LEADING BEYOND S-PARAMETERS

Beyond S-parameters

The ZVxPlus

An extension kit for Rohde and Schwarz ZVA and ZVT

April 2009 - v2

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

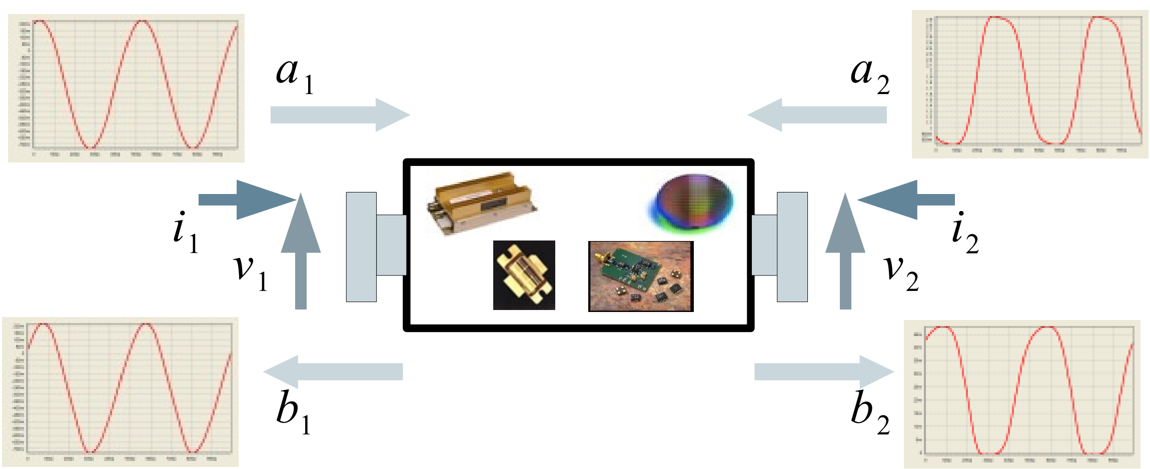
- Existing approaches
  - Power Measurements
  - Spectrum Analysis – Compression - TOI
  - Vector Signal Analysis - EVM
  - AM-AM and AM-PM
  - Source- and Load-pull

- 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

NMDG

The New Characterisation Technique

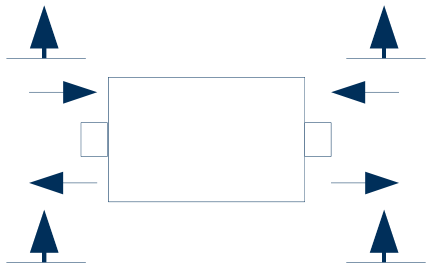
- **“Large-Signal Network Analysis”** is
  - Measuring the “complete” behaviour of a device under test
    i.e. the **v and i (or a and b) at all DUT ports** at the same moment
  - Accurately
  - Under almost realistic conditions
    - Excitation and mismatch
  - Using a single connection
    - Including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



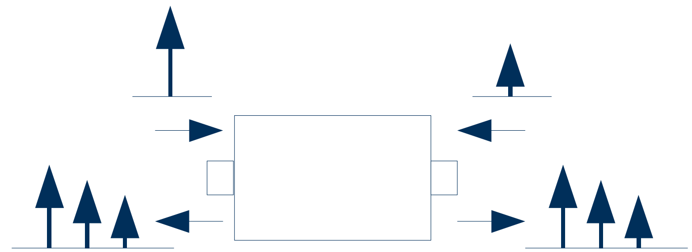
Key Benefits

- 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



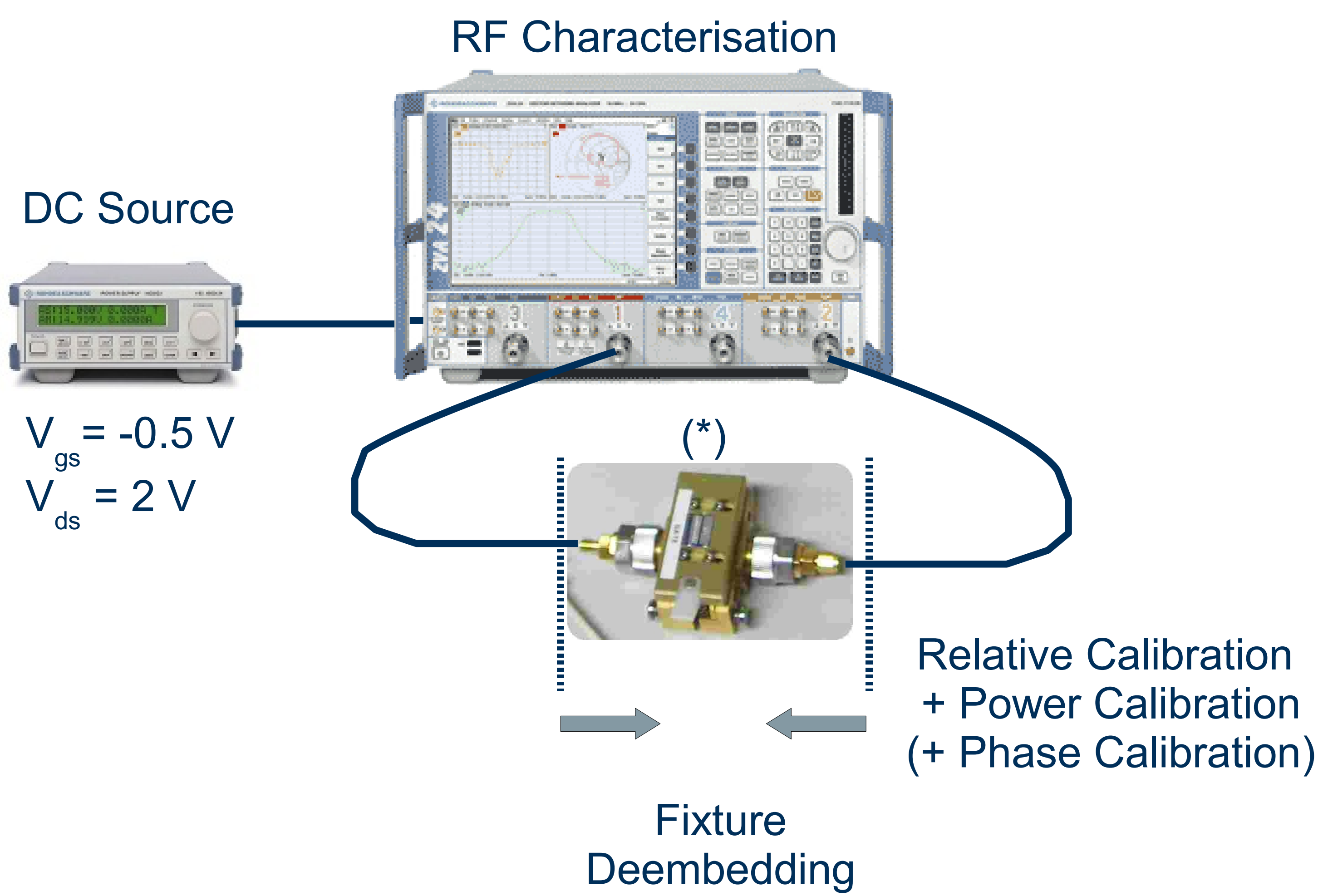
Linear



Nonlinear

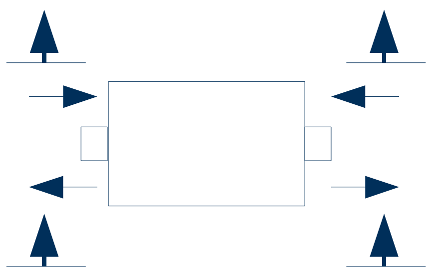
S-parameters → Power of Harmonics and Intermodulation → (ZVxPlus) → Phase of Harmonics

VNA Evolution: From Small-Signal To Large-Signal



(*) Commercial available FET

The VNA Evolution: Small-Signal Network Analysis

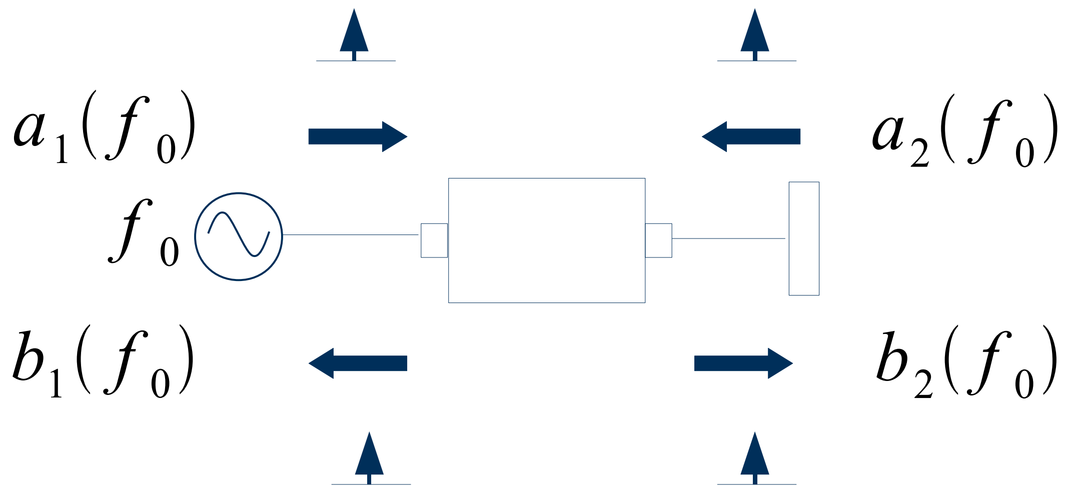


Linear

Nonlinear

S-parameters → Power of Harmonics and Intermodulation → (ZVxPlus) → Phase of Harmonics

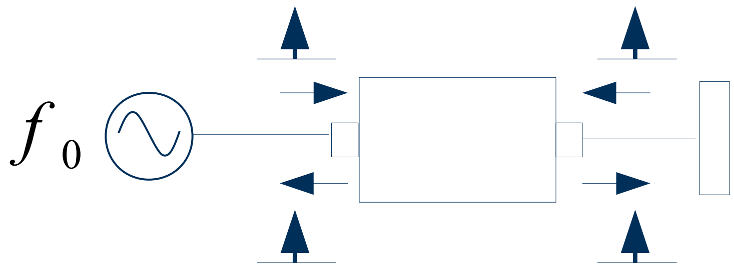
One VNA Measurement



Measuring:

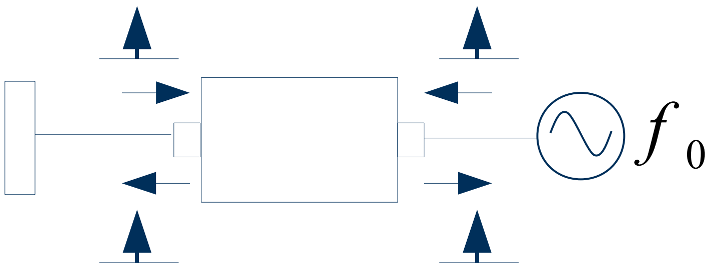
$$\frac{b_1(f_0)}{a_1(f_0)}, \frac{b_2(f_0)}{a_1(f_0)}, \frac{a_2(f_0)}{a_1(f_0)}$$

S-parameters



Forward Measurement

+



Reverse Measurement

+

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

Mathematics
[Linear Model]
[**SUPERPOSITION**]

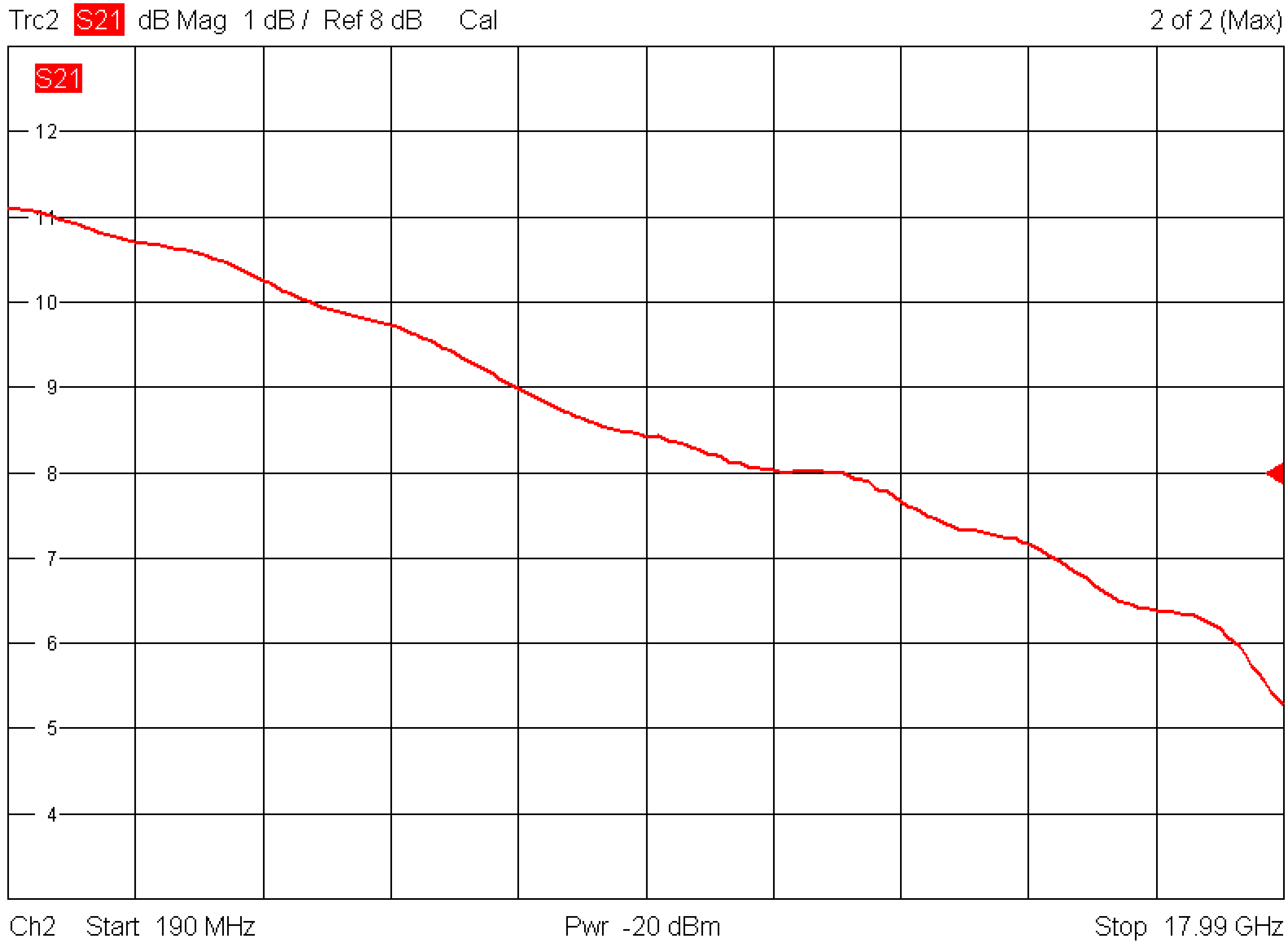
=

S-parameters

Behavioural Model

S-parameters

$P_{in} = -20\,\text{dBm}$



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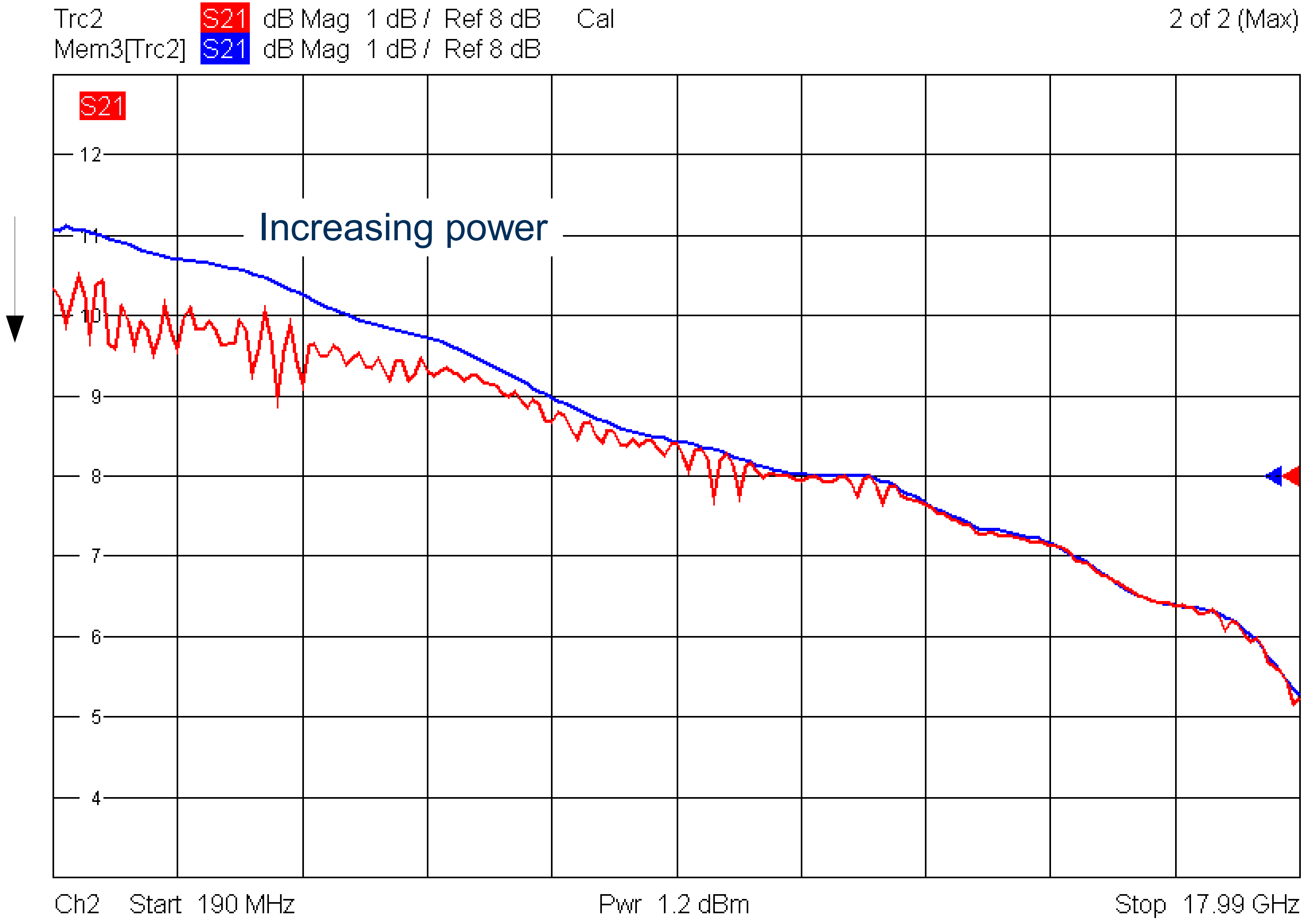
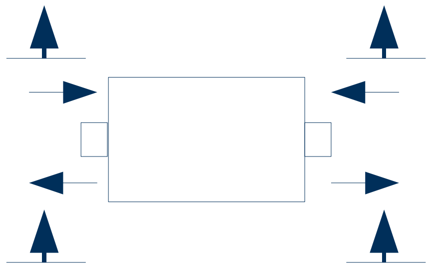
"Noisy" S-parameters ???

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

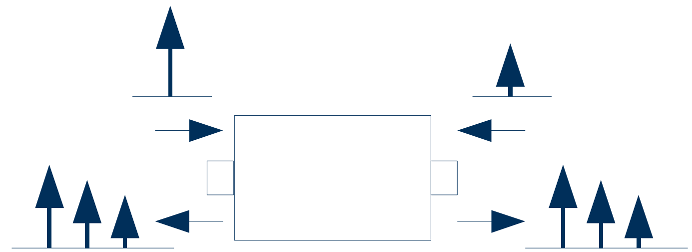


NMDG

The VNA Evolution: Large-Signal Characterisation



Linear

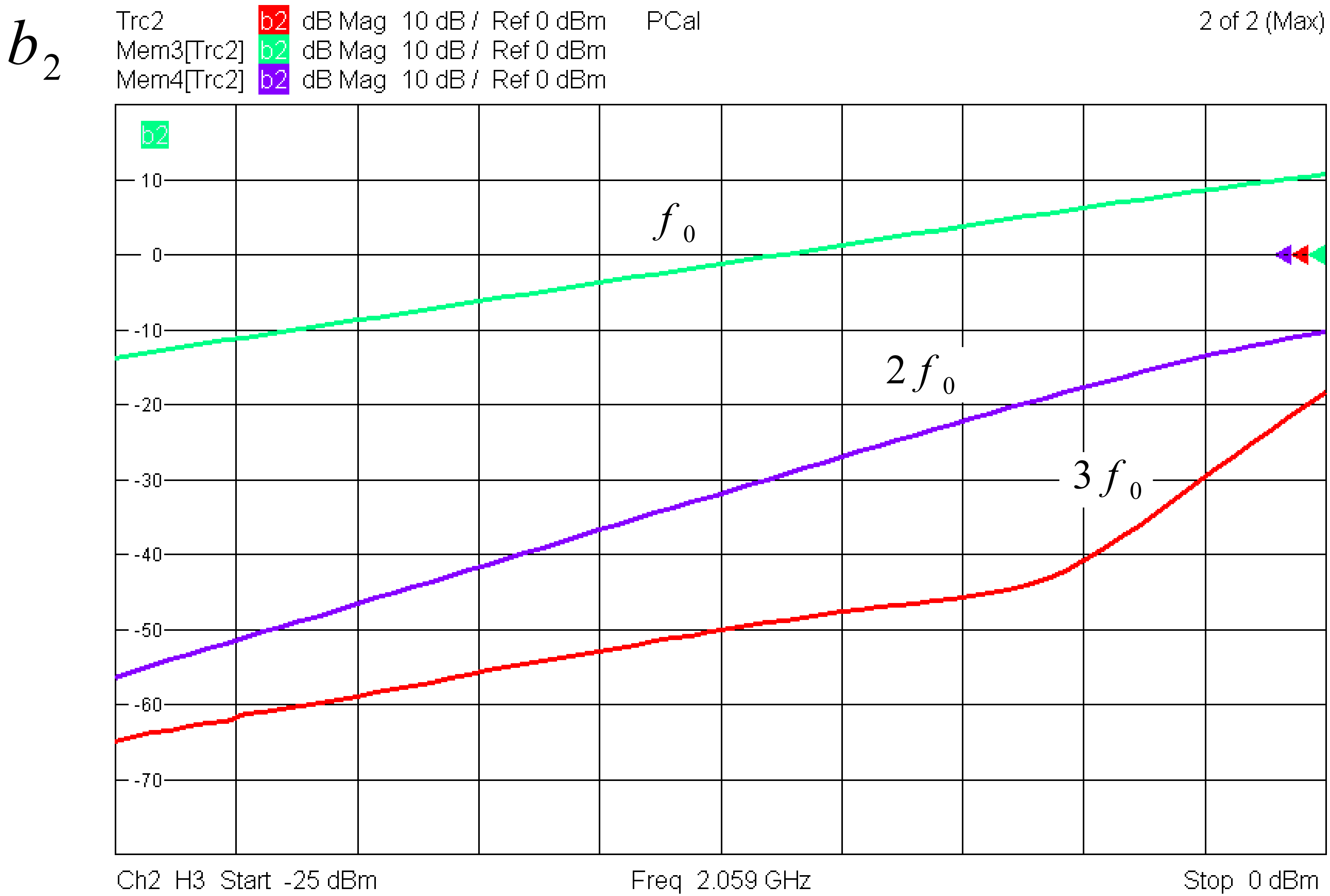


Nonlinear

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

Harmonic Characterisation in Power

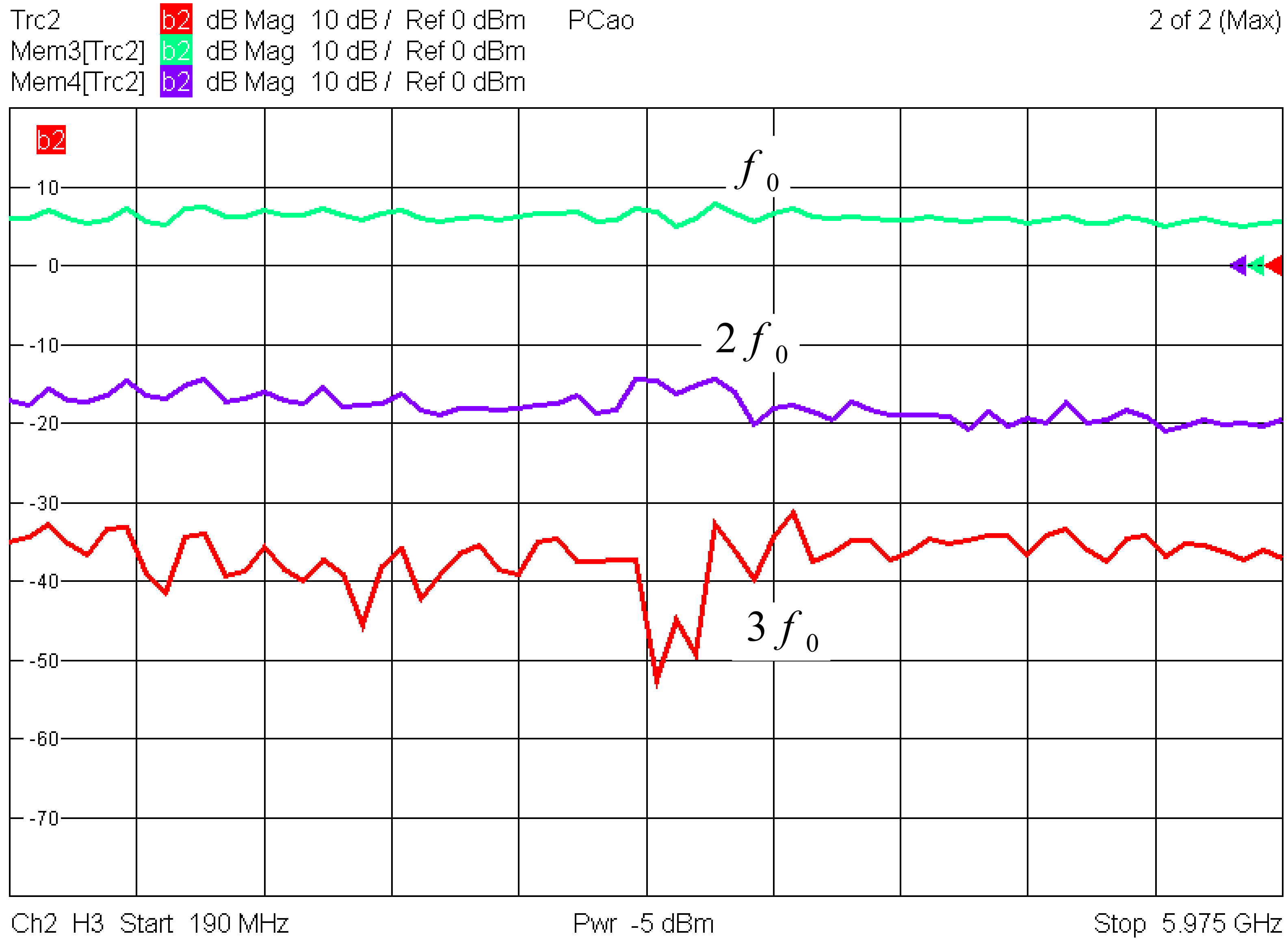
P_{in} : from -25 to 0 dBm at $f_0 = 2.059$ GHz



Harmonic Characterisation in Frequency

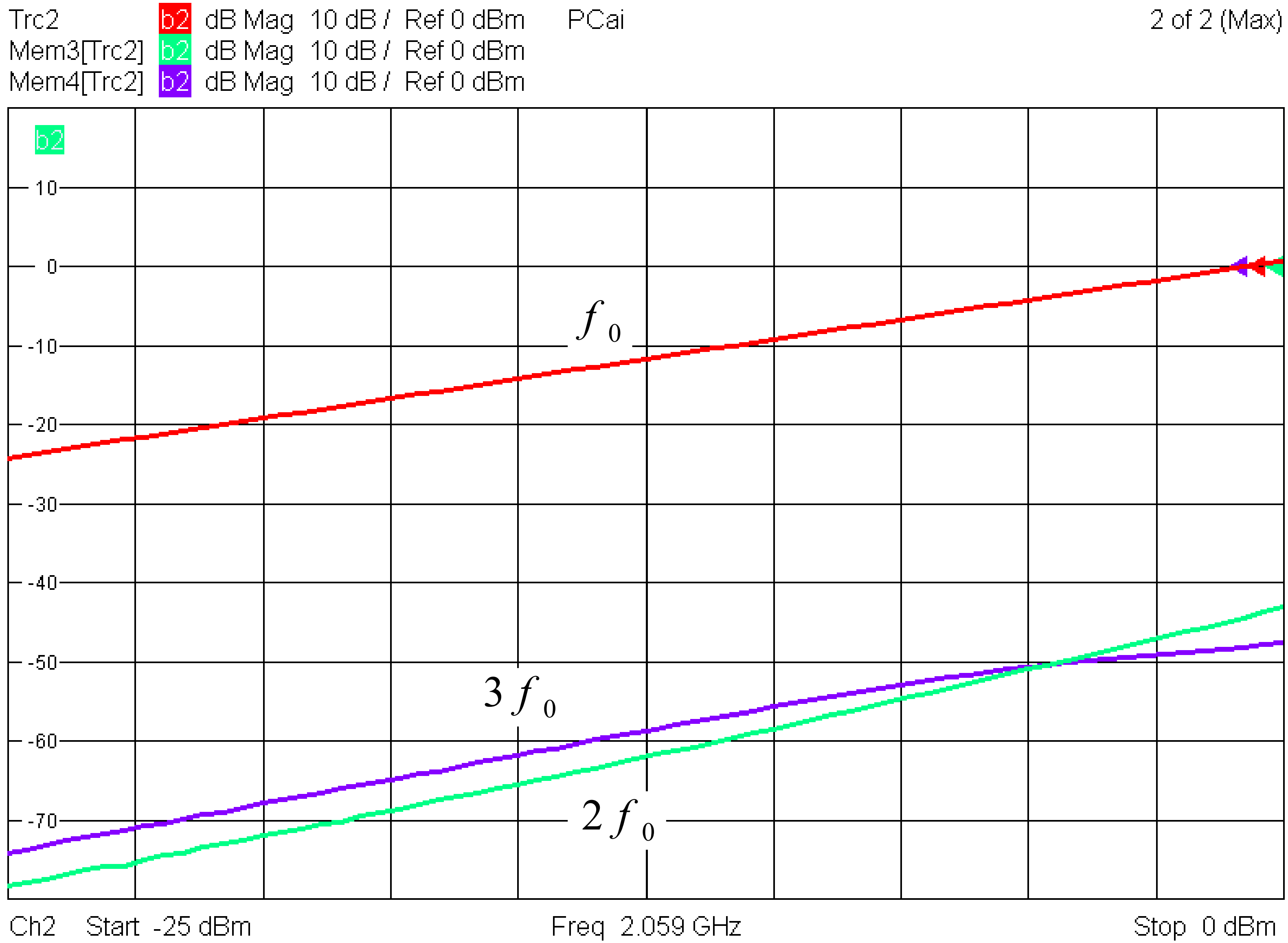
f_0: from 0.19 to $17.99\,\text{GHz}$ at $P_{in} = -5\,\text{dBm}$

b_2

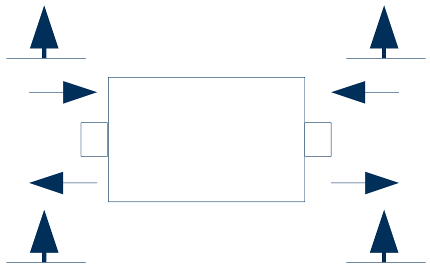


Harmonic Characterisation in Power

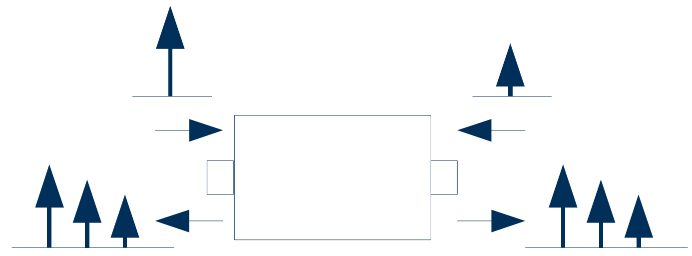
Harmonic Distortion of Source



The VNA Evolution: Large Signal Network Analysis

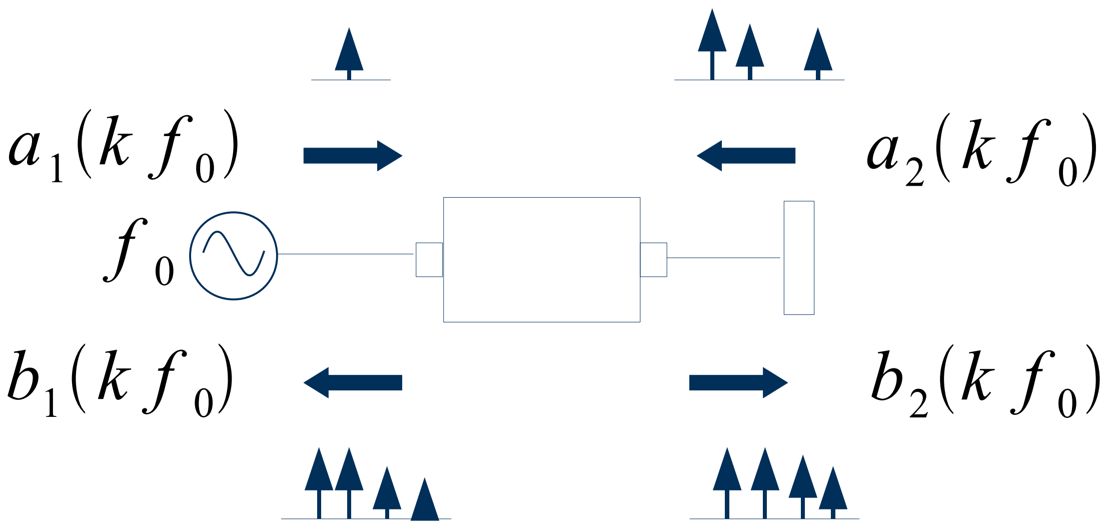


Linear



Nonlinear

One LSNA Measurement

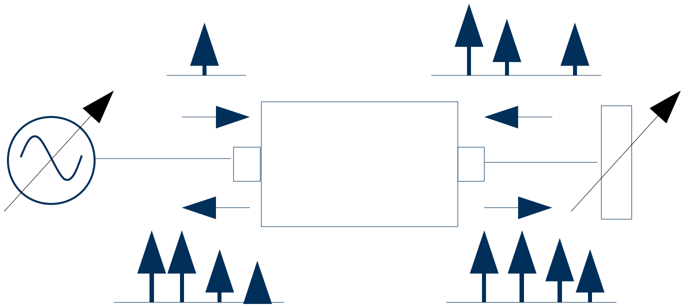


$$a_1(k f_0), b_1(k f_0), a_2(k f_0), b_2(k f_0)$$

Measuring: **OR**

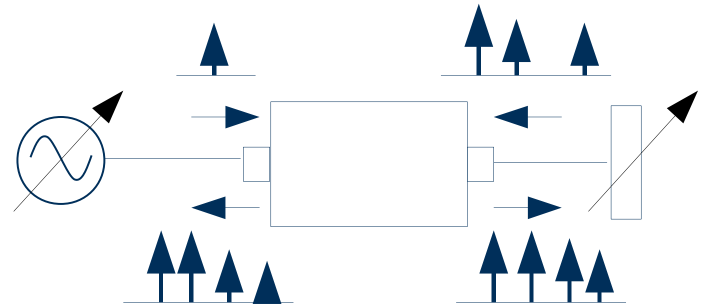
$$v_1(k f_0), i_1(k f_0), v_2(k f_0), i_2(k f_0)$$

???-parameters



Forward Measurement

+



Another Forward Measurement

+ ...

+

$$b_1 = F(a_1, a_2)$$
$$b_2 = G(a_1, a_2)$$

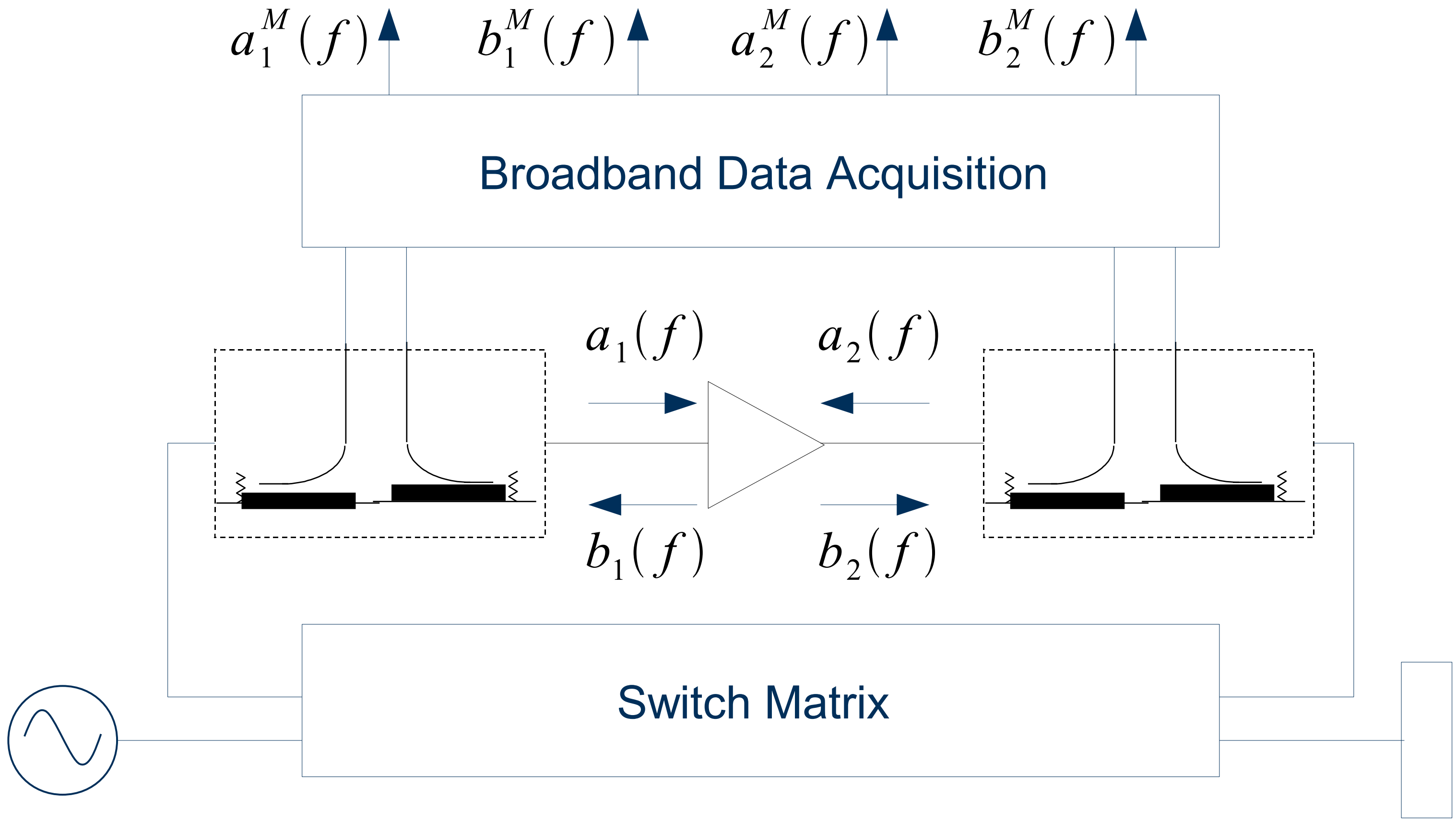
=

???-parameters

Mathematics
[Many possible Nonlinear Models]
[**NO SUPERPOSITION**]

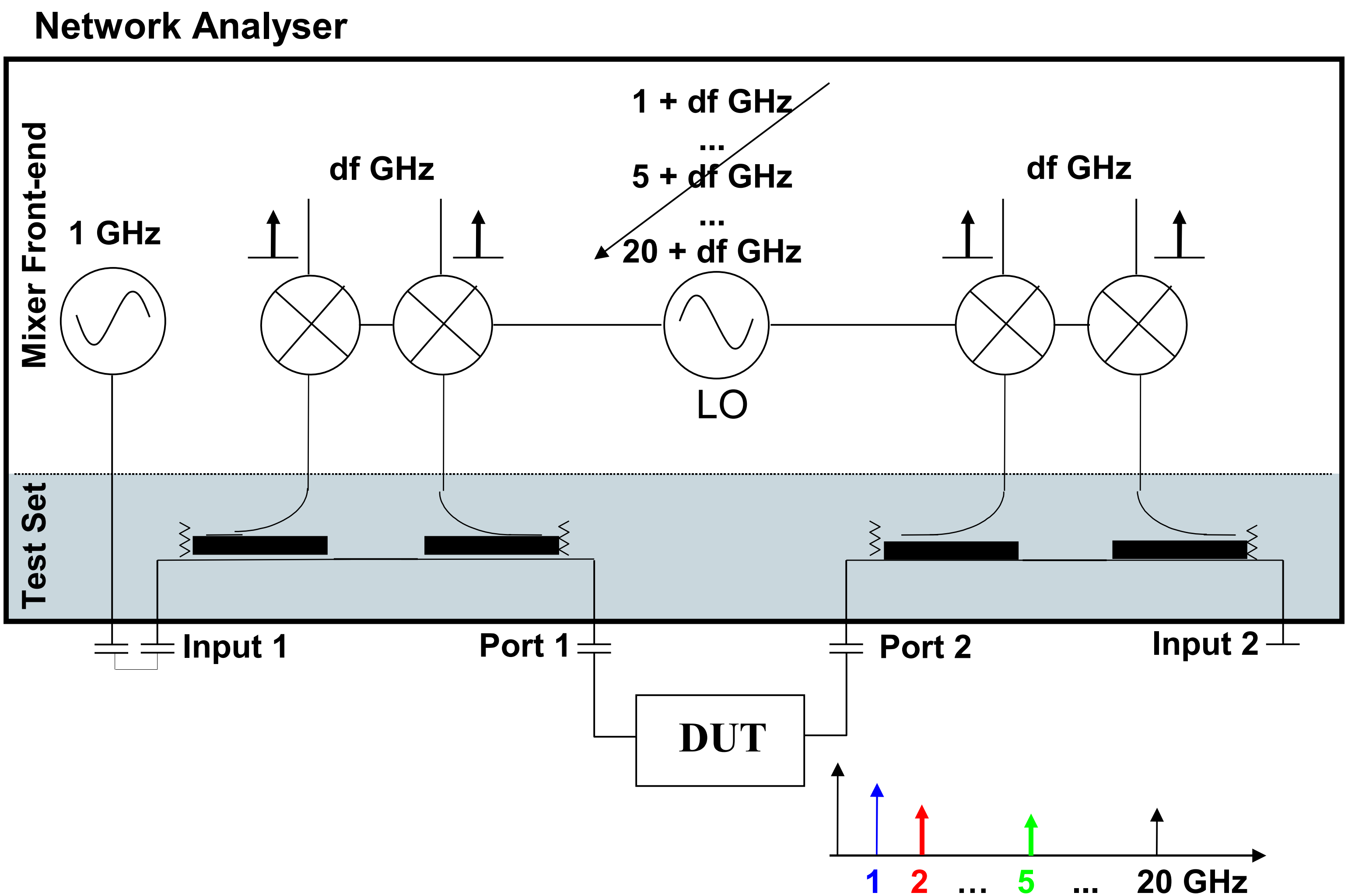
Behavioural Model
[**VALIDITY**]

Block Diagram of a Large-Signal Network Analyser



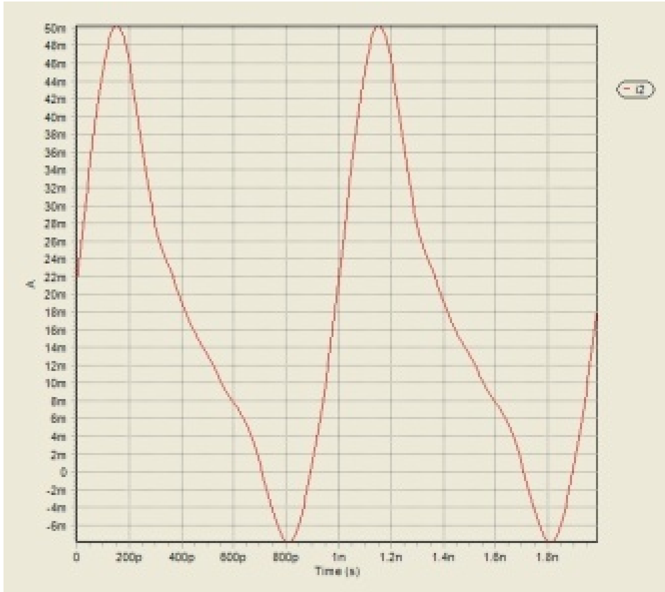
$$\begin{bmatrix} a_1 \\ b_1 \\ a_2 \\ b_2 \end{bmatrix}(f) = K(f) \begin{bmatrix} 1 & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{bmatrix}(f) \begin{bmatrix} a_1^M \\ b_1^M \\ a_2^M \\ b_2^M \end{bmatrix}(f)$$

Measuring Fundamental and Harmonics with a VNA

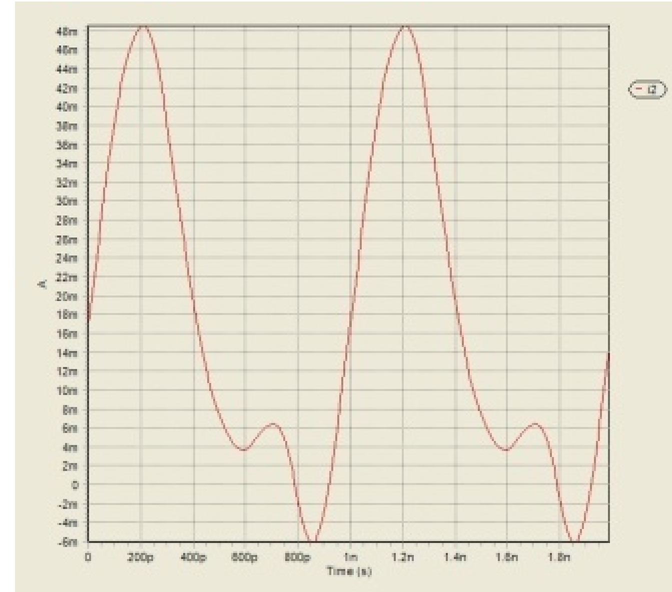


Time Domain measurement with a VNA

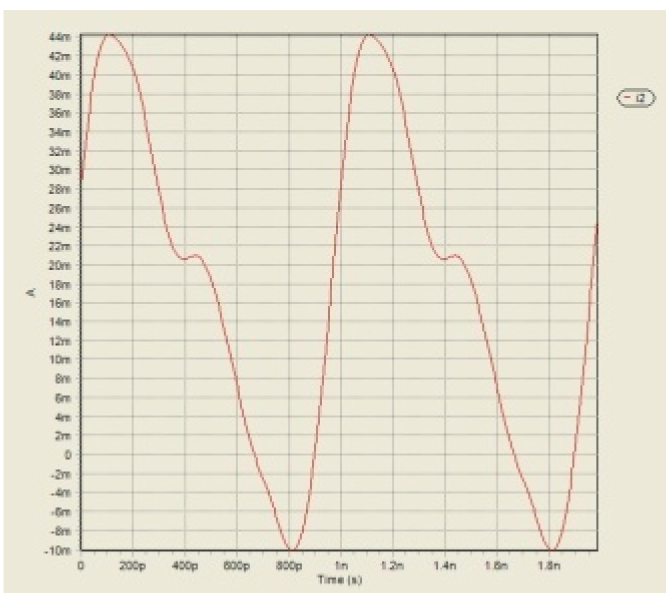
#1



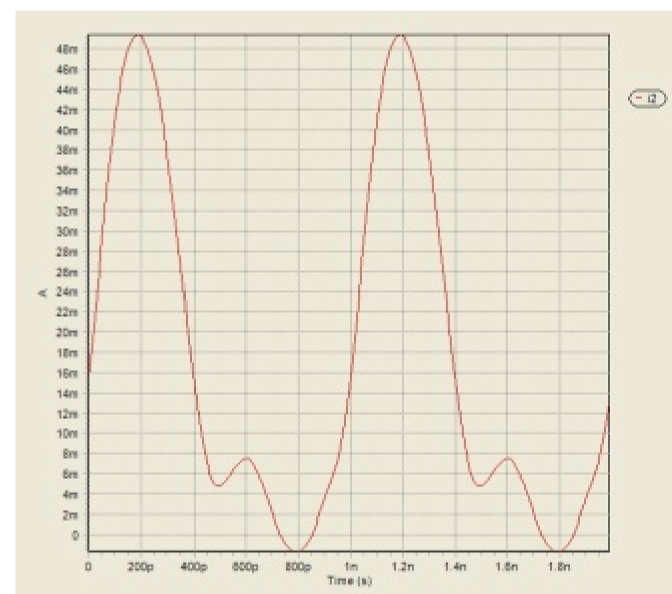
#2



#3



#4



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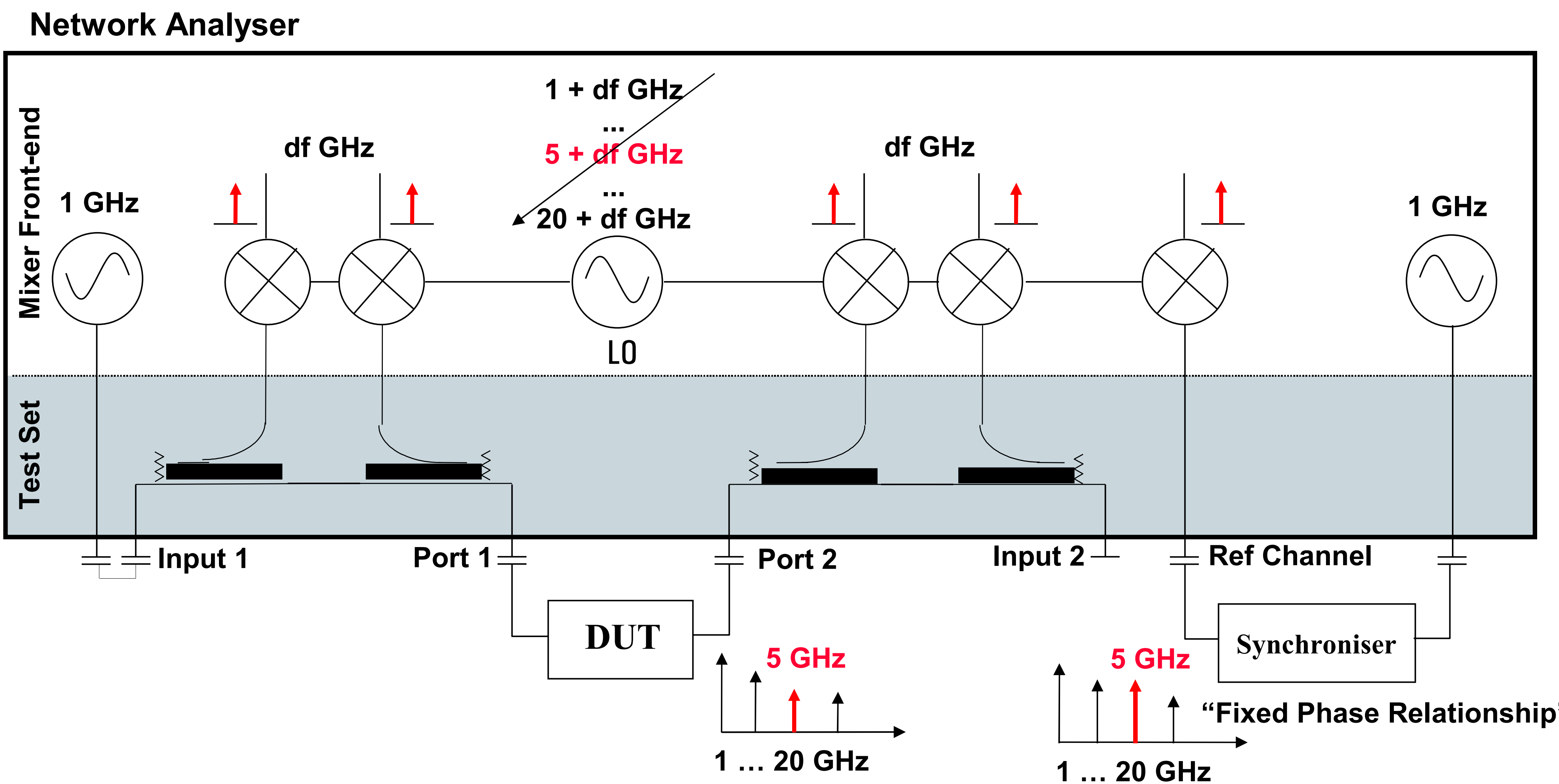
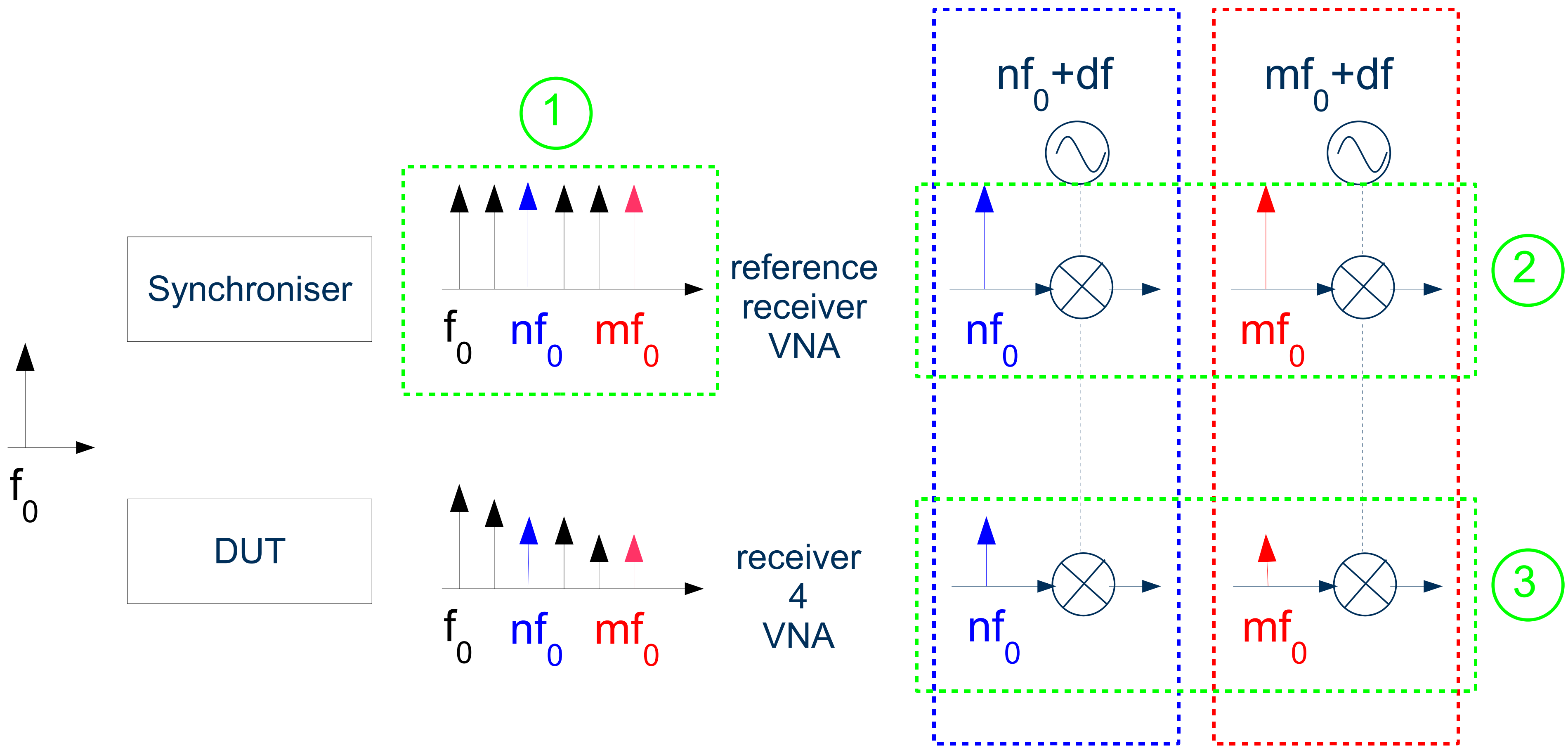


VNA as LSNA: Theory of Operation

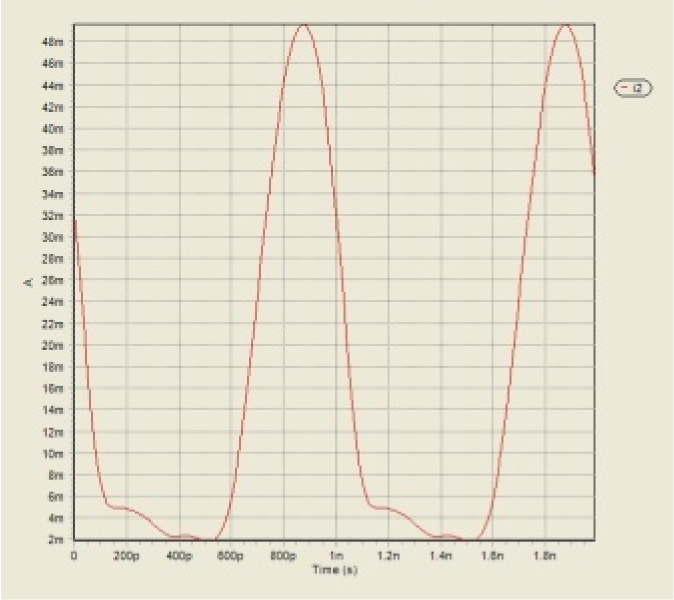


phase consistency between harmonics in
① ② ③

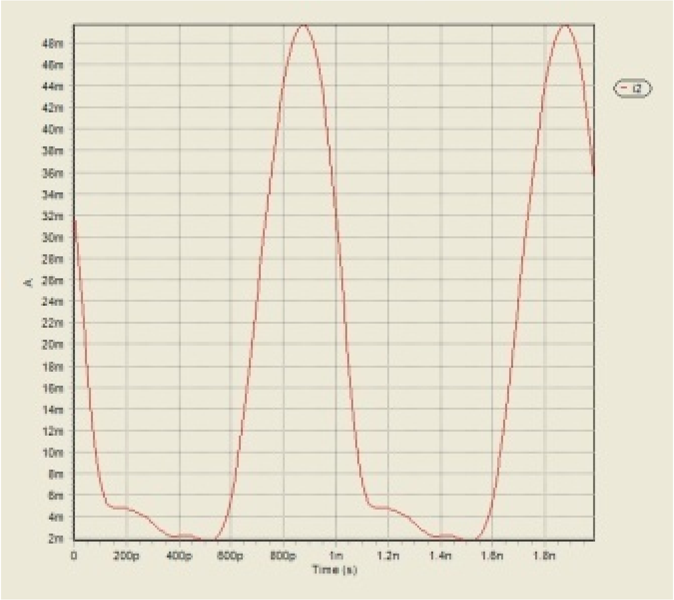
phase consistency between receivers
by simultaneous measurement
one frequency at the time

Synchronized Measurements with VNA as LSNA

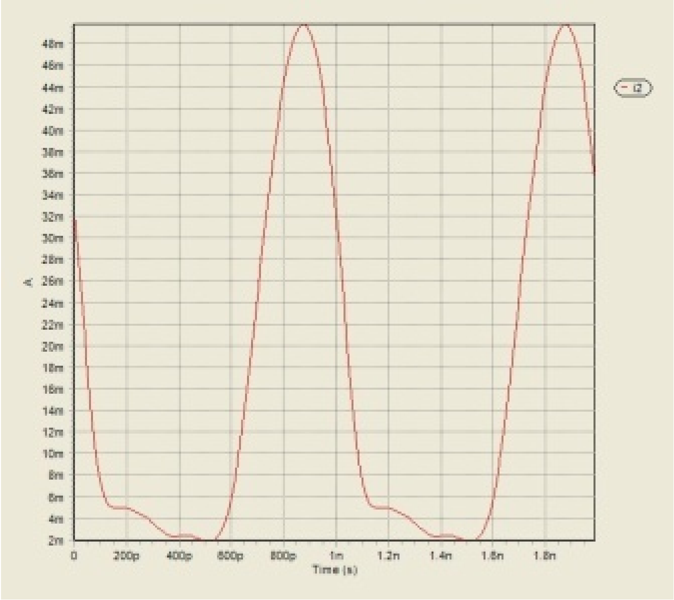
#1



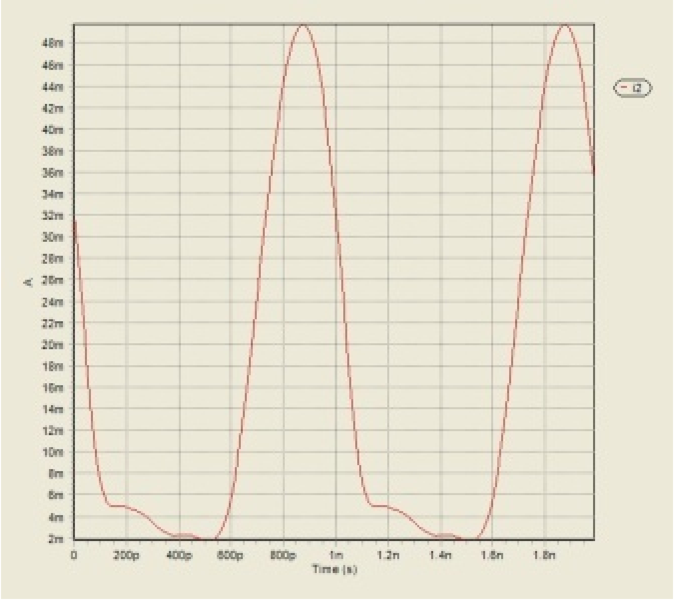
#2



#3



#4



References

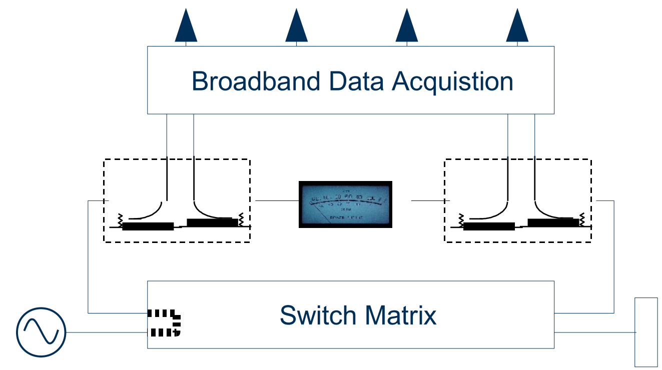
- U. LOTT, “Measurement of Magnitude and Phase of Harmonics Generated in Nonlinear Microwave Two-Ports”, *IEEE Transaction on Microwave Theory and Techniques*, vol. 37, n°10, October 1989, pp. 1506-1511
- D. BARATAUD, et al., "Measurements of time domain voltage/current waveforms at R.F. And microwave frequencies, based on the use of a Vector Network Analyzer, for the characterization of nonlinear devices. Application to high efficiency power amplifiers and frequency multipliers optimization", *IEEE Transactions on Instrumentation and Measurement*, vol. 47, n°5, October 1998, pp.1259-1264

Calibration Techniques

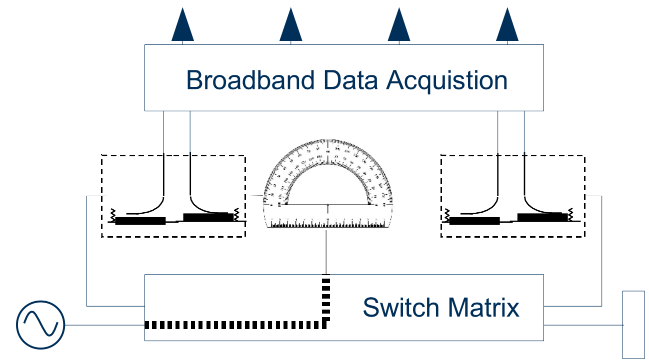
- <u>Step 1:</u> Relative Calibration Technique M_{ij}
  - Same as the regular VNA calibration
  - Traceable to standards

$$\begin{bmatrix} a_1 \\ b_1 \\ a_2 \\ b_2 \end{bmatrix}(f) = K(f) \begin{bmatrix} 1 & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{bmatrix}(f) \begin{bmatrix} a_1^M \\ b_1^M \\ a_2^M \\ b_2^M \end{bmatrix}(f)$$

- <u>Step 2:</u> Power calibration $|K|$
  - Power meter and sensor
  - Characterization of power distortion
  - Traceable to standards



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



- <u>Remark:</u> On-wafer and fixture calibration require additional steps

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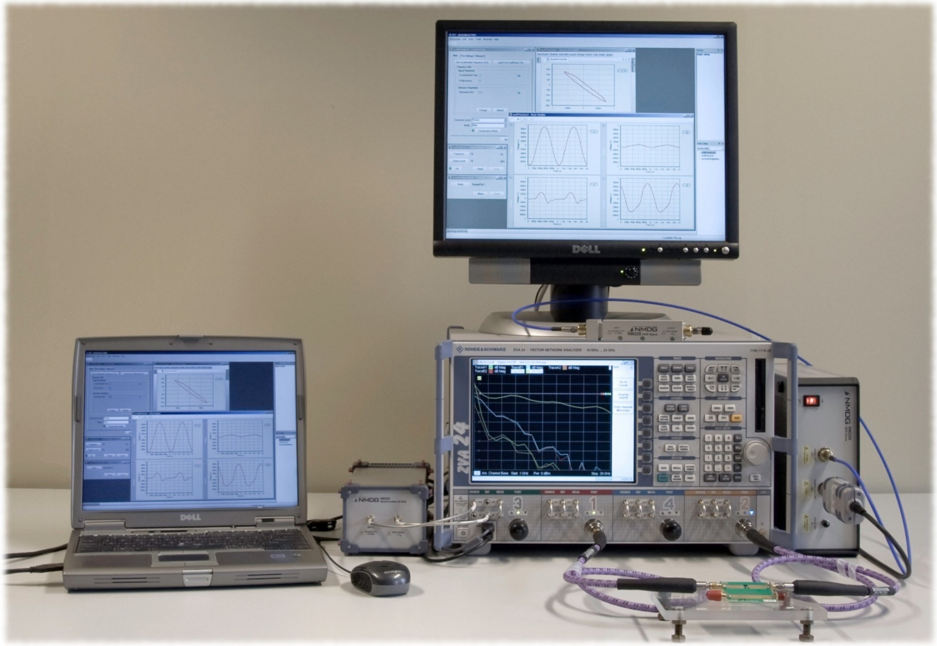
NM3xx ZVxPlus



ZVxPlus

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4-port ZVA or ZVT +
- direct gen. & rec. access (B16)
- frequency conversion (K4)
- meas. rec. step att. (opt.) (B3x)

Hardware +
- synchroniser
- harmonic phase ref.

Software
- 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

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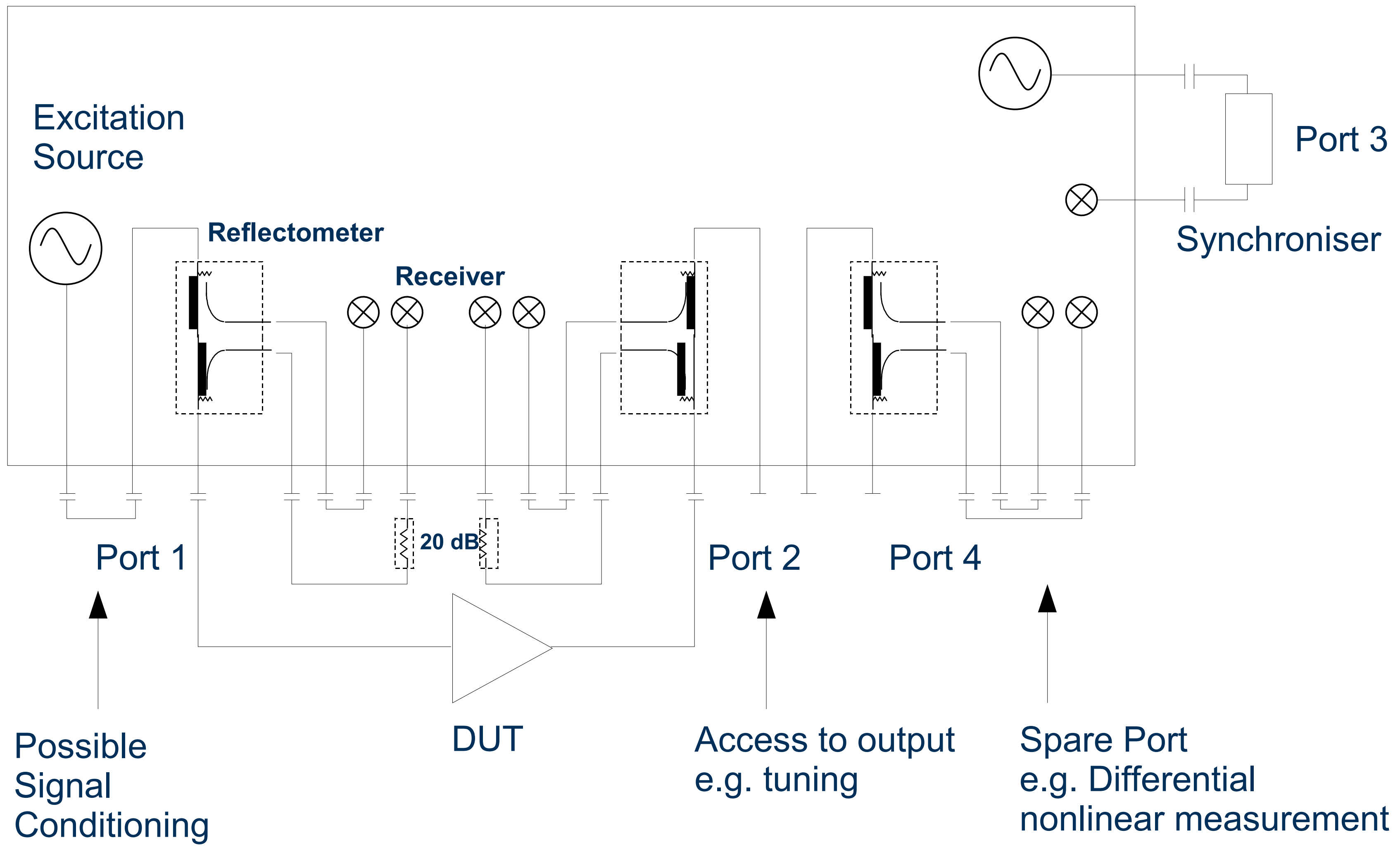
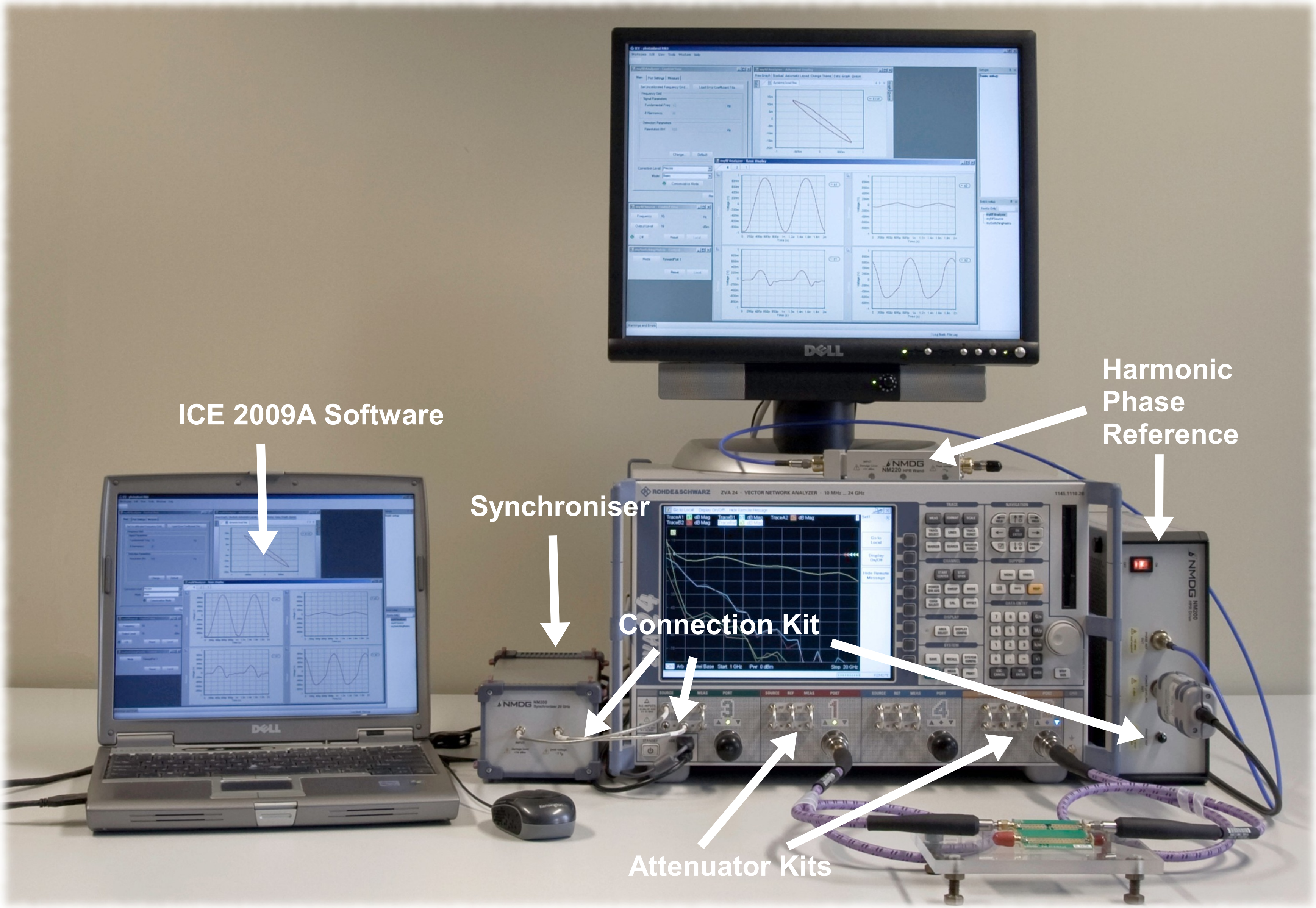
Blockdiagram of standard ZVxPlus



ZVxPlus Parts



ZVxPlus Details

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

based on a 4-port R&S®ZVA24	Value	Remarks:
Frequency range	600 MHz – 20 GHz	limited by phase calibration
Minimal frequency grid spacing	600 MHz	
Power level *	+10 dBm	@ Test port
Absolute phase uncertainty **		1 σ @ 20 GHz
using second internal source	0.6°	independent of IF BW, due to phase variations between the internal sources
using external source (locked to 10 MHz)	6°	@ 100 Hz IF BW, highly dependent on external source

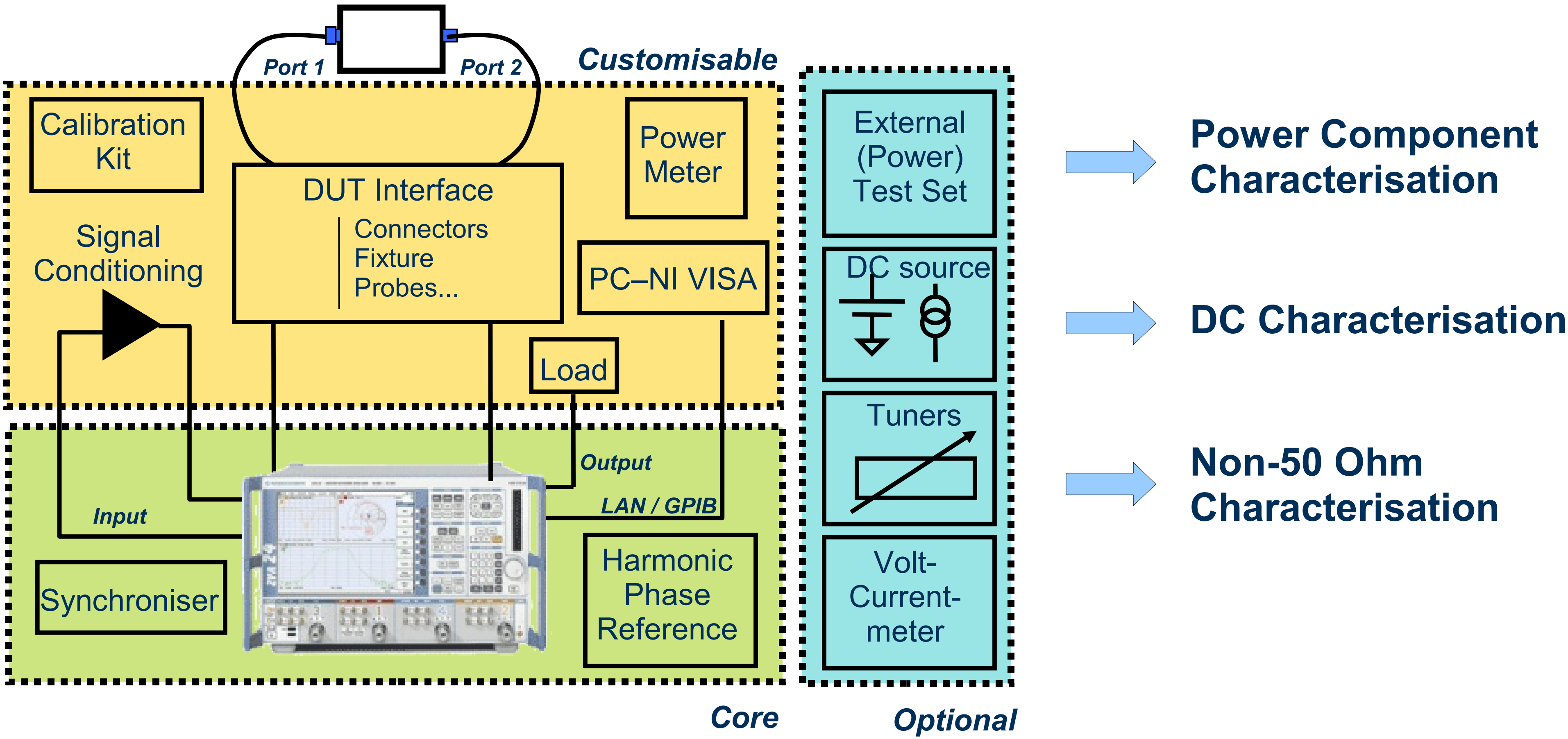
* *Power extension possible using optional step attenuators or external attenuators achieving maximum allowable power of +27 dBm with standard test set*

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

<u>Notes:</u> when additive noise is dominant, the phase standard deviation can be linked to the dBm standard deviation using the following:

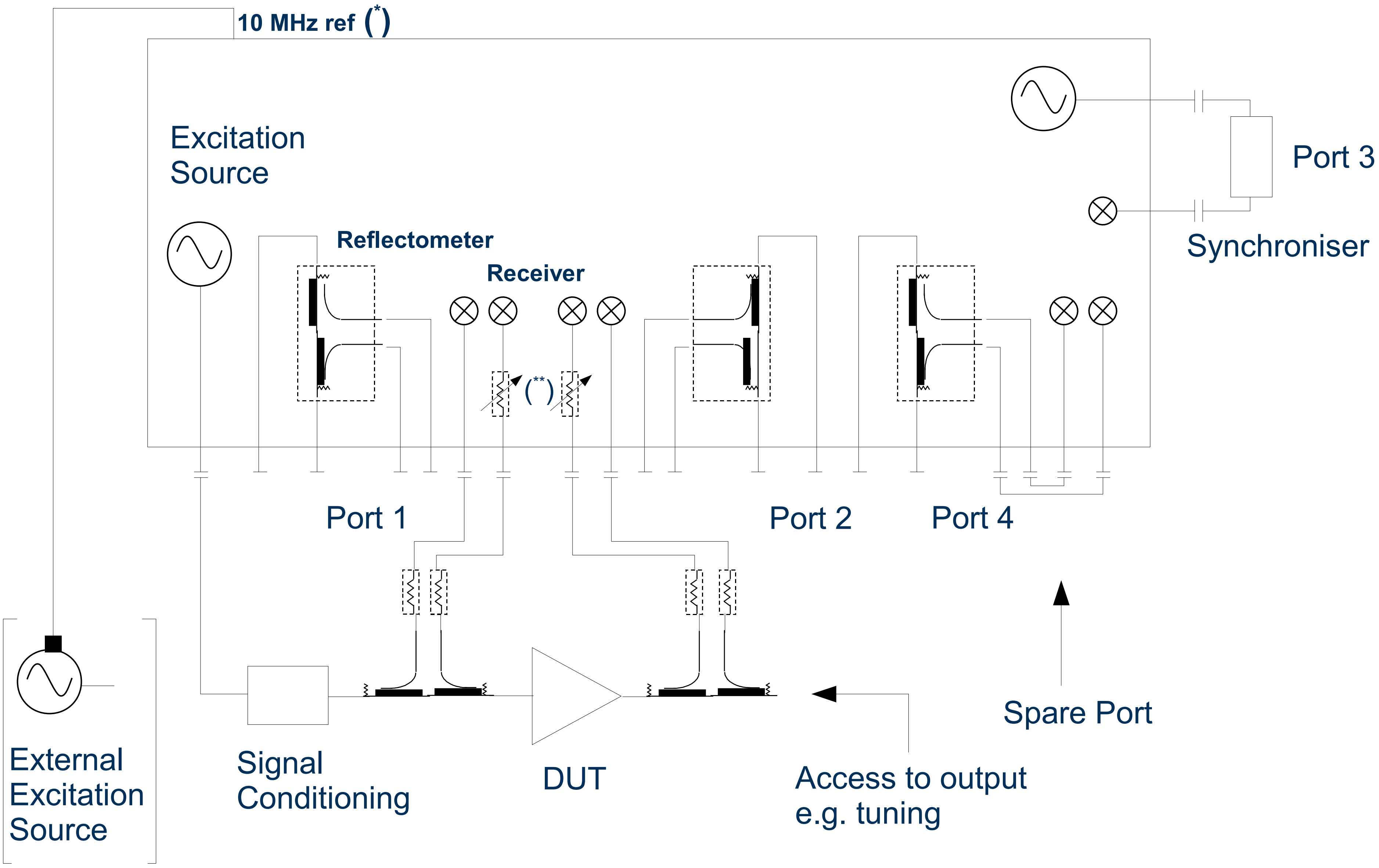
$$\sigma_{Phase(x)_{deg}} = \frac{180}{\pi}\frac{\ln(10)}{20}\sigma_{dBm(x)} \approx 6.6\,\sigma_{dBm(x)}$$

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



(*): 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

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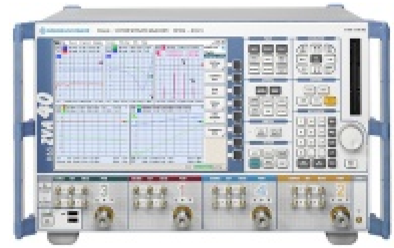
The Integrated Component Characterisation Environment

ICE: Integrated Component Characterization Environment

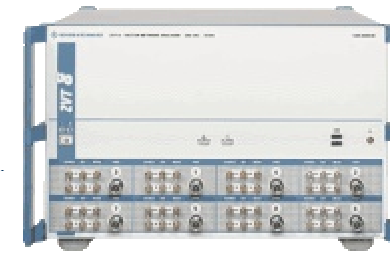
DC
CW
Tuner
...

Stimuli

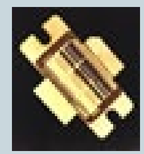


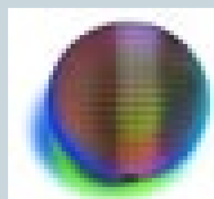
Receivers

DC Meters
VNA
LSNA
...



ICE





Calibration Technology

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

…

Diode,
Transistor,
Divider, Multiplier
Characterization

Model
Verification
and
Tuning

Real-time
Component
Characterization
and
Tuning

…

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

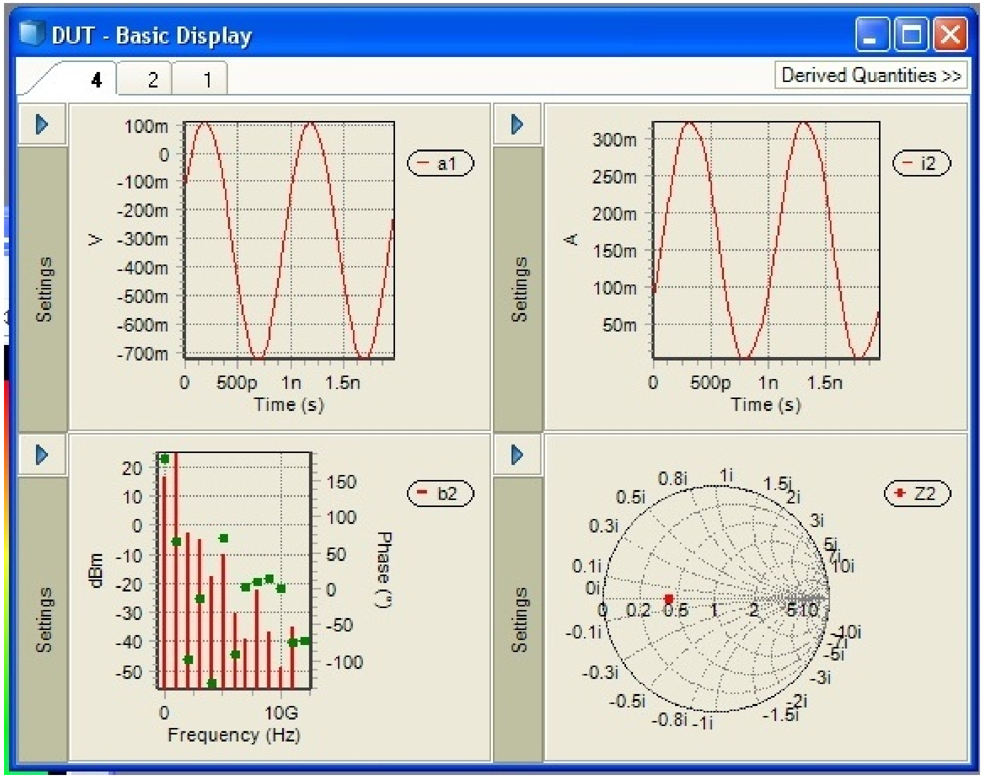
ICE: Key Benefits

- **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

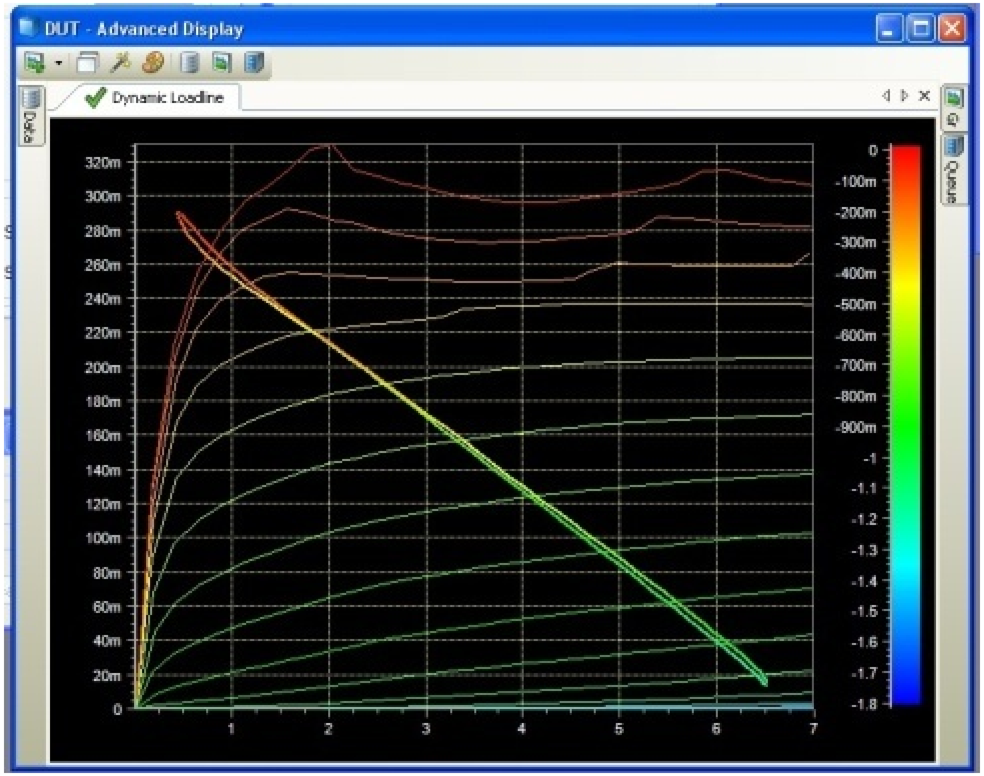
- **Accurate:**
  - Absolute DC and RF calibration methods for both connectorised and on-wafer components eliminating systematic errors up to the level of the component

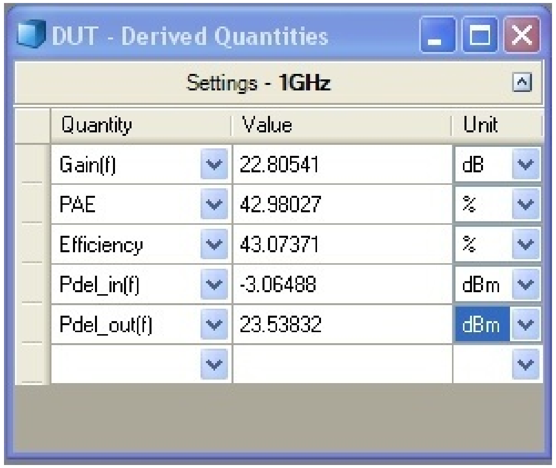
ICE Displays



Basic Display

Advanced Display





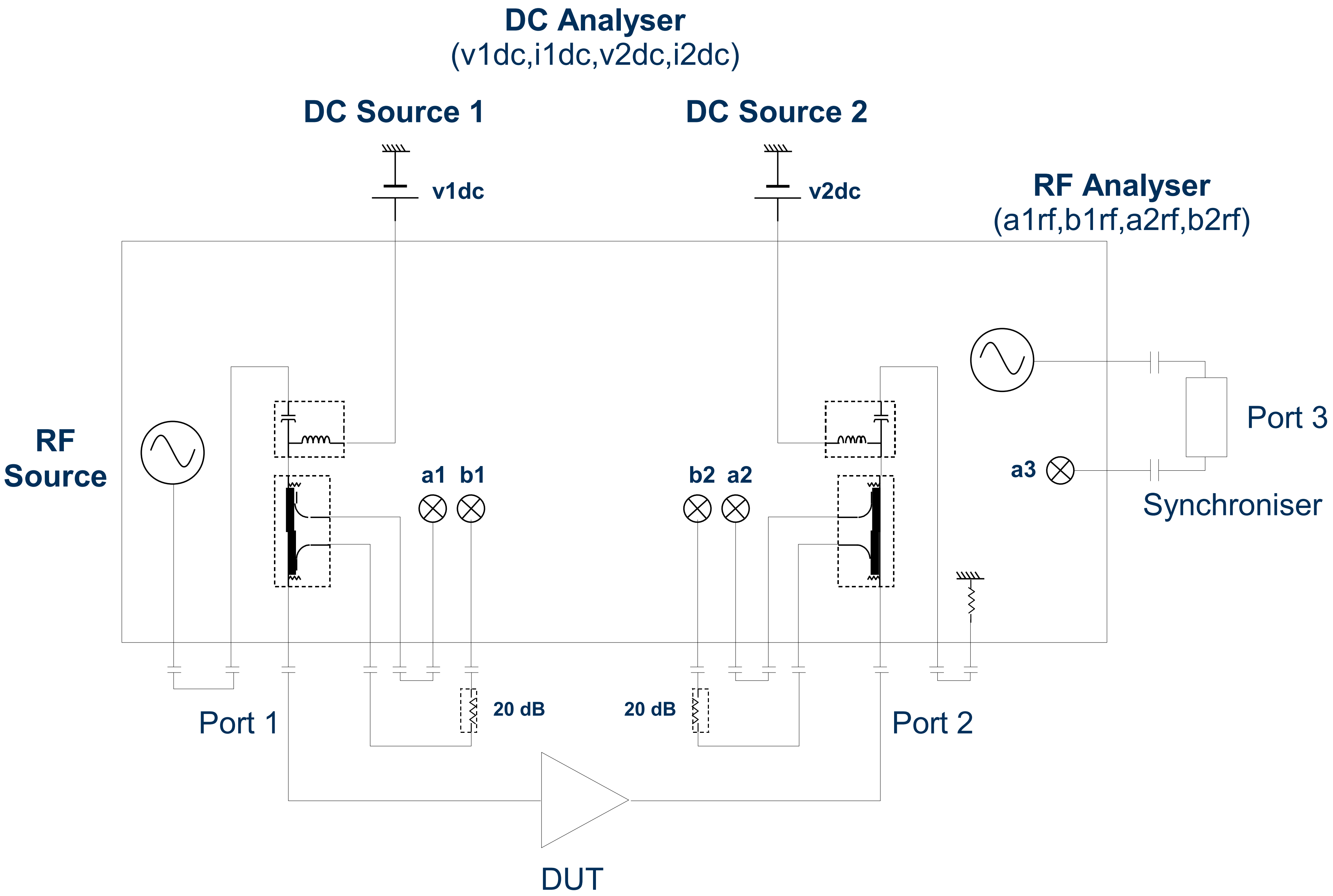
DUT - Derived Quantities

Settings - 1GHz

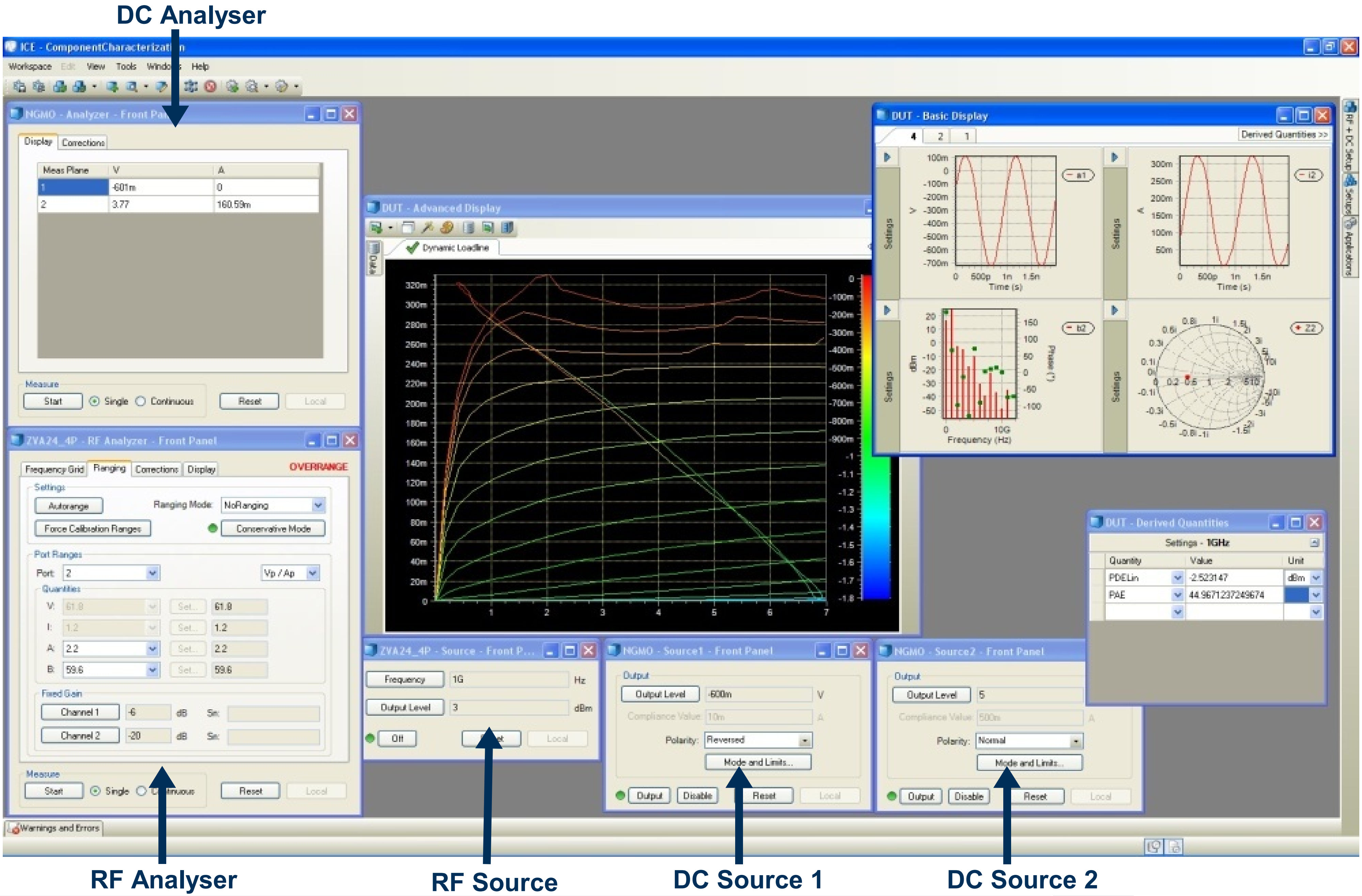
Quantity	Value	Unit
Gain(f)	22.80541	dB
PAE	42.98027	%
Efficiency	43.07371	%
Pdel_in(f)	-3.06488	dBm
Pdel_out(f)	23.53832	dBm

Derived Quantities

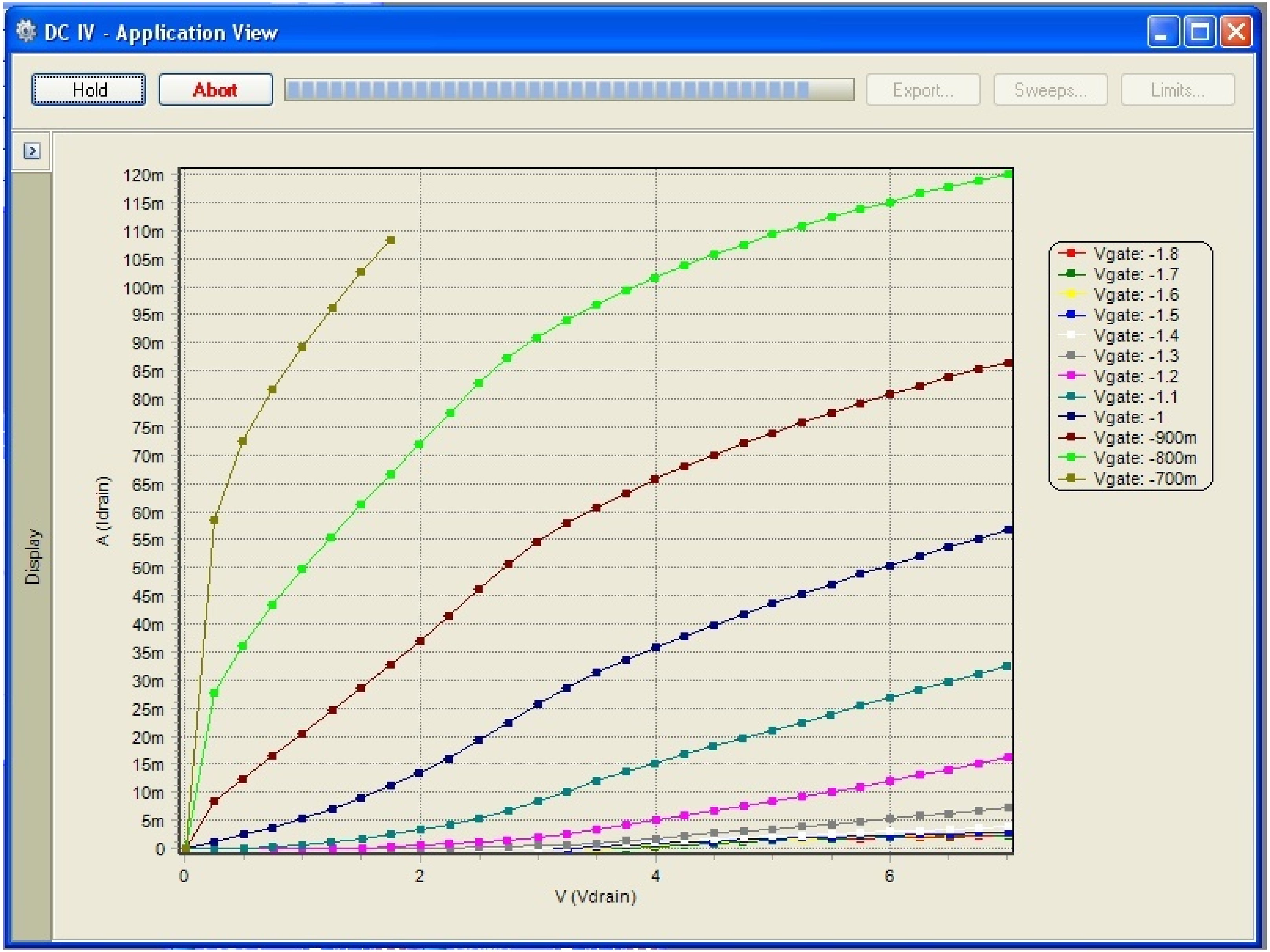
Classical Measurement Setup



ICE Environment



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

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