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ANACOM AUTORIDADE NACIONAL DE COMUNICAÇÕES

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

Diogo Ribeiro (IT-UA)
Pedro Cruz (IT-UA)
Nuno B. Carvalho (IT-UA)

INSTITUIÇÕES ASSOCIADAS:

INSTITUTO SUPERIOR TÉCNICO

Faculdade de Ciências e Tecnologia da Universidade de Coimbra

universidade de aveiro

PT Inovação

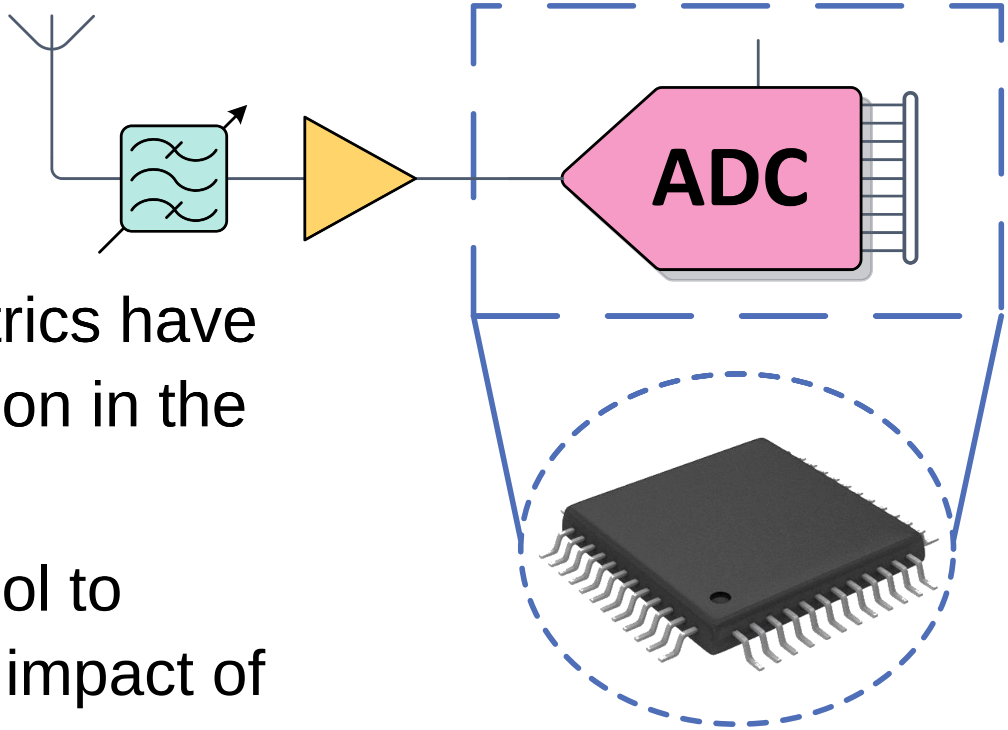
SIEMENS Communications

it instituto de telecomunicações

creating and sharing knowledge for telecommunications

Motivation:
The need for Mixed-Signal Instrumentation

- Metrics used for single converters – ADCs and DACs
  - DNL
  - INL
  - Hysteresis

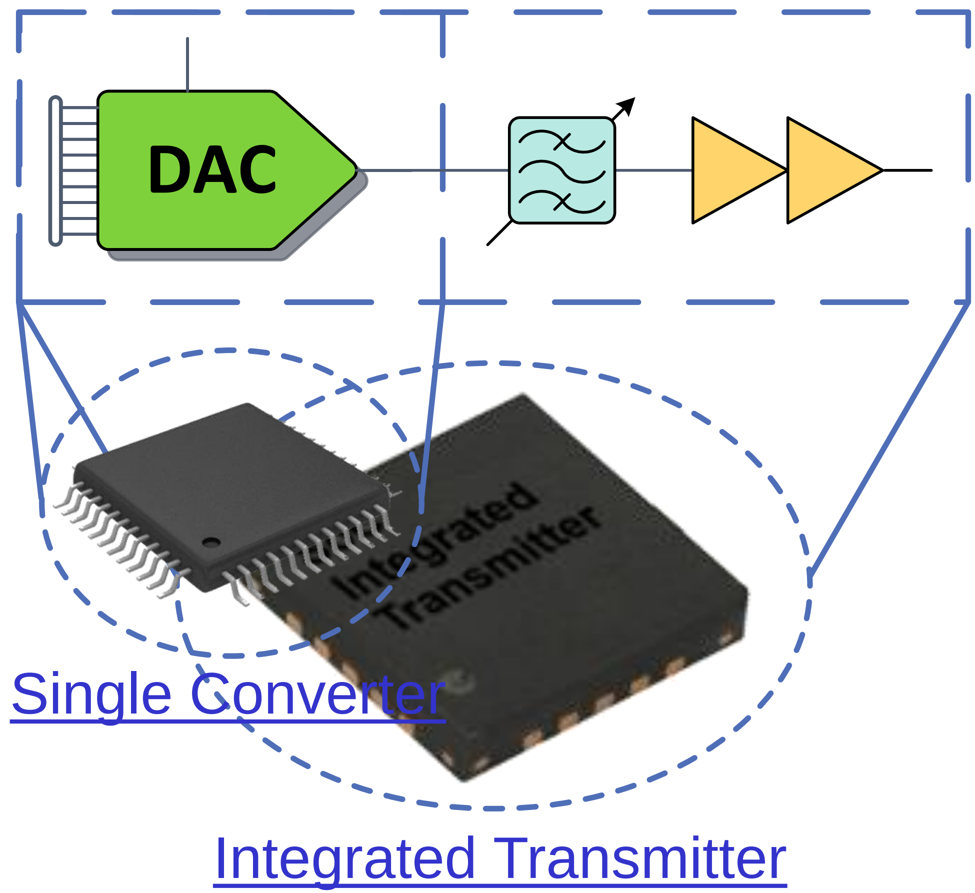


Single Converter

- 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

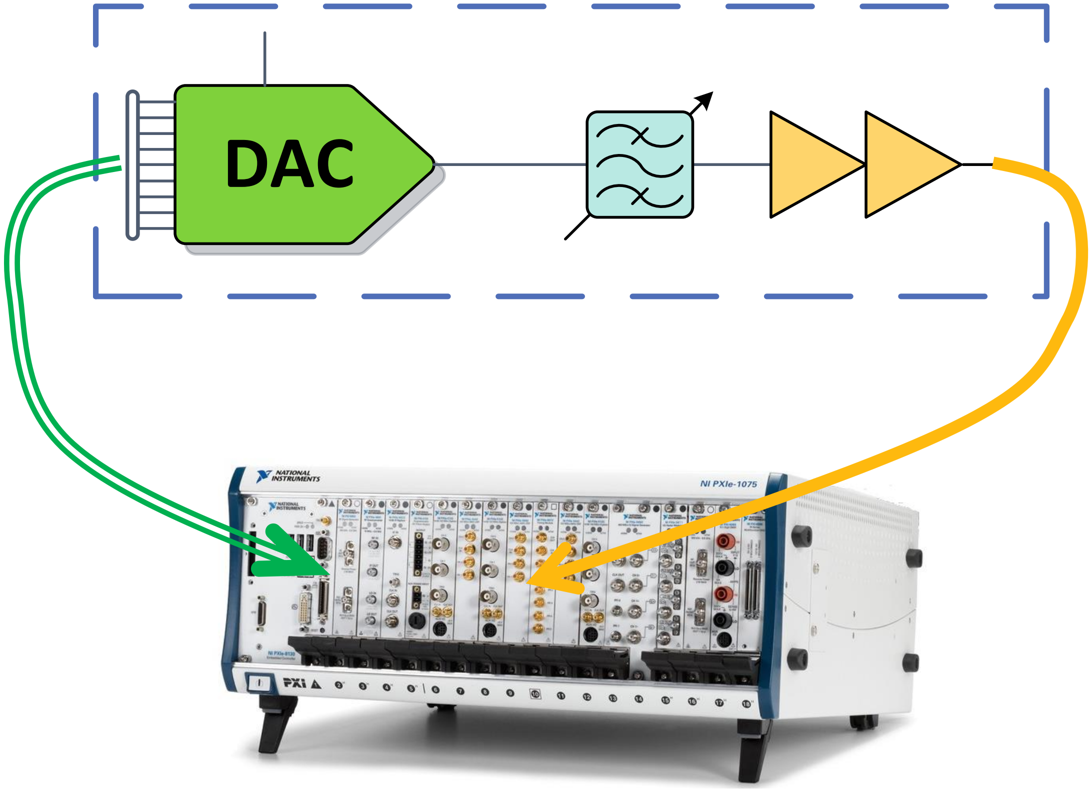
Motivation:
The need for Mixed-Signal Instrumentation

- 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



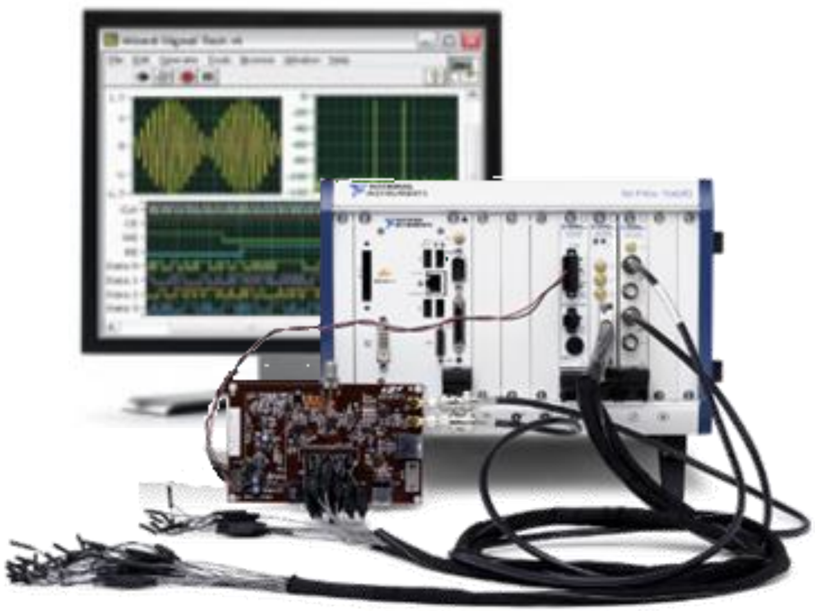
Motivation:
The need for Mixed-Signal Instrumentation

- 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
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There is no solution in the Instrumentation industry portfolio to characterize in a fast and simple way Mixed-Signal devices or radios

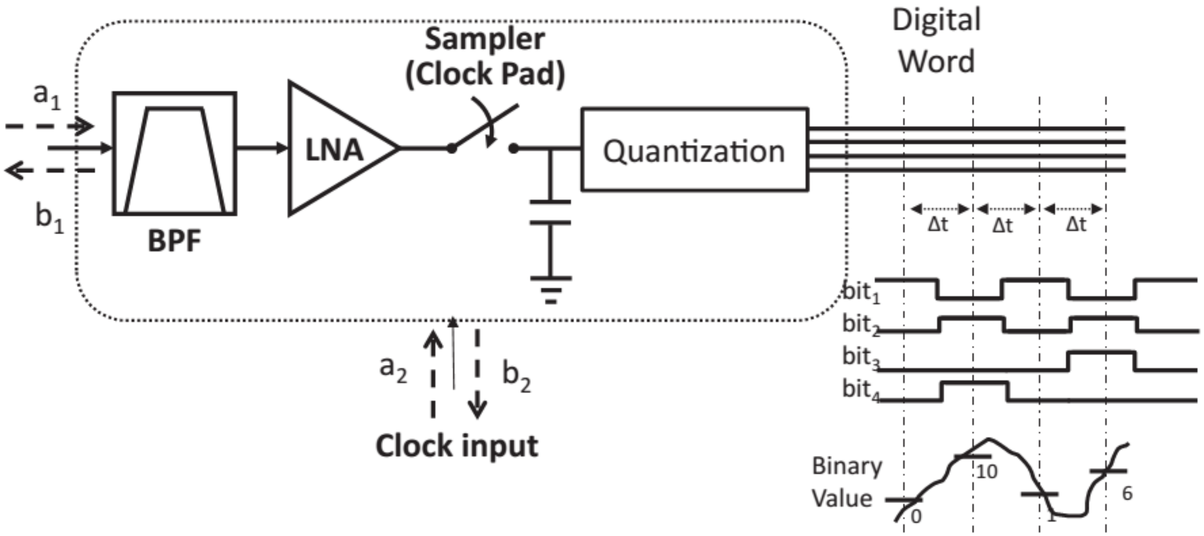
The Vision of a NEW Instrument

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**

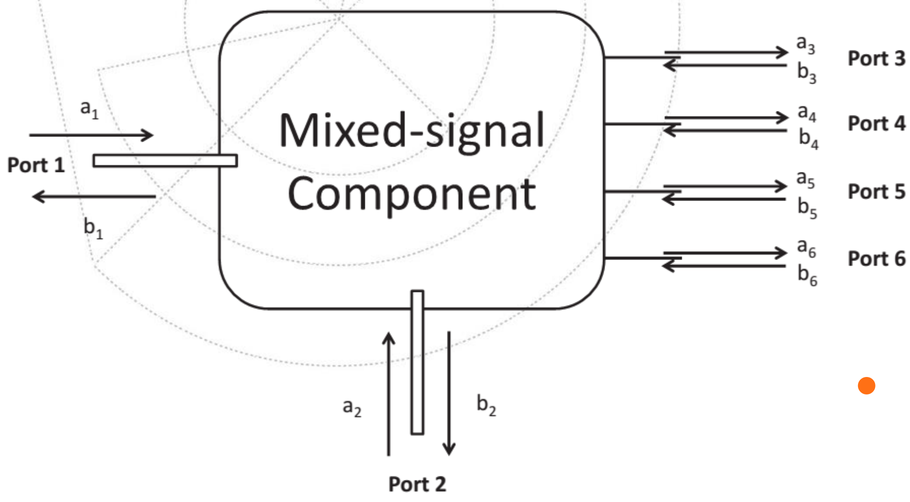
The general Mixed-Signal device

- 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

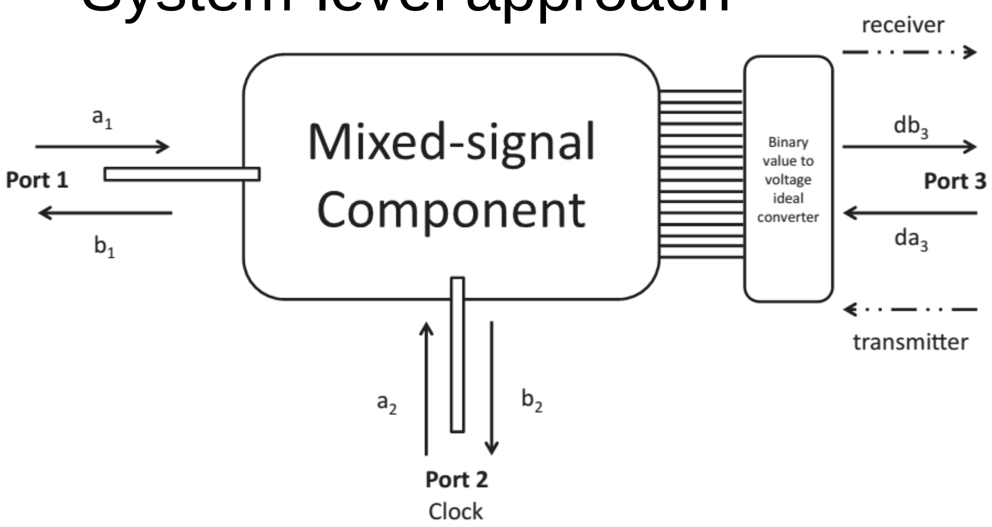


Analysis approaches

- Signal Integrity approach



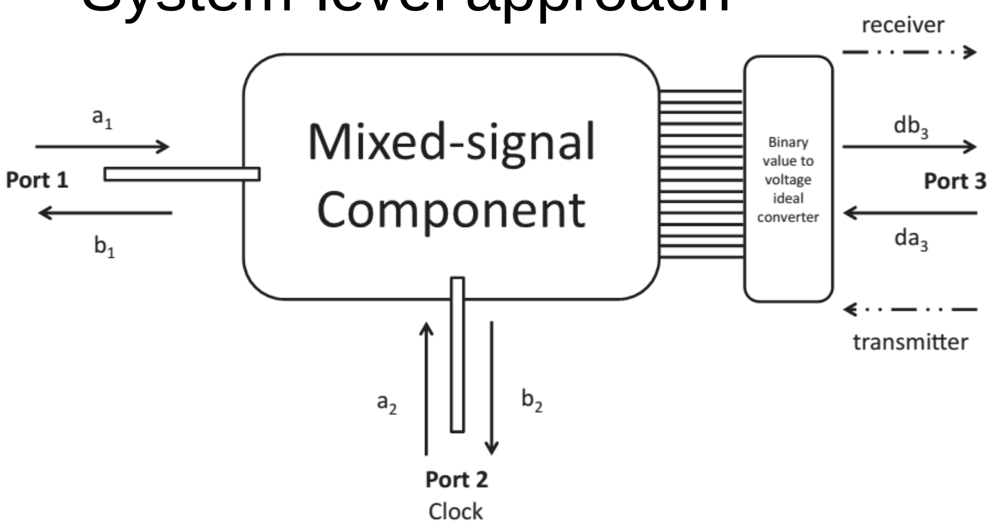
- System-level approach



Analysis approaches

D-parameters approach

- System-level approach



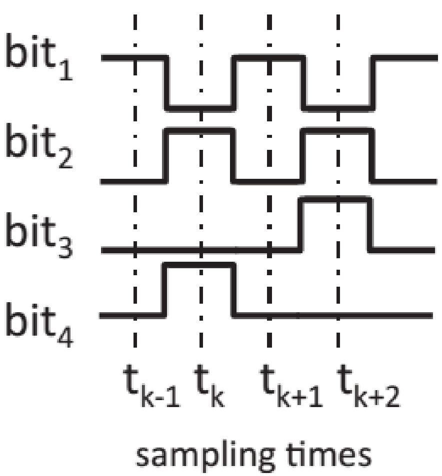
How to interpret the digital bus?

- Each digital word represents a voltage value

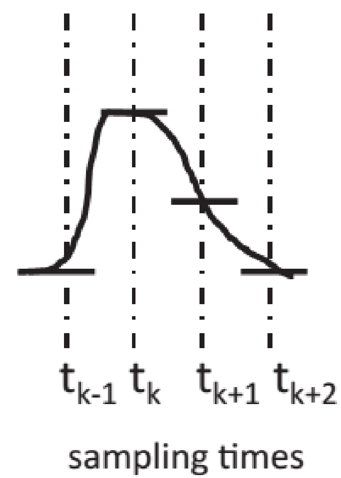
$$StateValue(t) = bit_N(t)\,2^{(N-1)} + bit_{N-1}(t)\,2^{(N-2)} + \ldots$$
$$+ bit_3(t)\,2^2 + bit_2(t)\,2^1 + bit_1(t)\,2^0$$

- Creating an hypothetical wave over time

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

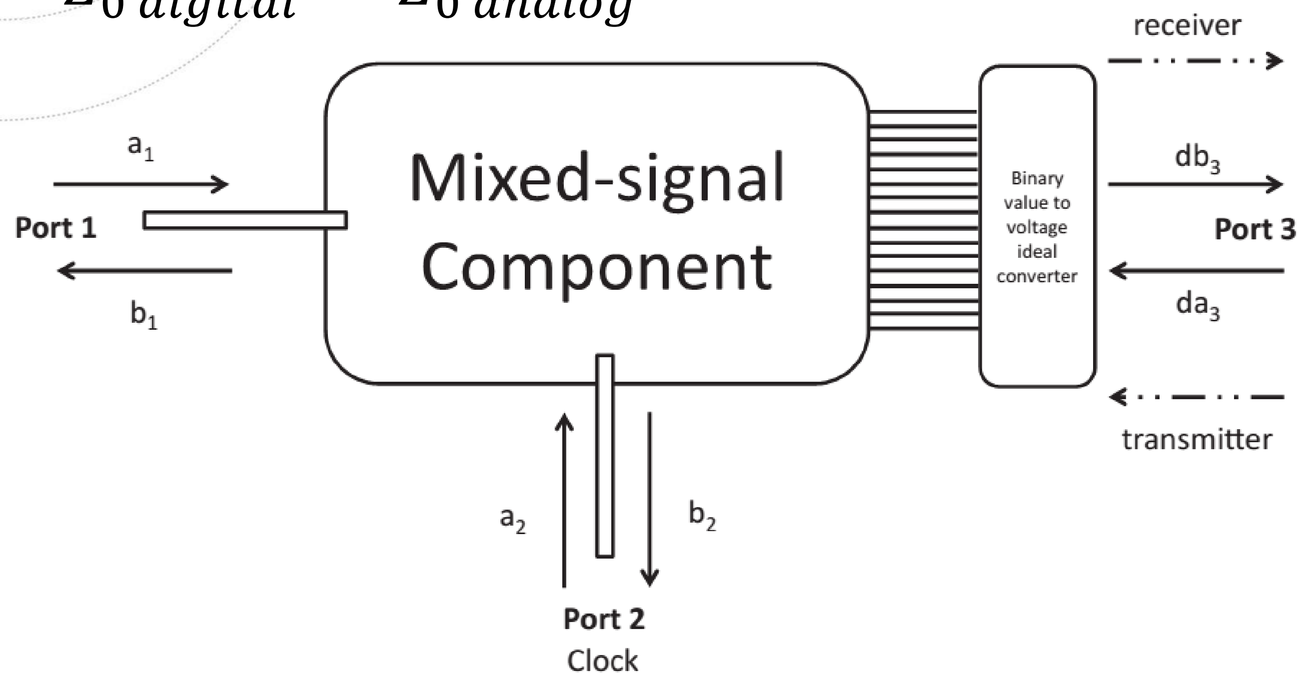


$$BinaryValue(t) = bit_4(t)2^3 + bit_3(t)2^2 + bit_2(t)2 + bit_1(t)$$



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
  - $Z_{0\,digital} = Z_{0\,analog}$

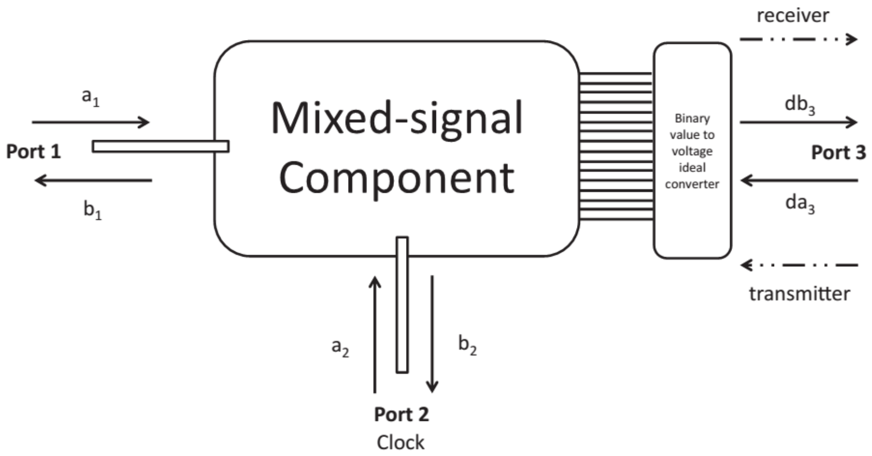


How to interpret the digital bus?

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

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

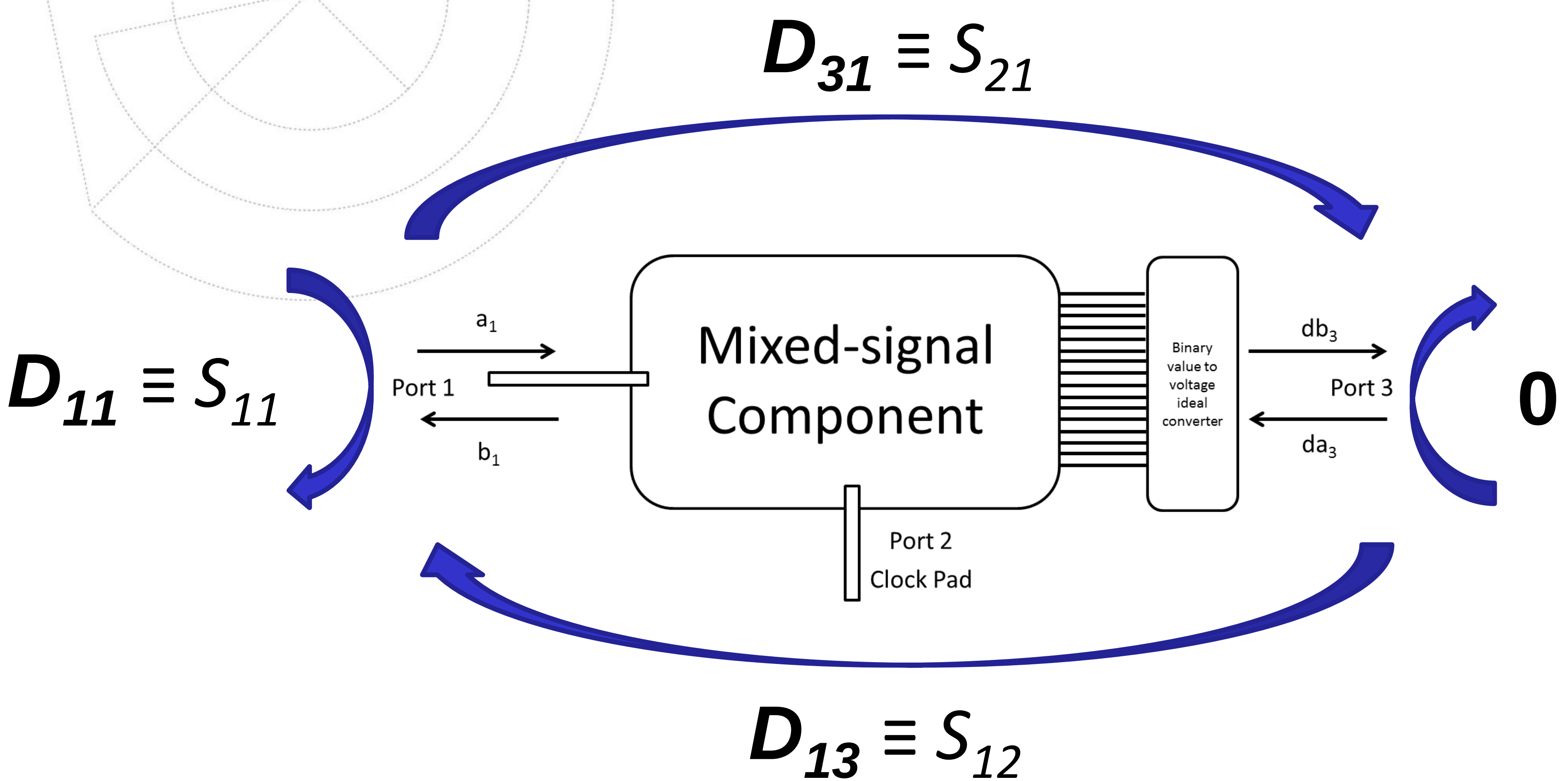
$$db_3 = \frac{V_{dig}}{\sqrt{Z_{0\,analog}}} \text{, only in receiver mode}$$



Formulating the Model

D-parameters

- Linear Formulation



Formulating the Model

D-parameters

- Linear Formulation

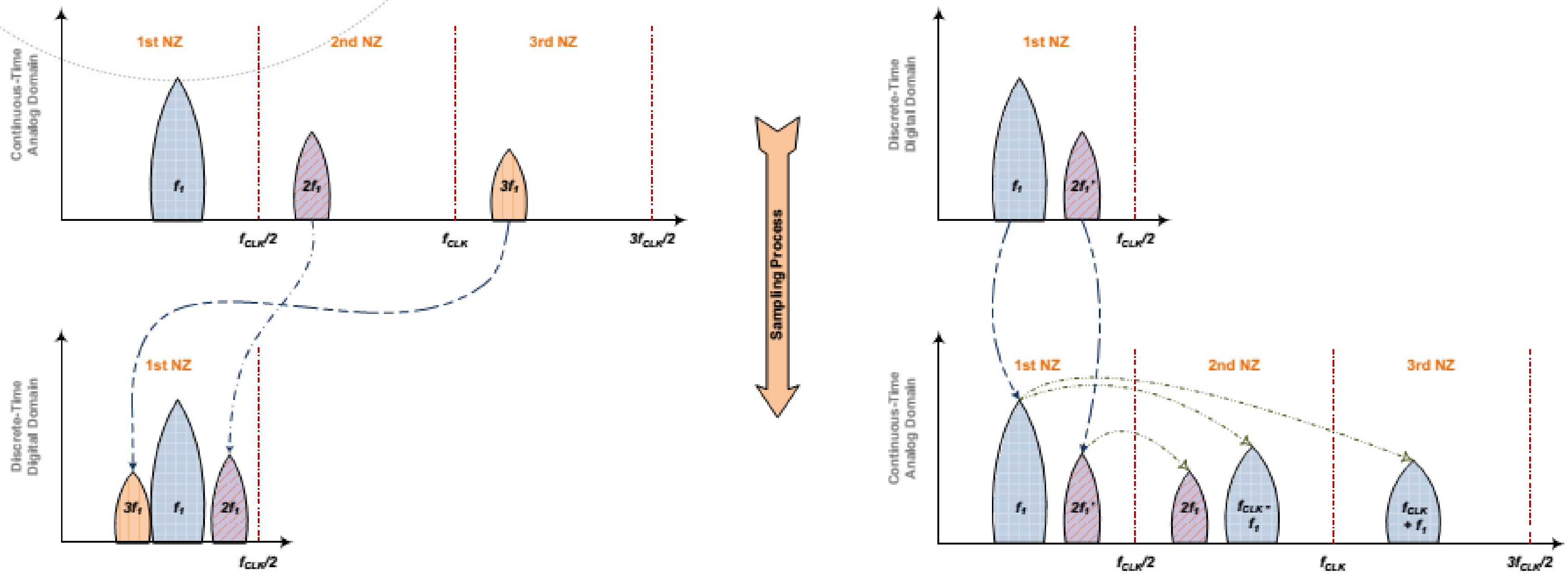
$$\begin{bmatrix} D_{11}(\omega) = S_{11}(\omega) = \left.\frac{b_1(\omega)}{a_1(\omega)}\right|_{a_2=\tilde{\alpha}, da_3=0} \\ D_{31_{a2CLK}}(\omega) = \left.\frac{db_3(\omega)}{a_1(\omega)}\right|_{a_2=\tilde{\alpha}, da_3=0} \\ D_{13_{a2CLK}}(\omega) = \left.\frac{b_1(\omega)}{da_3(\omega)}\right|_{a_2=\tilde{\alpha}, a_1=0} \\ D_{33}(\omega) = 0 \end{bmatrix}$$

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

D-parameters

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

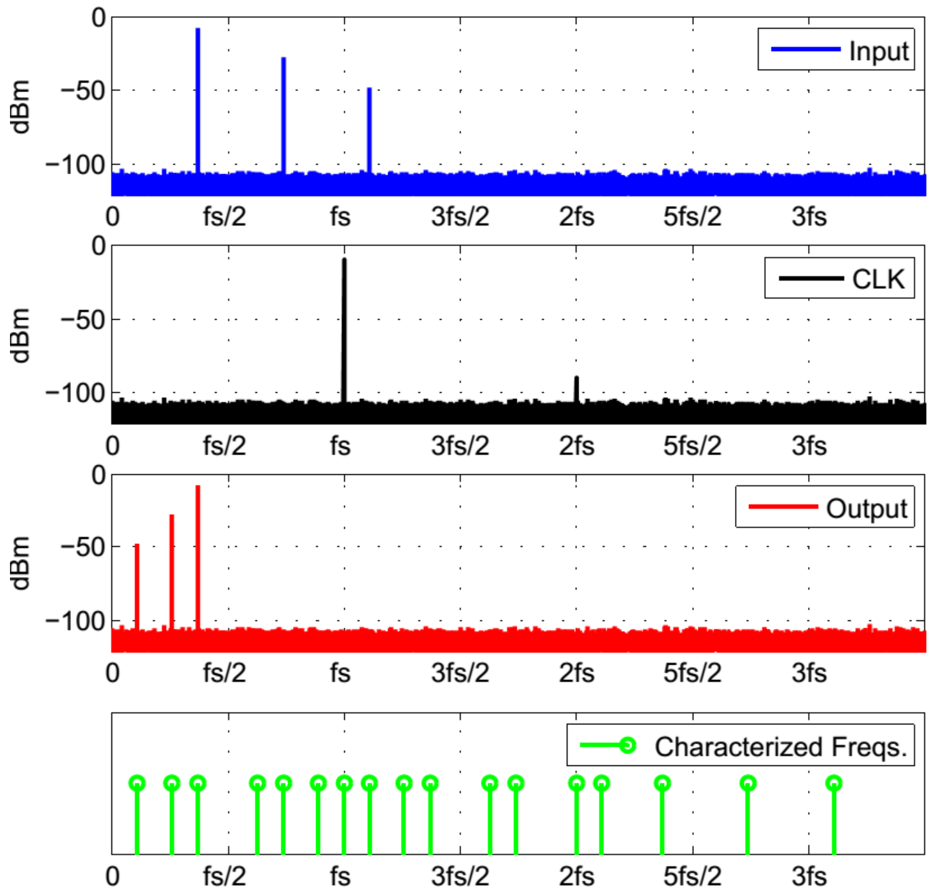
$$B_{pm} = D^F_{pm}|A_{11}|P^m + \sum_{qn} D^S_{pm;qn}\,|A_{11}|\,P^{m-n}\,A_{pm;qn} + \sum_{qn} D^T_{pm;qn}\,|A_{11}|\,P^{m+n}\,\mathrm{conj}(A_{pm;qn})$$

- Nonlinear multi-port (CLK signal included)

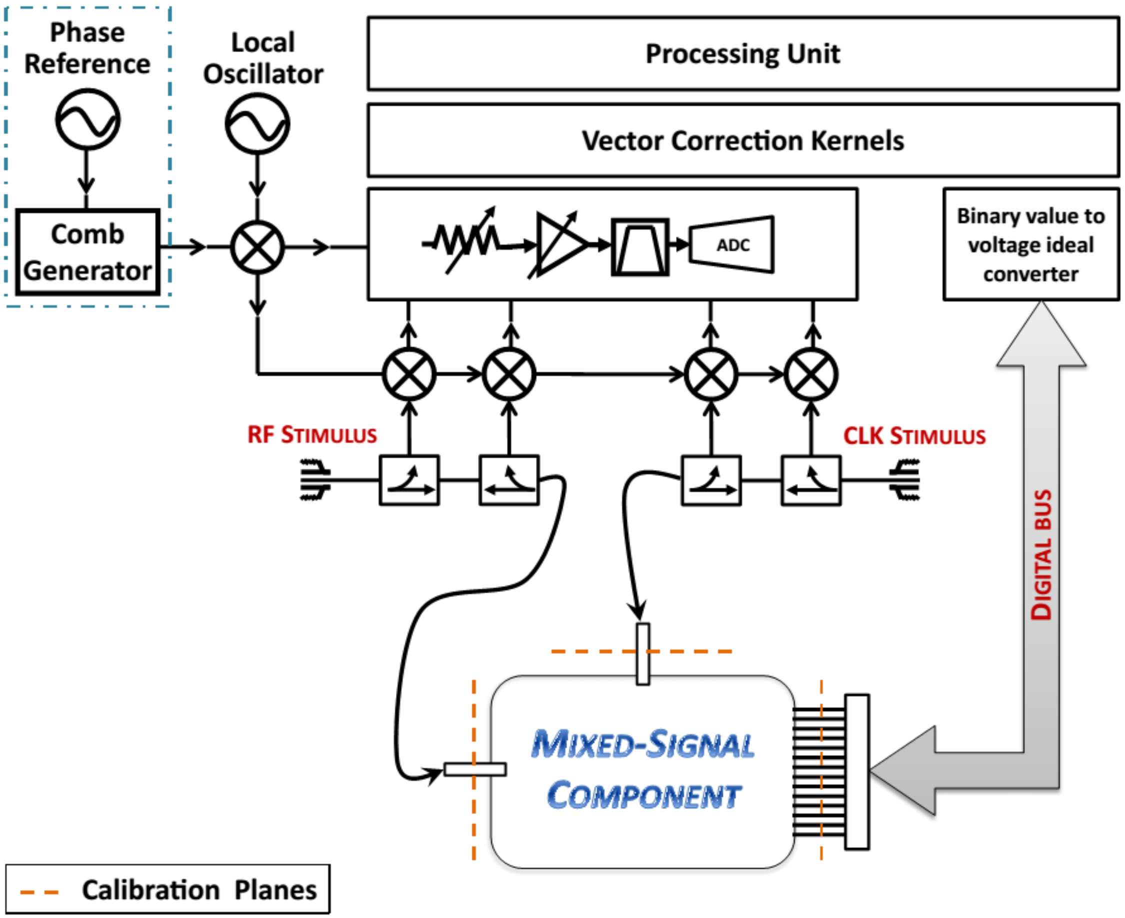
$$B_{p[m,h]} = D^F_{p[m,h]}(|A_{in[1,0]}|, |A_{clk[0,1]}|)P^m_{[1,0]} + \sum_{q[n,k]} \left\{ D^S_{p[m,h];q[n,k]}\,(|A_{in[0,1]}|, |A_{clk[1,0]}|)\,P^{m-n}_{[1,0]}\,A_{p[m,h];q[n,k]} \right\} + \sum_{q[n,k]} \left\{ D^T_{p[m,h];q[n,k]}\,(|A_{in[0,1]}|, |A_{clk[1,0]}|)\,P^{m+n}_{[1,0]}\,\mathrm{conj}(A_{p[m,h];q[n,k]}) \right\}$$

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 $f_S/2$

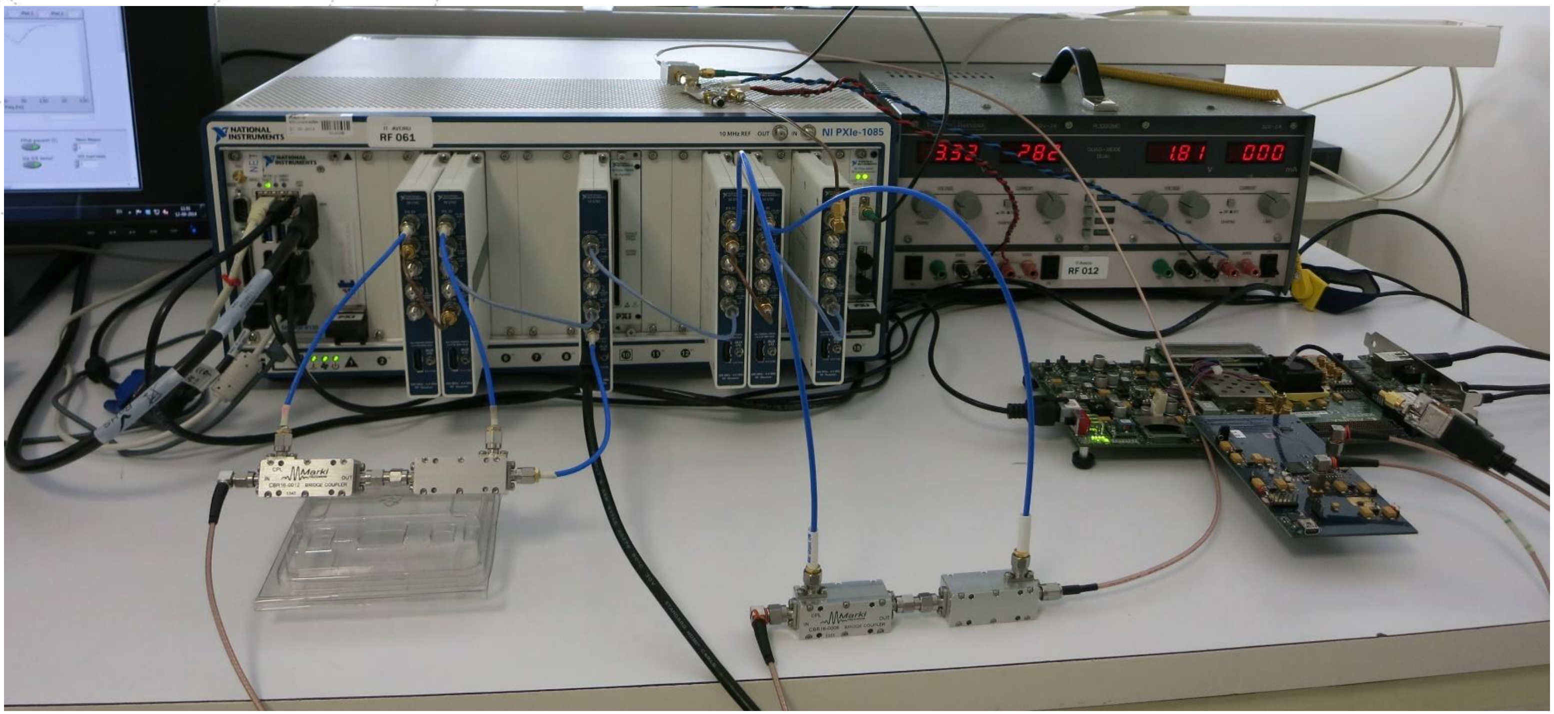


The actual instrument



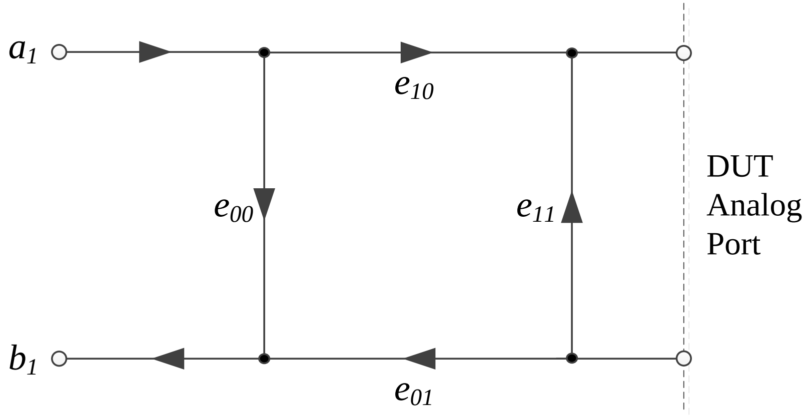
The actual instrument

- 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

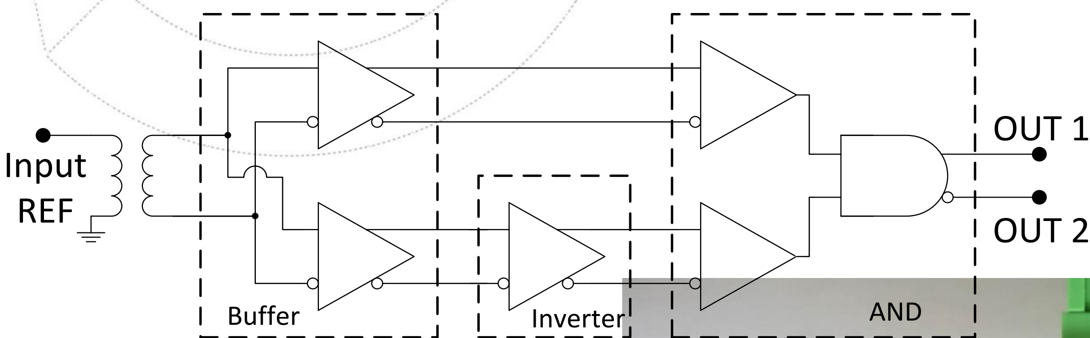


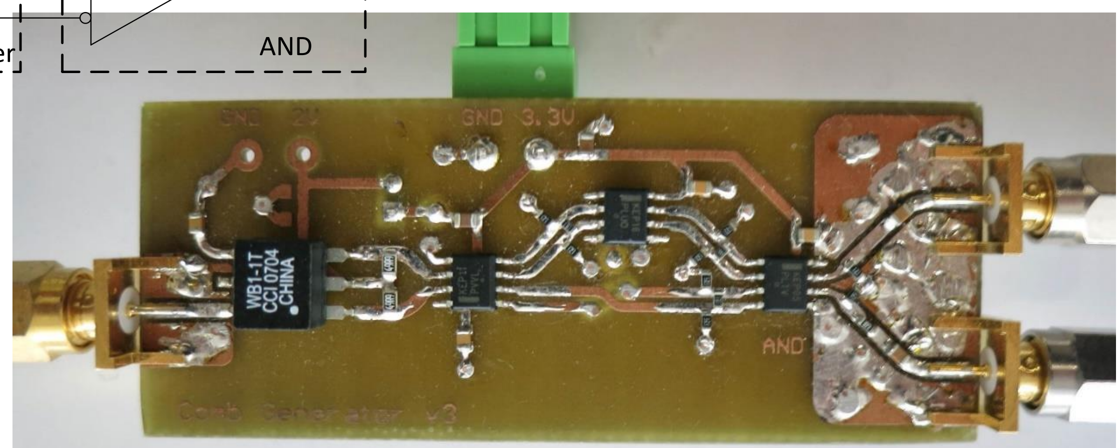
Why it is required?

Because phase relationship between frequencies and from analog to digital domains have to be known

Comb Generator Design

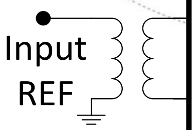
- Design based on digital ECL – fast rise and fall times
- Low-cost solution
- Good performance until 4GHz – at least





Comb Generator Design

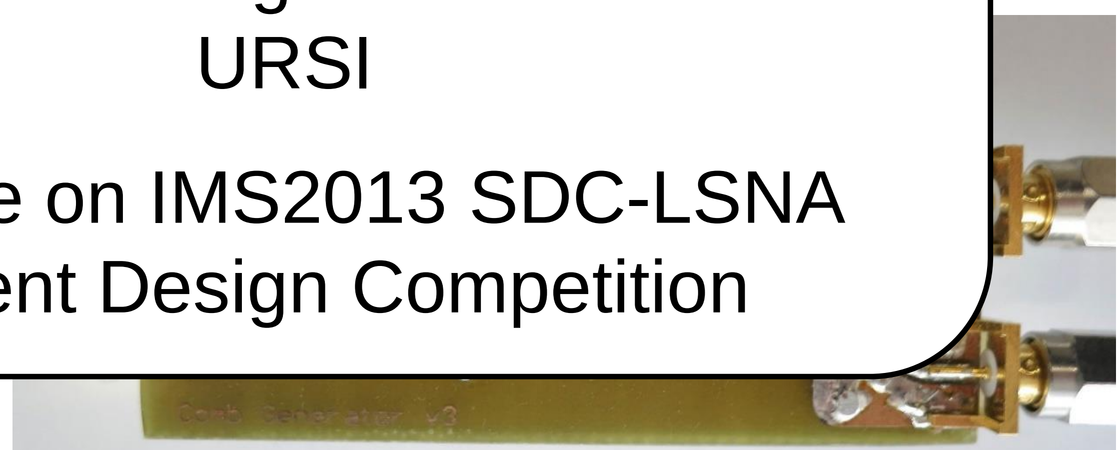
- Design based on digital ECL – fast rise and fall times
- Low-cost solution
-



Comb Generator Design: Winner of…

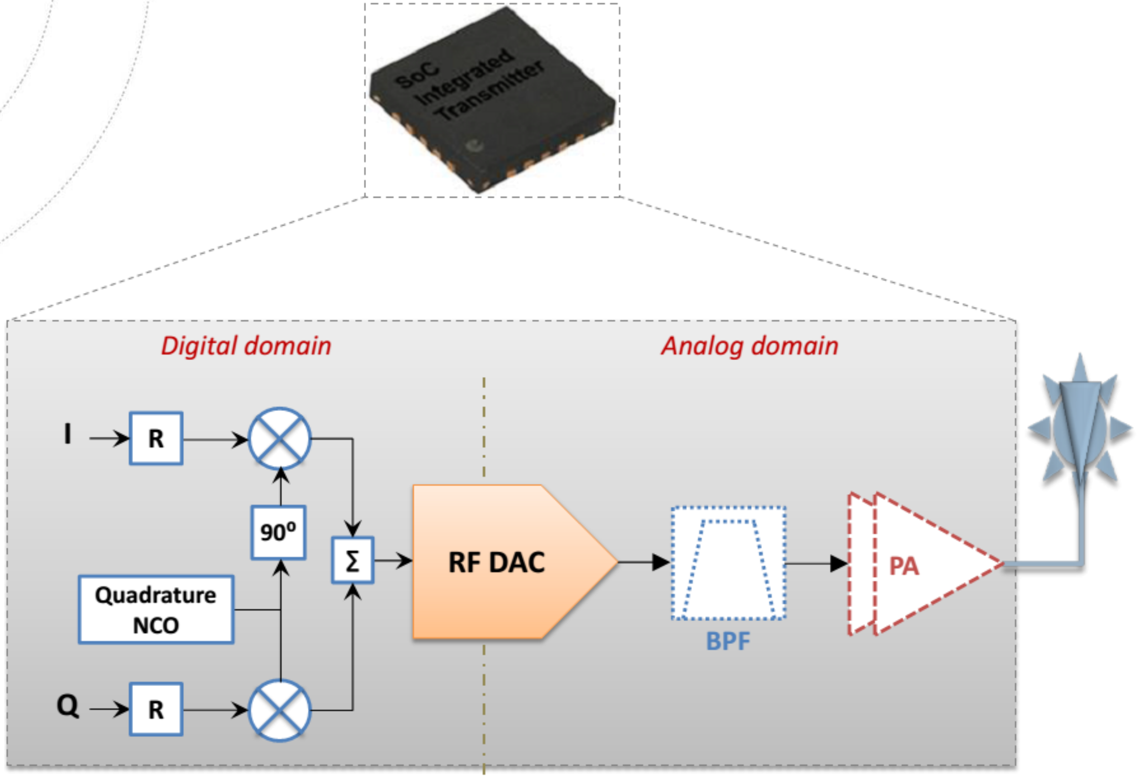
Best Student Paper Award on 6th Congress of Portuguese Committee of URSI

2nd place on IMS2013 SDC-LSNA Student Design Competition

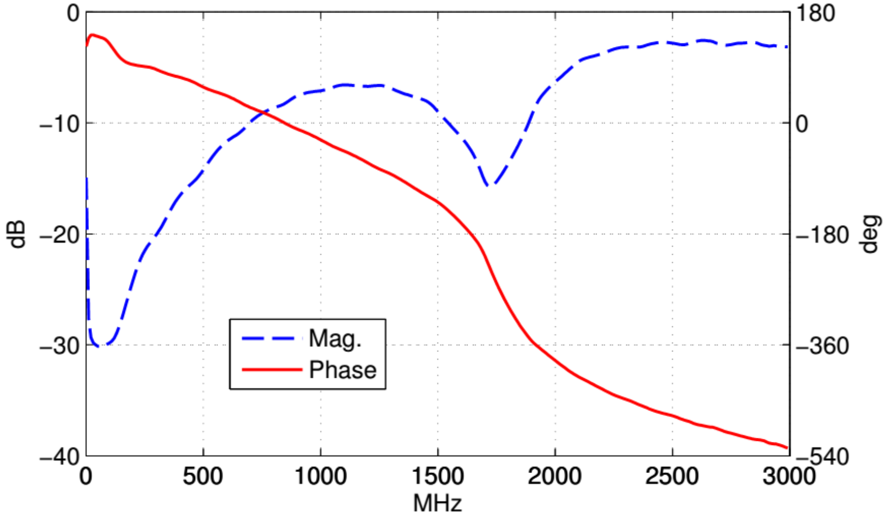


Application Examples

- Examples from components of a complete transmitter:



Application Examples
RF DAC – Linear approach

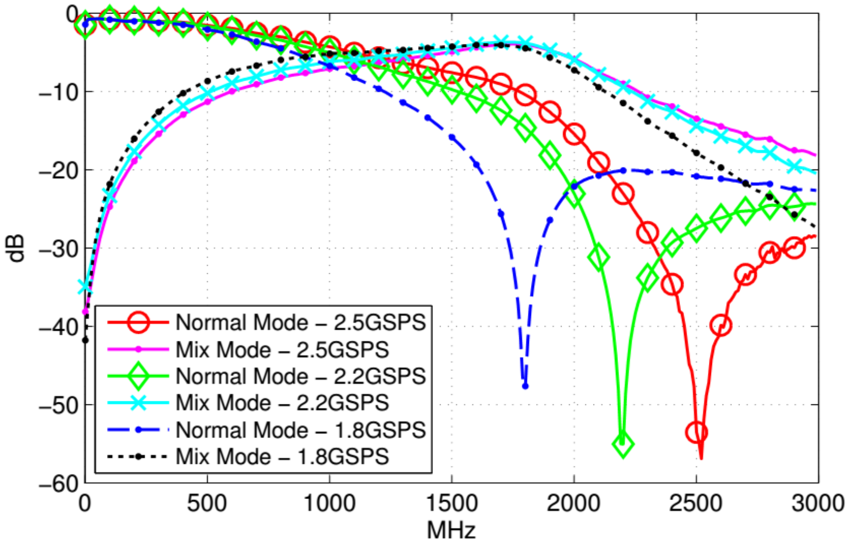


Magnitude and phase of D_{11}

(Completely analog relationships)

Magnitude of D_{13}

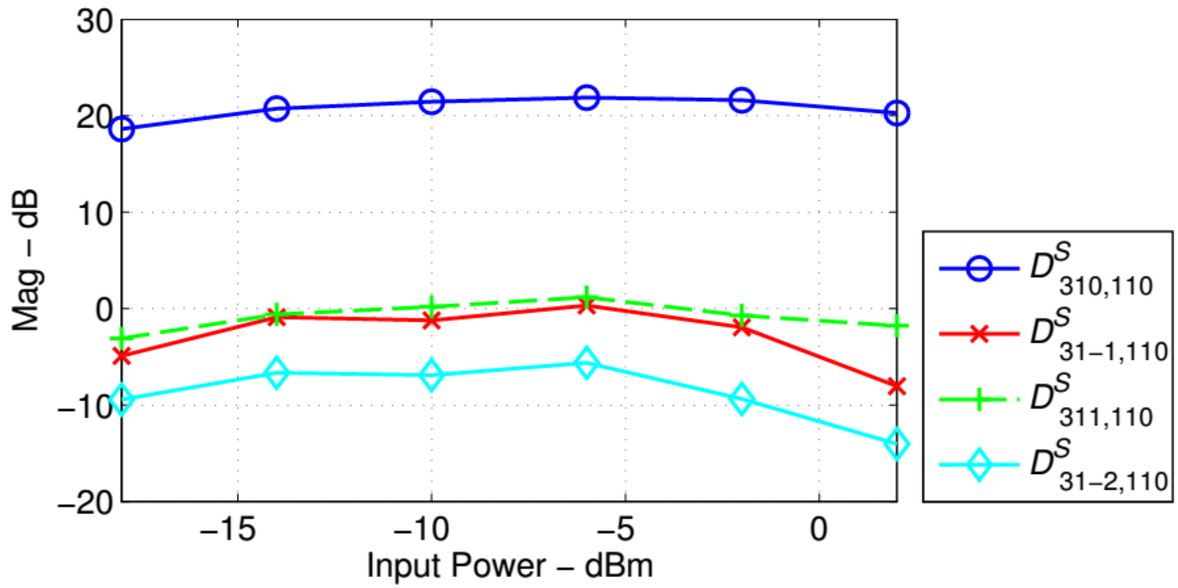
For different operation modes and CLK frequencies



Application Examples
DAC + PA – Nonlinear approach

- Magnitude of some kernels over input power

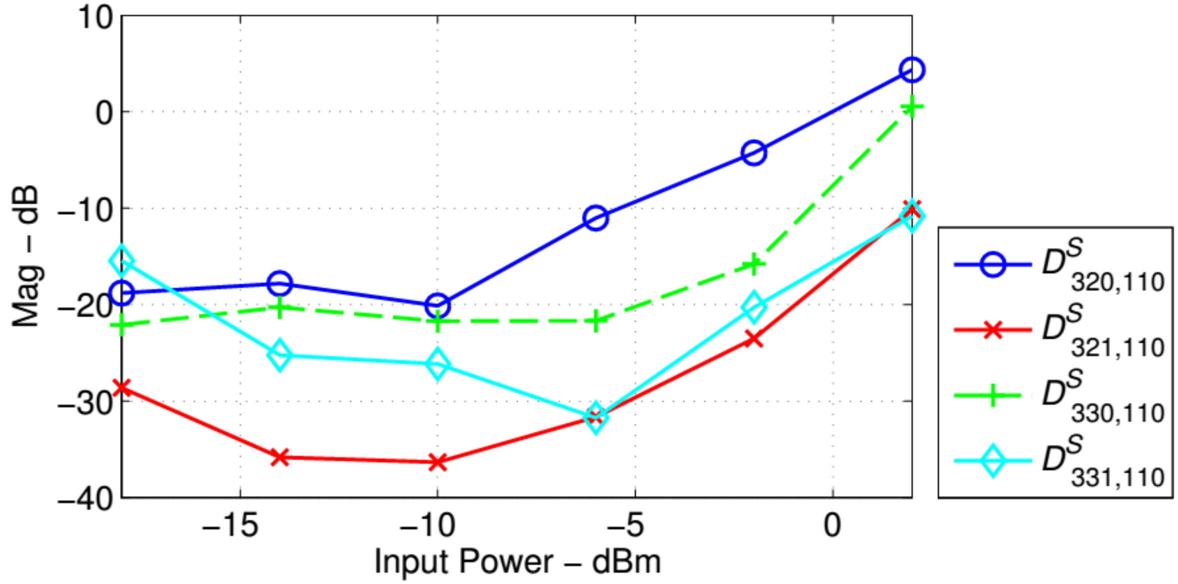
- Kernels relating the output fundamental at different Nyquist Zones with the input fundamental



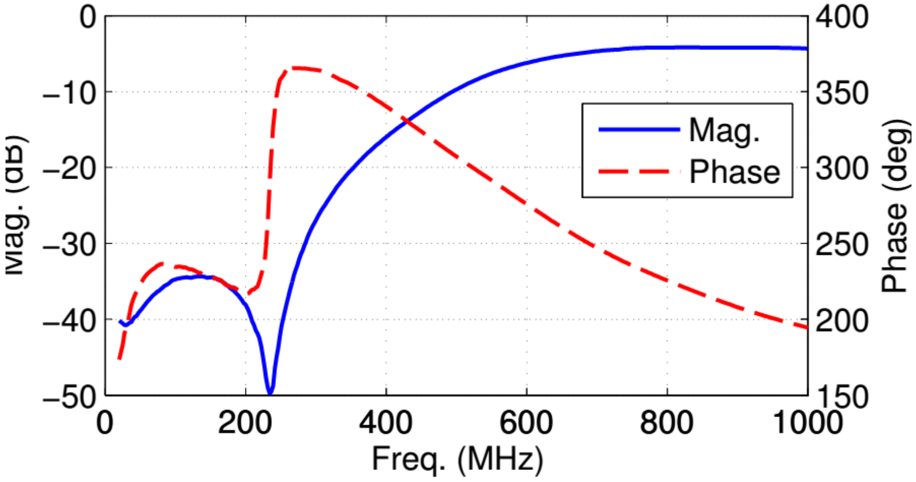
Application Examples
DAC + PA – Nonlinear approach

- Magnitude of some kernels over input power

- Kernels relating the output 2nd and 3rd harmonics with the input fundamental
  - Visible growth with the increase on input power

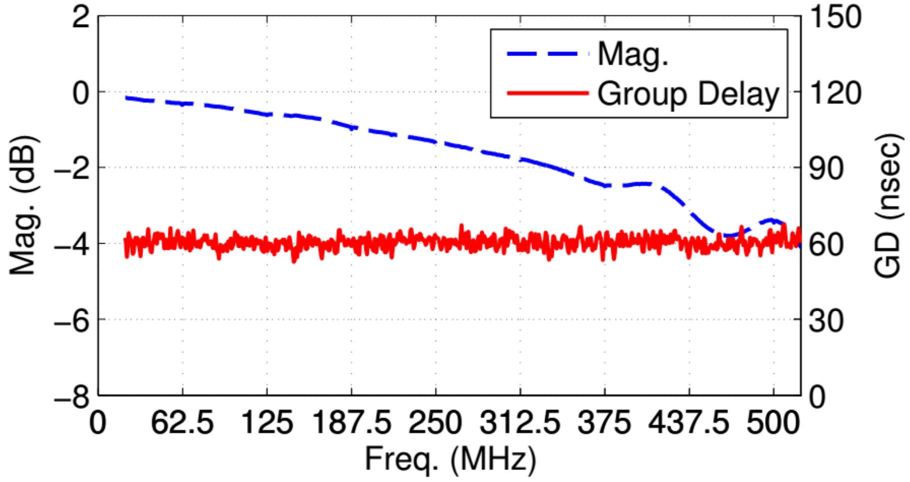


Application Examples
ADC – Linear approach



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!!!