**1st CREaTION Workshop**
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# Synchronous Frequency-Domain Measurements for the Extraction of X-parameters in Digital to Analog Transmitters

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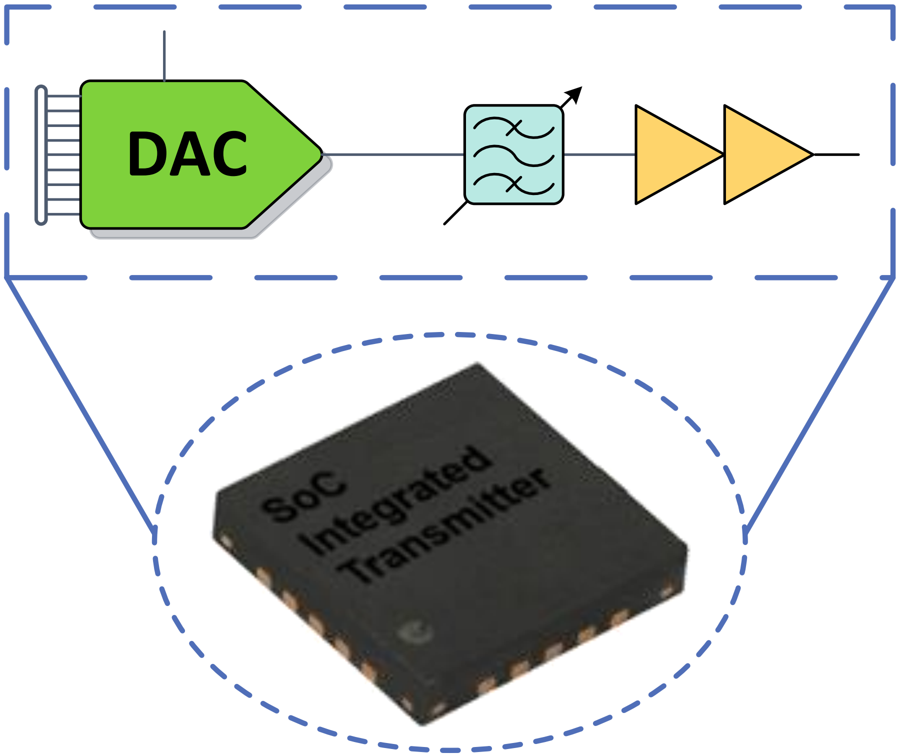
# Introduction & Motivation

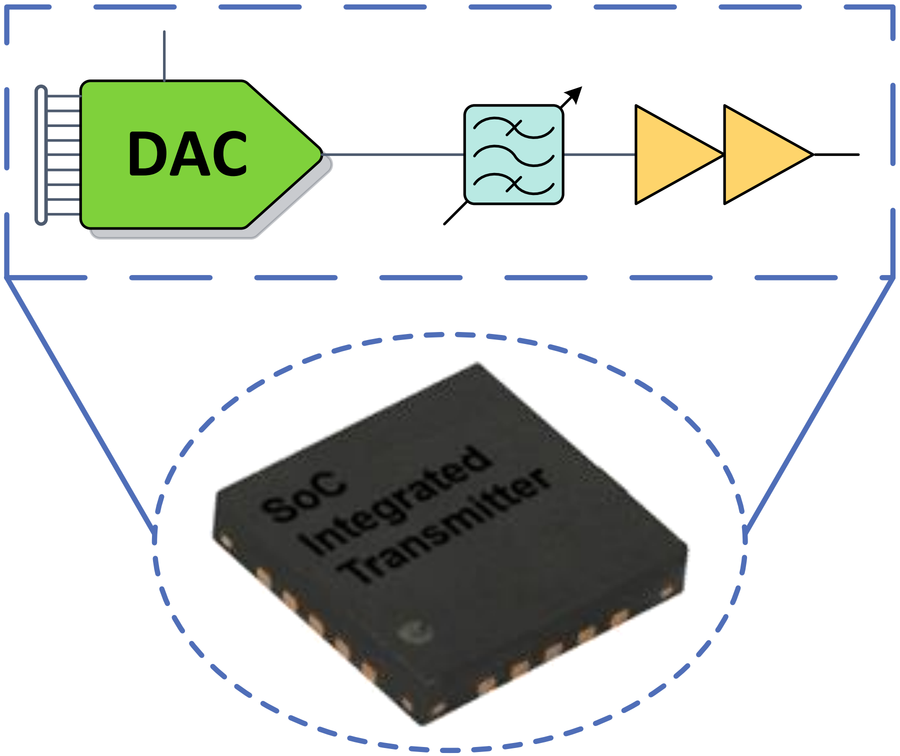
- The radio industry direction for the future is integration
- Integrated **digital to analog transmitters** are one of the most promising technologies
- Though, such components will pose “similar” problems (e.g., nonlinear distortion) as analog-based transmitters




D/A Integrated Transmitter

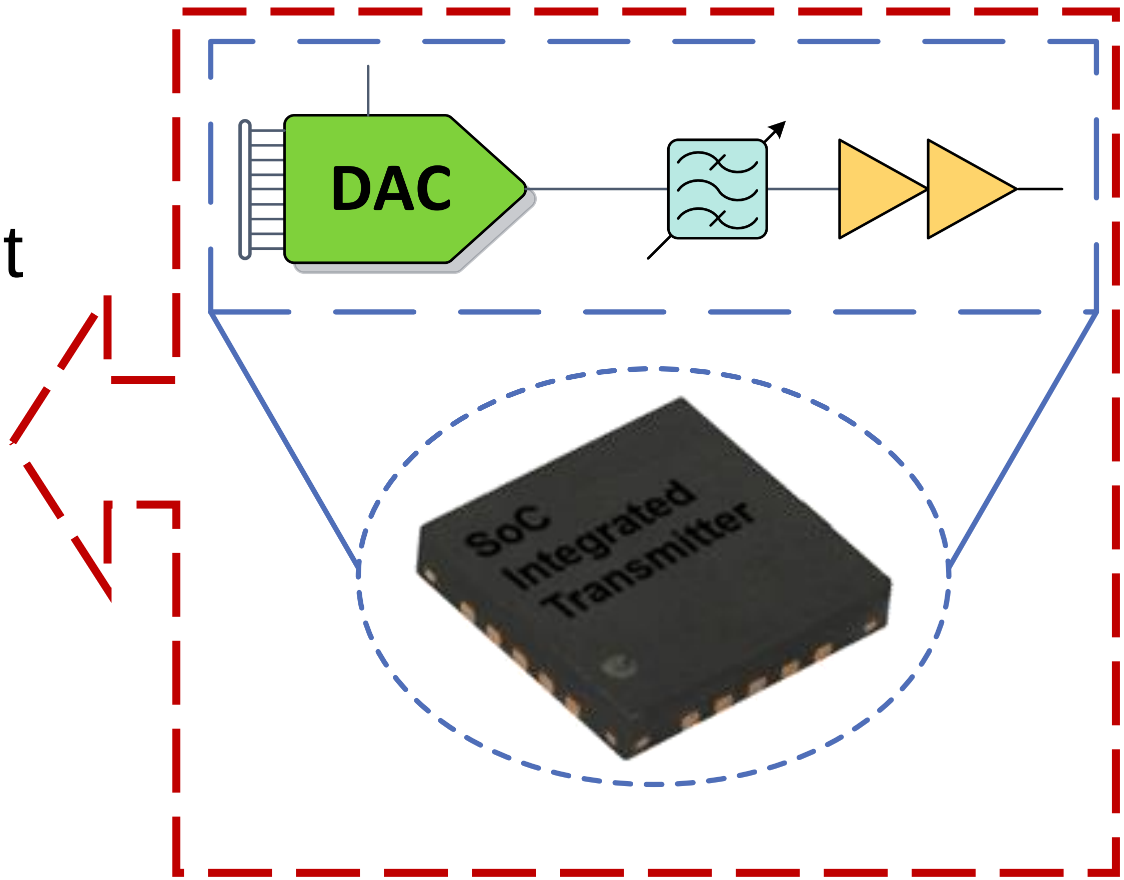
# Introduction & Motivation

- It is mandatory to develop models capable of describe the **linear and nonlinear behavior of mixed-signal** (analog/digital) systems or devices
- For **radios integrated in a single IC (SoC)**, it is difficult to measure the only-analog blocks apart from the mixed-signal ones



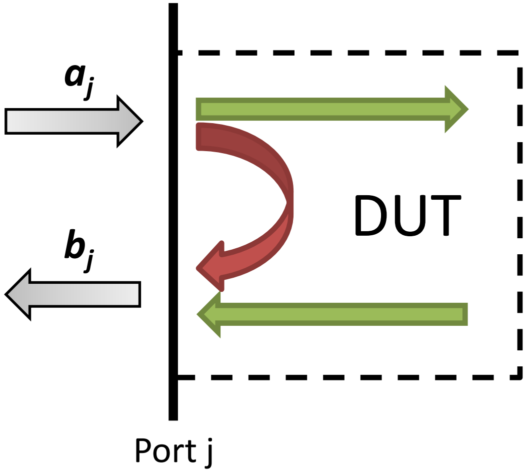
# Introduction & Motivation

- Suitable measurement methods and test benches are **essential to extract meaningful behavioral models**



# Motivation

- In short… The goal is to:
  - Characterize the entire digital to analog transmitter from an RF point-of-view
  - Use a **scattering waves** framework



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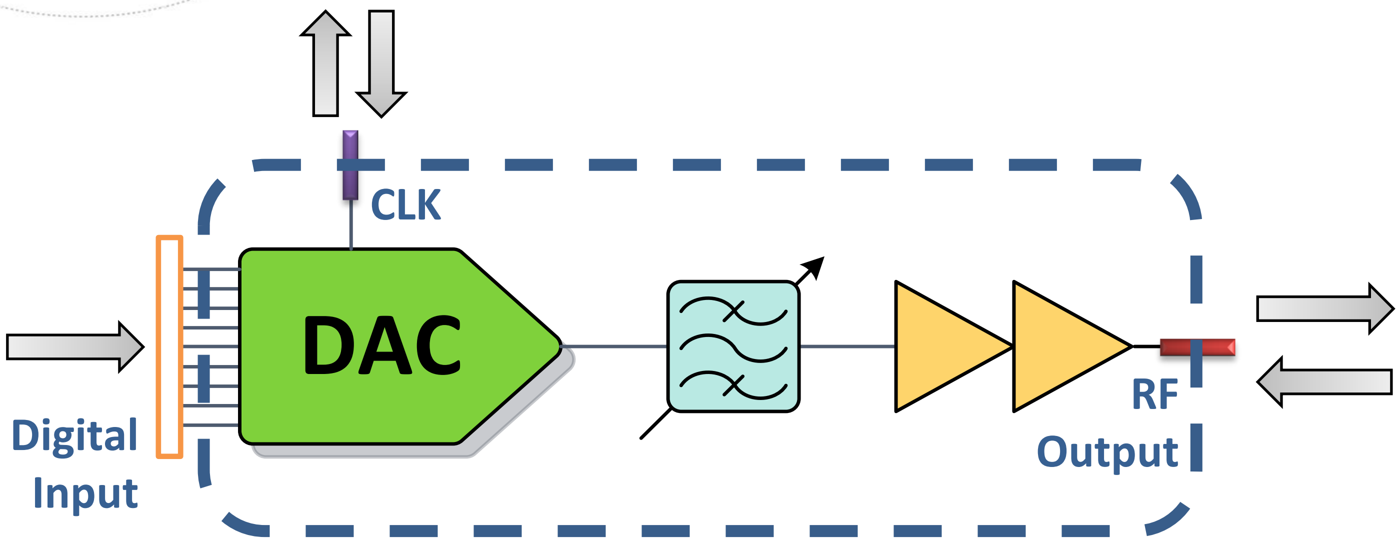


# X-Parameters for Mixed-Signal Devices

- X-Parameters are a superset of S-Parameters
- They are based on scattering waves
- But they require the measurement of absolute waves values for kernel extraction

- Instrumentation exists to directly extract the model in fully analog devices
- But what about **D/A integrated transmitters**??

# MEASUREMENT OVERVIEW

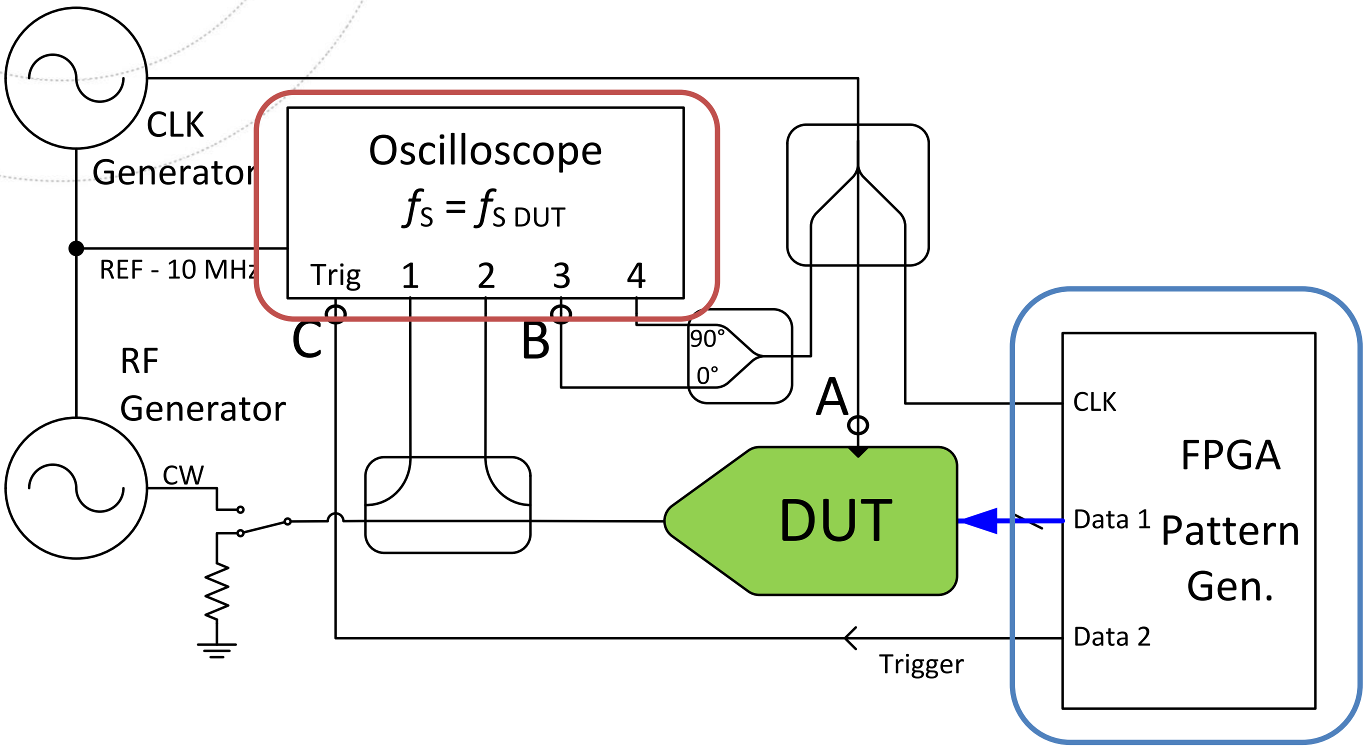
- Analog Signal
  - **Sampler-based** Receiver (**Oscilloscope**)
- $f_{S\ \text{Sampling Receiver}} = f_{S\ \text{DUT}}$
  - To simplify the synchronization problem

- Digital Signal
  - **FPGA** (Pattern Generator Like)

- Different pieces of hardware for each signal
  - ➢ **Synchronization issues will arise**

# Measurement Setup

- (Oscilloscope)
  - $f_{S\ \text{Sampling Receiver}} = f_{S\ \text{DUT}}$
- (FPGA)

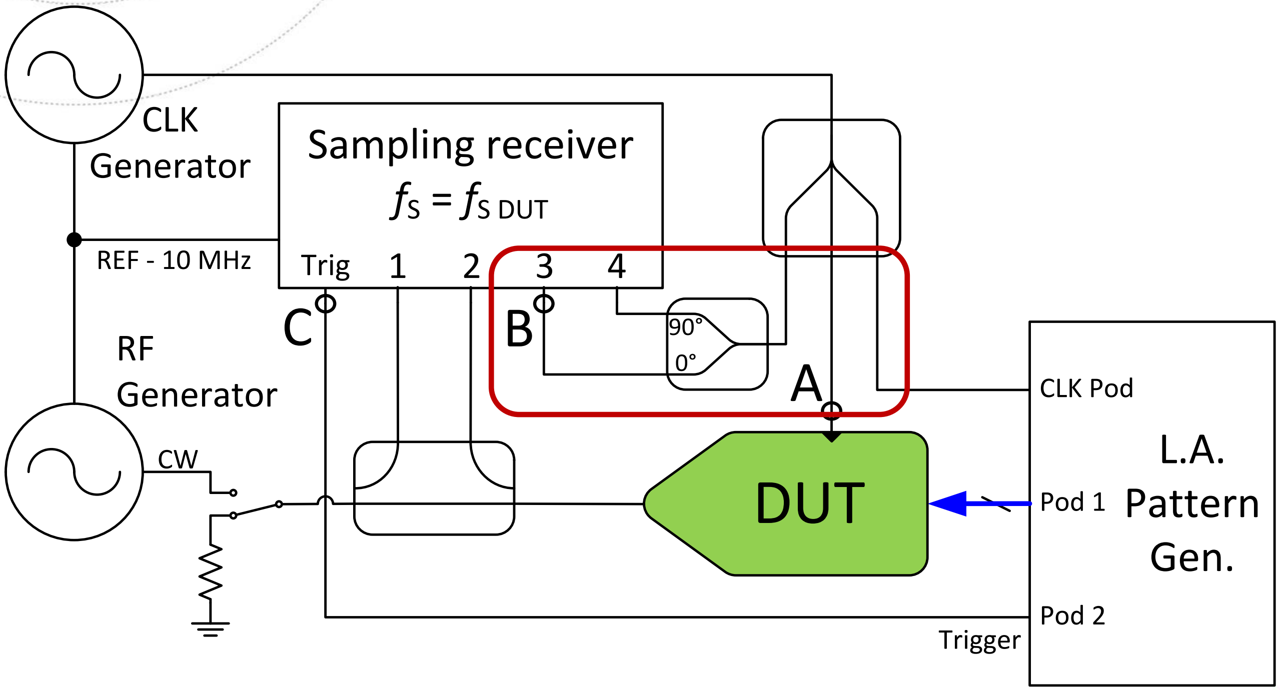


# Phase Alignment Procedure

- Since, $f_{S\ \text{Sampling Receiver}} = f_{S\ \text{DUT}}$
- Only a phase mismatch occur between:
  - The sampling instants of the analog signal
  - The sampling instants of the digital signal
- To synchronize both signals it is necessary:
  - To know the amount of phase shifting between sampling instants
  - Phase de-trend one of these signals, in this case, the analog sampled signal

# Phase Alignment Procedure

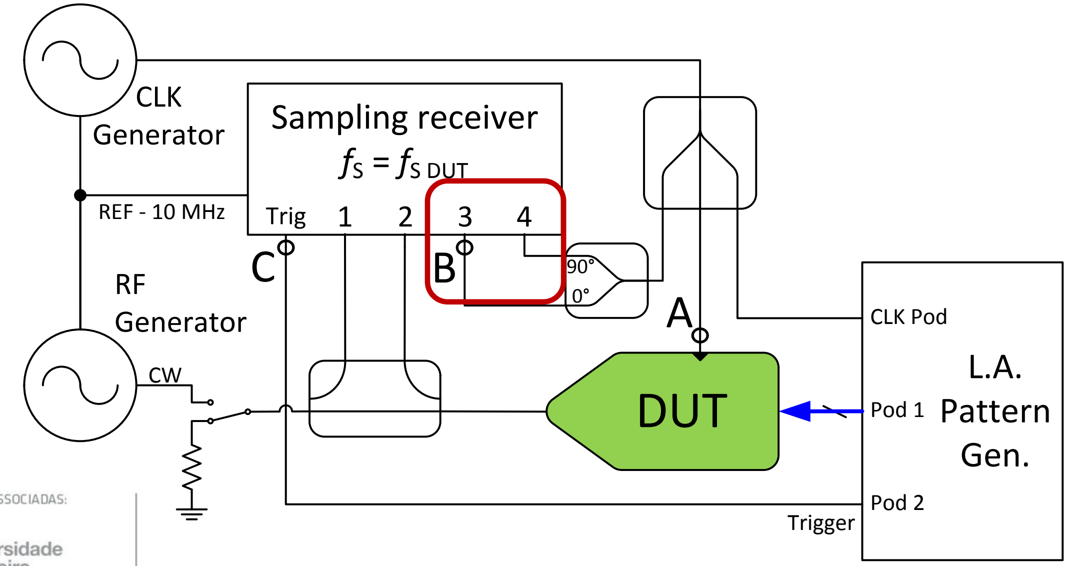
- How to know the amount of phase shift?
- Use a reference signal to track all the sampling instants…
- Reference Signal → DUT Clock Signal (Sinusoidal)



# Phase Alignment Procedure

- However, the reference signal received by the analog sampling receiver is a DC voltage, $V_3$ and $V_4$
- The following **trigonometric relation** is used to calculate its phase at the receiver sampling instant

$$\tan(\theta'_{analog}) = -\frac{V_4}{V_3}\frac{1}{\cos(\theta_e)} - \tan(\theta_e)$$




$\theta'_{analog}$ - wanted phase

$\theta_e$ - hybrid phase error

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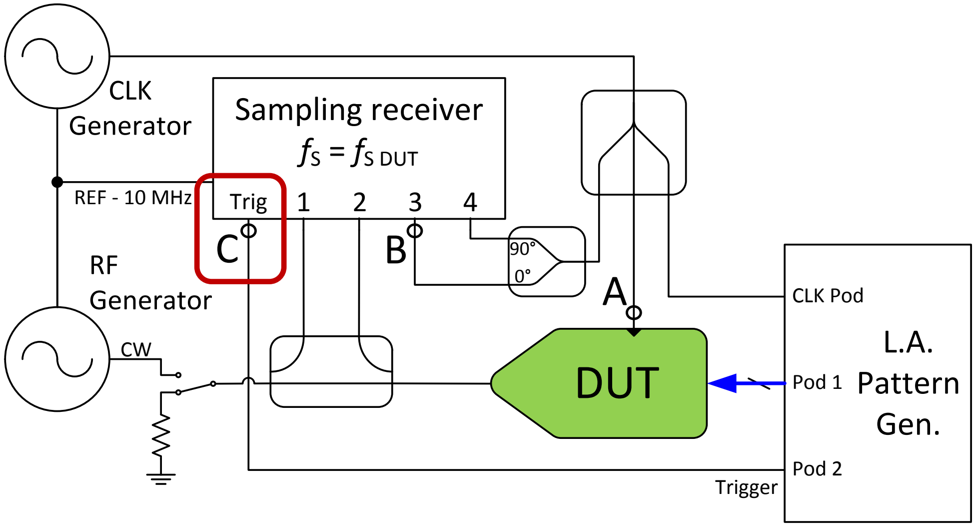
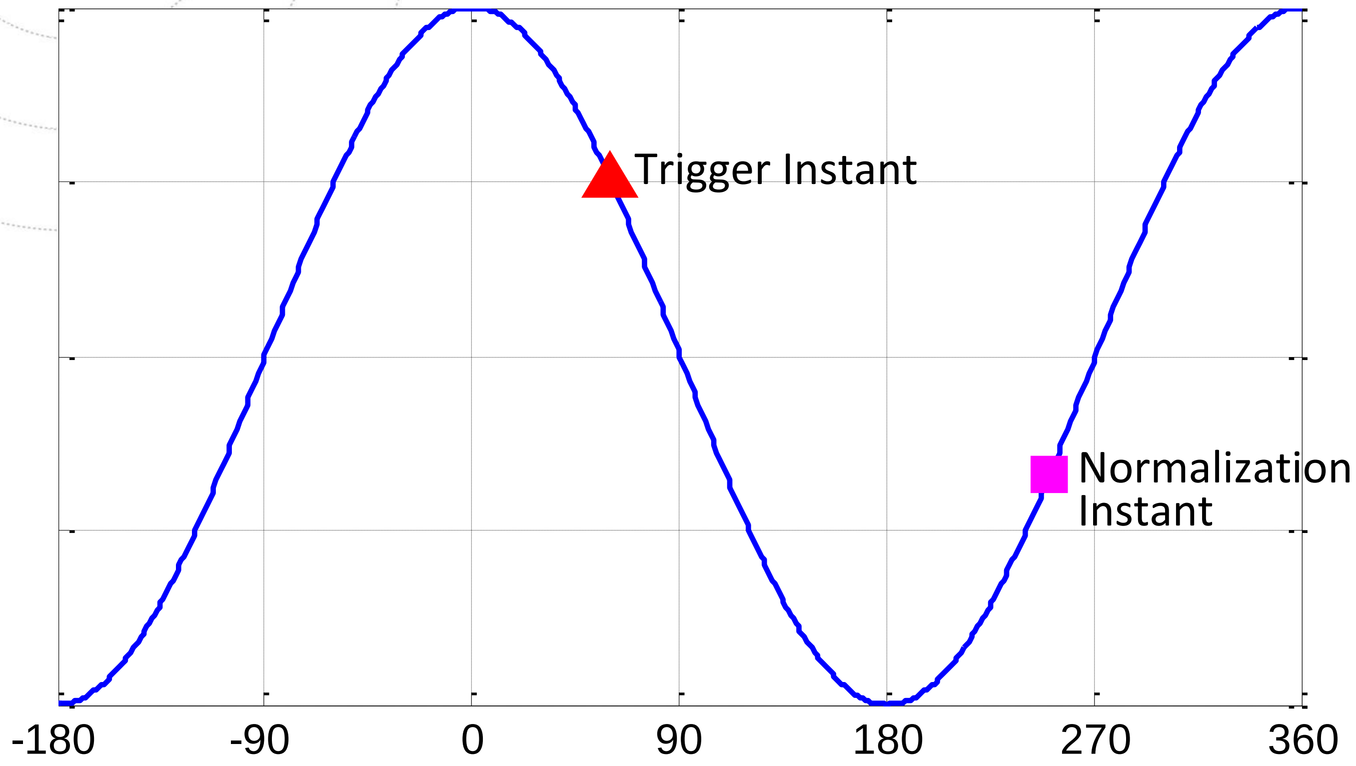
# Phase Alignment Procedure

- The **normalization instant** has been chosen to be:
  - -90° of the reference signal (at the **DUT reference plane**)
    - Sampling instant of the DUT
  - An ***a priori* measurement** is needed to know what this normalization instant means at the **analog receiver port plane**
- A **trigger signal** is used to indicate the begin of a measurement
  - Fed into the analog sampling receiver at **point C**



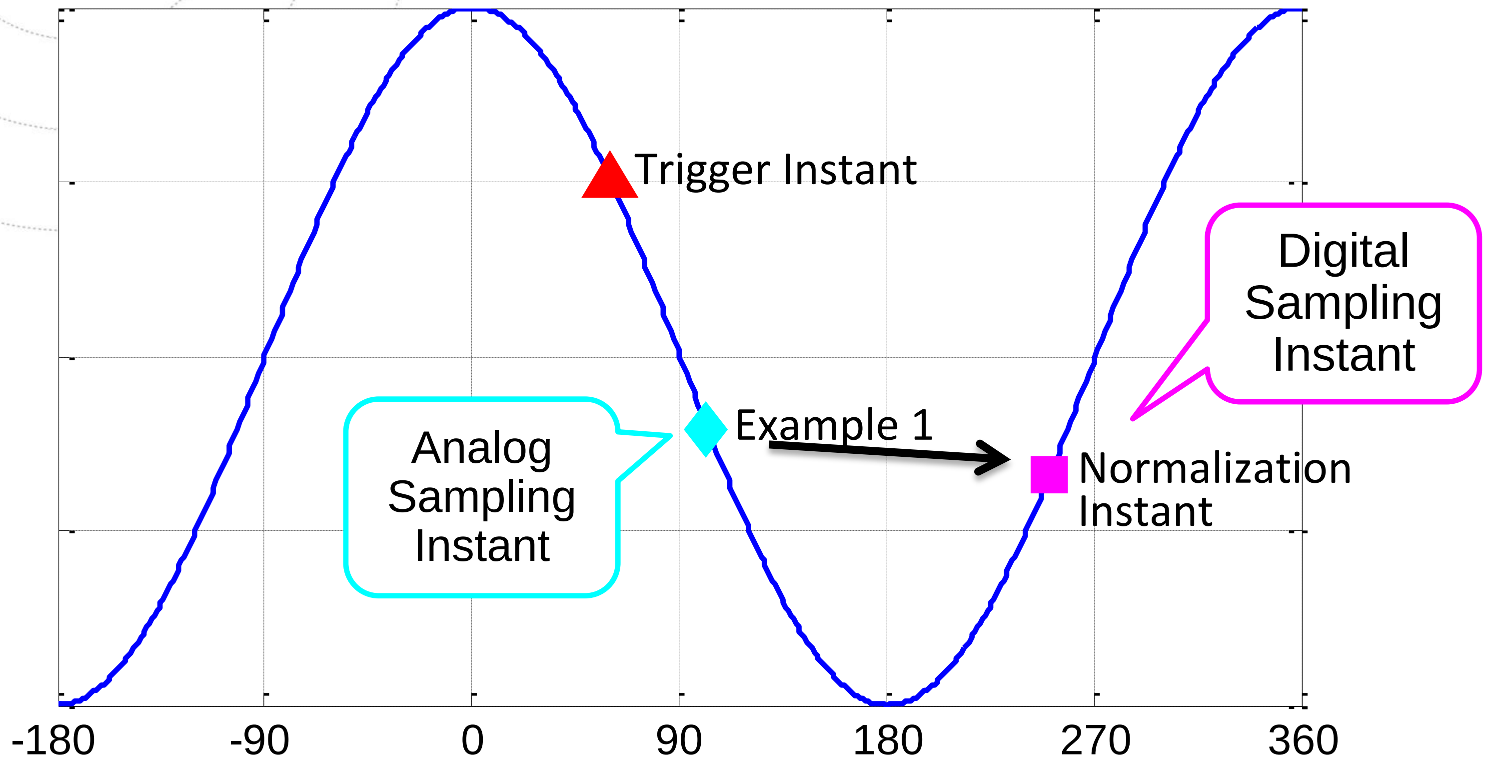
# Phase Alignment Procedure - Example

- **<u>Condition to met</u>**:
  - The trigger instant must be the **first event to happen**



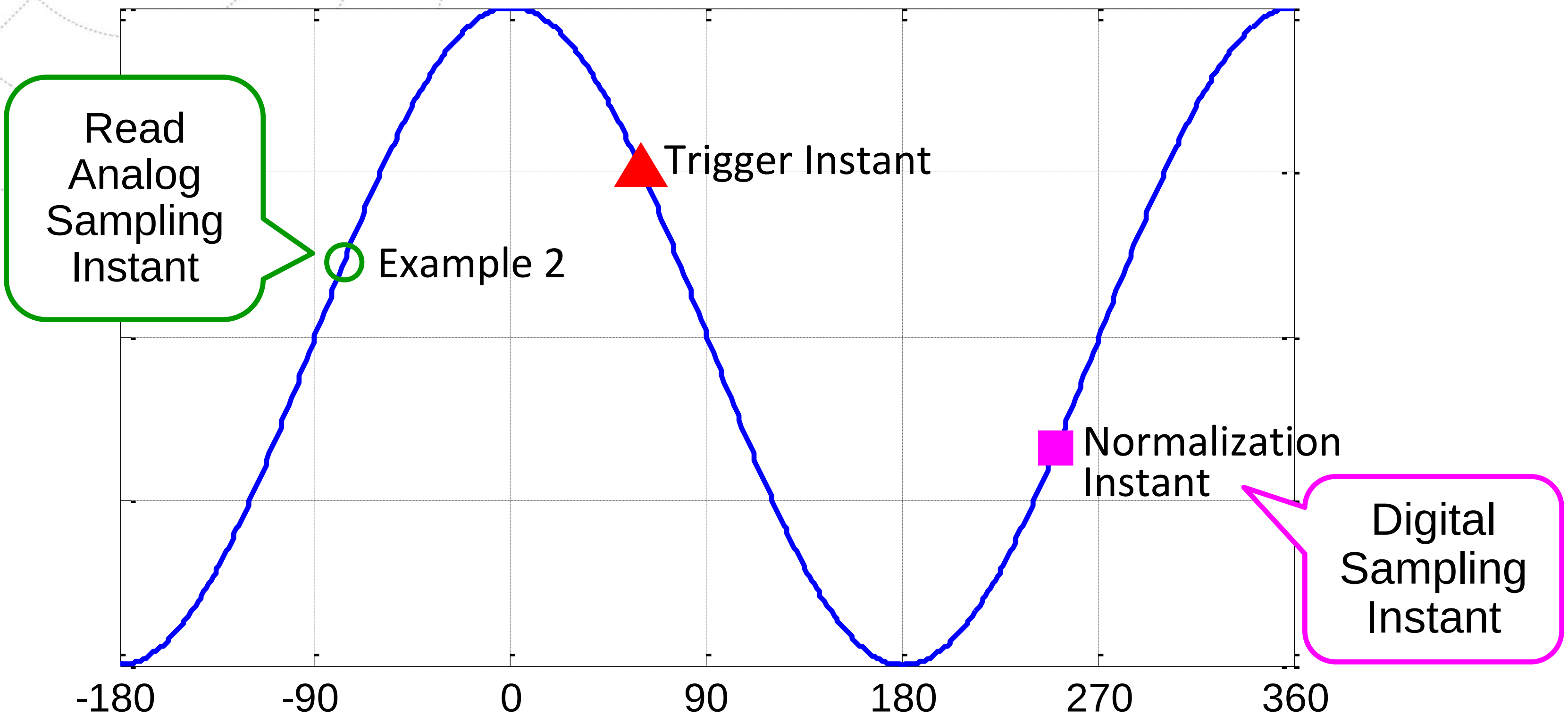
# Phase Alignment Procedure - Example 1

- Necessary phase shift ≈ +70°

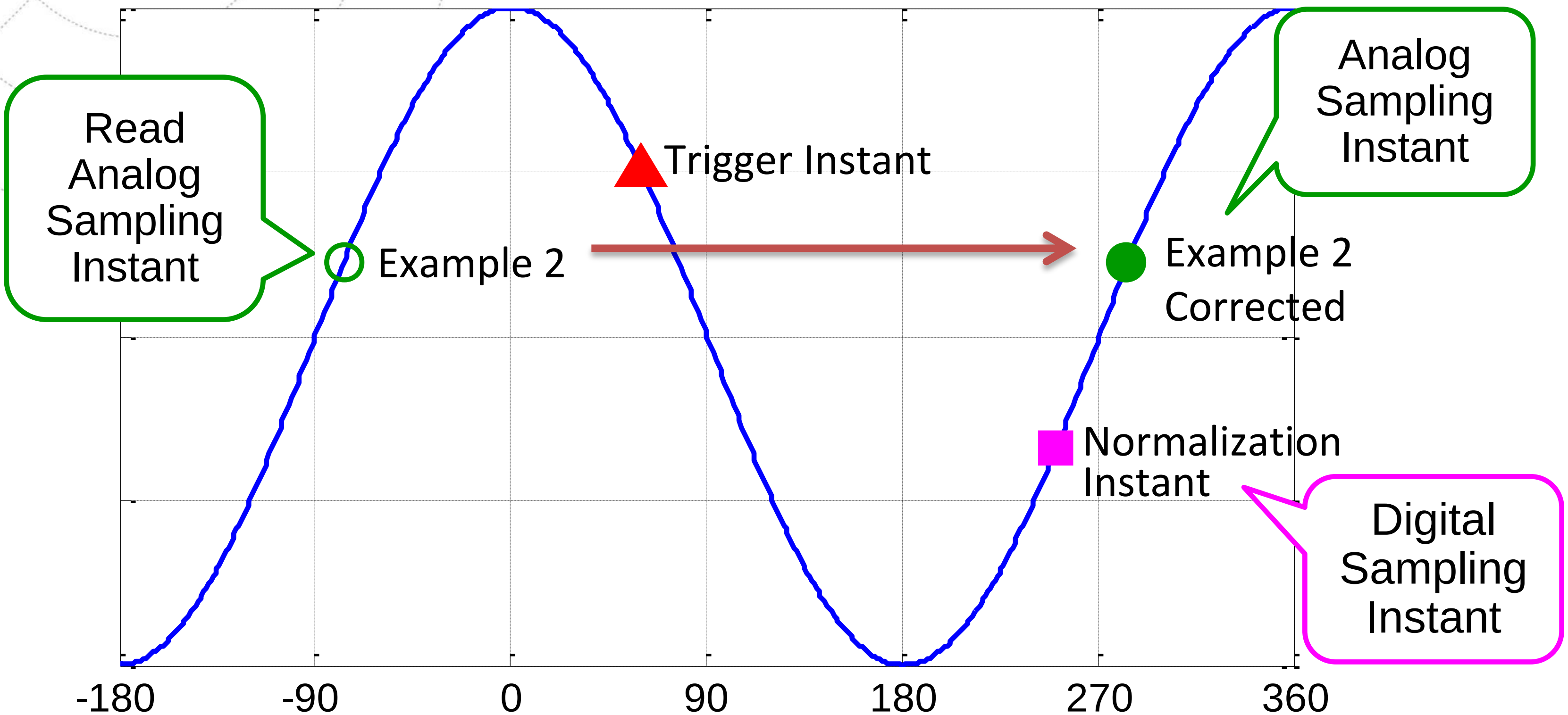


# Phase Alignment Procedure - Example 2

- Analog Sampling instant happens before the trigger instant
  - Necessary to correct this … Add it a period of 360º

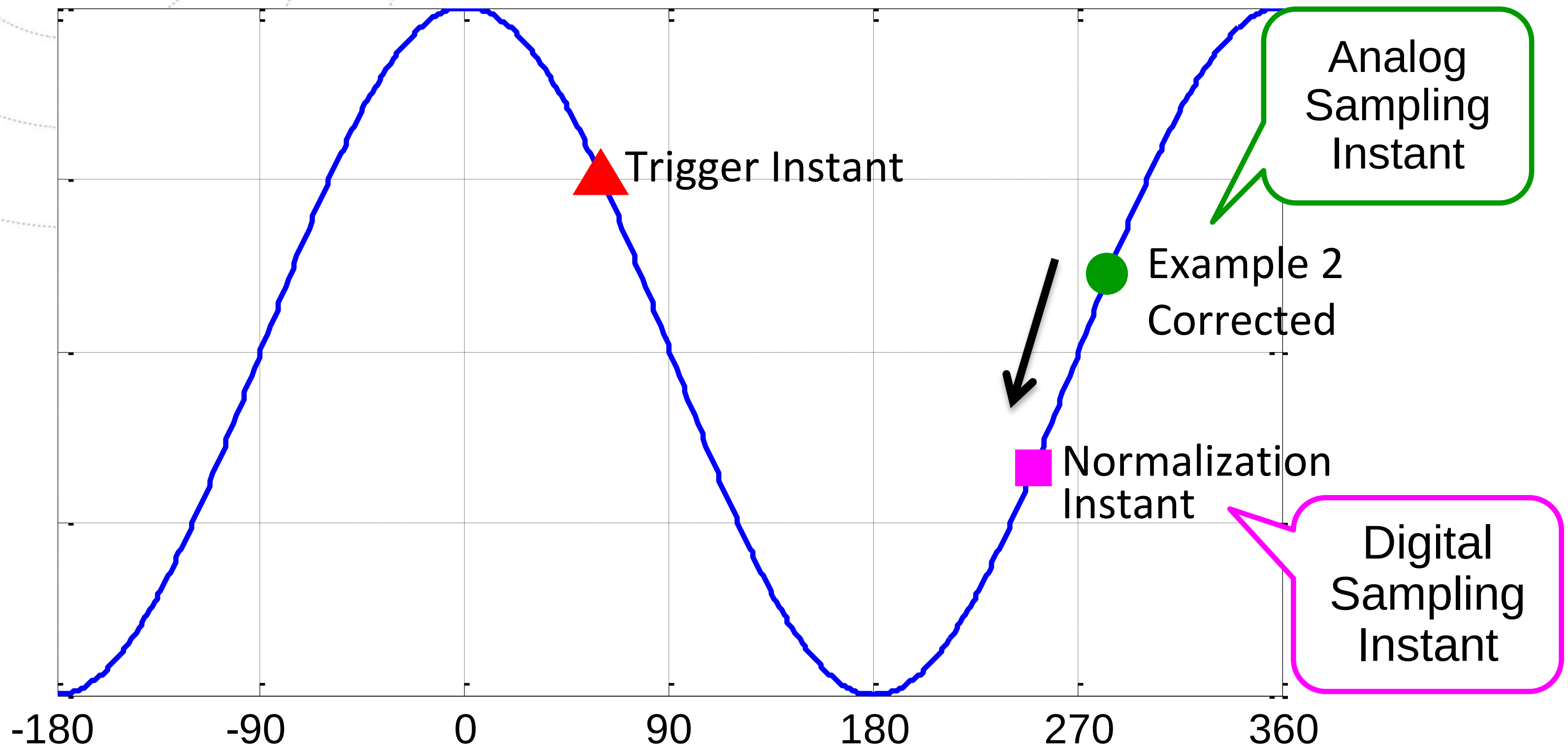


# Phase Alignment Procedure - Example 2



# Phase Alignment Procedure - Example 2

- Necessary phase shift ≈ -30°



# Phase Alignment Procedure

- Phase calculation is retrieved from the **correct bin** of the time domain signal **FFT transformation**
- To align the analog waves with the digital ones, the expression is used:

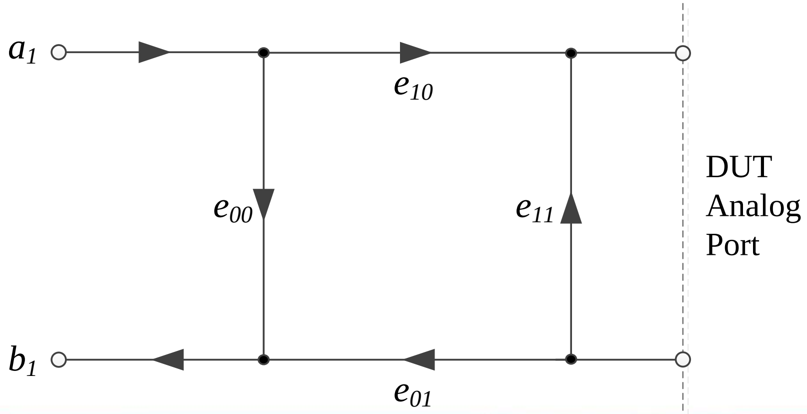
$$C_{k\ aligned} = C_k \cdot e^{\left(i\,\Delta\theta\ ^{f_k}/_{f_s}\right)}$$

- $\Delta\theta = \theta_{norm} - \theta_{analog}$
- $f_s \rightarrow$ sampling frequency
- $C_k \rightarrow$ FFT bin of the signal to be aligned, at index *k*
- $f_k \rightarrow$ frequency of the previous index *k*
- $C_{k\ aligned} \rightarrow$ FFT bin of the aligned signal, at index *k*

# Phase Alignment Procedure

## Analog Waves Calibration

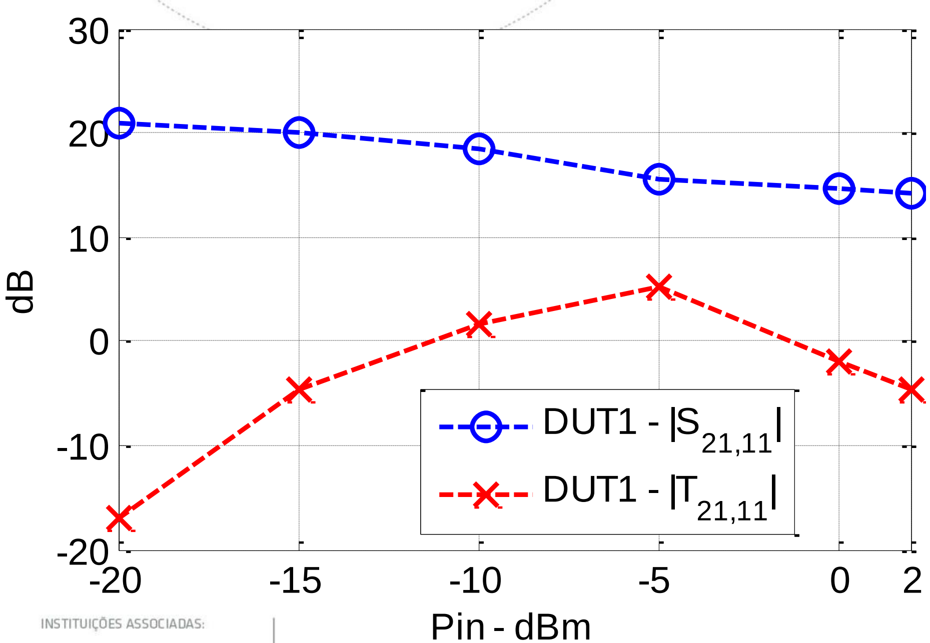
- To correct the measured analog wave quantities
  - A calibration scheme was employed before the **phase alignment procedure**
  - It is based on a 4-term error model
- To individually know the $e_{01}$ and $e_{10}$ error terms an approach similar to the absolute calibration scheme used on NVNAs was used
  - SOL + Absolute Thru

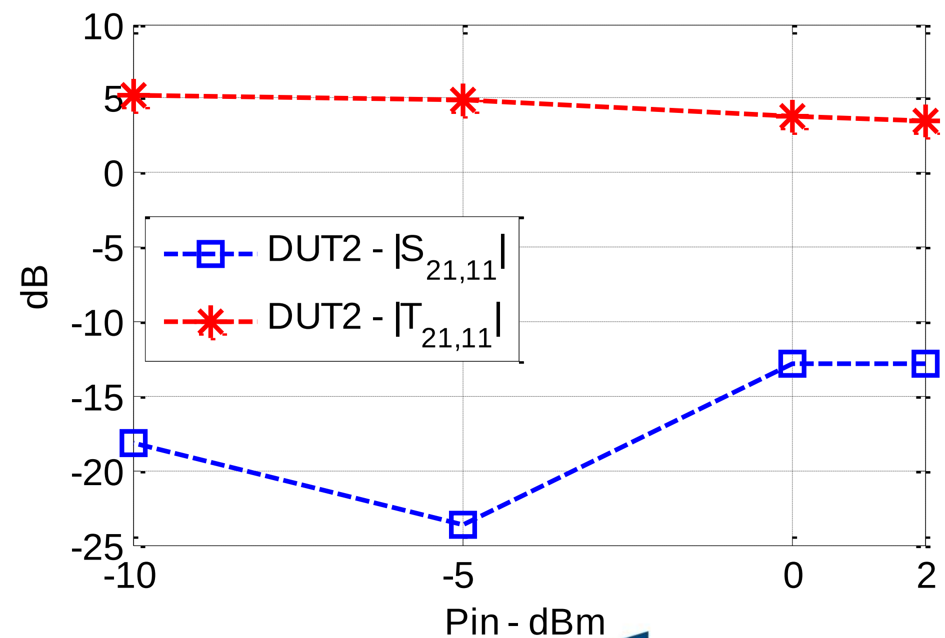


# Measurement Results

- **DUT1** → DAC + low-pass filter + PA
- **DUT2** → DAC + band-pass filter + PA

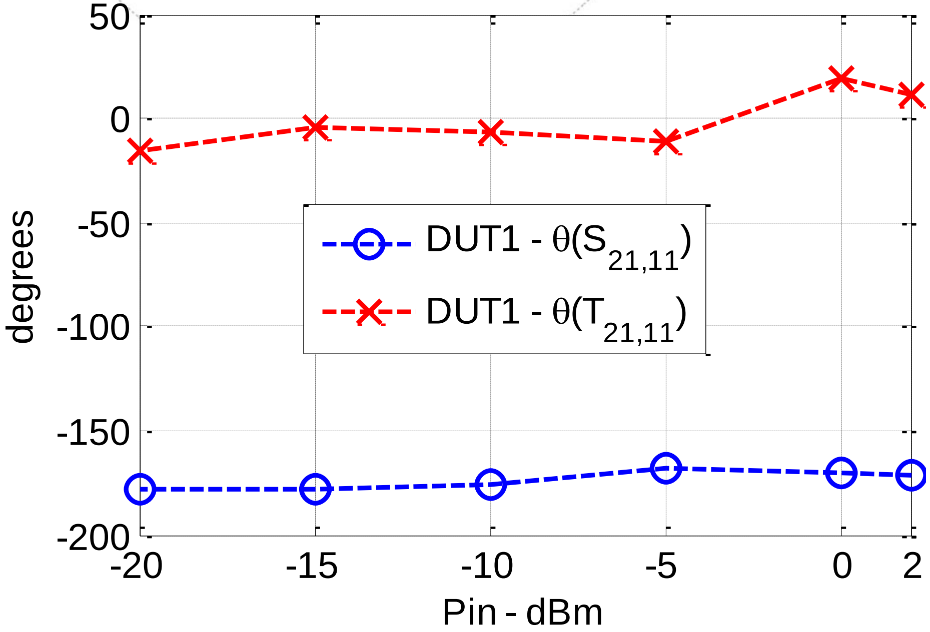
- **DUT1** - $S_{21,11}$ parameter is dominant
  - 1st Nyquist zone → direct phase response
- **DUT2** - $T_{21,11}$ parameter is dominant
  - 2nd Nyquist zone → conjugate phase response

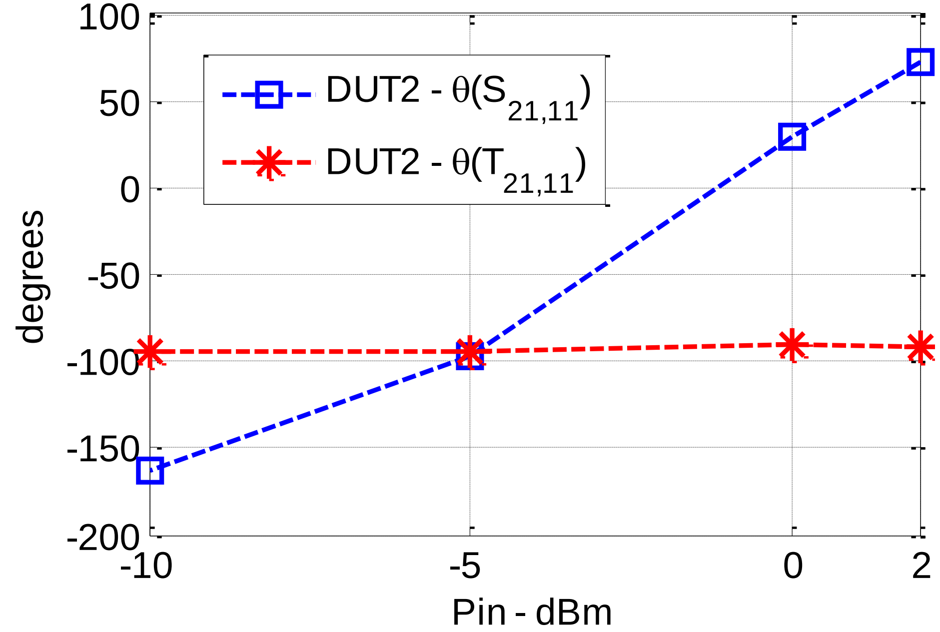


# Measurement Results

- Phase values for the same parameters were also extracted
- With a high repeatability from extraction to extraction

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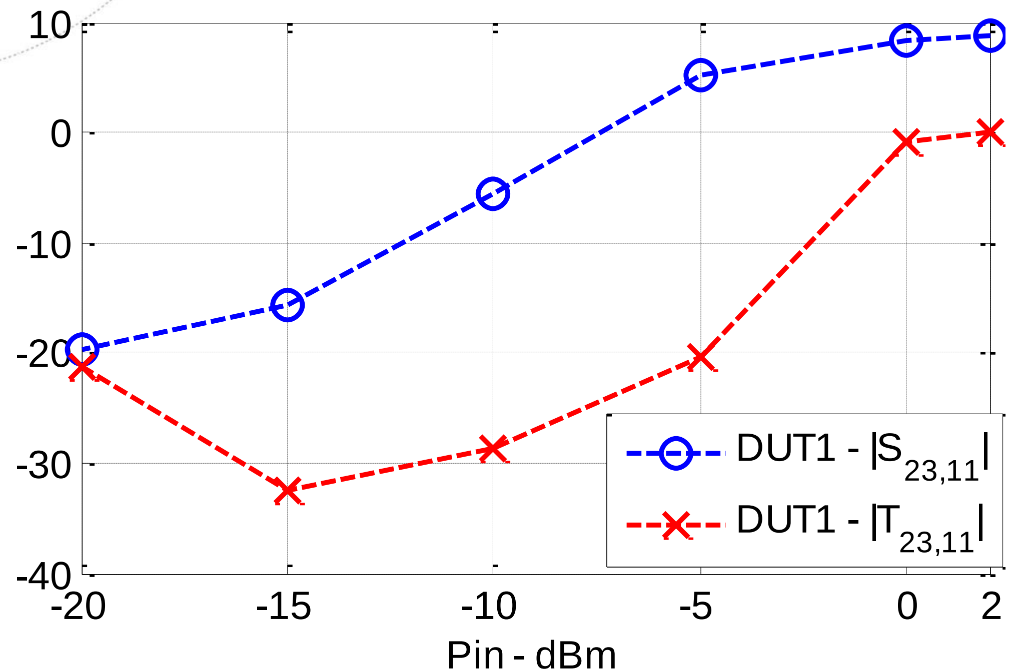
# Measurement Results - DUT1

- Magnitude and phase behaviors of **$S_{23,11}$** and **$T_{23,11}$**
- The contribution of the fundamental at the input to the **third harmonic at the output** increase as expected

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# Conclusion

- A first approach to the extraction of **X-parameters** of complete **Digital to Analog integrated transmitters** has been presented
- The extraction validity was proved with meaningful measurements of different **D/A transmitter DUT's**
- These measurements mimic the expected behavior of such an integrated transmitter

# Thank you!!!