Seminario Agilent

Dispositivi non lineari: una breve introduzione dei Parametri X e del Nonlinear Vector Network Analyzer
Evolution of the Tools & Measurements

**TOOLS:**
SS & Oscilloscope
Grease pens and Polaroid cameras
Slotted line
Power meter

**MEASUREMENTS:**
Bode plots
Gain
SWR
Scalar network analyzers
Y & Z parameters

**TOOLS:**
Vector Network Analyzer

**MEASUREMENTS:**
Gain
Input match
Output match
Isolation
Transconductance
Input capacitance

**TOOLS:**
NA
SA/SS/NFA
Power meter
Oscilloscope
DC Parametric Analyzer

**MEASUREMENTS:**
Gain compression, IP3, IMD
PAE, ACPR, AM-PM, BER
Constellation Diagram, EVM
GD, NF, Spectral Regrowth
ACLR, Hot “S22”
Agenda

• Steps and Architectures in Network Analysis
• Nonlinear VNA and X-Parameter
Classic VNA Block Diagram
Network Analysis Step 1: S Parameter (1965)

Linear or nonlinear networks operating with signals sufficiently small to cause the networks to respond in a linear manner, can be completely characterized by parameters measured at the network terminals without regard to the contents of the networks.

- Relatively easy to obtain at high frequencies (measure voltage traveling waves with a vector network analyzer don't need shorts/opens which can cause active 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 compute H, Y, or Z parameters from S-parameters if desired;
- Can easily import and use S-parameter files in our electronic-simulation tools.

Modern VNA Block Diagram

- **Source 1**: Pulse modulator
- **Source 2**: Pulse modulator
- **Noise receivers**: 10 MHz - 3 GHz, 3 - 26.5 GHz
- **Test port 1**: To receivers
- **Test port 2**: +28V (for noise source)
- **Test port 3**: LO
- **Test port 4**: Rear panel
- **Mechanical switch**: RF jumpers
- **Signal combiner**: Impedance tuner for noise figure measurements
Agilent Technologies has developed X-parameters.

X-parameters represent and analyze the nonlinear behavior of RF components in a much more robust and complete manner. As an extension of S-parameters under large-signal operating conditions, they are driven into saturation (the real-world operating environment) and then measured under these conditions.
Agenda

- Steps and Architecture in Network Analysis
- Nonlinear VNA and X-Parameter
Designing a Power Amplifier (1)

The designer wants to drive the amplifier into the **nonlinear region** (large signal) to get the **maximum output power** as well as to extract the **maximum efficiency**.
Under large-signal conditions there are nonlinear effects:
- distort waveforms (time domain),
- harmonics, inter-modulations... (frequency domain).
**S-parameters can only analyze and model the linear behavior.**
Current Techniques for a Non-linear Device

Data sheets for amplifiers often have both linear and non-linear information

**Linear parameters**

**S=parameters**

**Non-linear parameters**

<table>
<thead>
<tr>
<th>FREQENCY (MHz)</th>
<th>S11</th>
<th>S21</th>
<th>S12</th>
<th>S22</th>
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<td>MAG</td>
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<td>97.2</td>
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</table>

**POWER DERATING CURVE**

**OUTPUT POWER & IM3 vs. INPUT POWER**

**Pout vs Pin**

**IMD**

**OUTPUT POWER vs. FREQUENCY**

**OUTPUT POWER vs. INPUT POWER**

**PAE**

**P1dB**

**Frequency (GHz)**

**Input Power (dBm)**

**Output Power (dBm)**

**VDS=10V**
A [new]-parameter file like a 3-D CAD file

The “library” contains all the necessary information
X-parameter Concept
X-parameters come from the Poly-Harmonic Distortion (PHD) Framework

\[ B_{1k} = F_{1k}(A_{11}, A_{12}, \ldots, A_{21}, A_{22}, \ldots) \]
\[ B_{2k} = F_{2k}(A_{11}, A_{12}, \ldots, A_{21}, A_{22}, \ldots) \]
Harmonic Superposition Principle

• In general, we are working under large-signal, nonlinear operating conditions. The superposition principle (parameters of individual components are sufficient to determine the parameters of any combination of those components) is not valid.

• In many practical cases (power amplifiers stimulated with a narrowband input signal) there is only one dominant large-signal input component present (A11). All other input components (the harmonic frequency components) are relatively small. In that case, we will be able to use the superposition principle for the relatively small input components.

• This is called the harmonic superposition principle.
Harmonic Superposition Principle

- (to keep the graph simple) Only consider the presence of the $A_{1m}$ and $B_{2n}$ components (neglect the presence of the $A_{2m}$ and $B_{1n}$).

- Case $A_{11} \neq 0$. $A_{1m}$ and $B_{2n}$ are indicated by black arrows. Note harmonic components for the $B_{2n}$ components.

- Leave the $A_{11}$ the same and add a small $A_{12}$ component (second harmonic at the input). This will result in a deviation of the output spectrum $B_2$. The same holds for a third harmonic and a fourth harmonic.

- The harmonic superposition principle holds when the overall deviation of the output spectrum $B_2$ is the superposition of all individual deviations.
The [new] X-parameter

Classic S-parameters: only linear behavior and ignore nonlinear behavior (harmonic, intermodulation, higher order mixing effects).

X-parameters capture linear behavior and linearize nonlinear behavior about a large signal operating point (LSOP).

NVNA measures X-parameters stimulating the DUT with a single large tone at port 1 and, in the same time, injecting additional small tones at both ports 1 and 2 at all harmonics of interest.

At least two phase-offset small tones must be injected at each port/frequency of interest in order to extract the corresponding X-parameters.
Injecting a large tone at port 1
Injecting a drive and probe tone at port 1
Injecting a drive tone at port 1 and probe tone at port 2
Measuring $B_{2,3}$ which is the Port2 output value at $3^{rd}$ harmonic ($3f_0$).

$X^{(F)}_{2,3} \ldots + X^{(S)}_{23,gh} \ldots + X^{(T)}_{23,gh} \ldots$

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

- **On-frequency**
- **Upper sideband**
- **Lower sideband**
Scattering Parameters

### S-Parameters – Linear System Description

\[ b_i = \sum_k S_{ik} \cdot a_k \]

\[ b_1 = S_{11} a_1 + S_{12} a_2 \]
\[ b_2 = S_{21} a_1 + S_{22} a_2 \]

### X-Parameters – Linear and Nonlinear System Description

\[ b_{ij} = X^{(F)}_{ij} (|A_{11}|) P^j + \sum_{k,l \neq (1,1)} (X^{(S)}_{ij,k,l} (|A_{11}|) P^{j-l} \cdot a_{kl} + X^{(T)}_{ij,k,l} (|A_{11}|) P^{j+l} \cdot a_{kl}^*) \]

- **On-frequency**
- **Upper sideband**
- **Lower sideband**

\[ |A_{11}| = \text{Large signal drive to the amplifier input port (port #1) at the fundamental frequency (#1)} \]

### Definitions

- \( i = \text{output port index} \)
- \( j = \text{output frequency index} \)
- \( k = \text{input port index} \)
- \( l = \text{input frequency index} \)

**For example:** \( X^{T}_{22,11} \)

**Means:**
- \( \text{output port} = 2 \)
- \( \text{output frequency} = 2 \) (2\(^{nd}\) harmonic)
- \( \text{input port} = 1 \)
- \( \text{input frequency} = 1 \) (fundamental)
Understanding X-parameter display

X-parameters: $X^F_p$, $X^S_{pq}$ and $X^T_{pq}$

Both the $p$ and $q$ terms are described by a Port and Harmonic combination.

For example: $X^S_{21,13}$

Parameters for each possible (port, harmonic) selection of $p$

For example: for $p=(2,1)$, and assuming 3 harmonics of interest:

$$X^F_{21}$$

$(X^S_{21,11}), (X^T_{21,11})$

$(X^S_{21,12}), (X^T_{21,12})$

$(X^S_{21,13}), (X^T_{21,13})$

$(X^S_{21,21}), (X^T_{21,21})$

$(X^S_{21,22}), (X^T_{21,22})$

$(X^S_{21,23}), (X^T_{21,23})$

For a 2-port device, with 3 harmonics of interest at each port:

- there are 6 possible (port, harm) combinations for $p$.
- each combination yields 13 parameters,

Total of $6 \times 13 = 78$ X-param
X-parameters reduce to S-parameters

\[ B_{ik} = X_{ik}^{(F)}(|A_{11}|)P^k + X_{ik,jl}^{(S)}(|A_{11}|)P^{k-l}a_{jl} + X_{ik,jl}^{(T)}(|A_{11}|)P^{k+l}a_{jl}^* \]

Reduces to (linear) S-parameters in the appropriate limit
X-parameters revolutionize the Characterization, Design, and Modeling of nonlinear components and systems

X-parameters are the mathematically correct extension of S-parameters to large-signal conditions.

- Measurement and simulation based, device independent, identifiable from a simple set of automated NVNA measurements or directly from ADS circuit-level designs
- Fully nonlinear (Magnitude and phase of distortion)
- Cascadable (correct behavior in even highly mismatched environment)
- Extremely accurate for high-frequency, distributed nonlinear devices

Measure X-parameters
- or-
Generate X-parameters from circuit-level designs

X-parameter Component: Simulate using X-parameters

ADS, SystemVue & Genesys: Design using X-parameters
X-parameters is actually a large data library -- X-param is measured with many variables --

Measurement takes from tens of minutes to a several hours depending on the size of the “library”
### Data Blocks per applied RF power

#### DC Bias voltages

<table>
<thead>
<tr>
<th>freq(real)</th>
<th>A1(complex)</th>
<th>B1(complex)</th>
<th>A2(complex)</th>
<th>B2(complex)</th>
<th>I1(real)</th>
<th>I2(real)</th>
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#### RF Input Power

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<th>B1(complex)</th>
<th>A2(complex)</th>
<th>B2(complex)</th>
<th>I1(real)</th>
<th>I2(real)</th>
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END
Calibration

Three step calibration process:

1) SOLT or TRL style calibration

2) Absolute receiver calibration using a power meter/sensor

3) Receiver phase calibration using Agilent’s new comb generator.
NVNA System Configuration

- X-Parameter extraction/multi-tone source
- Amplitude Calibration
- Vector Calibration
- Phase Calibration
- Phase Reference

Standard PNA-X Network Analyzer
Measurement Display
1. Nonlinear Component Characterization

* Absolute amplitude and cross frequency relative phase of measured spectra traceable to standards lab

* Data displayed in frequency, time and power domains:
  - ‘a’ and ‘b’ waves versus sweep domain
  - V and I versus sweep domain
  - V versus I, I versus V

**Frequency Domain**
1. Nonlinear Component Characterization

* Absolute amplitude and cross frequency relative phase of measured spectra traceable to standards lab

* Data displayed in frequency, time and power domains:
  - ‘a’ and ‘b’ waves versus sweep domain
  - V and I versus sweep domain
  - V versus I, I versus V

Time Domain
1. Nonlinear Component Characterization

* Absolute amplitude and cross frequency relative phase of measured spectra traceable to standards lab

* Data displayed in frequency, time and power domains:
  - ‘a’ and ‘b’ waves versus sweep domain
  - V and I versus sweep domain
  - V versus I, I versus V

Power Domain
1. Nonlinear Component Characterization

* Absolute amplitude and cross frequency relative phase of measured spectra traceable to standards lab

* Data displayed in frequency, time and power domains:
  - ‘a’ and ‘b’ waves versus sweep domain
  - V and I versus sweep domain
  - V versus I, I versus V

Customize Domain: V/I
2. X-parameter measurement

**Frequency Domain**

<table>
<thead>
<tr>
<th>Format</th>
<th>Display</th>
<th>Parameter</th>
<th>Measure</th>
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<tbody>
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<td><strong>Log Mag</strong></td>
<td><strong>Domain</strong></td>
<td>X-parameters</td>
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<td><strong>Port, Harm</strong></td>
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<tr>
<td><strong>Polar</strong></td>
<td><strong>Power</strong></td>
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![Graphs of X-parameter measurements](image_url)
2. X-parameter measurement

Power Domain

![Graphs showing X-parameter measurement in the Power Domain](image-url)
Three-port X-parameter
Two-tone X-parameter
Pulse envelope domain
Three-port X-parameter measurements

- Characterizing the nonlinear behavior of mixers and converters
- Accurate three-port X-parameter models that can be imported into ADS simulators
- Cascading both amplifiers and mixers in system designs
- Accurate simulation results for system designs
Two-tone X-parameter measurements

X-parameter measurements have been expanded to include two-tone large signal stimuli to a device. When a two-tone signal is applied to a nonlinear device, it produces a number of mixing products which occur around the fundamental frequency as well as the harmonics. The NVNA has the ability to measure all these mixing products providing a much richer characterization of the device’s nonlinear behavior.

A single tone stimulus signal produces harmonics

A two-tone stimulus signal produces inter-modulation products around each of the harmonic frequencies
Nonlinear pulse envelope domain

Gain key insights into understanding memory effects in active nonlinear devices. Low frequency effects from thermal/heating or contributions from biasing circuits to high frequency effects from frequency limiting matching circuits can complicate analyzing component behaviors. NVNA pulse envelope domain measures the vector corrected amplitude and phase of the fundamental and harmonic pulse envelopes of your DUT. Displayed data indicates how the nonlinear behaviors of your device are changing over time, giving you a powerful tool in analyzing the nonlinear root issues and then validating the design changes.

Configuration, Cal and Meas (Waves and Harmonics): menu Utility > Measurement Domain... > Envelope Domain
NVNA and ADS
Don’t you have this problem?
device model model takes time and is not accurate

Modeling: I need a couple of months

I want to start my design now!

My simulation gave me a great answer but the reality is…

-2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0
-2.5 2.5
-70
-60
-50
-40
-30
-20
-10
-80
0
freq, MHz
Spectrum_out
Transmitted Spectrum

simulated ACPR

measured ACPR
X-parameter enables 3 activities to run in parallel

Before

- Process dev.
- Modeling
- Amplifier design
- Module design

After

- Process dev.
- [X] Meas
- Amplifier design
- [X] Sim
- [X] Meas
- Module design
- Module designers can start design with the simulated X-param then with the measured X-param

Amp designers can start design without waiting for the model

New technologies like GaN
NVNA and ADS

X-parameters in conjunction with ADS design and simulation tools minimize design iterations, speed simulation and deterministically model the nonlinear behavior of your active components. This can significantly reduce the time to market for component, module, and system design.
S Parameter

NA

S Parameter

ADS
Component Char. NVNA

Component Char. ADS

-20dBm Input

0dBm input

-0.6  -0.5  -0.4  -0.3  -0.2  -0.1  0.0  0.1  0.2  0.3
-0.6  -0.5  -0.4  -0.3  -0.2  -0.1  0.0  0.1  0.2  0.3

-10  -8   -6   -4   -2   0    2    4    6    8    10

0.0  0.2  0.4  0.6  0.8  1.0  1.2  1.4  1.6  1.8  2.0

time, nsec

time, nsec

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X Parameter
NVNA

X Parameter
ADS
ADS
S-parameter vs X-parameter

**S-par**

**Transmission**

**Reflection**

**Output Voltage**

**X-par**

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Power Amplifier Design
X-Parameter Example on GaN amplifier

- 32 Watt 1.2 GHz GaN (Gallium Nitride) Amplifier,
  - PAE (Pout-Pin)/(Vdc*Idc) on datasheet: 55%

1. Measured with PNA-X/NVNA this amplifier and obtained X-parameters.
2. Loaded the measured X-parameters into ADS
3. Performed simulation in ADS:
   - ADS predicted an PAE of 75%,
     by using optimum output impedance matching circuitry on 1\textsuperscript{st}, 2\textsuperscript{nd} and 3\textsuperscript{rd} harmonic.
4. Realized PCB for this amplifier,
   following the ADS suggestion for optimization
5. Measured the PCB (with amplifier mounted on it) with PNA-X/NVNA
   - Actual measured PAE was 75%
   - Matches ADS prediction
   - By using this X-par approach we could achieve 20% better PAE.
NVNA X-parameter System – Power budget (120W)

Application Note 1408-19: High Power Amplifier Measurements using Agilent's Nonlinear Vector Network Analyzer
High Power X-parameter Measurement System
Component manufacturers start to make X-Parameters available to their customers

**X-Parameter Modeling for Cellular Applications**

Significantly reduces development time on 2G/3G Power Amplifier and Front-End Modules

Leveraging a partnership with Agilent Technologies, Skyworks now supports the X-parameter models for nonlinear network analysis in its line of power amplifier modules (PAMs) and front-end modules (FEMs) for the cellular market. For Skyworks’ customers, this means faster, more accurate modeling information for 2G/3G applications to reduce design cycles, lower operating costs, and accelerate time-to-market.

Agilent’s X-parameter include vector measurement from 10 MHz to 13 GHz and represent a new category of nonlinear network parameters for high-frequency design. Now designers can quickly generate a non-linear model from Skyworks’ PAMs and FEMs to accurately measure, display, and simulate the full amplitude and phase information of each spectral component in non-linear designs.

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**Agilent MMICs**

- Highly linear mixers
- High power/high fidelity amplifiers
- High TOI attenuators
- Microwave MEMS
- X-parameters available

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Agilent is using X-parameters for the internal design and also selling ICs to the external customers with X-parameter files.
Summary

The NVNA nonlinear measurements with full match correction and accurate amplitude and cross frequency relative phase information provide a new standard in accuracy and insight of the behaviors of nonlinear components.