1A1 Modular Machine Learning for Behavioral Modeling of Microelectronic Circuits and Systems

PIs: M. Raginsky & A. Cangellaris
Students: X. Ma, N. Sevuktekin

Year 2 Allocation $96,000
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Project Definition

- Objective: theoretical foundations and modular algorithms for ML-driven design, simulation, and verification of high-complexity, multifunctional electronic systems.
- Relevance to Industry: improve time-to-market and mitigate overly pessimistic designs using ML and probabilistic modeling.

Progress

- Implementation in Matlab and Python (Tensorflow + Keras), VAE-based probabilistic generative modeling of S-parameters for interconnects with manufacturing variability
- Publications: X. Ma, M. Raginsky, A. Cangellaris, “Machine learning methodology for inferring network S-parameters in the presence of variability,” accepted to IEEE Signal and Power Integrity Workshop, 2018

Results and Significance

- Application of VAE to probabilistic generative modeling of interconnect response in the presence of manufacturing variability, with relaxed functional constraints (with X. Ma).
- Full probabilistic characterization of dc operating points of electronic circuits in the presence of variability (with N. Sevuktekin).

Future Outlook

- Develop theory and algorithms for small-signal analysis of electronic circuits in the presence of variability
- Stochastic behavioral models of components and systems = Probabilistic Programs
**VAEs for Inference of S-Parameters in the Presence of Variability**

- **Benefits**
  - A generative modeling technique: yields an explicit probabilistic model that can approximately mimic the probability distribution of the training data
  - Predicted S-parameters can be post-processed using Vector Fitting or another scheme as appropriate

- **Rationale**
  - Geometric/material properties deviate from design value due to fluctuations in manufacturing process
  - Component variability affects electrical behavior and has impact on system performance

- **Data-driven probabilistic modeling of system behavior**
  - No prior knowledge on the source of variability (e.g., unknown distribution)
  - Limited samples available corresponding to realizations of stochastic system

### Validation Example

#### Fixed parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>10</td>
<td>cm</td>
</tr>
<tr>
<td>Trace Width</td>
<td>50</td>
<td>m</td>
</tr>
<tr>
<td>Dielectric Loss Tangent</td>
<td>tan</td>
<td>0.02</td>
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</tbody>
</table>

#### Varying parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Distribution</th>
<th>Mean</th>
<th>Standard deviation (%)</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trace Spacing</td>
<td>Gaussian</td>
<td>60</td>
<td>10 (low f.) / 3 (high f.)</td>
<td>m</td>
</tr>
<tr>
<td>Substrate Height</td>
<td>Gaussian</td>
<td>40</td>
<td>Same as above</td>
<td>m</td>
</tr>
<tr>
<td>Dielectric Permittivity</td>
<td>$\varepsilon_r$</td>
<td>Gaussian</td>
<td>3.7</td>
<td>-</td>
</tr>
</tbody>
</table>
Empirical Evaluation (1/2)

blue solid: 1000 prediction samples; green dashed: 950 validation samples
Empirical Evaluation (2/2)


<table>
<thead>
<tr>
<th></th>
<th>Low frequency</th>
<th>High frequency</th>
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<tbody>
<tr>
<td>Common pole</td>
<td>VAE</td>
<td>Common pole</td>
</tr>
<tr>
<td>0.1695</td>
<td>0.1712</td>
<td>0.2854</td>
</tr>
<tr>
<td>0.2125</td>
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</table>
Summary and Future Plans

• A data-driven approach to behavioral modeling of components and systems
  o Easy sampling of stochastic behavior of interconnected modules
  o Facilitates subsequent simulation and stochastic modeling

• Opens the gateway to probabilistic programming
  o Variational Autoencoder specifies a directed graphical model, which can be coded as a probabilistic program
  o Composes well with other algorithms (e.g., Vector Fitting)

• Probabilistic characterization of dc operating points and small-signal behavior of stochastic circuits
  o Characterize the effect of component variability in terms of concentration inequalities: fluctuation of dc operating point and small-signal operating characteristic around “nominal” design points
  o Identify dependence on circuit topology, individual component characteristics