Analog and Digital combined: Mixed-Signal Design and Verification in MATLAB and Simulink

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MathWorks, Germany
Agenda

- Analog/Mixed-Signal Design Challenges
- Case Studies
  - Analog-Digital-Converter
    - Modelling on different levels of abstraction
    - Architectural Exploration
  - Digital Pre-Distortion
    - Device characterisation (transistor-level simulation, measurement)
    - Device modelling
    - Compensation algorithm development
    - Verification
- Summary
Classical Mixed-Signal Design

- Limited analog design abstractions
- Design trade-offs difficult
- No run-time analog/digital links
- Slow design iterations

Specification isolated from verification

Disconnected teams

SPECIFICATION

DESIGN

VHDL, Verilog

SPICE

PROTOTYPE

Digital Hardware

Analog Hardware

TEST & VERIFICATION
Model-Based Mixed-Signal Design

- Design & simulation speed
  - rapid construction
  - design abstractions

- Design links
  - multiple domains (analog, digital, network, …)
  - multiple tools (ModelSim, Spectre…)
  - specification and verification
  - system-level and test equipment
Simulink for Mixed-Signal Design

- Laplace transforms
- Variable step ODE solvers
- Zero crossings and discontinuities
- Feedback control loops, VCOs, PLLs, phase detectors
- Circuit-level Modeling:
  - SimPowerSystems
  - SimElectronics
- Spice Co-Simulation
Case Study: ADC Design
<table>
<thead>
<tr>
<th>Case study</th>
<th>What we’ll show</th>
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<tbody>
<tr>
<td>Analog-Digital Converter</td>
<td>Introduction to methods – sigma-delta ADC</td>
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<td>Design abstractions</td>
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<td></td>
<td>Analog/digital in same model</td>
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</table>
Ideal tool features

Wish list

Intuitive

Quick & easy to build

Analog & digital together

Fast

Data Weighted Averaging for Simulink
Marko Neitola - University of Oulu
Case study: ADC design

Purpose:
- Introduce methods using straight forward design

Design Challenge:
- Sigma-delta ADC to process AM signals around 1,600 kHz
Demo: Simulink Introduction

Simple model to illustrate concepts:

- Controlling blocks
- Time handling
- Analog and digital in same model
Demo: ADC built from (almost) scratch

Second-order sigma-delta ADC

- Rapid model construction
- Feedback
- Filter design
Demo: Circuit elements

Switched capacitor ADC
- Circuit elements
- Mixed-behavioral and circuit design
More complex ADCs & DACs possible

Improved Modeling of Sigma-Delta Modulator Non-Idealities in SIMULINK, A. Fornasari, P. Malcovati and F. Maloberti, ISCAS 2005

Modeling of Switched-Capacitor Delta–Sigma Modulators in SIMULINK, Hashem Zare-Hoseini, Izzet Kale, and Omid Shoaei, IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, 2005
Case Study: Digital Pre-Distortion
Why DPD?

- High PAPR for OFDM systems
- Standards and regulators require low leakage
- Real power amplifiers distort at higher powers
- Back-off mode very inefficient

Can we have efficiency *and* low distortion?
What is Digital Pre-Distortion?

- Power amplifier distorts signal
- Digitally pre-distort signal
- Predisortion + power amplifier = ideal result
PA and DPD modeling solutions require:

- Signal generation capabilities
- Test & measurement interfaces
- Link to transistor-level simulators (e.g. Mentor Graphics Questa ADMS)
- Powerful linear algebra tools
- Advanced signal processing capabilities
- Time domain simulation capabilities
Modeling Challenges

Device Characterization

- Generate Waveform
  - MATLAB, Simulink
- Simulate PA I&Q (transistor-level)
  - Instrument Control Toolbox
- Measure PA I&Q (physical device)
  - HDL Verifier
  - Mentor Graphics Questa ADMS

Abstract Device Modeling

- Extract Behavioural Model Parameters
  - MATLAB, Signal Processing Toolbox
- Verify Model Performance
  - HDL Verifier
  - Mentor Graphics Questa ADMS

Algorithm Development

- Extract DPD Model Parameters
  - MATLAB, Signal Processing Toolbox
- Simulate Algorithm Performance
  - Simulink, DSP System Toolbox

Physical Verification

- Verify Algorithm Performance
  - Instrument Control Toolbox
Waveform Generation

- MATLAB and extensions provide rich set of ready-to-use algorithms
  - Pre-defined
  - Parametrizable

```matlab
%% Create OFDM like waveform
Nbins = 1024; % IFFT size (number of QAM symbols)
h = modem.qammod(64); % 64-QAM for each symbol
u = zeros(Nbins*20,1); % 20 OFDM symbols
for i = 1:20
    x = randint(Nbins-1,1,64);
y = [0; modulate(h,x)];
u((i-1)*Nbins+(1:Nbins)) = ifft(y);
end
x = repmat(u, 4, 1); % repeat the waveform
% after pulse shaping
DataL = length(x);
```
Interface to Transistor-Level Simulators

- Integration of Spice-level transistor netlist simulation in system-level testbench
- Stimuli generation and result analysis in MATLAB/Simulink
**Example: Interface to Transistor-Level Simulators**

- **Device Characterization**
  - Generate Waveform
  - Simulate PA I&Q (transistor-level)
  - Measure PA I&Q (physical device)

- **Algorithm Development**
  - Abstract Device Modeling
  - Extract Behavioral Model Parameters
  - Verify Model Performance
  - Extract DPD Model Parameters
  - Simulate Algorithm Performance

- **Physical Verification**
  - Verify Algorithm Performance

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**HDL Verifier**

QPSK Modulation with Nonlinear DPD in HDL

Center Frequency: 1 GHz

**MathWorks**

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Interface to Transistor-Level Simulators

Device Characterization

- Generate Waveform
- Simulate PA I&Q (transistor-level)
- Measure PA I&Q (physical device)

Abstract Device Modeling
- Extract Behavioral Model Parameters
- Verify Model Performance

Algorithm Development
- Extract DPD Model Parameters
- Simulate Algorithm Performance
- Verify Algorithm Performance

Physical Verification

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Co-Simulation with Analog Simulators

via 3rd party solution:

- Cadence
  - OrCAD SLPS
  - Virtuoso AMS Designer Simulink Integrator

- Mentor Graphics
  - Questa ADMS
Interfacing to Test & Measurement Equipment

- Typical lab setup for device characterization

- **Generate Waveform**
- **Simulate PA I&Q** (transistor-level)
- **Measure PA I&Q** (physical device)

**Device Characterization**

- **Abstract Device Modeling**
  - Extract Behavioral Model Parameters
  - Verify Model Performance

- **Algorithm Development**
  - Extract DPD Model Parameters
  - Simulate Algorithm Performance

- **Physical Verification**
  - Verify Algorithm Performance

- **RF Power Meter**
- **Spectrum Analyzer**
- **Signal Generator**
- **Base Station Power Amplifier**
- **MATLAB**
Interfacing to Test & Measurement Equipment

- Equipment setup, e.g. waveform download to signal generator
- Execution control
- Upload of measurement results

%% Download signal
% Separate out the real and imaginary data in the IQ Waveform
wave = [real(IQData); imag(IQData)];
wave = wave(:)';  % transpose the waveform

% Write the data to the instrument
n = size(wave);
disp(sprintf('Starting Download of
binblockwrite(deviceObject,wave,'ui
fprintf(deviceObject,'');
disp('...done!');

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Behavioural Modeling of RF Amplifiers

- Memory polynomial model\(^1\) used

\[ y_{MP}(n) = \sum_{k=0}^{K-1} \sum_{m=0}^{M-1} a_{km} x(n-m) |x(n-m)|^k \]

- \(K = \) order of the model, \(M = \) memory depth

- Only diagonal terms considered

Behavioural Modeling of RF Amplifiers

Abstract

Device Modeling

Extract Behavioural Model Parameters

Verify Model Performance

MATLAB code for solving for \( a \):

\[
\begin{align*}
    y_{MP}(n) &= \sum_{k=0}^{K-1} \sum_{m=0}^{M-1} a_{km} x(n-m)x(n-m)^k \\
    \begin{bmatrix}
        y_n \\
        y_{n+1} \\
        \vdots \\
        y_{n+p}
    \end{bmatrix} &= 
    \begin{bmatrix}
        x(n) & x(n-1) & \cdots & x(n-M+1)x(n-M+1)^{K-1} \\
        x(n+1) & x(n+1-1) & \cdots & x(n-M+2)x(n-M+2)^{K-1} \\
        \vdots & \vdots & \ddots & \vdots \\
        x(n+p) & x(n+1+p) & \cdots & x(n-M+1+p)x(n-M+1+p)^{K-1}
    \end{bmatrix} \begin{bmatrix}
        a_{00} \\
        a_{01} \\
        \vdots \\
        a_{K-1,M-1}
    \end{bmatrix} + 
    \begin{bmatrix}
        \varepsilon_n \\
        \varepsilon_{n+1} \\
        \vdots \\
        \varepsilon_{n+p}
    \end{bmatrix}
\end{align*}
\]

- MATLAB code for solving for \( a \):

\[
\text{>> a_coef = x_terms \backslash y;}
\]

- "\" operator calculates LMS solution.
Behavioural Modeling of RF Amplifiers

- Verifying match between measured data and model response
DPD Algorithm Development & Verification

- Power amplifier model is:
  \[ y_{MP}(n) = \sum_{k=0}^{K-1} \sum_{m=0}^{M-1} a_{km} x(n-m)x(n-m)^k \]

- We want the reverse, which is:
  \[ x(n) = \sum_{k=0}^{K-1} \sum_{m=0}^{M-1} a_{km} y(n-m)y(n-m)^k \]

- DPD + PA = Ideal
DPD Algorithm Development & Verification

Same MATLAB code as before:

- Parameters fit by:

  ```matlab
  >> a_coef = x_terms \ y;
  ```

- Model results given by:

  ```matlab
  >> y = x_terms * a;
  ```
DPD Algorithm Development & Verification

- Time-based simulation model
HW-based Algorithm Verification

Physical Verification

Verify Algorithm Performance

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Summary
Model-Based Mixed-Signal Design

- **Design & simulation speed**
  - rapid construction
  - design abstractions

- **Design links**
  - multiple domains (analog, digital, ...)
  - multiple tools (ModelSim, Spectre...)
  - specification and verification
  - system-level and test equipment
# Products mentioned

<table>
<thead>
<tr>
<th>Product name</th>
<th>What it does</th>
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<tbody>
<tr>
<td>MATLAB</td>
<td>Algorithms, analysis, visualization</td>
</tr>
<tr>
<td>Simulink</td>
<td>System simulation and design</td>
</tr>
<tr>
<td>SimPowerSystems</td>
<td>Behavioral circuit models</td>
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<tr>
<td>Instrument Control Toolbox</td>
<td>Linking behavioral models to test &amp; measurement</td>
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<tr>
<td>HDL Verifier</td>
<td>Co-simulation link to 3\textsuperscript{rd} party HDL simulators (e.g. Mentor Graphics ModelSim, Questa ADMS, Cadence Incisive)</td>
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Some customers…

<table>
<thead>
<tr>
<th>Customer</th>
<th>Use case</th>
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<tbody>
<tr>
<td>Atmel</td>
<td>RF Front End for DVB</td>
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<tr>
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<td>Analog-digital co-design and verification</td>
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<td>IDT-Newave</td>
<td>Audio chipset</td>
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<td>Rapid simulation of PLLs</td>
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<td>Realtek</td>
<td>Voiceband codec</td>
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<td>Analog-digital design</td>
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<tr>
<td>RFMD</td>
<td>Video transceiver</td>
</tr>
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<td>System-level/SPICE cosimulation</td>
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<tr>
<td>Fujitsu</td>
<td>40 Gbit/s Serdes</td>
</tr>
<tr>
<td></td>
<td>Rapid system simulation</td>
</tr>
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More Information

- Internet:  
  http://www.mathworks.de/

- Mixed-Signal Library:  
  http://www.mathworks.de/programs/mixed-signal/

- Contact us:  
  - contact@MathWorks.de  
  - Your local Sales Representative
Questions?
Thank you!