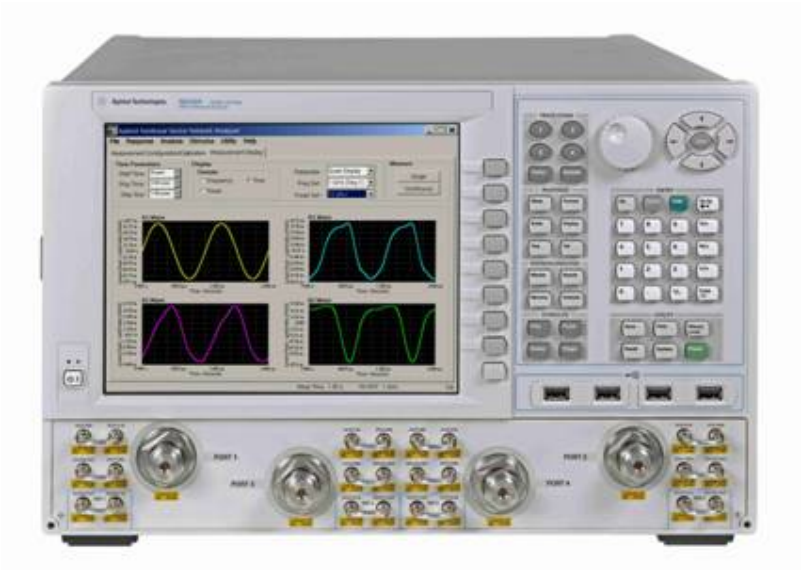
# *Agilent NVNA & X-Parameters*

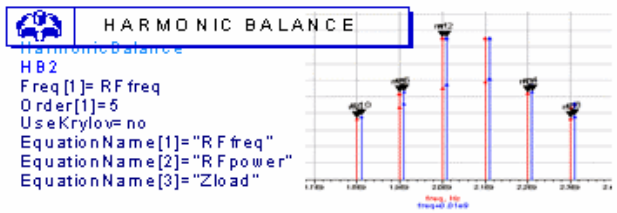
## *The new paradigm for nonlinear measurements, modeling, and simulation with ADS of nonlinear components*



NVNA:
Measure device X-parameters

ADS:
Simulate using X-parameters

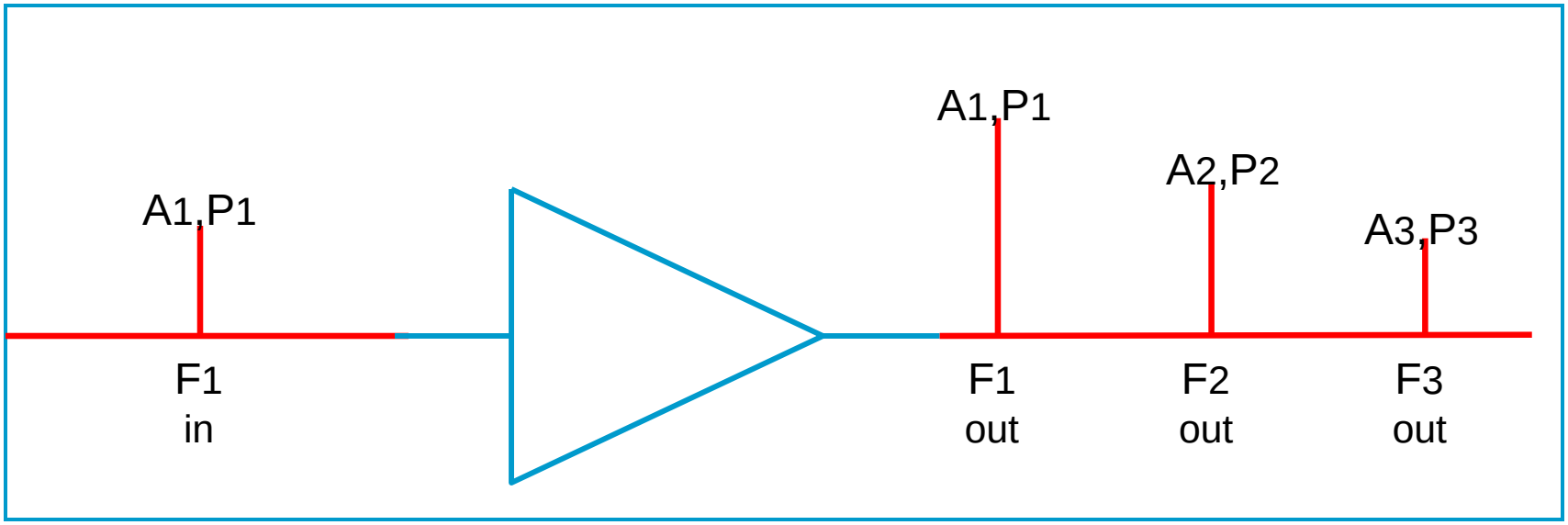
ADS:
Design using X-parameters



# Measuring nonlinearities for use directly in design

Wouldn’t it be nice if you could measure and display the full amplitude and phase information of each spectral component?

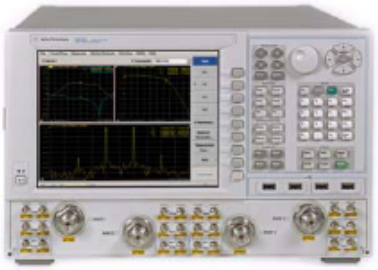
Wouldn’t it be even nicer to then use it directly in ADS harmonic balance or circuit envelope simulation?

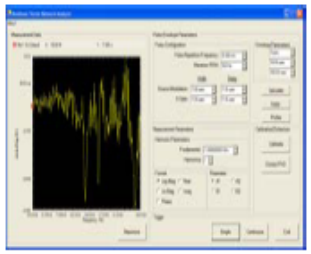


# Nonlinear Vector Network Analyzer (NVNA): *The new industry standard for nonlinear measurements*

***Fast, Accurate, and Easy to Use !***

Network Analyzer + Phase Reference + Software = NVNA





***The most innovative HP/Agilent instrument in 25 years!***

***Co-developed by CTD and HFTC***

NVNA = PNA-X + Phase Ref. ckt.
+ Application SW and calibration (mag and phase)
+ ADS-simulation application with *X-parameter measurement* **option**

NVNA measures *Magnitude and Phase* of all relevant frequency components (cross-frequency coherence) necessary to measure X-parameters!

# S-parameters: linear measurement, modeling, & simulation

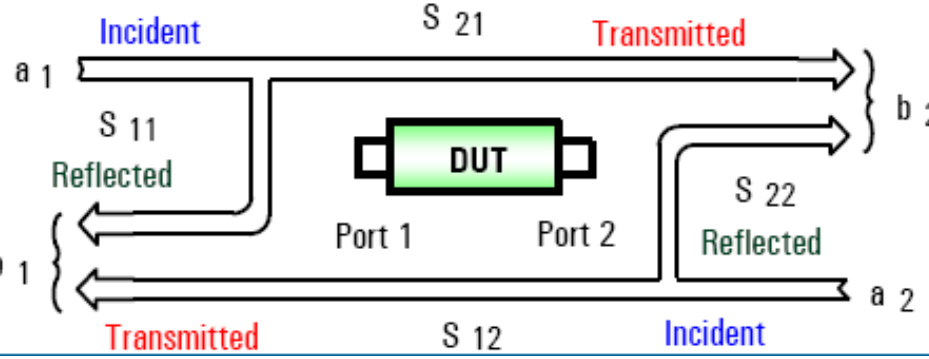
- Easy to measure at high frequencies
  - measure voltage traveling waves with a (linear) vector network analyzer (VNA)
  - don't need shorts/opens which can cause devices to oscillate or self-destruct
- Relate to familiar measurements (gain, loss, reflection coefficient ...)
- Can cascade S-parameters of multiple devices to predict system performance
- Can import and use S-parameter files in electronic-simulation tools (e.g. ADS)
- BUT: No harmonics, No distortion, No nonlinearities, ...
  Invalid for nonlinear devices excited by large signals, despite *ad hoc* attempts

**Linear Simulation:**
Matrix Multiplication

***S-parameters***

$$b_1 = S_{11}a_1 + S_{12}a_2$$
$$b_2 = S_{21}a_1 + S_{22}a_2$$

**Measure with linear VNA:**
Small amplitude sinusoids




**Model Parameters:**
Simple algebra

$$S_{ij} = \left.\frac{b_i}{a_j}\right|_{\substack{a_k = 0 \\ k \neq j}}$$

# What are X-Parameters?

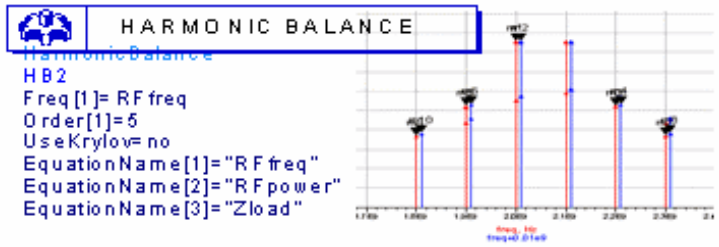
X-parameters are the mathematically correct superset of S-parameters, applicable to both large-signal and small-signal conditions, for linear and nonlinear components
*The math exists!*

We can measure, model, & simulate with X-parameters
Each part of the puzzle has been created The pieces now fit together seamlessly

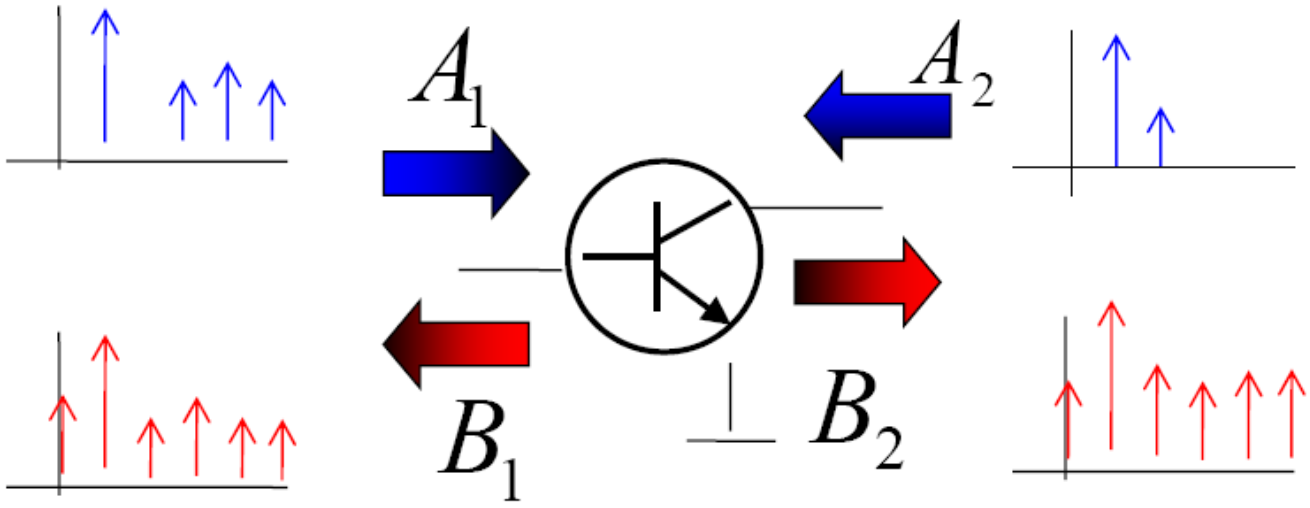
NVNA:
Measure device X-parameters

ADS:
Simulate using X-parameters

ADS:
Design using X-parameters



# X-parameters come from the Poly-Harmonic Distortion (PHD) Framework




$$B_{1k} = F_{1k}(DC, A_{11}, A_{12}, \ldots, A_{21}, A_{22}, \ldots)$$
$$B_{2k} = F_{2k}(DC, A_{11}, A_{12}, \ldots, A_{21}, A_{22}, \ldots)$$

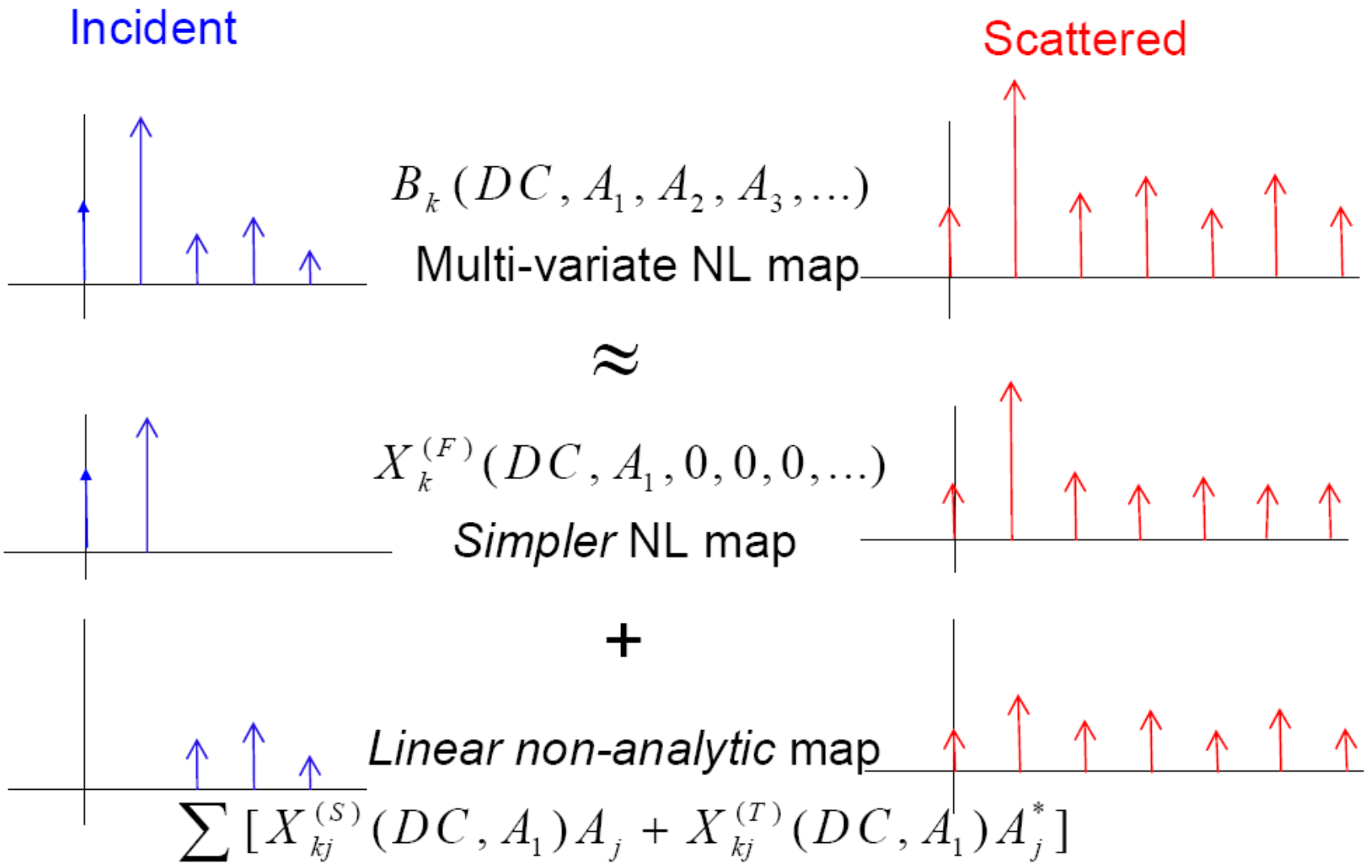
Port Index ↗ ↖ Harmonic (or carrier) Index

Spectral map of complex *large* input phasors to *large* complex output phasors
Black-Box description holds for transistors, amplifiers, RF systems, etc.

$$B_{e,f} = X^{(F)}_{ef}(|A_{11}|)P^f + \sum_{g,h} X^{(S)}_{ef,gh}(|A_{11}|)P^{f-h} \cdot A_{gh} + \sum_{g,h} X^{(T)}_{ef,gh}(|A_{11}|) \; P^{f+h} \cdot A^*_{gh}$$

Simplest X-parameterss — approximate general — mapping

# X-parameter Concept: Approxs. to NL Mapping



# X-Parameters: Why They are Critical:

$$B_{e,f} = X^{(F)}_{ef}(|A_{11}|)P^{f} + \sum_{g,h} X^{(S)}_{ef,gh}(|A_{11}|)P^{f-h}\cdot A_{gh} + \sum_{g,h} X^{(T)}_{ef,gh}(|A_{11}|)\ P^{f+h}\cdot A^{*}_{gh}$$

$$P = e^{j\varphi(A_{11})}$$

"New" Terms!

Cascaded Nonlinear Amplifiers: Nonlinear effects of mismatch versus drive

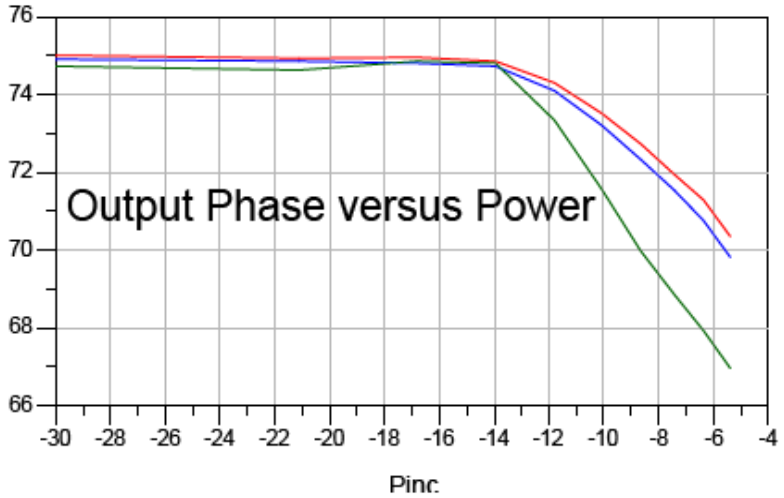

- Unambiguously identifiable (simple, automated extraction) from automated set of measurements
- Fully nonlinear vector quantities (Magnitude *and* phase of all harmonics)
- Extremely accurate for high-frequency, distributed nonlinear circuits
- Cascadable (correct behavior in mismatched environment)

# Results: Design of Cascade vs. Measurement of Cascade

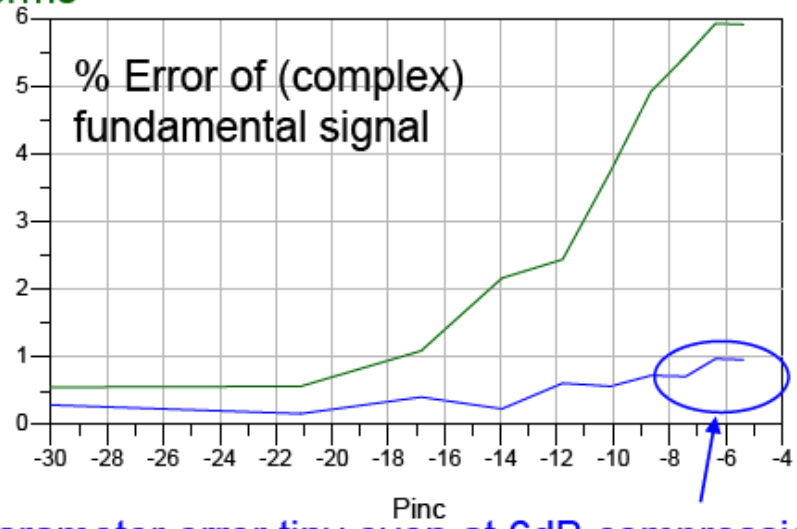
Objective: Design nonlinear circuits in ADS
from NVNA-measured X-parameter component data

X-parameters are superior to Hot S22

Cascaded Measurement
Cascaded Design with X-parameters
Cascaded Design with "Hot S-parameters" but No $X^{(T)}$ terms




Similar results hold at harmonics




X-parameter error tiny even at 6dB compression

"X-parameters enable predictive nonlinear design from NL data"

# NVNA System Configuration

**X-Parameter extraction/multi-tone source**

*New!!* Agilent NVNA

**Standard PNA-X Network Analyzer**

**Amplitude Calibration**

**Vector Calibration**

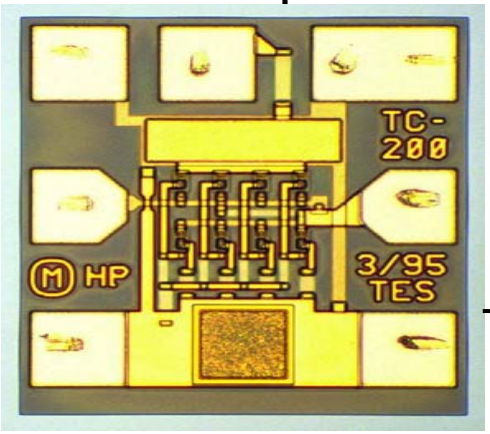
**Phase Calibration**

*New!!* Agilent Calibrated **Phase Reference**

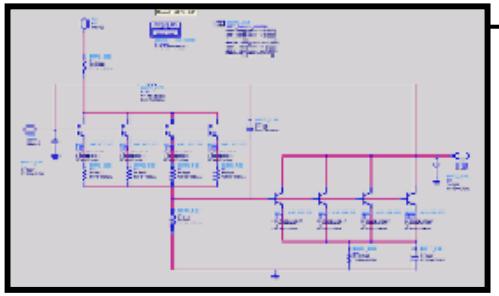
**Phase Reference**

# Black-Box Characterization & Behavioral Modeling

Actual Amp Circuit




Generate Behavioral Model

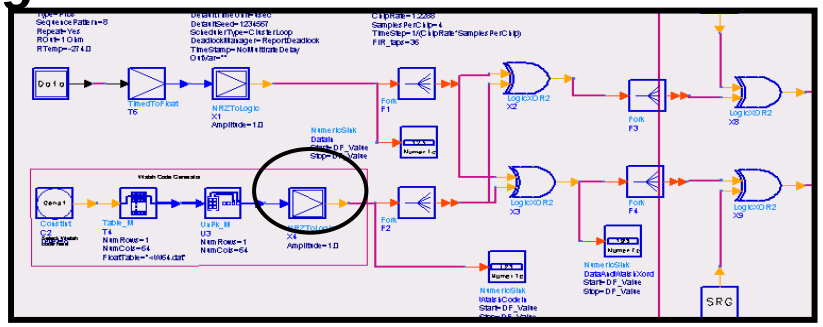


Detailed Circuit Model (SPICE/ADS) of IC

## Measurement-Based Model

- Circuit models don't exist
- Completely protect design IP

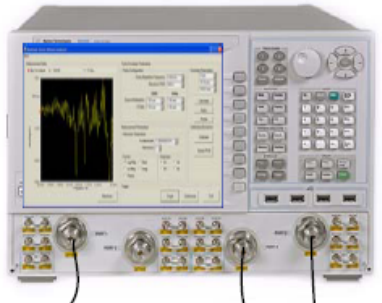
***Design of Module or Instrument Front End***



# PHD Framework: Simulating with Measured Data

Once measured, the X-parameters can be *immediately* used for design in ADS

NVNA




Measure X-Parameters

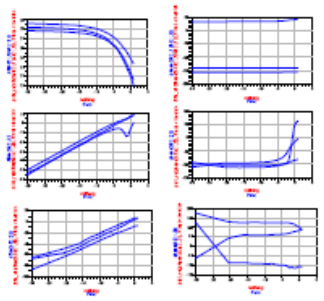
MDIF File

Script generates PHD model component

ADS

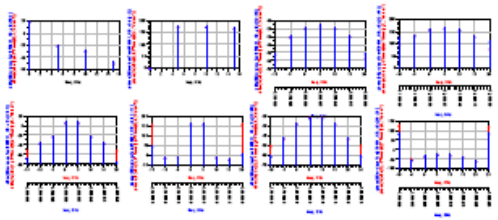
Harmonic Balance:

Captures magnitude and phase of harmonics, frequency dependence, and mismatch effects



Envelope:

Accurately simulate narrowband multi-tone or complex stimulus



NVNA Application

**Take X-parameter measurements**

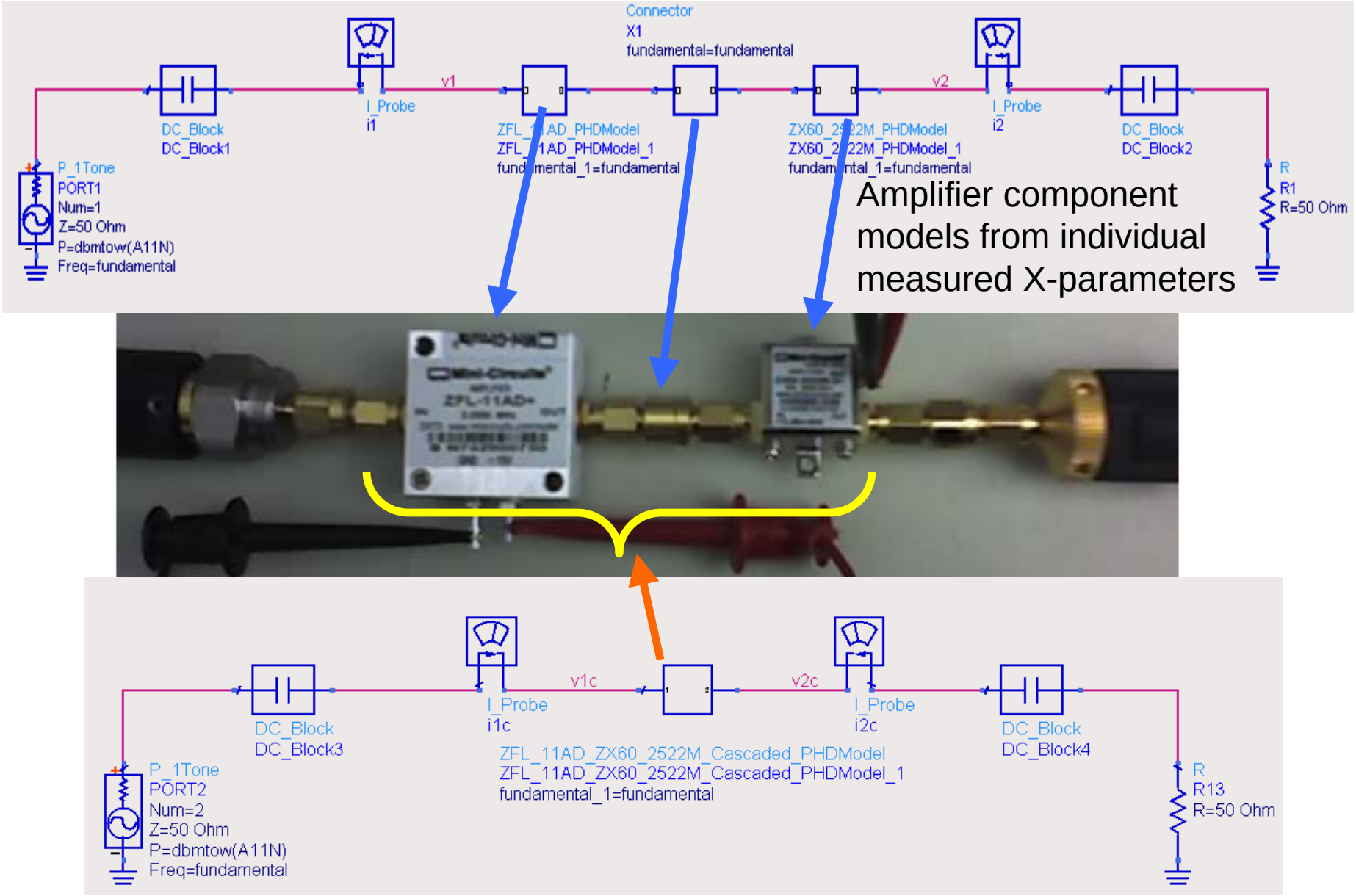
Memory Interface

Agilent PHD Code

**Extract X-parameters**
**Export model file**

**Works in HB and Envelope,**
Not in Transient

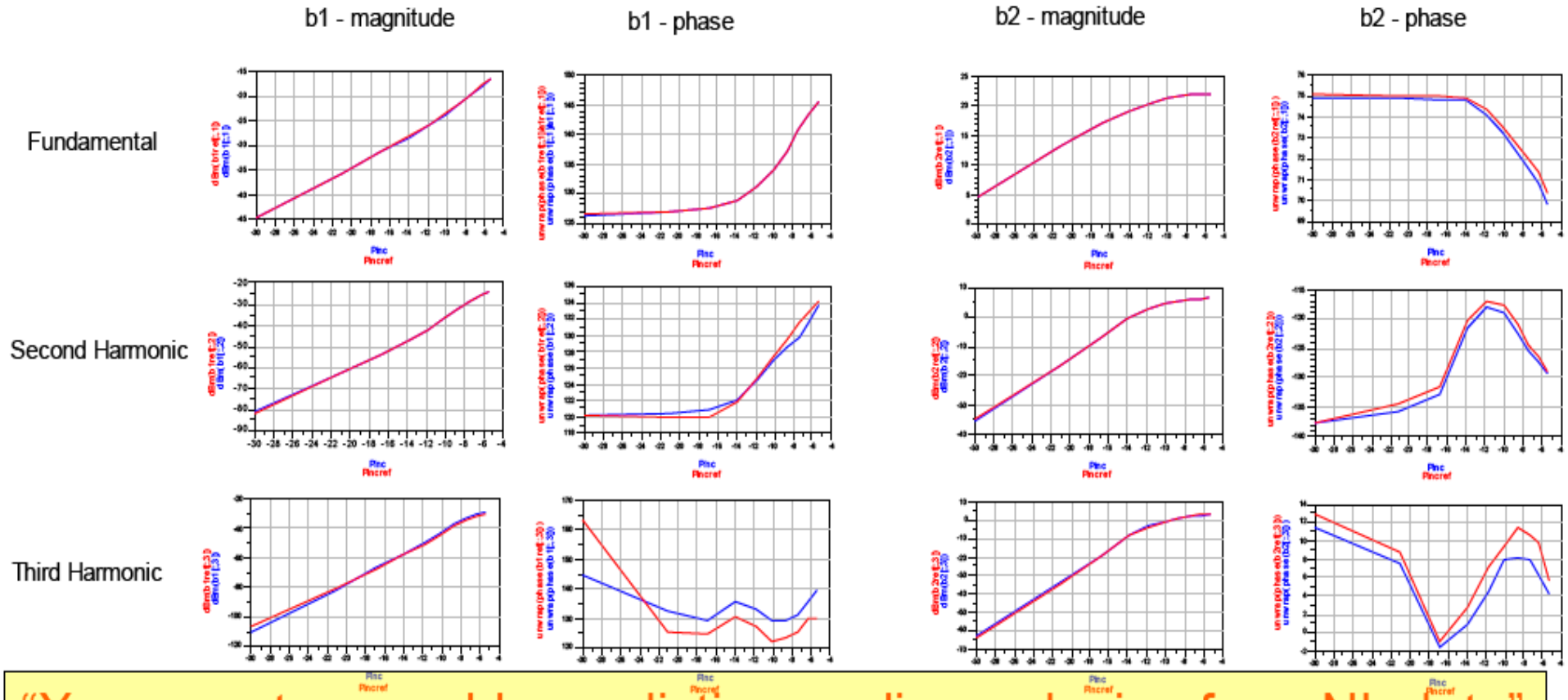
# Example: X-Parameters Verification



# Results Cascaded Simulation vs. Measurement

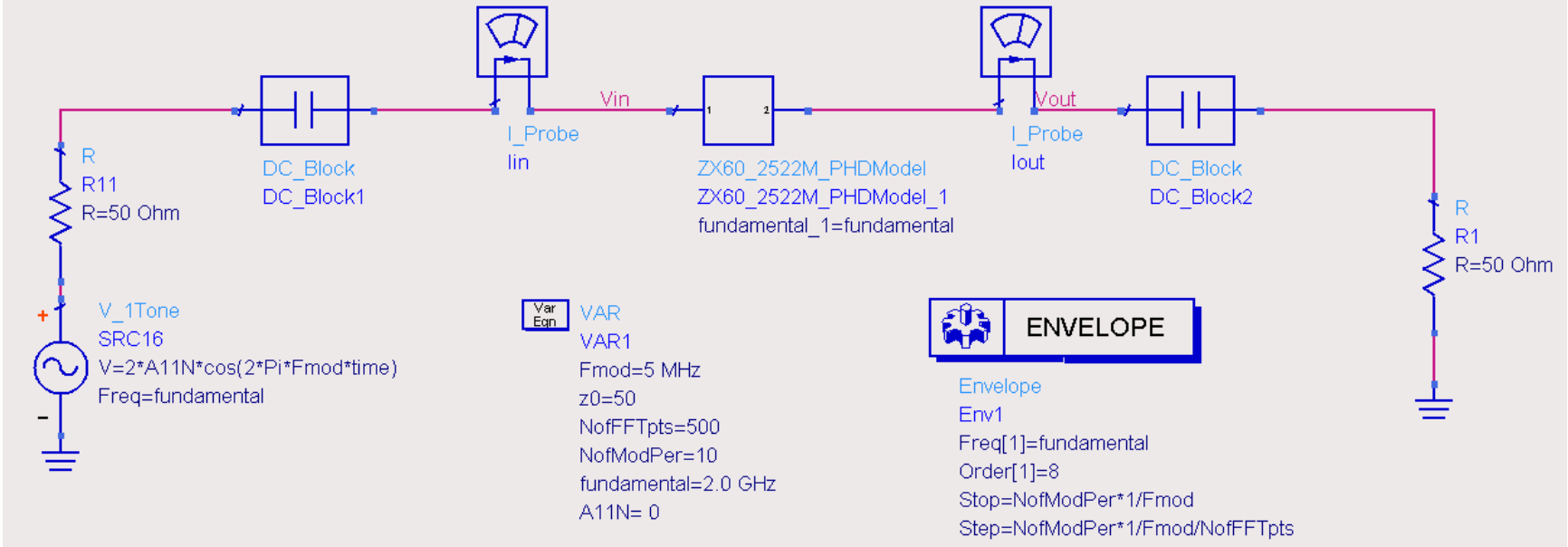
Red: Cascade Measurement

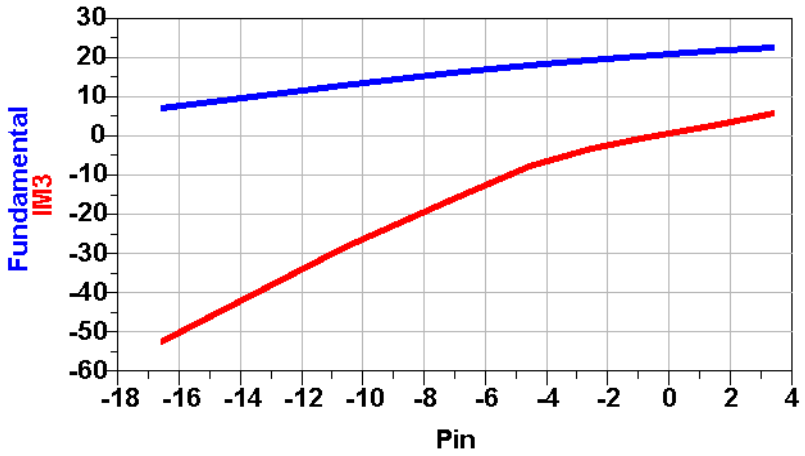
Blue: Simulation of Cascaded Models

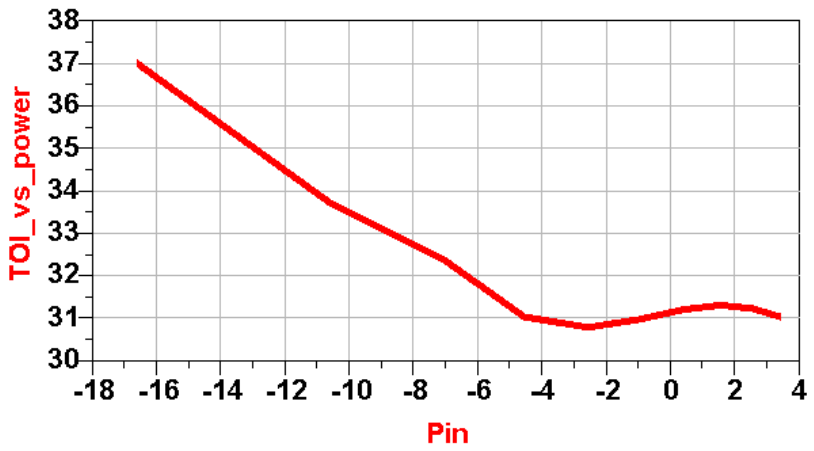



"X-parameters enable predictive nonlinear design from NL data"

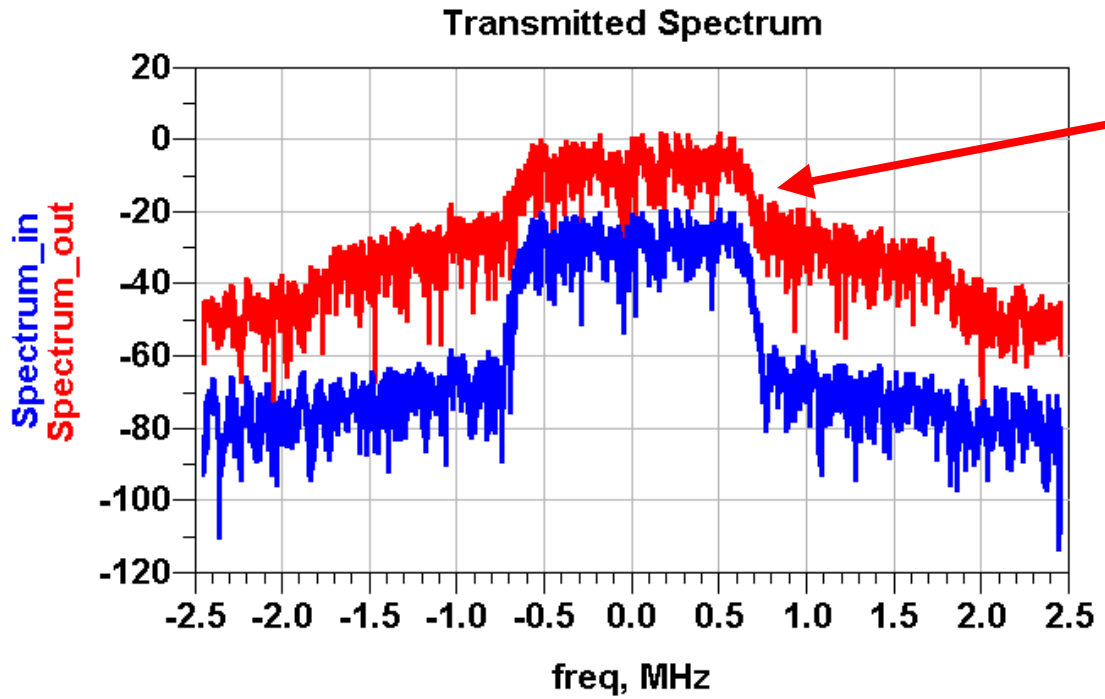
# Third Order Intercept Simulation



# Input / Output Spectrums & ACPR



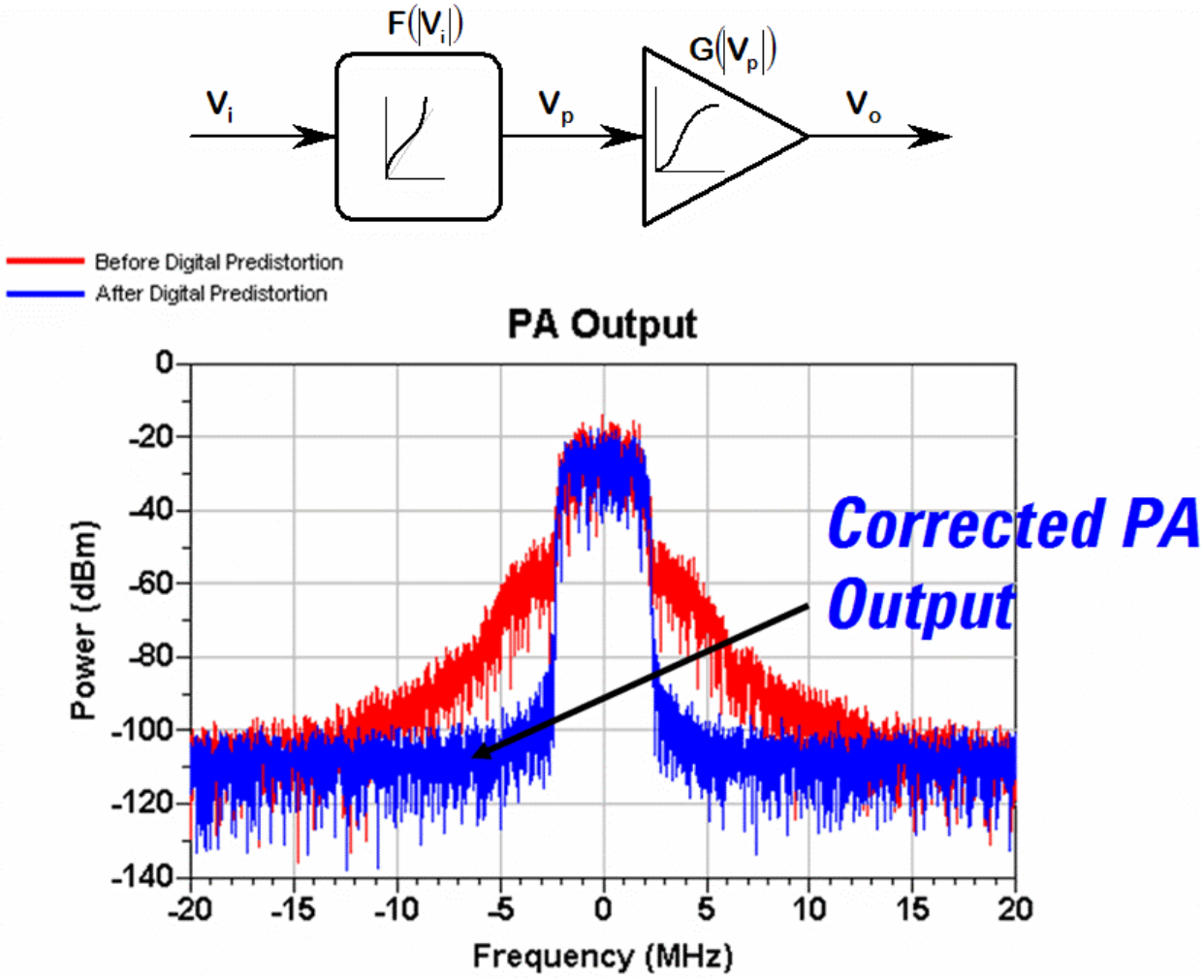

**Spectral Re-growth**

| TransACPR(1) | TransACPR(2) |
|---|---|
| -37.651 | -35.469 |

| ChannelPower_dBm |
|---|
| 20.038 |

| PAE |
|---|
| 9.987 |

# PA Linearization using X-Parameters in ADS Digital Pre-Distortion Linearization Design Guide



# Summary

- X-parameters are a mathematically correct superset of S-parameters for nonlinear devices under large-signal conditions
- X-parameters (for two-port devices under large-signal excitation from a single large input tone in this offering) can be accurately measured by automated set of experiments on the new Agilent NVNA instrument
- Together with the PHD Framework, measured X-parameters can be used in ADS to design nonlinear circuits
- All pieces of the puzzle are available and they fit together!