buffer block (Lucent ME W2013 RFIC)
- 360 nodes, signal up to 80KHz, LO at 178MHz
- LTV macromodel accuracy (Time-Varying Pade)
  - size 2: upconversion xfer fn matches to 300kHz
  - size 10: upconversion xfer fn matches to 400MHz!
- Speedup more than 500
Oscillators: Nonlinear MM

- Critical in communication system designs
  - VCOs, PLLs, LOs, synchronization, ....

- **Difficult for SPICE:**
  - Inaccurate + extremely time-consuming

- Complex autonomous dynamics

- Existing hand-based macromodels miss qualitative phenomena
  - *injection locking*

- **Automated nonlinear MM...**
Osc MM captures injection locking

Unlocked regime

Locked regime

65x times speedup (for 2-node ckt); much greater for bigger oscillators
Nonlinear MM Progress

- **Weak:** JR (98), JRP (99-00), Li/Pileggi (NORM, 03)
- **Strong:** Rewienski/White (99-00), Dong/JR (03)
- **LTV:** JR/JRP (97)
- **Oscillators:** Li/JR (03)

- **Pockets of progress**
  - Not comprehensive like LTI
  - General problem **very difficult**
  - Dimensionality explosion (polynomial order, # regions)
Summary/Conclusions

- Automated MM **will** become practical
  - future system designs need it
  - (still) young area, much potential

- Hard problem: no single method will solve it all
  - pockets of elegant, useful, broadly applicable mathematical methods...
  - ...plus application-specific, roll-up-your-sleeves methods
  - Need to patch together **all approaches for useful, practical solutions**
Summary/Conclusions

- Common, open, easy-to-use infrastructure important: coalesce everyone’s contributions
  - Significantly more complicated algorithms, better structuring, modularity needed
  - Open standards: avoid further balkanization of analog EDA
Summary/Conclusions

• **Litmus test:**

**Designer acceptance and involvement**

“Despite all of the benefits associated with analog top-down design, there remains a strong resistance against adopting this methodology. Many analog designers (at least so far) are content to maintain the status quo. Because most of the tools are new, many designers are unaware of their availability. This lack of awareness is further compounded by a natural resistance to change long-established procedures. Additionally, there’s a learning curve associated with the new analog tools.” - EE Times, 2001
Acknowledgments

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