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Large Signal Network Analyzer with Trigger for Baseband & RF System Characterization with Application to K-Modeling & Output Baseband Modulation

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MISES Non-Linear RF Lab
Background and Motivation

- Need for correlated vectorial measurement of baseband and RF signals in multi-port communication circuits or systems
  - **Example of Applications:**
    - Acquire mixed-signal measurement data for K-model extractions (*K-models are behavioral model of communication circuits from DSP to RF antenna which relies on the I & Q representation for both RF and baseband signals*)
    - Characterize memory effects & imbalance in mixers and IQ modulators
    - Acquire non-linear multi-port Volterra coefficients in power amplifiers (PAs) to facilitate their linearization using input (IBM) and output (OBM) baseband modulation linearization
Talk Outline

• Triggered LSNA measurement setups
  – time and frequency synchronization

• IQ imbalance in IQ modulators
  – K-modeling of IQ modulator
  – Compensation of IQ imbalance
  – Associated error analysis

• Measurement of 3-port (2 in RF and 1 in baseband) Volterra non-linear coefficients in a PA

• Linearization of a Class AB PA with IBM and OBM
The addition of a measurement trigger to the LSNA introduces a time reference for the modulation.
Envelop Stabilization of modulated RF signals

- A two-tone (894 and 896 MHz) RF signal is applied at the input of the DUT
- The same stable envelope is displayed for different LSNA measurements

Measurement 1

Measurement 2

Measurement 3

Measurement 4

and so on

• A two-tone (894 and 896 MHz) RF signal is applied at the input of the DUT
• The same stable envelope is displayed for different LSNA measurements
Experimental Setup for K-Modeling of IQ modulator for a given modulation frequency

- The modulator is placed between port 1 & 2
- The FPGA testbed generates the I & Q signals of frequency $\omega_m$
- Our goal is to extract the linear K-model of the IQ modulator:

Linear K model:

$$
\begin{bmatrix}
I_{RF}(t) \\
Q_{RF}(t)
\end{bmatrix} =
\begin{bmatrix}
k_{11}(\omega_m) & k_{12}(\omega_m) \\
k_{21}(\omega_m) & k_{22}(\omega_m)
\end{bmatrix}
\begin{bmatrix}
I_{BB}(t) \\
Q_{BB}(t)
\end{bmatrix}
$$
Extraction of the K-Model of the IQ modulator

• The I and Q signals are selected to generate the upper side band $\omega_2$
• The $M_i$ and $\phi_i$ terms of the lower side-band $\omega_1$ arises from the imbalance of the IQ modulator
• The linear K-model is then found to be:

$$ K_{MOD} = \begin{bmatrix} k_{11}(\omega) & k_{12}(\omega) \\ k_{21}(\omega) & k_{22}(\omega) \end{bmatrix} = M_1 \begin{bmatrix} \cos(\phi_1 - \phi_0) & \sin(\phi_1 - \phi_0) \\ \sin(\phi_1 - \phi_0) & -\cos(\phi_1 - \phi_0) \end{bmatrix} + M_2 \begin{bmatrix} \cos(\phi_2 - \phi_0) & -\sin(\phi_2 - \phi_0) \\ \sin(\phi_2 - \phi_0) & \cos(\phi_2 - \phi_0) \end{bmatrix} = M_1 P_1 + M_2 P_2 $$
IQ Imbalance Correction using 2 methods

These methods rely on the predistortion of I and Q:

- **Method I**
  \[ K_{FPGA2} = M_2 P_2 (K_{MOD})^{-1} \]

- **Method II** uses a physical model where gain imbalance \( \varepsilon \), phase imbalance \( \Theta \) between the quadrature oscillators
  
  \[
  K_{FPGA1} = \begin{bmatrix}
  \left(1 + \frac{\varepsilon}{2}\right)\cos\frac{\Theta}{2} & -\left(1 + \frac{\varepsilon}{2}\right)\sin\frac{\Theta}{2} \\
  -\left(1 - \frac{\varepsilon}{2}\right)\sin\frac{\Theta}{2} & \left(1 - \frac{\varepsilon}{2}\right)\cos\frac{\Theta}{2}
  \end{bmatrix}
  \]
IQ Imbalance Correction Results for Method I

- Implementing the IQ correction of Method I in the FPGA reduces the imbalance of the IQ modulator (see improvement shown).
- An overall isolation of 36 dBc is obtained for 1 MHz modulation frequency.
Compensation of IQ Imbalance Results for Methods I & II Combined

Cascading the two IQ conversion methods in the FPGA yields an isolation of 43 dBc for the LSB and 46 dBc for the USB for the IQ imbalance at 1 MHz modulation frequency.
Measurement Reproducibility & Error
Analysis for K-Model Measurements

- Variation of $\Phi_1 = \varphi_1 - \varphi_0$ & $\Phi_2 = \varphi_2 - \varphi_0$ (trigger-out & in)
- SDV ($\sigma_{\varphi_1} = 12.15$ and $\sigma_{\varphi_2} = 11.2$ & $\sigma_{\varphi_1} = 0.1$ and $\sigma_{\varphi_2} = 0.03$)
- Phase error (1MHz): $\Delta \phi = \omega_m \tau_{jitter} \leq \omega_m \tau_{rising} / 2 = 0.36$
Input & output baseband modulation (I/OBM) linearization

\[ Y_{md-}(\omega, \omega_m) = \frac{b_2(\omega - \omega_m)}{a_1(\omega) a_3(\omega_m)} \]

\[ Y_{md+}(\omega, \omega_m) = \frac{b_2(\omega + \omega_m)}{a_1(\omega) a_3(\omega_m)} \]
Given the incident waves $a_1$ and $a_3$ we obtain the transmitted waves $b_2$

The OBM Volterra coefficients $Y_{md-}$ and $Y_{md+}$ are then obtained using:

$$Y_{md-} (\omega, \omega_m) = \frac{b_2 (\omega - \omega_m)}{a_1 (\omega) a_3 (\omega_m) *}$$

$$Y_{md+} (\omega, \omega_m) = \frac{b_2 (\omega + \omega_m)}{a_1 (\omega) a_3 (\omega_m)}$$
Experimental Setup for the Extraction of $Ymd^-$ & $Ymd^+$ with Triggered LSNA

- The LSNA measures the input tone $a_1$ and output tones $b_2$
- The trigger determines the phase of the baseband signal $a_3$
Lower and upper sidebands IMD3 cancellation with IBM & OBM

The cancellation of the IMD3 cannot be achieved for the same phase and amplitude of $a_3$ for the LSB and USB due to memory effects.
Conclusion

• Presented triggered LSNA measurement setup providing the means to correlate together the amplitude and phase of the baseband and RF signals in multi-port communication systems
• Extracted a linear K-model for modeling the IQ imbalance of an IQ modulator
• Used linear K-model to reduce the IQ imbalance to 43 and 46 dBc isolation for the LSB and USB respectively
• Demonstrated the application of the triggered LSNA to the measurement of the $Y_{md}$ Volterra non-linear coefficients
• Observed the presence of memory effects in IBM and OBM linearization