Beyond S-parameters

The ZVxPlus

An extension kit for Rohde and Schwarz ZVA and ZVT
Outline

- The WHY and HOW of “Large Signal Network Analysis”
  - Introduction to Large Signal Network Analysis (LSNA)
  - The VNA Evolution, VNA vs LSNA measurement
  - How to upgrade from a VNA to a LSNA? Theory of Operation
  - What about calibration?

- The NM300 ZVxPlus
  - Hardware and specifications
  - Software - The Integrated Component Characterisation Environment (ICE)
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The Market Trend

- RF and HF Components and Circuits = “More for Less”
  - Higher efficiency (power & bandwidth)
  - More complex (circuits & modulation schemes)
  - Smaller, cheaper, shorter time to market

- Nonlinear behaviour of components can no longer be ignored
- Interaction between instruments and devices may lead to wrong conclusions
- Existing characterisation techniques are no longer sufficient

Growing need to characterise the nonlinear behaviour of components in time and frequency domain at DUT reference plane
Existing Characterisation Techniques

- Existing approaches
  - Power Measurements
  - Spectrum Analysis – Compression - TOI
  - Vector Signal Analysis - EVM
  - AM-AM and AM-PM
  - Source- and Load-pull

- The problem
  - “Limited visibility”
    - Lacking the basic information to gain insight
    - Difficult to perform a step by step diagnostics
  - Instrument – component interaction
    - Impact on (assumed) excitations
    - Impact on results and specifications
  - Different setups
    - Different skill sets
    - Different calibration techniques
The New Characterisation Technique

- “Large-Signal Network Analysis” is
  - Measuring the “complete” behaviour of a device under test i.e. the $v$ and $i$ (or $a$ and $b$) at all DUT ports at the same moment
  - Accurately
  - Under almost realistic conditions
    - Excitation and mismatch
  - Using a single connection
    - Including small-signal analysis
Key Benefits

- Deal with the “More for Less” market trend
  - for diodes, transistors, amplifiers, multipliers, dividers, ...

- Better – More complete
  - better characterisation = improved and “LSNA-certified” models and design kits
  - better large-signal models = better design
  - better design = reduction of the number of design cycles
  - testing under realistic conditions: excitations & mismatch conditions

- Faster
  - single connection for small- and large-signal characterisation
  - measuring basic information, i.e. PAE, Pin, Pout, ... are simple derived quantities

- At reduced cost
  - applicable from device to system level
  - from R&D to T&M
The VNA Evolution

- Linear
- Nonlinear

S-parameters → Power of Harmonics and Intermodulation → Phase of Harmonics

ZVxPlus
VNA Evolution: From Small-Signal To Large-Signal

DC Source

\[ V_{gs} = -0.5 \, \text{V} \]
\[ V_{ds} = 2 \, \text{V} \]

RF Characterisation

Relative Calibration + Power Calibration (+ Phase Calibration)

Fixture Deembedding

(*) Commercial available FET
The VNA Evolution: Small-Signal Network Analysis

S-parameters → Power of Harmonics and Intermodulation → Phase of Harmonics

Linear

Nonlinear

ZVxPlus
One VNA Measurement

Measuring:

\[
\frac{b_1(f_0)}{a_1(f_0)}, \frac{b_2(f_0)}{a_1(f_0)}, \frac{a_2(f_0)}{a_1(f_0)}
\]
S-parameters

\[ f_0 \quad \text{Forward Measurement} \quad + \quad \text{Reverse Measurement} \quad + \quad b_1 = S_{11}a_1 + S_{12}a_2 \quad b_2 = S_{21}a_1 + S_{22}a_2 \quad = \quad \text{S-parameters} \]

Mathematics
[Linear Model]
[SUPERPOSITION]

Behavioural Model
$P_{in} = -20 \text{ dBm}$
"Noisy" S-parameters ???

$P_{in} = 0 \text{dBm}$

Increasing power
The VNA Evolution: Large-Signal Characterisation

Linear

Nonlinear

S-parameters → Power of Harmonics and Intermodulation → Phase of Harmonics

ZVxPlus
Harmonic Characterisation in Power

$P_{in}$: from $-25$ to $0$ dBm at $f_0 = 2.059$ GHz

$b_2$

<table>
<thead>
<tr>
<th>Trc2</th>
<th>Mem3[Trc2]</th>
<th>Mem4[Trc2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>dB Mag</td>
<td>dB Mag</td>
<td>dB Mag</td>
</tr>
<tr>
<td>10 dB / Ref 0 dBm</td>
<td>10 dB / Ref 0 dBm</td>
<td>10 dB / Ref 0 dBm</td>
</tr>
</tbody>
</table>

Graph showing harmonic frequencies $f_0$, $2f_0$, and $3f_0$. The graph plots power levels against frequency.
Harmonic Characterisation in Frequency

\( f_0 : \) from 0.19 to 17.99 GHz at \( P_{\text{in}} = -5 \text{ dBm} \)

\( b_2 \)

\( b_2 \) dB Mag 10 dB / Ref 0 dBm PCao
Mem3[Trc2] b2 dB Mag 10 dB / Ref 0 dBm
Mem4[Trc2] b2 dB Mag 10 dB / Ref 0 dBm

2 of 2 (Max)
Harmonic Characterisation in Power

Harmonic Distortion of Source

![Graph showing harmonic distortion with f_0, 2f_0, and 3f_0]

- Trc2: dB Mag 10 dB / Ref 0 dBm
- Mem3[Trc2]: dB Mag 10 dB / Ref 0 dBm
- Mem4[Trc2]: dB Mag 10 dB / Ref 0 dBm

2 of 2 (Max)
The VNA Evolution: Large Signal Network Analysis

Linear

Nonlinear

S-parameters ➞ Power of Harmonics and Intermodulation ➞ Phase of Harmonics

ZVxPlus
One LSNA Measurement

Measuring:

\[ a_1(kf_0), b_1(kf_0), a_2(kf_0), b_2(kf_0) \]

OR

\[ v_1(kf_0), i_1(kf_0), v_2(kf_0), i_2(kf_0) \]
Forward Measurement

Another Forward Measurement

\[ b_1 = F(a_1, a_2) \]
\[ b_2 = G(a_1, a_2) \]

\[ \text{Mathematics} \]
[Many possible Nonlinear Models]
[NO SUPERPOSITION]

\[ \text{Behavioural Model} \]
[VALIDITY]

\[ \text{???-parameters} \]
Block Diagram of a Large-Signal Network Analyser

\[
\begin{bmatrix}
a_1 \\
b_1 \\
a_2 \\
b_2 
\end{bmatrix}(f) = K(f)
\begin{bmatrix}
1 & M_{12} & M_{13} & M_{14} \\
M_{21} & M_{22} & M_{23} & M_{24} \\
M_{31} & M_{32} & M_{33} & M_{34} \\
M_{41} & M_{42} & M_{43} & M_{44} 
\end{bmatrix}(f)
\begin{bmatrix}
a_1^M \\
b_1^M \\
a_2^M \\
b_2^M 
\end{bmatrix}(f)
\]
Measuring Fundamental and Harmonics with a VNA

Network Analyser

Mixer Front-end

Test Set

Input 1 → Port 1 → Port 2 → Input 2

DUT

1 GHz

df GHz

1 + df GHz

...  

5 + df GHz

...  

20 + df GHz

LO

1 GHz

1 2 ... 5 ... 20 GHz
Time Domain measurement with a VNA
Measuring Fundamental and Harmonics with a VNA

Network Analyser

Mixer Front-end

1 GHz

df GHz

1 + df GHz

... 5 + df GHz

... 20 + df GHz

LO

Test Set

Input 1

Port 1

DUT

Input 2

Ref Channel

Synchroniser

“Fixed Phase Relationship”

1 GHz

df GHz

1 … 20 GHz

5 GHz

1 … 20 GHz

5 GHz
VNA as LSNA: Theory of Operation

phase consistency between harmonics in 1 2 3

phase consistency between receivers by simultaneous measurement one frequency at the time
Synchronized Measurements with VNA as LSNA

#1

#2

#3

#4
References


Calibration Techniques

- **Step 1:** Relative Calibration Technique
  - Same as the regular VNA calibration
  - Traceable to standards

- **Step 2:** Power calibration $K$
  - Power meter and sensor
  - Characterization of power distortion
  - Traceable to standards

- **Step 3:** Phase calibration $\Phi(K)$
  - Phase reference generator
  - Characterization of phase distortion
  - Traceable to NIST standard

- **Remark:** On-wafer and fixture calibration require additional steps
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NM3xx ZVxPlus

ZVxPlus =

4-port ZVA or ZVT + Hardware + Software

- direct gen. & rec. access (B16)
- frequency conversion (K4)
- meas. rec. step att. (opt.) (B3x)
- synchroniser
- harmonic phase ref.
- configuration
- absolute calibration
- measurements
Key Capabilities

- Connectorised and on wafer calibration and measurement
- Fundamental and Harmonics in amplitude and phase
- Incident and Reflected Waves or Voltages and Currents
- Frequency and Time Domain
- Over range detection and range adaptation
- Support for power applications
- 3D Dynamic load-line, mapping DC and HF conditions
- Derived measurement quantities
- Custom integration with Source – and Load-pull
Blockdiagram of standard ZVxPlus

- **Excitation Source**
- **Reflectometer**
- **Receiver**
- **DUT**
- **20 dB**
- **Access to output e.g. tuning**
- **Spare Port e.g. Differential nonlinear measurement**
- **Port 1**
- **Port 2**
- **Port 3**
- **Port 4**

Possible Signal Conditioning

- **Synchroniser**

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ZVxPlus Parts

ICE 2009A Software

Synchroniser

Connection Kit

Harmonic Phase Reference

Attenuator Kits
NM300 600MHz-20GHz Kit includes:

- 1x NM400 Synchronizer 600MHz-20GHz, enabling the reconstruction of time waveforms

- 1x NM200 Harmonic Phase Reference Drive Box + 1x NM210 Harmonic Phase Reference Wand 600MHz-20GHz, supporting the required phase calibration

- 1x NM301 3.5mm Connection Kit, including cables and adapters

- 1x ICE 2009A Software License

- One year warranty and support
ZVxPlus Options

Adapter Kits

- **NM300-10** 2.4mm to 3.5mm Adapter Option for NM301, required for R&S® ZVA50

Attenuator Kits, required *per port* when corresponding internal step attenuator is missing (option B31 and/or B32)

- **NM300-20** 20GHz attenuator option for R&S® ZVT20 / R&S® ZVA24
- **NM300-40A** 20GHz attenuator option for R&S® ZVA40
  
  or

- **NM300-40B** 40GHz attenuator option for R&S® ZVA40
- **NM300-50A** 20GHz attenuator option for R&S® ZVA50
  
  or

- **NM300-50B** 50GHz attenuator option for R&S® ZVA50
## NM300 ZVxPlus: Specifications

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency range</td>
<td>600 MHz – 20 GHz</td>
<td>limited by phase calibration</td>
</tr>
<tr>
<td>Minimal frequency grid spacing</td>
<td>600 MHz</td>
<td></td>
</tr>
<tr>
<td>Power level *</td>
<td>+10 dBm</td>
<td>@ Test port</td>
</tr>
<tr>
<td>Absolute phase uncertainty **</td>
<td></td>
<td>1 σ @ 20 GHz, independent of IF BW, due to phase variations between the internal sources @ 100 Hz IF BW, highly dependent on external source</td>
</tr>
<tr>
<td>using second internal source</td>
<td>0.6°</td>
<td></td>
</tr>
<tr>
<td>using external source (locked to 10 MHz)</td>
<td>6°</td>
<td></td>
</tr>
</tbody>
</table>

* Power extension possible using optional step attenuators or external attenuators achieving maximum allowable power of +27 dBm with standard test set

** Using one R&S®ZVA internal source to drive Synchroniser @ 600MHz

**Notes:** when additive noise is dominant, the phase standard deviation can be linked to the dBm standard deviation using the following:

\[
\sigma_{\text{Phase}(x)_{\text{deg}}} = \frac{180}{\pi} \frac{\ln(10)}{20} \sigma_{\text{dBm}(x)} \approx 6.6 \sigma_{\text{dBm}(x)}
\]
**Customisation and Options**

**Core:** ZVx and ZVxPlus

**Customisable:** required and supplied by customer or at additional cost

**Optional:** depending on characterisation needs, supplied by customer or at additional cost
BlockDiagram of customised ZVxPlus for Power Applications

10 MHz ref (')

Excitation Source

Reflectometer

Receiver

Port 1

Port 2

Port 4

Synchroniser

Port 3

External Excitation Source

Signal Conditioning

DUT

Access to output e.g. tuning

Spare Port

(): impact on phase noise

("): optional step attenuator option
More than waveforms

- Large-Signal Component Characterisation, Design and Test is **MORE** than showing waveforms alone

- Therefore, NMDG developed a evolutionary platform resonating with customer needs

**ICE**

= The Integrated Component Characterisation Environment
ICE: Integrated Component Characterization Environment

DC
CW
Tuner

Stimuli

Receivers
DC Meters
VNA
LSNA

ICE

“Real-Time” and Complete Stimulus – Response Characterization
Active Components and Circuits

Diode,
Transistor,
Divider,
Multipler
Characterization

Model
Verification
and
Tuning

Real-time
Component
Characterization
and
Tuning

Calibration
Technology

...
What is ICE?

- A Graphical User Interface environment
- Centred around complete characterisation of active RF / HF components and circuits in a “stimulus – response” sense using only one connection
- Bringing together the necessary hardware and software for proper component characterisation in its different aspects
- Providing a unified calibration and measurement approach across different types of receivers
- Supporting different types of test signals and impedance environments
- Allowing application development and deployment independent of hardware specifics
- Usable and scalable from R&D into test, reducing the cost of test
ICE: Key Benefits

- **Easy:**
  - Easy controls for different types of instruments
  - Easy calibration wizards for connectorised and **on wafer** calibration
  - Step by step wizard to create your customised setup
  - Easy to use displays for voltage / current and wave quantities in different domains at any port of a device
  - Easy to configure displays combining different variables into one display

- **Fast:**
  - **"Fire and go"** ... ready to measure in seconds thanks to preconfigured setups
  - Real-time feedback on device performance while tuning stimuli

- **Accurate:**
  - Absolute DC and RF calibration methods for both connectorised and on-wafer components eliminating systematic errors up to the level of the component
ICE Displays

Basic Display

Derived Quantities

Advanced Display
Classical Measurement Setup

DC Analyser
\[(v1dc, i1dc, v2dc, i2dc)\]

DC Source 1

DC Source 2

RF Analyser
\[(a1rf, b1rf, a2rf, b2rf)\]

RF Source

Port 1

20 dB

Port 2

20 dB

DUT

Port 3

Synchroniser

a1 b1

v1dc

b2 a2

v2dc

a3
ICE Environment

DC Analyser

RF Analyser
RF Source
DC Source 1
DC Source 2
Applications with ICE
Conclusion

• With an incremental investment on a suitable R&S ZVA or ZVT, it is possible to characterise devices with one single connection
  • in small-signal behaviour with S-parameters
  • in large-signal harmonic behaviour under realistic conditions with complete input and output waveforms
• The accurate and complete large-signal harmonic measurements enable new insights in component behaviour, leading faster to
  • better semiconductor technologies
  • better models and design kits
  • better designs
  • faster ways of testing, possibly in non-50 Ohm environments

For more information  info@nmdg.be
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