Towards a Complete Behavioral Modeling Framework for Mixed-Signal Devices: Presenting the D-parameters

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Motivation: The need for Mixed-Signal Instrumentation

- Metrics used for single converters – ADCs and DACs
  - DNL
  - INL
  - Hysteresis
- However, these metrics have no direct interpretation in the microwave field
- There is no direct tool to understand the real impact of these non-idealities on the overall SDR performance
Motivation: The need for Mixed-Signal Instrumentation

- The industry direction for the future is integration
- For entire SDRs integrated in a single IC, it is impossible to measure the only-analog blocks apart from the mixed-signal ones
Motivation: The need for Mixed-Signal Instrumentation

• It is mandatory to develop models capable of describe the linear and nonlinear behavior of any mixed-signal system or device
Motivation: The need for Mixed-Signal Instrumentation

- Available instrumentation for mixed-signal devices…
  - Not much!!!
- The Mixed-Signal oscilloscope allows to observe at the same time digital and analog signals
  - But, it is not oriented for characterization
- Suitable measurement methods are essential to extract models
Motivation:
The need for Mixed-Signal Instrumentation

- Available instrumentation for mixed-signal devices...
- Not much!!!
- The Mixed-Signal oscilloscope allows to observe at the same time digital and analog signals...
- But, it is not oriented for characterization.
- Suitable measurement methods are essential to extract models.

There is no solution in the Instrumentation industry portfolio to characterize in a fast and simple way Mixed-Signal devices or radios.
The Vision of a NEW Instrument

In short...

• This intends to be the base of a new instrument for SDRs and Mixed-Signal Devices

• It should enable to direct and easily:
  • Test their linear and nonlinear performance
  • Retrieve microwave related metrics
  • Extract a trustable model for simulation
The general Mixed-Signal device

- An analog-to-digital or digital-to-analog converter
  - Plus analog subsystems
- It is always have (at least):
  - One analog input/output
  - One CLK input
  - One digital input/output
Analysis approaches

- Signal Integrity approach

- System-level approach
Analysis approaches

D-parameters approach

- System-level approach
How to interpret the digital bus?

• Each digital word represents a voltage value

$$StateValue(t) = bit_N(t) \cdot 2^{(N-1)} + bit_{N-1}(t) \cdot 2^{(N-2)} + \ldots + bit_3(t) \cdot 2^2 + bit_2(t) \cdot 2^1 + bit_1(t) \cdot 2^0$$

• Creating an hypothetical wave over time

$$V_{dig}(t) = \frac{StateValue(t) \times V_{ppFullScale}}{2^N - 1}$$

BinaryValue(t) = bit_4(t) \cdot 2^3 + bit_3(t) \cdot 2^2 + bit_2(t) \cdot 2 + bit_1(t)$$
How to interpret the digital bus?

• But what is the characteristic impedance of the digital port?
  
• The same of the analog port will be used
  
• \( Z_{0\text{ digital}} = Z_{0\text{ analog}} \)
How to interpret the digital bus?

- $Z_{0\,\text{digital}} = Z_{0\,\text{analog}}$
- That results in the following:

$$da_3 = \frac{V_{\text{dig}}}{\sqrt{Z_{0\,\text{analog}}}} \text{, only in transmitter mode}$$

$$db_3 = \frac{V_{\text{dig}}}{\sqrt{Z_{0\,\text{analog}}}} \text{, only in receiver mode}$$
Formulating the Model

- Linear Formulation

\[ D_{31} \equiv S_{21} \]

\[ D_{11} \equiv S_{11} \]

\[ D_{13} \equiv S_{12} \]
Formulating the Model

- Linear Formulation

\[
D_{11}(\omega) = S_{11}(\omega) = \frac{b_1(\omega)}{a_1(\omega)} \bigg|_{a_2=\tilde{\alpha}, da_3=0}
\]

\[
D_{31a_2CLK}(\omega) = \frac{db_3(\omega)}{a_1(\omega)} \bigg|_{a_2=\tilde{\alpha}, da_3=0}
\]

\[
D_{13a_2CLK}(\omega) = \frac{b_1(\omega)}{da_3(\omega)} \bigg|_{a_2=\tilde{\alpha}, a_1=0}
\]

\[
D_{33}(\omega) = 0
\]

Where \( \tilde{\alpha} \) is the CLK complex waveform value

- Parameters extracted for a specific CLK condition
Formulating the Model

- Nonlinear formulation…
- Nonlinear distortion can be monitored as the generation of spectrum components (that are not included in the input)
Formulating the Model

- Nonlinear Formulation…
- Based on the Poly-Harmonic Distortion (PHD) theory
- Nonlinear 2-ports

\[ B_{pm} = D_{pm}^F A_{11} |P|^m + \sum_{qn} D_{pm;qn}^S A_{11} |P|^{m-n} A_{pm;qn} \]

\[ + \sum_{qn} D_{pm;qn}^T A_{11} |P|^{m+n} \text{conj}(A_{pm;qn}) \]

- Nonlinear multi-port (CLK signal included)

\[ B_{p[m,h]} = D_{p[m,h]}^F (|A_{in[1,0]}|, |A_{clk[1,0]}|) P_{1,0}^m + \sum_{q[n,k]} \left\{ D_{p[m,h];q[n,k]}^S (|A_{in[0,1]}|, |A_{clk[1,0]}|) P_{1,0}^{m-n} A_{p[m,h];q[n,k]} \right\} \]

\[ + \sum_{q[n,k]} \left\{ D_{p[m,h];q[n,k]}^T (|A_{in[0,1]}|, |A_{clk[1,0]}|) P_{1,0}^{m+n} \text{conj}(A_{p[m,h];q[n,k]}) \right\} \]
Formulating the Model

- Nonlinear Formulation problems:
- There are a large number of characterization tones that contain no information
  - For example in the digital port that only as a representation until $f_s/2$
The actual instrument
The actual instrument

- How the currently prototype looks like…
- Based on a National Instruments PXI system
Calibration requirements

• To individually know the $e_{01}$ and $e_{10}$ error terms an approach similar to the absolute calibration scheme used on NVNAs was used
  • Short + Open + Load (SOL)
  • Absolute Thru → Absolute Phase Calibration through the use of a Comb Generator

Why it is required?
Because phase relationship between frequencies and from analog to digital domains have to be known
Comb Generator Design

- Design based on digital ECL – fast rise and fall times
- Low-cost solution
- Good performance until 4GHz – at least
Comb Generator Design

- Design based on digital ECL – fast rise and fall times
- Low-cost solution

Comb Generator Design: Winner of…

Best Student Paper Award on 6th Congress of Portuguese Committee of URSI

2nd place on IMS2013 SDC-LSNA Student Design Competition
Application Examples

• Examples from components of a complete transmitter:
Application Examples
RF DAC – Linear approach

Magnitude and phase of $D_{11}$
(Completely analog relationships)

Magnitude of $D_{13}$
For different operation modes and CLK frequencies
Application Examples
DAC + PA – Nonlinear approach

- Magnitude of some kernels over input power
- Kernels relating the output fundamental at different Nyquist Zones with the input fundamental
Application Examples
DAC + PA – Nonlinear approach

- Magnitude of some kernels over input power
- Kernels relating the output 2\textsuperscript{nd} and 3\textsuperscript{rd} harmonics with the input fundamental
  - Visible growth with the increase on input power
Application Examples
ADC – Linear approach

Magnitude and phase of $D_{11}$
(Completely analog relationships)

Magnitude and Group Delay of $D_{31}$
Group Delay measured matches the datasheet value for the employed CLK frequency
Conclusions

- A complete framework for characterizing mixed-signal devices was successfully developed
  - For both SoCs and full discrete component systems
- This type of characterization is of fundamental importance, not only for SDR system designers
  - And also for DPD designers for PA optimization
- In short… the D-parameters framework was presented, instrumentation for its extraction was discussed, and some examples were given to show the importance of the proposed approach
Thank you!!!