Efficient Optimization of the Integrity Behavior of Analog Nonlinear Devices Using Surrogate Models

C. Gazda\textsuperscript{1}, D. Vande Ginste\textsuperscript{1}, H. Rogier\textsuperscript{1}, I. Couckuyt\textsuperscript{1}, T. Dhaene\textsuperscript{1}, K. Stijnen\textsuperscript{2} and H. Pues\textsuperscript{2}

\textsuperscript{1} Department of Information Technology (INTEC), Ghent University, Ghent, Belgium
\textsuperscript{2} Melexis Technologies N.V., Tessenderlo, Belgium
Overview

- Introduction
  - Modeling of (analog) ICs – why does it matter?
  - Surrogates – what and why?
  - State-of-the-art

- Case study: voltage regulator (VR)
  - Principle – functional and noisy behavior

- Modeling of VR
  - Model architecture
  - Surrogates – construction parameters

- Model application
  - Prediction of integrity behavior
  - Optimization of integrity behavior

- Conclusions
(Surrogate) Modeling of integrity behavior of (analog) ICs – why does it matter?

Accurate and fast (behavioral) models needed
**Surrogates**: cheap approximations of complex functions

- Good accuracy
- Short run time
- Suitable for optimization purposes
- Hide the intellectual property (IP)
Recent literature: successful techniques, based on surrogate modeling, e.g. [1], [2]

Focus was on modeling digital circuits, more specifically on the input/output buffers of ICs

Today: nonlinear analog circuits (typically susceptible to radio frequency (RF) noise)

We need to model functional AND noisy behavior


- **Voltage regulator (VR):** essential part of many ICs, provides constant and stable voltage
- Unfortunately, this analog, nonlinear circuit is susceptible to noise and interference
Case study

- Investigated circuit: nonlinear *analog* voltage regulator MLXTC883
  - → 21 transistors, 123 passive components
  - → $V_{\text{in,DC}}=5\text{V}$, $V_{\text{out,DC}}=3.3\text{V} \pm 100\text{mV}$
- When subjected to RF noise: *output voltage drops!!*

Two parameters:
- $f_{\text{noise}}$ (150 kHz – 1 GHz)
- $V_{\text{in,RF}}$ (0V – 20 V)
Behavioral model of VR with pertinent components:

- Input impedances for DC and RF noise
- DC output voltage

Model architecture
Pertinent components of model architecture
replaced by **surrogates** (mathematical models),
starting from simulation data (samples) of original netlist.
Surrogates - construction

- **Type:** artificial neural networks (ANN)
  - accurate for highly nonlinear functions

- **Measure:** 5-fold cross-validation
  - efficient model validation

- **Error function:** mean square error with weights
  - modeling process focused on crucial region
Surrogates - construction

- **Initial design:** Latin Hypercube Design
  - efficient coverage of design space

- **Sample selector:** Lola-Voronoi
  - Adaptive selection of samples (sequential design)
  - Lola (Local linear approximation): ensures high accuracy where nonlinear behavior is detected
  - Voronoi tessellation: guarantees a sufficiently dense sampling in the complete design space
Surrogates - construction

- Model properties and performance indicators:
  - 252 samples in \((f_{\text{noise}}, V_{\text{in,RF}})\) design space, obtained via Harmonic Balance analysis of the VR’s Spectre netlist, using Agilent’s Advanced Design System (ADS)
  - Cross-validation target accuracy: 0.3%
  - ANNs: 4 layers; 3 to 10 neurons per layer
  - < 5 hours on an Intel(R) Core(TM)2 Quad Q6700 CPU @ 2.67 GHz, 8 GB of RAM, and with 64-bit Windows Vista
Direct Power Injection (DPI): principle

- Place VR on a PCB together with all components necessary for its proper functioning
- Add RF noise (via bias tee) and observe behavior of VR
- Sweep noise frequency (150 kHz – 1 GHz) and noise power (0 dBm – 30 dBm):
  - If output of VR varies less than 100 mV → VR passes test
Surrogate-based behavioral model integrated into ADS

- Behavioral model
- Package model
- Scattering parameters
- Bias tee
- Optional decoupling capacitor
DPI test: no decoupling capacitor

Results:

- Behavioral model accurately predicts DPI test result, but 90 times faster!
- VR fails DPI test over large frequency range
- Extra precautions must be added
Results:

- VR performs much better during DPI test
- To cover complete test range, optimal capacitor should be found
- Behavioral model accurately verifies effectiveness of added precautions
DPI test: with optimal decoupling capacitor 100nF

Results:
- Behavioral model allows to successfully find the optimal capacitor, but 114 times faster!
- VR passes DPI test over complete frequency range
Conclusions

- Purpose of surrogate modeling:
  - Crucial to reduce total time-to-market and production costs
  - Hide your IP

- Voltage regulator:
  - Commonly used circuit with complex integrity behavior

- Surrogate-based behavioral model:
  - Allows analysis and optimization of integrity behavior of nonlinear analog circuit subjected to RF noise
  - Easy to integrate back into traditional design environment
  - Very short simulation time and excellent accuracy

- Further reading:
Thank you!!

Questions?