Did you miss a previous IMS ?

International Microwave Symposium
2–7 June 2013, Seattle

International Microwave Symposium
1-6 June 2014
Tampa Bay, Florida

Many previous MTT-11 sponsored workshops are available online at

www.mtt11.org

Large Signal Network Analyzer: Past and future of the LSNA

T. Reveyrand[1], T. Inoue[2] and Z. Popović[1]

[1]University of Colorado at Boulder
[2]National Instruments

Outline

- Origins and history of the LSNA
- Commercially available NVNAs
- Applications
- Software approach
- Hardware approach
- Conclusion

1983

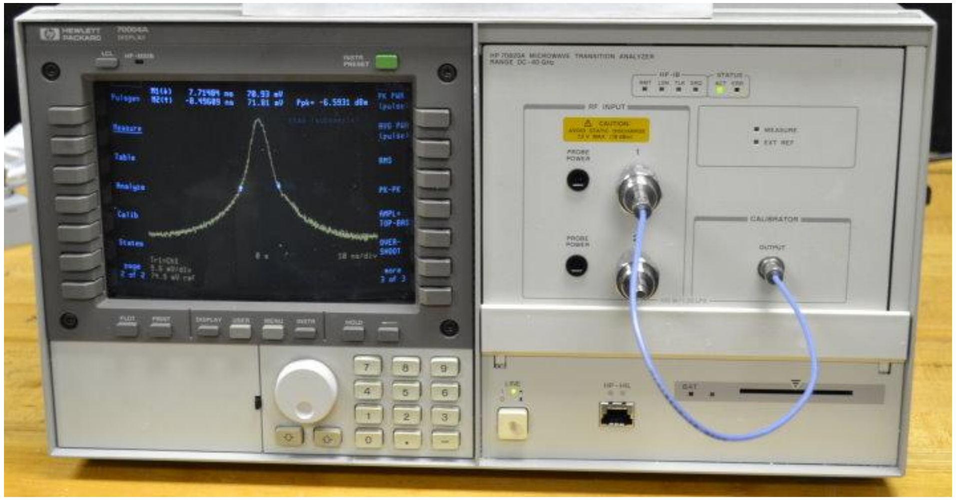
HP 8409

1985

HP 8510

HP 8510 in HP catalog from 1985 to 2001 (split with Agilent).

Pictures from http://www.hpmemory.org/



An HP 70820A microwave transition analyzer on an HP 70000 series mainframe.

1991

HP 70xxx

The Microwave Transition Analyzer: A Versatile Measurement Set for Bench and Test (1991)
HP Product Note 70820-1 [Download]

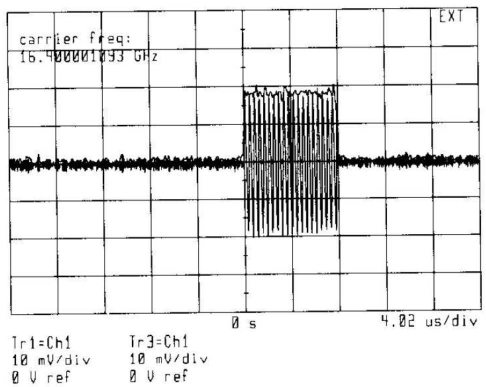
500 Hz -40 GHz

2 channels

- Frequency and Power
- Vector voltage
- Network Analysis
- Power Sweeps
- Sampled Spectrum Analysis
- Array Processing

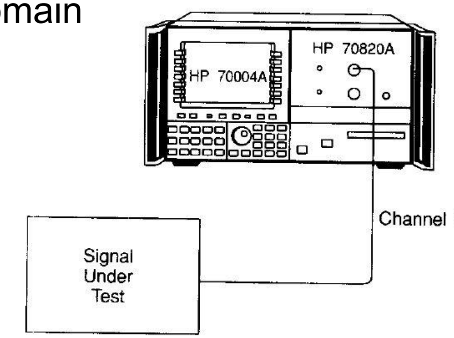
HP 70820A Microwave Transition Analyzer

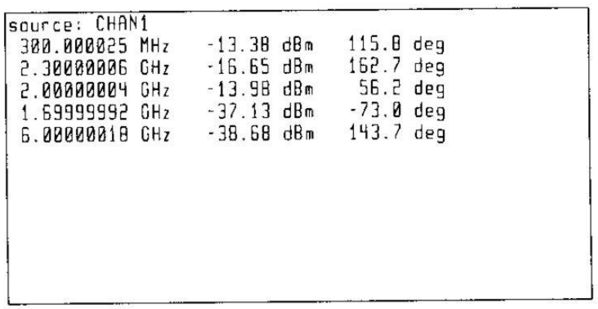
Pulsed RF measurements



Pulsed RF shape directly display (>1us)

Frequency Domain

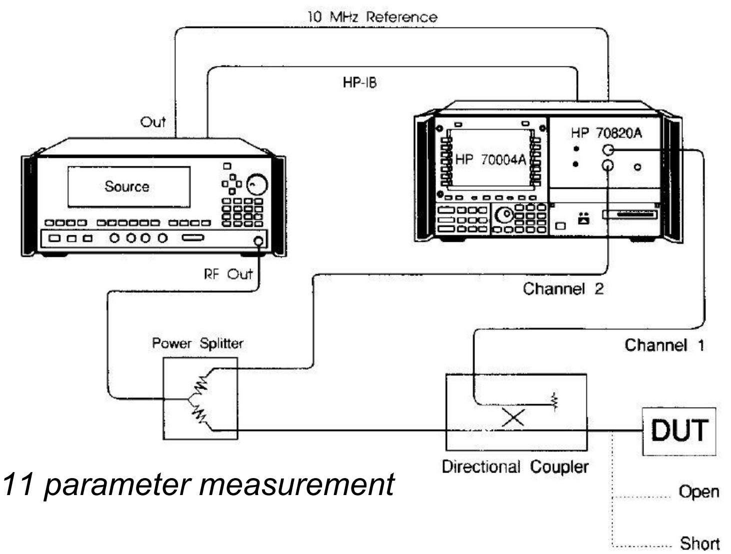



source: CHAN1

300.000025 MHz	-13.38 dBm	115.8 deg
2.30000006 GHz	-16.65 dBm	162.7 deg
2.00000004 GHz	-13.98 dBm	56.2 deg
1.69999992 GHz	-37.13 dBm	-73.0 deg
6.00000018 GHz	-38.68 dBm	143.7 deg

Up to five CW signals with their harmonics MAG and PHASE measurements

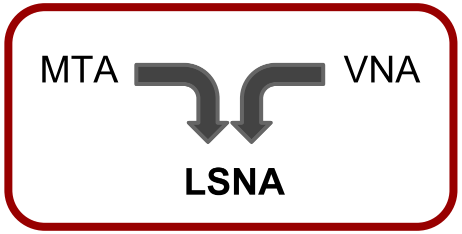
Vectorial Analysis Domain



S11 parameter measurement

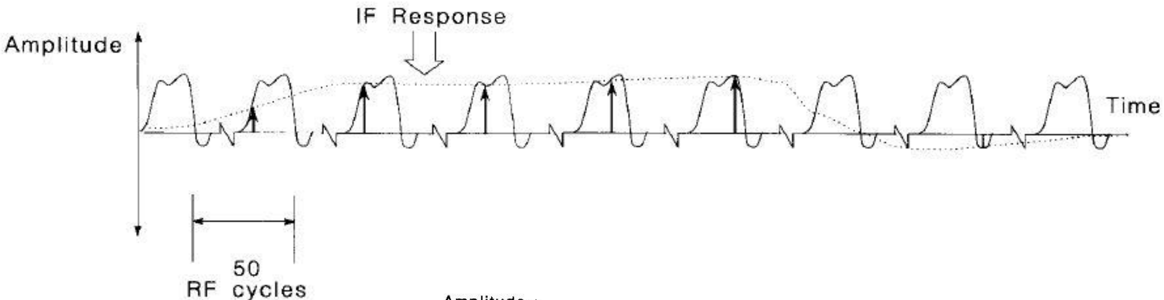
10 MHz Bandwidth
1024 points
Frequency Calibrated

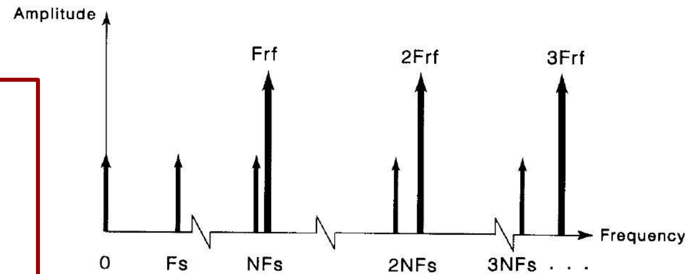
Compression point = 0 dBm
Noise floor = -75 dBm
Harmonic Distortion < -65 dB



Figures from HP Product Note 70820-1

MTA's Principle





Sub-sampling
=
Mixing with
a comb generator

Example

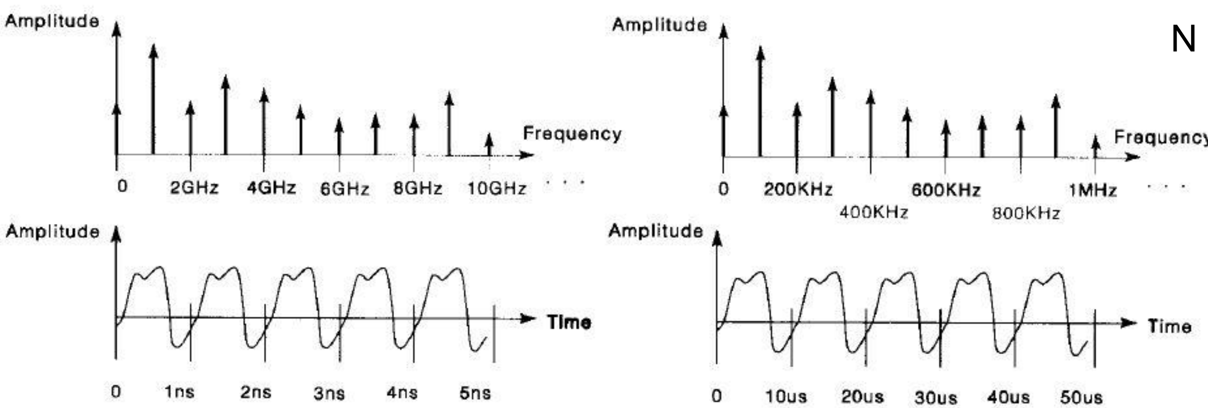
from HP Product Note 70820-1

f_{RF}=1 GHz

f_{IF}=100 kHz

$f_{IF}= f_{RF}- N.f_{Fs}$

N = 49	⇌	f_{Fs} = 20 406 122 Hz
N = 50	⇌	f_{Fs} = 19 998 000 Hz
N = 51	⇌	f_{Fs} = 19 605 882 Hz
N = 52	⇌	f_{Fs} = 19 228 846 Hz

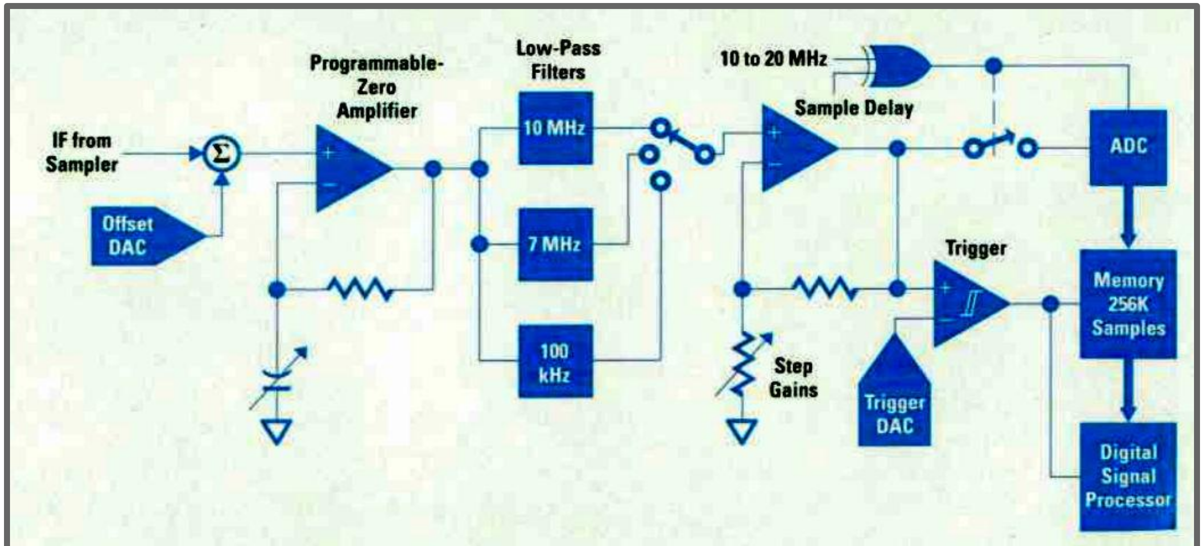


a. RF signal b. IF signal

Frequency allocation in :

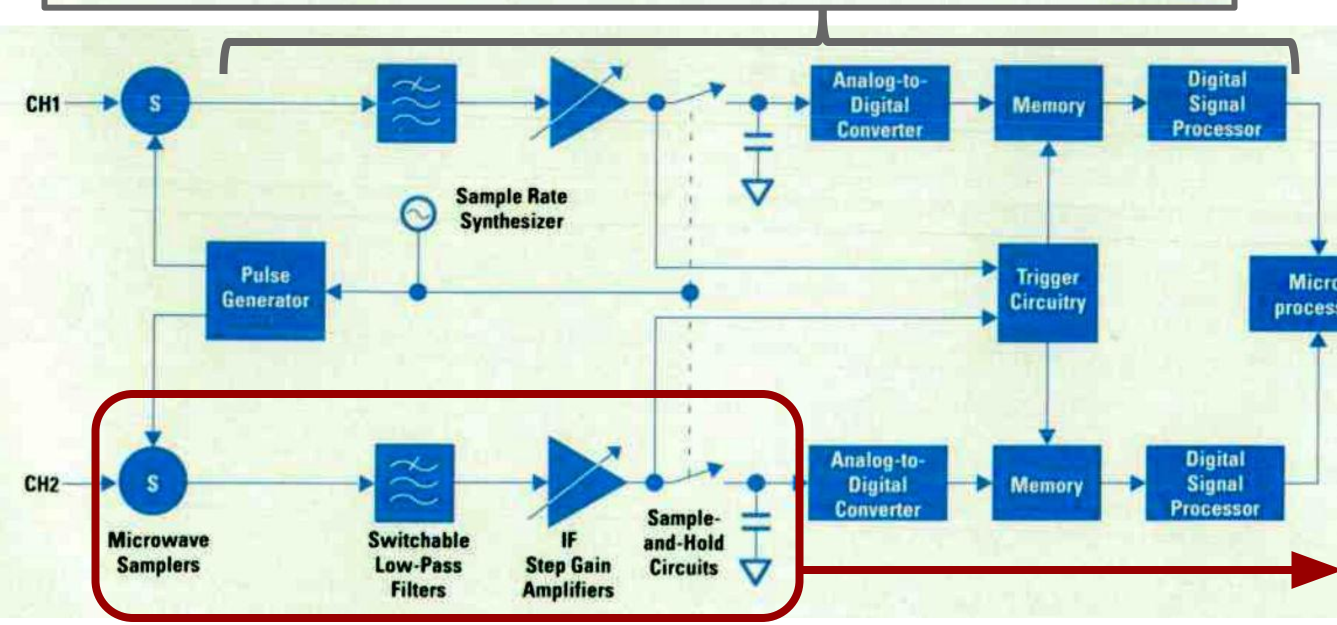
- A LSNA ;
- An Harmonic Balance Simulation

MTA’s block diagram



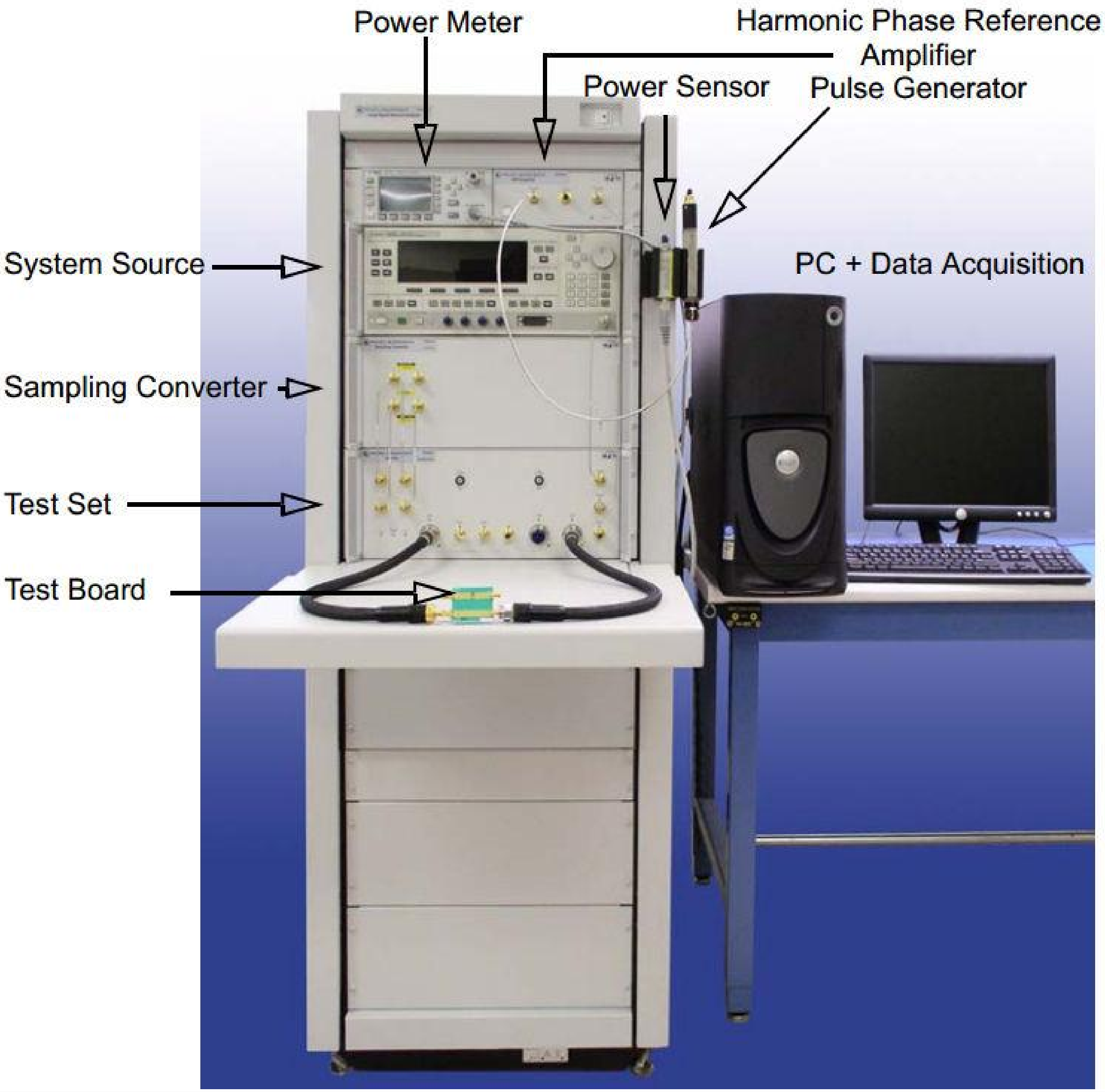
Pictures from “Hewlett Packard Journal”, October 1992 [Download]

A MTA is basically a sparse frequency domain SCOPE



SINGLE CHANNEL LSNA’s DOWNCONVERTER

Agilent / Maury LSNA



2000's

Commercial LSNA system

Started in 1994 by HP-NMDG under the name NNMS

4 channels receivers
+
2 bi-directional couplers

ADC evolution from VXI (Agilent version) to PCI (Maury version)

But the sampling converter is based on discontinued MTA receivers.

Subsampling frequency:
16-20 MHz
RF bandwidth:
50 GHz

Picture from MT4463 Data Sheet [Download]

VTD SWAP X-402

VTD (founded in 2008) was a spin-off from
Jan Verspecht bvba (Belgium) and
XLIM labs (Limoges University, France)

2008-2012

The last LSNA

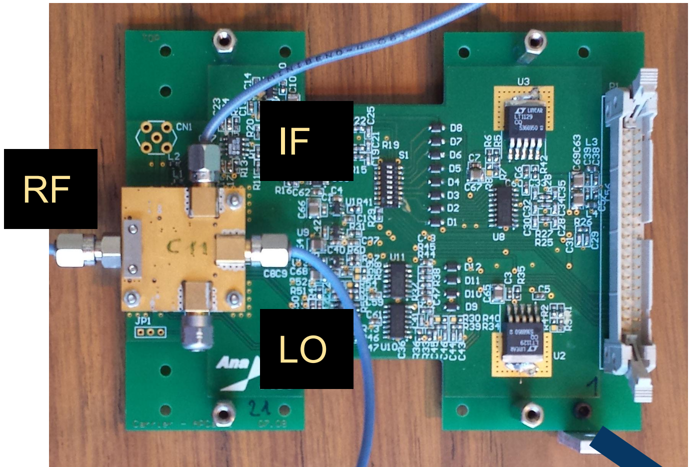
LSNA redesigned from scratch

Sampling converters board
(including pulse shaping)
originally developed by Anapico
http://www.anapico.com/

Subsampling frequency:
600-1200 MHz
RF bandwidth:
30 GHz

VTD has been acquired by Agilent Technologies Inc. on June 2012

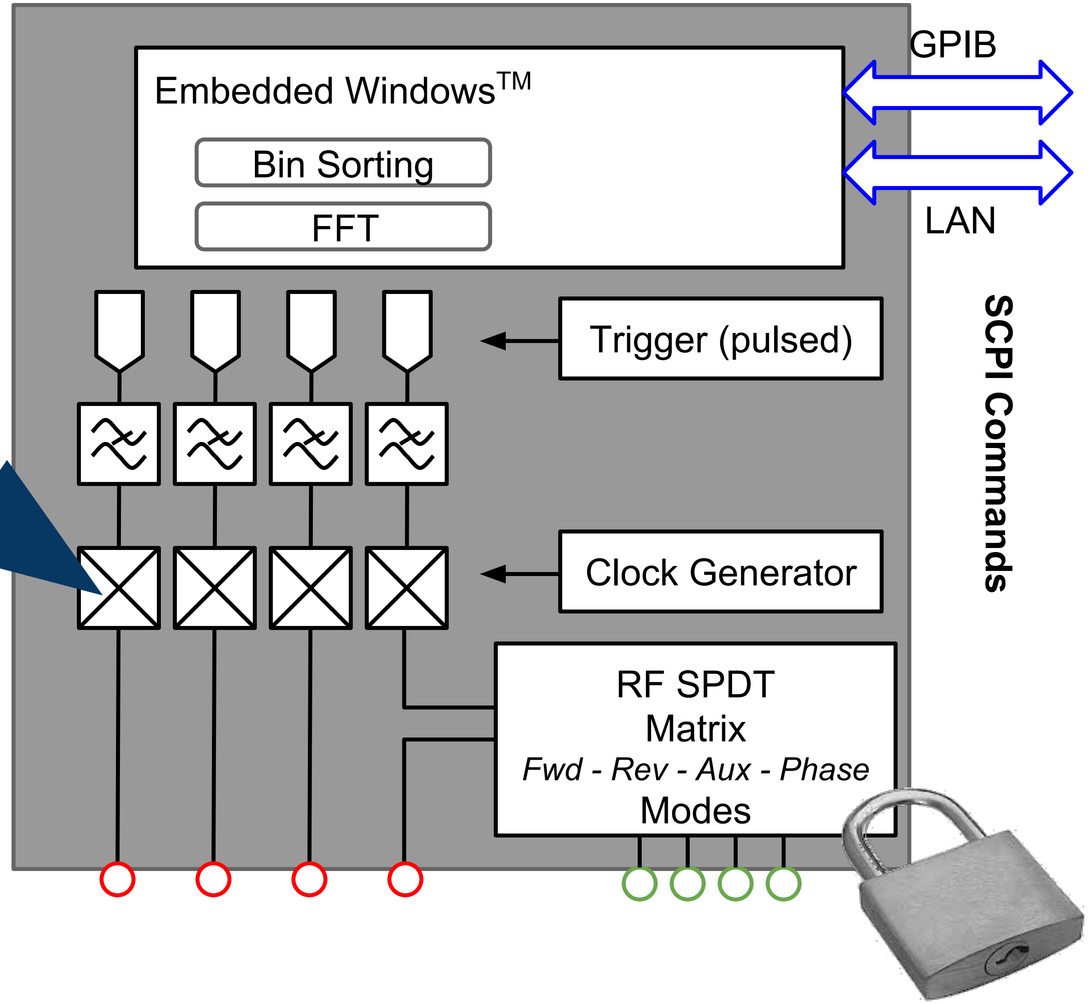
INTO THE SWAP



One of the four sub-samplers

- All-in-one downconverter box including the RF switch matrix
- External bi-directional couplers
- Smart SCPI commands to get only important data
- No GUI

A LSNA receiver is a sparse frequency domain analyzer but NOT a SCOPE



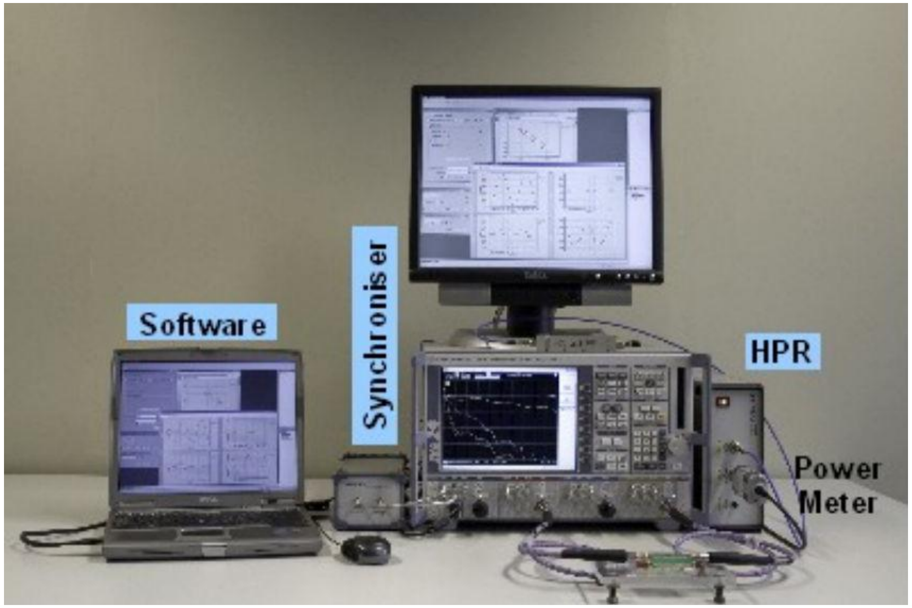
And now ?

The LSNA is dead, long live The NVNA!

NO WAY!

WHY?

Agilent PNA-X
(with Non-Linear option)



Rohde & Schwarz ZVA
(ZVxPlus option powered by NMDG)

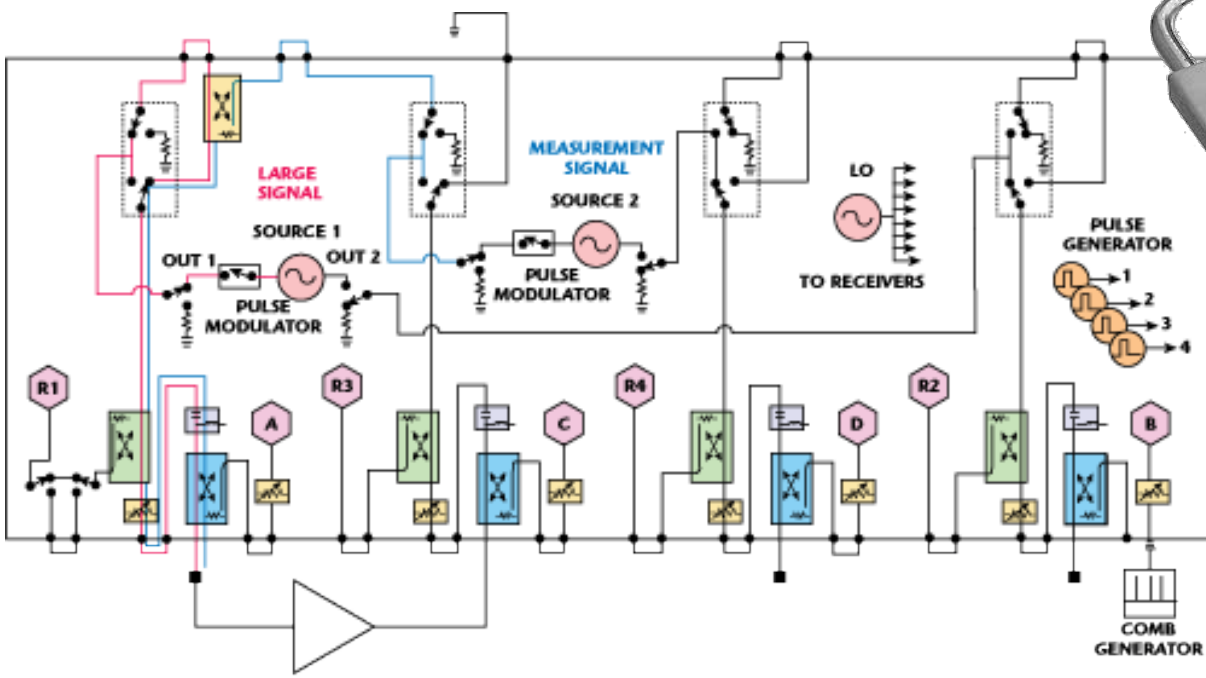
Single shot subsampling acquisition = sequential mixer-based acquisitions

D. Barataud et al.
“Measurements of time-domain voltage/current waveforms at RF and microwave frequencies based on the use of a vector network analyzer for the characterization of nonlinear devices-application to high-efficiency power”
IEEE Trans. on Instrumentation and Measurement,
Vol. 47, no 5, pp 1259-1264, 1998
[Link]

- 4-ports VNA in receiver mode ;
- 2 comb generators

EXTENSIVE HARDWARE

NVNA Hardware



Agilent PNA-X
with Non-linear Option

(figure from Microwave Journal)

OK, BUT WHY DO I NEED A NVNA/LSNA?

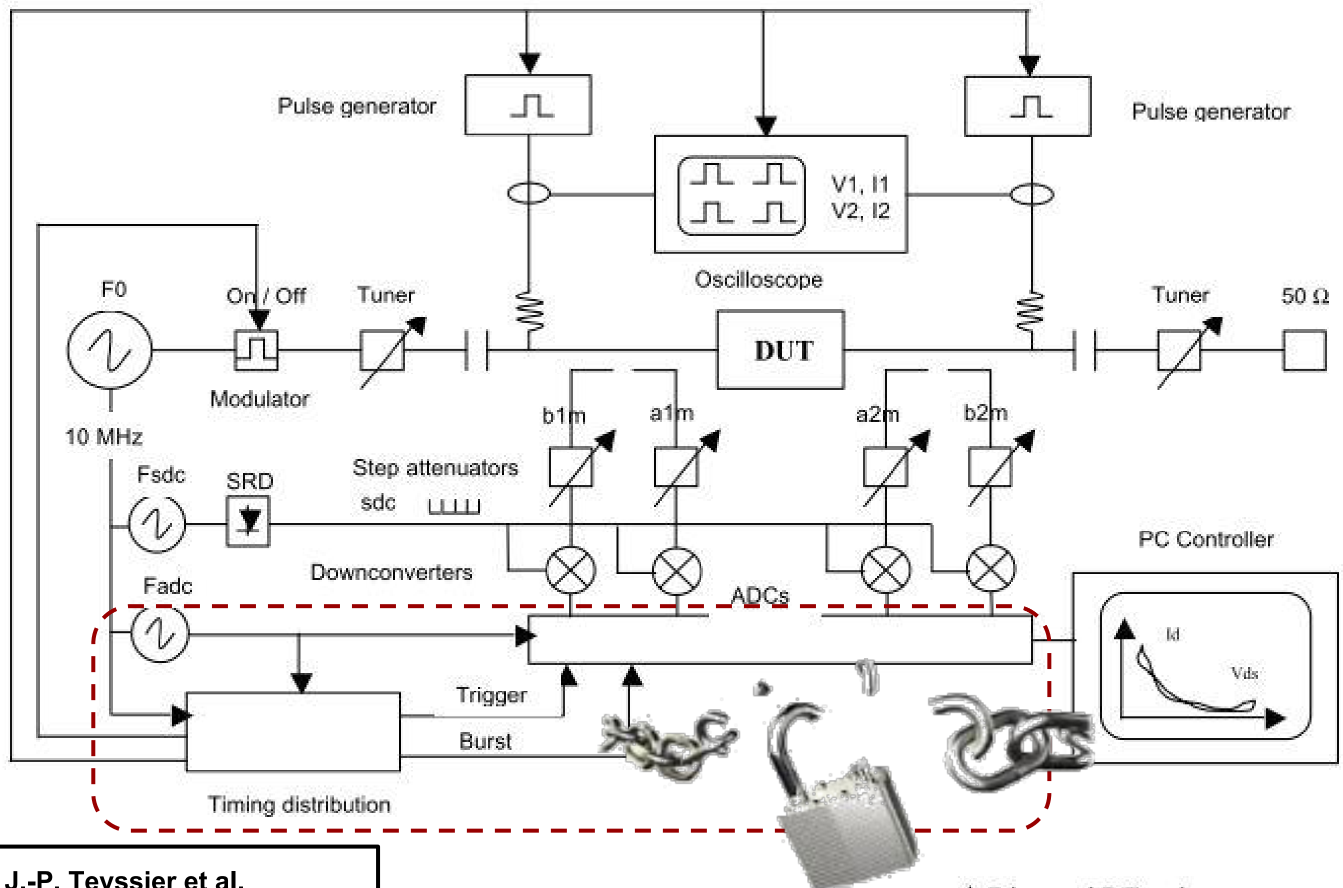
Instrumentation Improvement

- Pulsed RF measurements (Hardware)
- Pulsed RF measurements (Software)

Improve PA efficiency

- Class-F Validation of a MMIC PA
- Harmonic Injection PA Design
- Outphasing Experiments
- Envelope Tracking Analysis...

Pulsed RF (Hardware)



Example:

F0 = 1 GHz
Fsdc = 19.6 MHz

Fi = 400 kHz

Fadc = 12.8 MHz

Samples = 2048

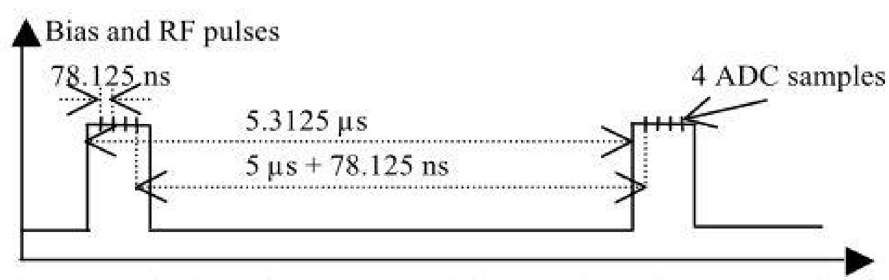
FFTbin = k.64

ADC Acquisition:

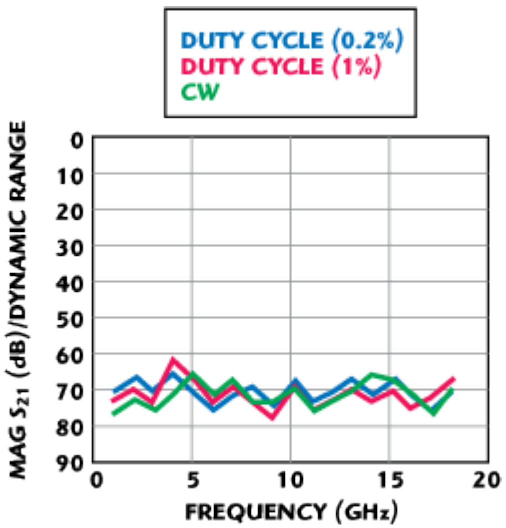
512 burst of 4 samples

J.-P. Teyssier et al.
"Large-Signal Time Domain Characterization of Microwave Transistors under RF Pulsed Conditions"
57th ARFTG Conference (Spring), 2001
[Link]

CALIBRATION IN CW



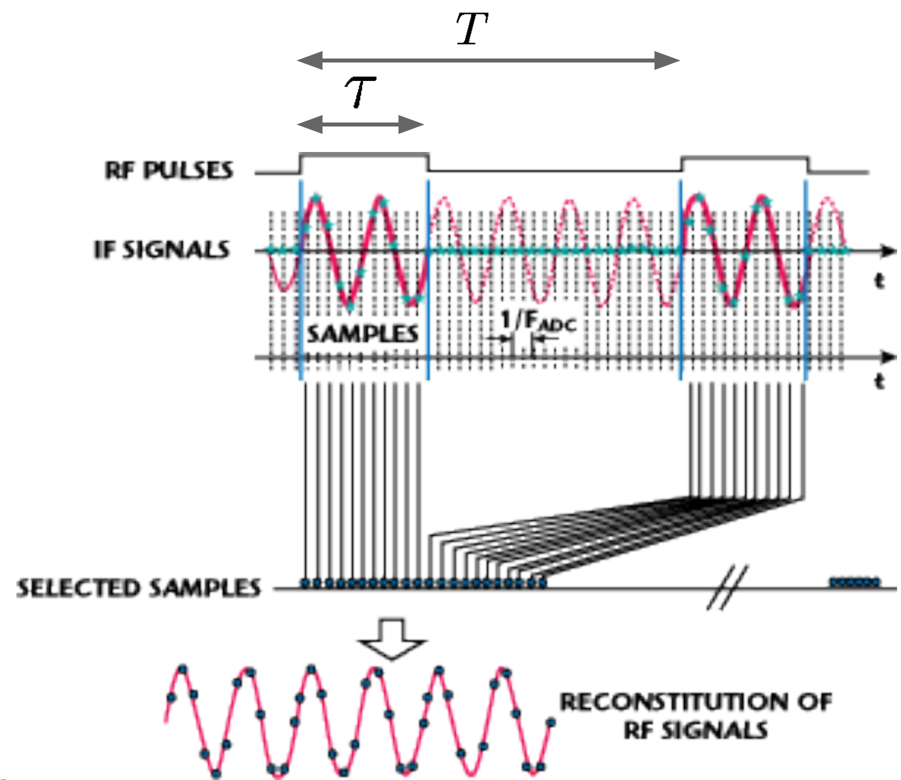
Hardware embedded in SWAP X-402



Result:
Dynamic Range not correlated with Duty cycle

VNA Dynamic loss

$$20.\log_{10}\left(\frac{T}{\tau}\right)$$



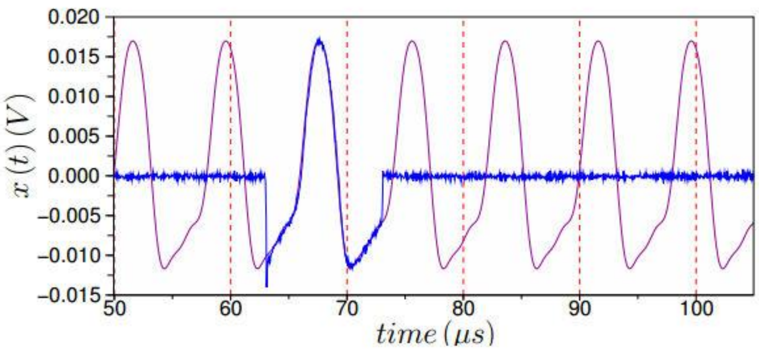
J. Faraj et al.
"A Repetitive Sampling Receiver for Pulsed Time Domain Load-Pull", Microwave Journal, September, 2011 [Link]

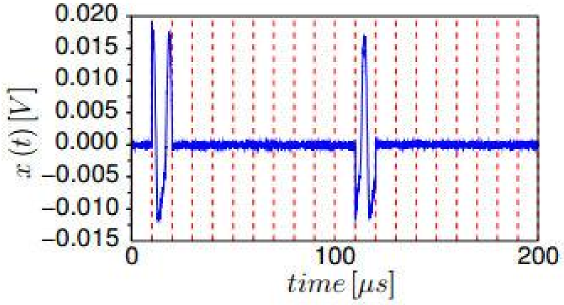
TABLE I

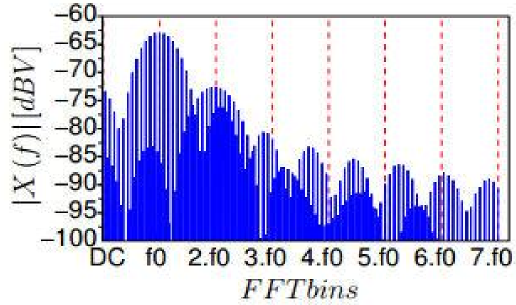
ACQUISITION MEASUREMENTS TIME FOR DIFFERENT DUTY CYCLES

Duty Cycle (%)	(1/10)100	(1/100)100	(1/1000)100
Acquisition Measurement Time	10 μs	100 μs	1000 μs

Pulsed RF (Software)



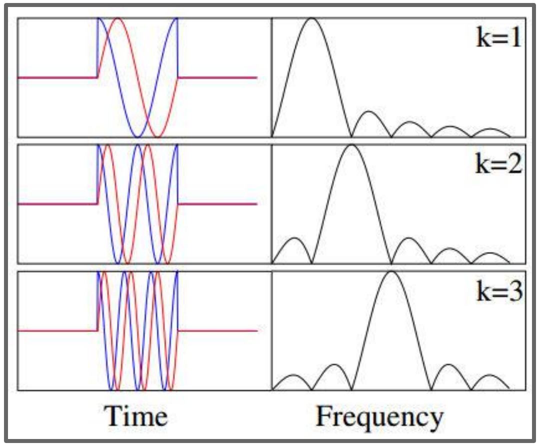


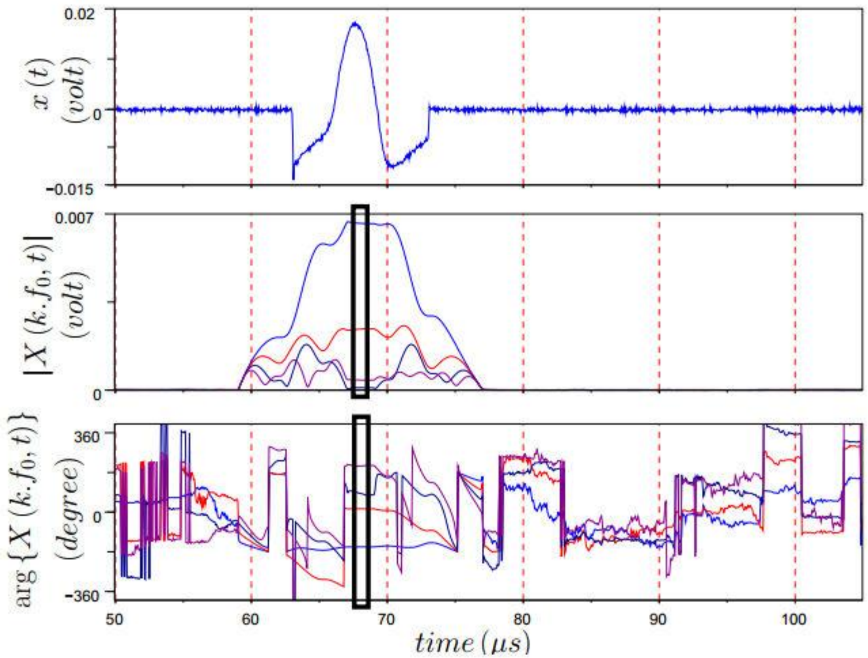


CALIBRATION IN CW

FFT after
ADC acquisition

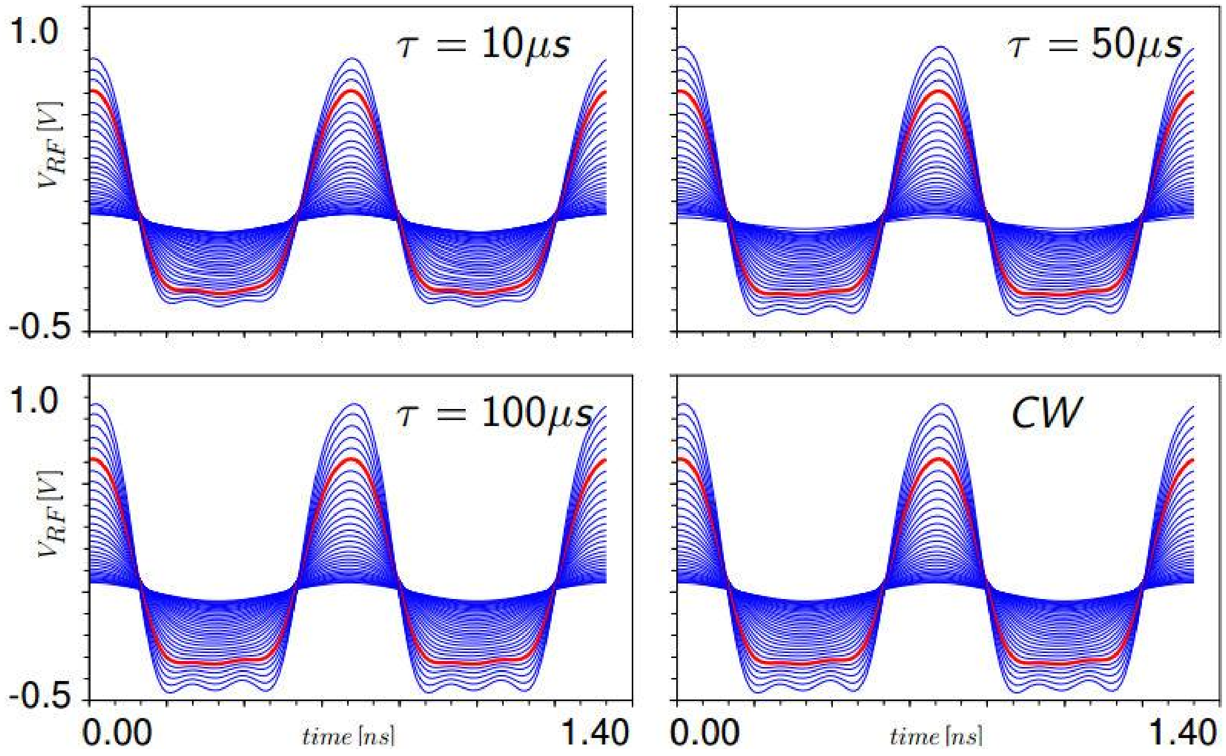
Replace FFT with STFT
(Short Time Fourier Transform)





Pulsed RF (Software)

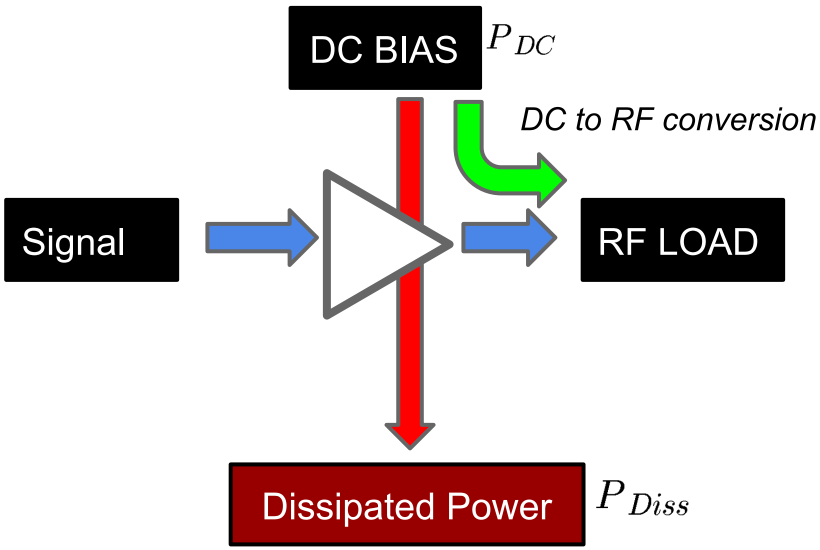
$f_{RF} = 1.5GHz$ $T_{\psi} = 8\mu s$ $k \in \{1, 2, 3, 4\}$



T. Reveyrand, Z. Popović
"A new method to measure pulsed RF time domain waveforms with a sub-sampling system"
IEEE IMS 2012.
[Download]

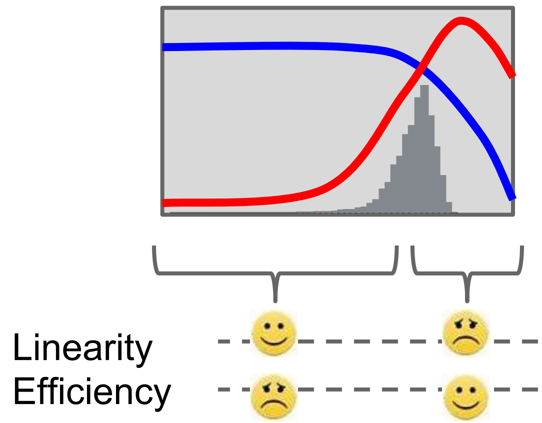
- Compatible with CW and pulsed signals
- Adaptive method
- No trigger
- Pulse's width and period (τ, T) not required

Chasing the efficiency

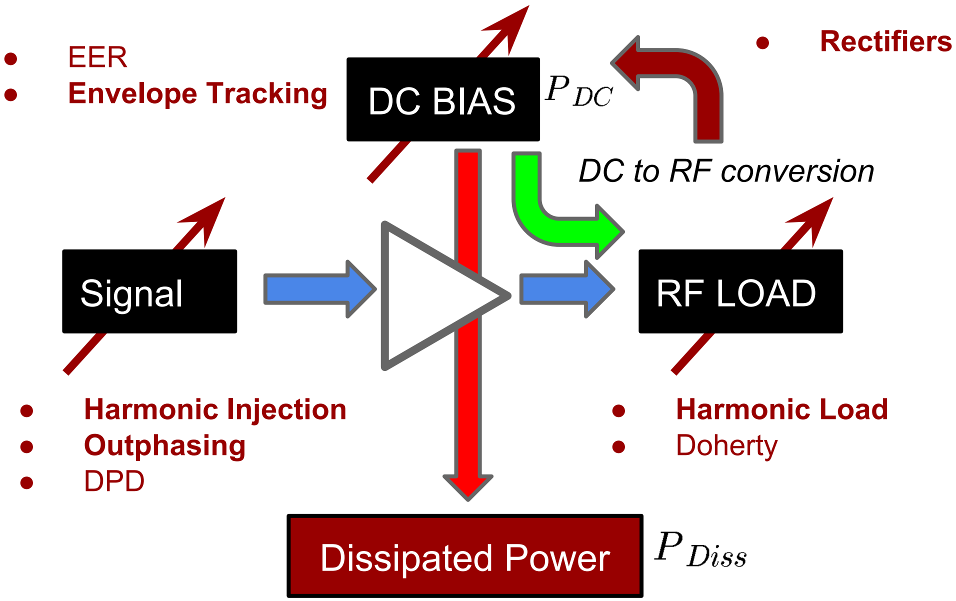


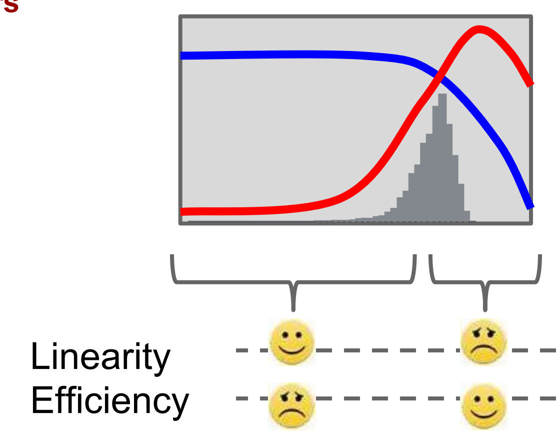
$$PAE(\%) = \frac{P_{Diss}}{P_{DC}}$$

Power Gain
Efficiency (PAE)



Chasing the efficiency





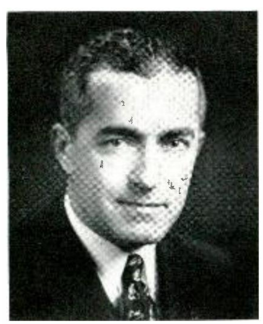
$$PAE(\%) = \frac{P_{Diss}}{P_{DC}}$$

Power Gain

Efficiency (PAE)

BACK TO THE **30's**

H. Chireix

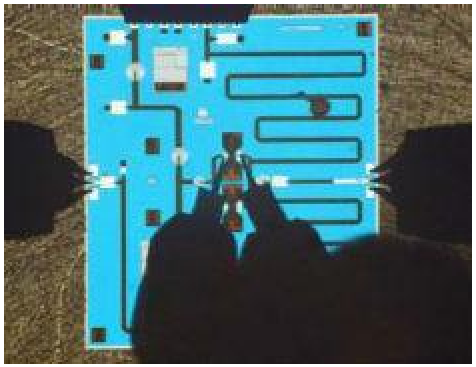


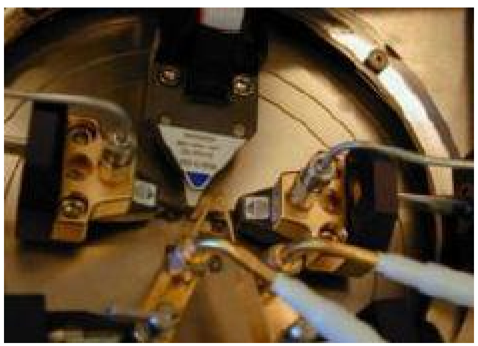
W. H. Doherty

LSNA's Applications

- Class-F Power Amplifier
- Harmonic Injection
- Outphasing
- Rectifiers
- Envelope Tracking

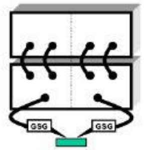
HIP: Class-F Validation





T. Reveyrand et al.
"Calibrated Measurements of Waveforms at Internal Nodes of MMICs with a LSNA and High Impedance Probes"
62nd ARFTG, Fall, 2003
[Download]

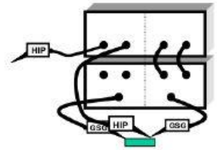
1. NVNA calibration (LRRM)



$$\begin{pmatrix} v1 \\ i1 \\ v2 \\ i2 \end{pmatrix}_{LSNA} = \begin{bmatrix} \alpha_1 & \beta_1 & 0 & 0 \\ \gamma_1 & \delta_1 & 0 & 0 \\ 0 & 0 & \alpha_2 & \beta_2 \\ 0 & 0 & \gamma_2 & \delta_2 \end{bmatrix} \cdot \begin{pmatrix} r1 \\ r2 \\ r3 \\ r4 \end{pmatrix}_{LSNA}$$

→ Ref. plane = voltage standard

2. Calibration with 1 HIP



- HIP @ ref. plane
- « Sweep-sin »
- Measurements :
  - > V_2 (NVNA calibrated)
  - > V_{HIP} (raw data)

→ $\tilde{K}(f) = \dfrac{v_2(f)}{v_{HIP}(f)}$

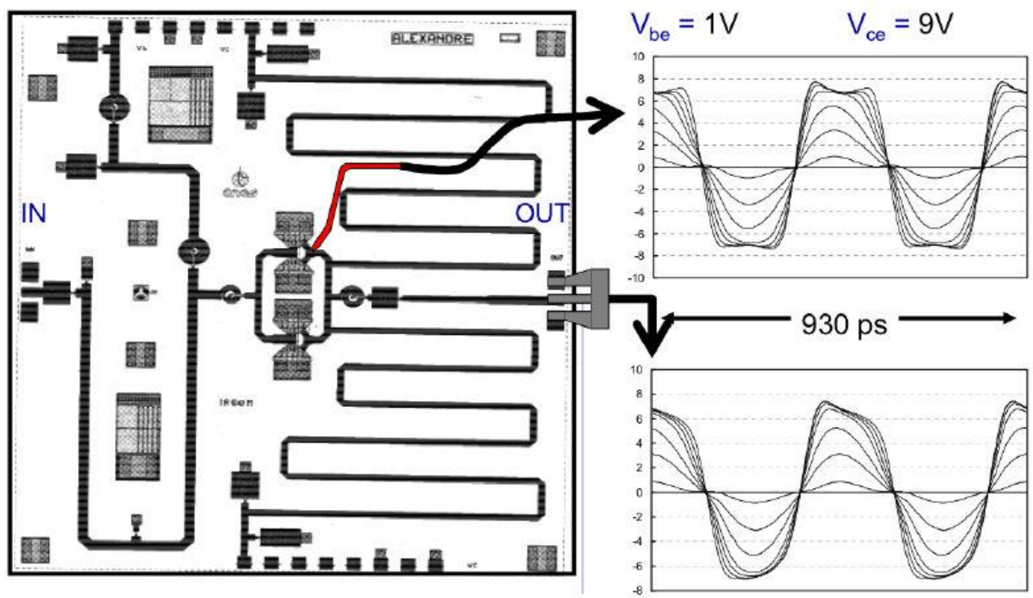
3. Define a new error-matrix (NVNA + 2 HIPs)

Measurement of 2 voltages

$$\begin{pmatrix} v1 \\ i1 \\ v2 \\ i2 \end{pmatrix} = \begin{bmatrix} \tilde{K}_1 & 0 & 0 & 0 \\ 0 & \tilde{K}_2 & 0 & 0 \\ 0 & 0 & \alpha_2 & \beta_2 \\ 0 & 0 & \gamma_2 & \delta_2 \end{bmatrix} \cdot \begin{pmatrix} r1 \\ r2 \\ r3 \\ r4 \end{pmatrix}$$

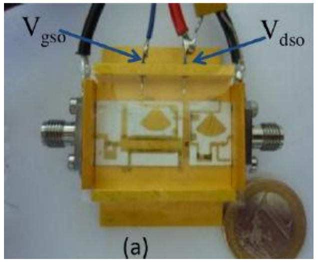
v1(t) ⇔ v1(t)
i1(t) ⇔ v2(t)

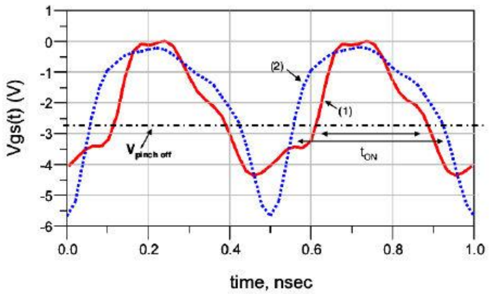
Method requires access to:
- Raw Data
- Calibration Measurements
- Error-terms

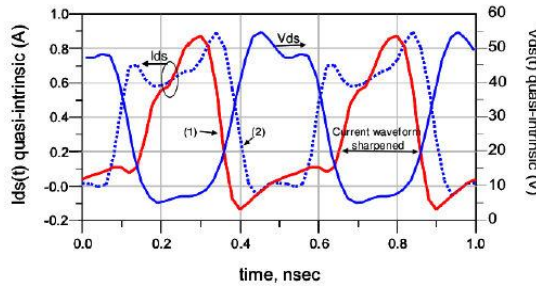


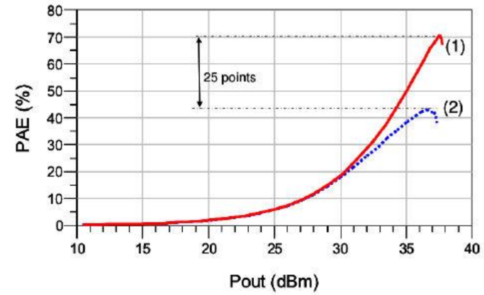
Harmonic Injection

1. Single Stage PA with both fo and 2.fo at input: Non-linear model optimized on LSNA measurements

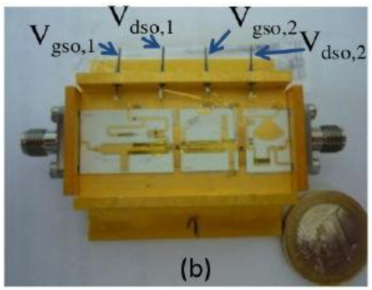


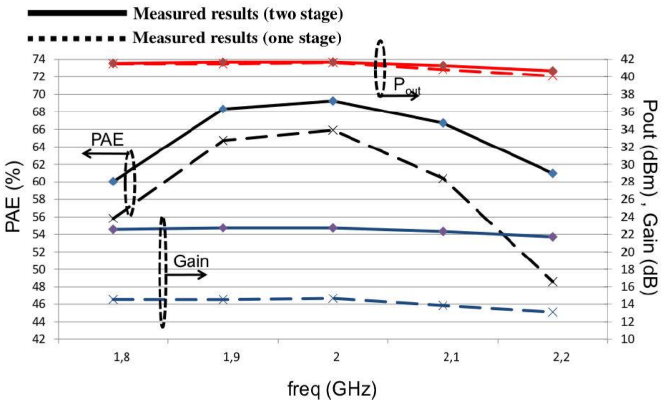




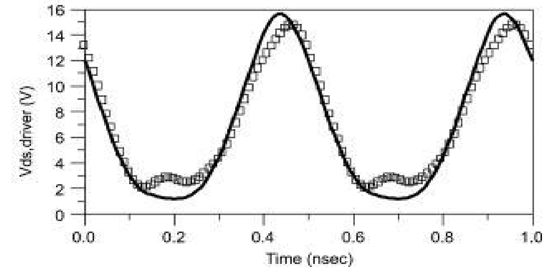


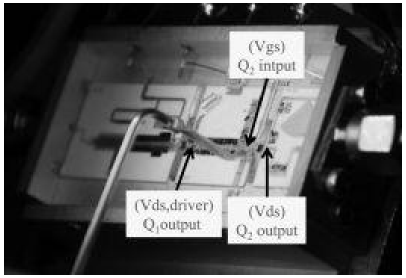
2. Using the 2.fo from the driver: design of the interstage

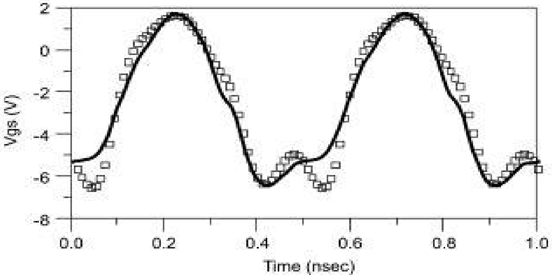




3. HIP validation

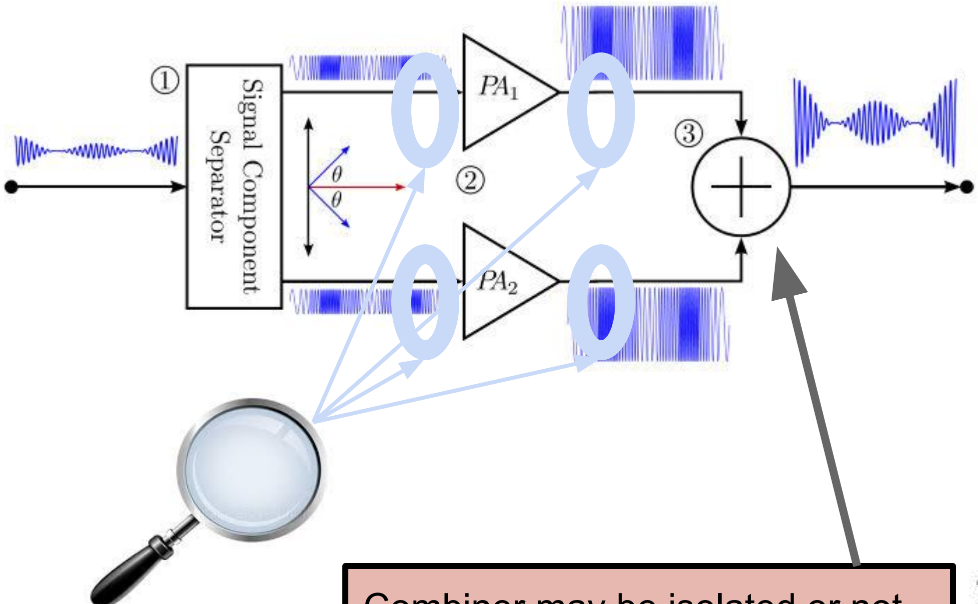






A. Ramadan et al.
"Two Stage GaN HEMT Amplifier With Gate Source Voltage Shaping for Efficiency Versus Bandwidth Enhancements"
IEEE Trans. on MTT, Vol. 59, No 3, pp.699 - 706, 2011
[Download]

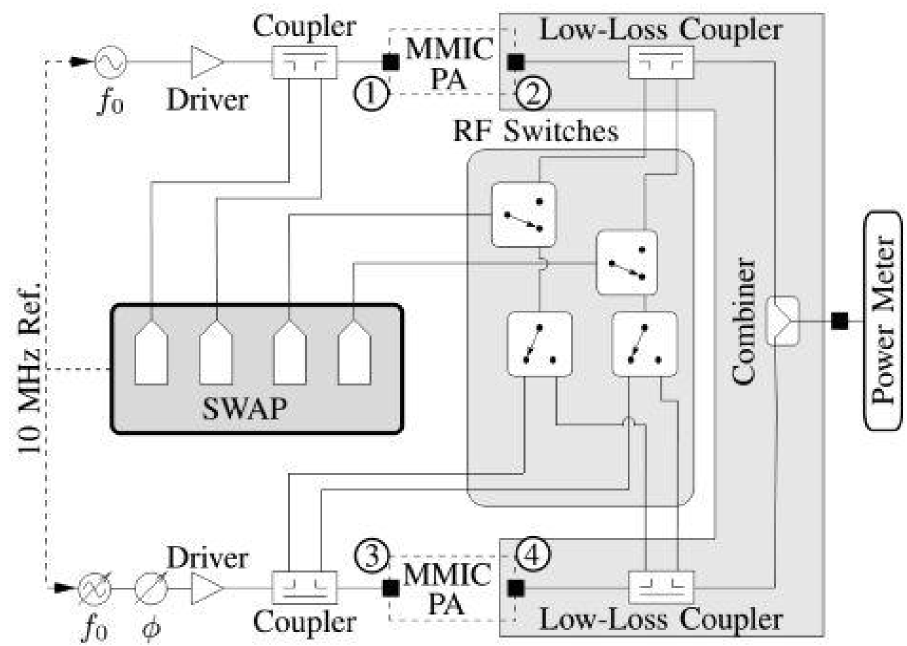
Outphasing Principle: Phase modulated constant input power (high PAE)



Combiner may be isolated or not

Dedicated 4-ports LSNA

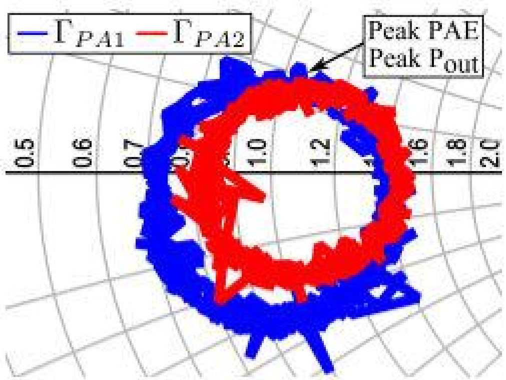
This method requires the stack of several calibration matrix and a customizable test-set.

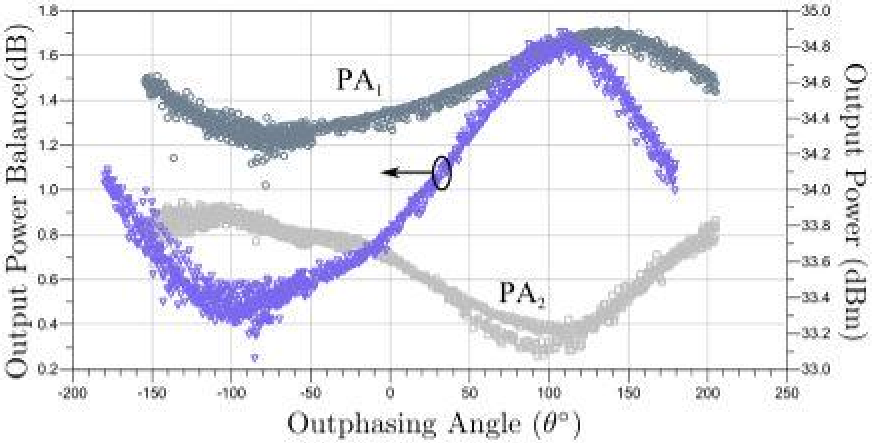


M. Litchfield et al.
"X-Band Outphasing Power Amplifier with Internal Load Modulation Measurements"
EuMW 2014
[Download]

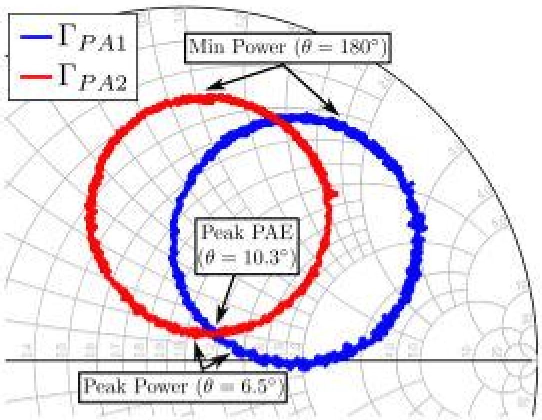
Load-Modulation Measurements

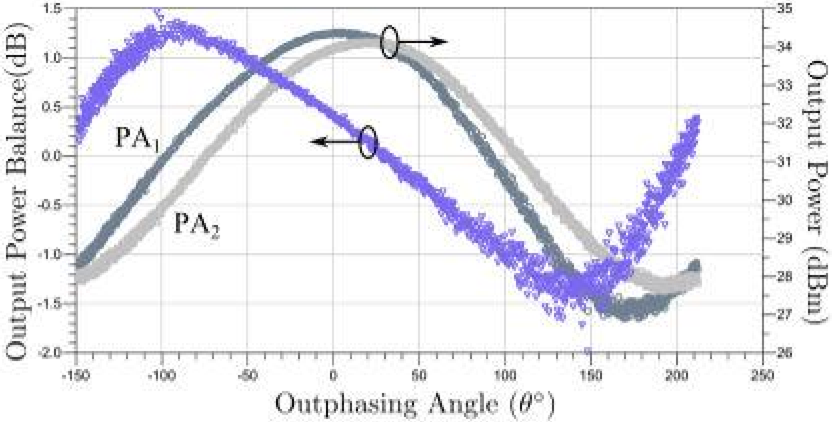
ISOLATED COMBINER

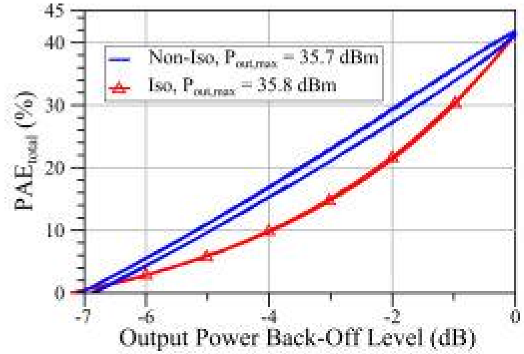




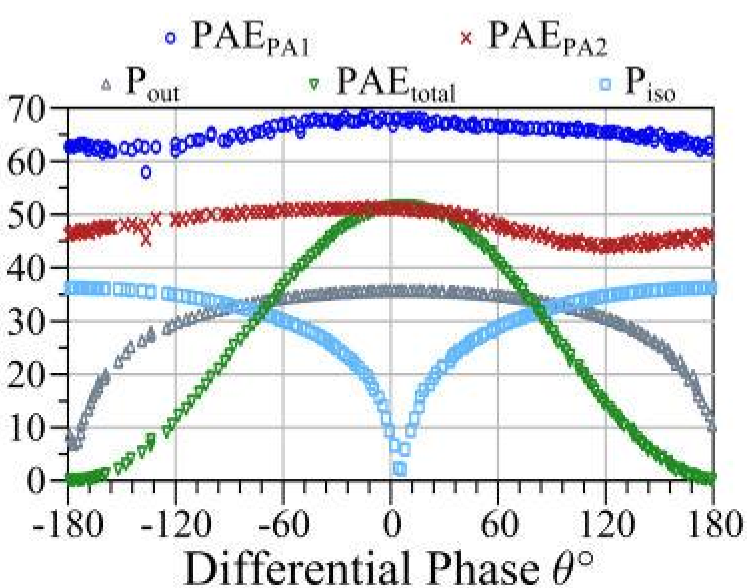
NON-ISOLATED COMBINER



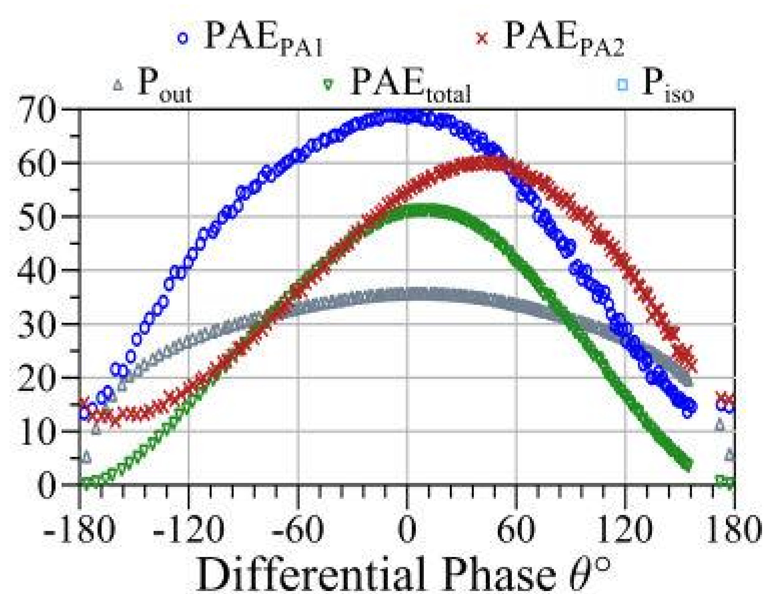




Isolated Combiner

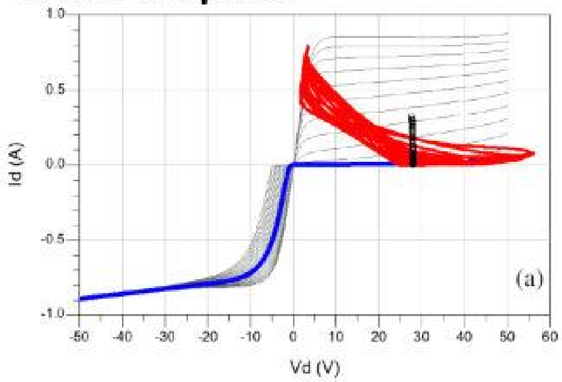


Non-Isolated Combiner

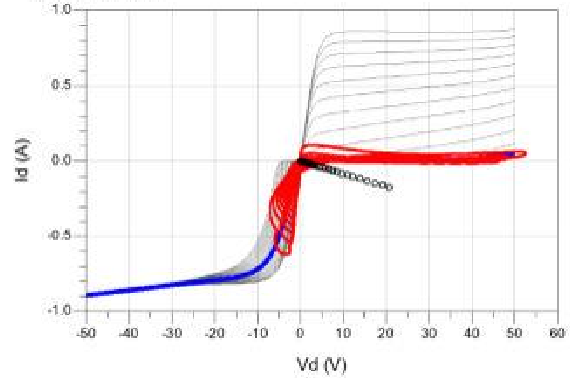


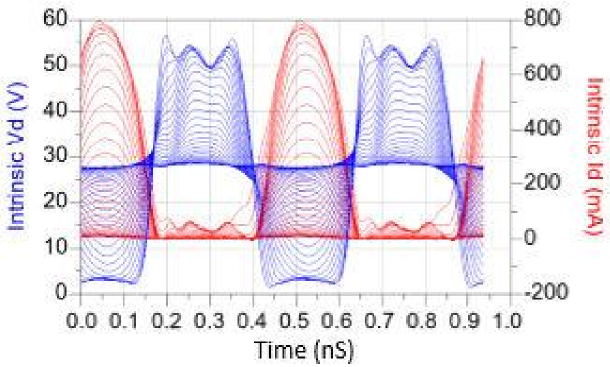
HEMT-based Rectifiers

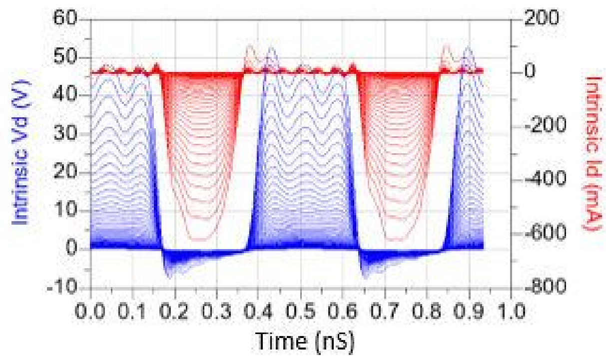
Power Amplifier



Rectifier





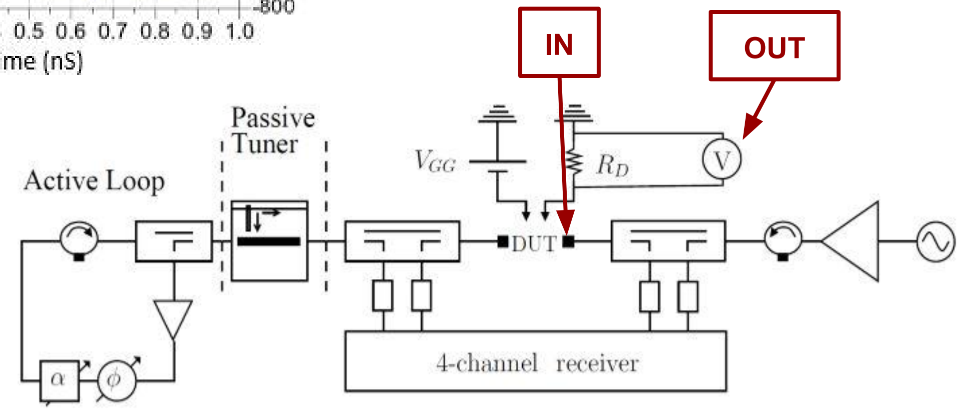


Simulations at intrinsic current-source

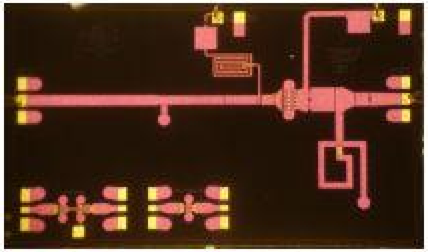
M. Litchfield et al.
"High-Efficiency X-Band MMIC GaN Power Amplifiers Operating as Rectifiers"
IEEE MTT-S, 2014
[Download]

Unconventional Load-Pull Setup

Setup for Rectifiers

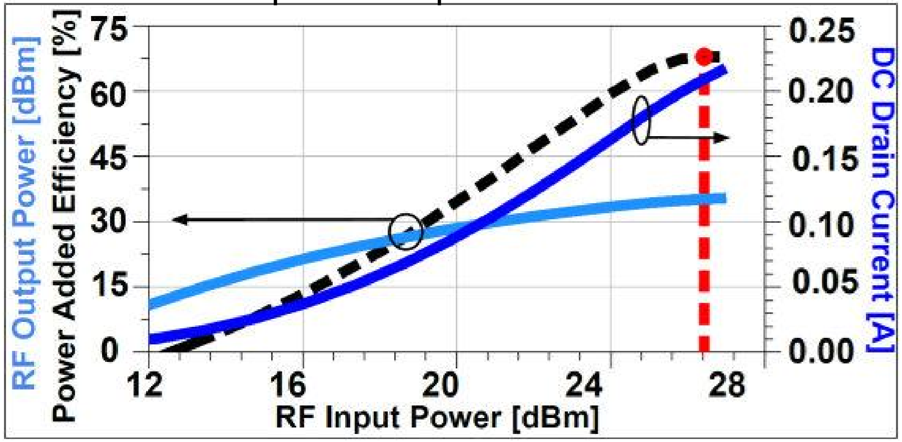


One Circuit...



fo = 10.1 GHz

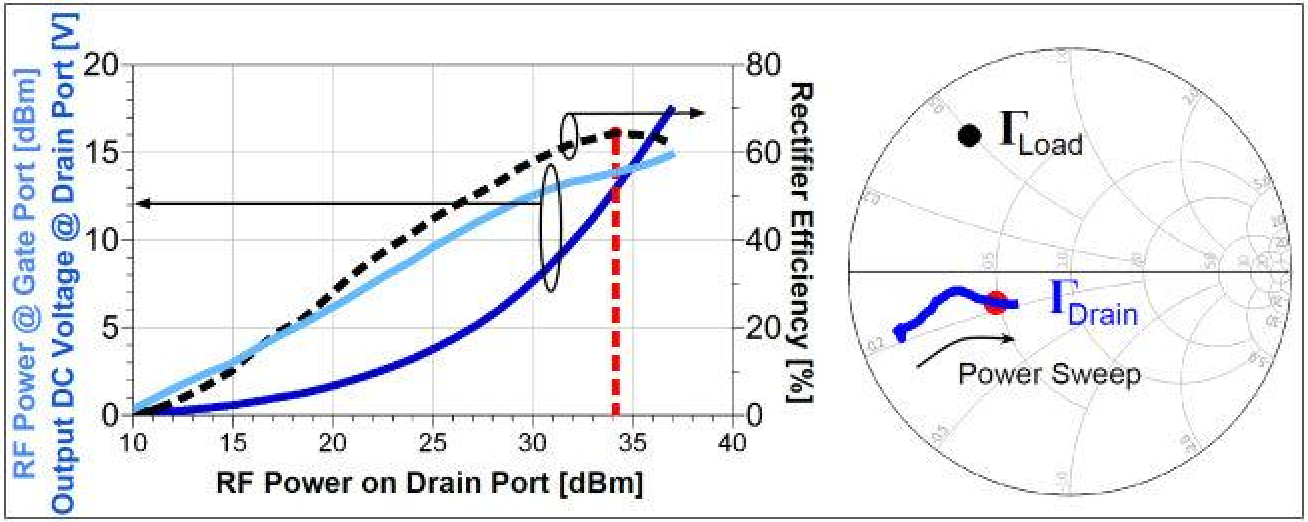
...is either a RF power amplifier…



PAE = 67%
Drain Eff = 78%
Pin = 26 dBm
Pout = 35 dBm

Vgg = -4.0 V
Vdd = 20 V

...or a RF power rectifier!

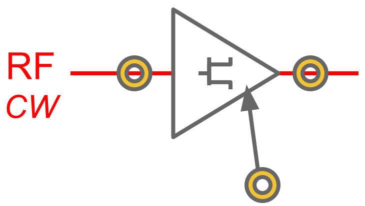


Eff = 64%

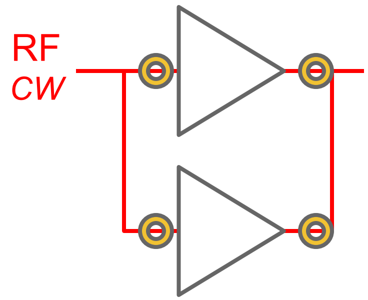
Vgg = -4.7 V
RD = 100 Ω

Zload = 8.45 + j.24.5 Ω

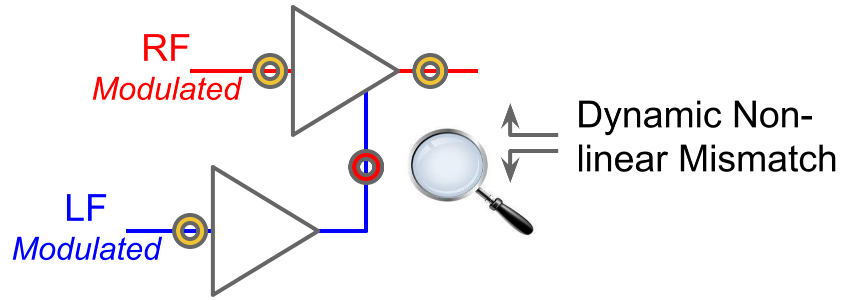
Envelope Tracking



Standard PA



Outphasing
&
Doherty



RF PA + Supply Modulator

Simulation Tool	**Harmonic Balance**	**Harmonic Balance**	**Envelope Transient**

The measurement setup is on progress. It will be presented at the end of this presentation… Thank you for your patience.

LET'S TALK ABOUT THE LSNA SOFTWARE…

Hardware IS Software

Setup	Hardware	Software
VNA	VNA	S-parameters AC Simulation
NVNA	VNA	LSSP Simulation X-Parameters
	VSA (4-channels)	Envelope Simulation
LSNA	RF Scope (4-channels)	SPICE Simulation
	Samplers or THAs	Harmonic Balance Envelope Simulation

SINGLE SHOT ACQUISITION INCLUDING RF HARMONICS

COMPRESSED SAMPLING

A LSNA is basically a software oriented instrumentation.

VNA is a S-Parameter Simulation.

LSNA is an Harmonic Balance Core.

The user has to define a more complicated environment than for a VNA.

<u>LSNA IS NOT A VNA.</u>

THE CONTROL SOFTWARE CAN NOT BE A "CLICK'N GO" INTERFACE.

Instrumentation Software

	Standard LSNA (HP / Agilent / Maury)	*VTD SWAP*
Commercial LSNA Software	*Mathematica*	*Embedded*
User LSNA Software	*Mathematica* *Matlab* *Scilab* *...*	*C#* *Scilab* *...*

Graphical User Interface is very restricted:

Good for standard application (multi-harmonic load-pull) ;
Bad for exotic measurements

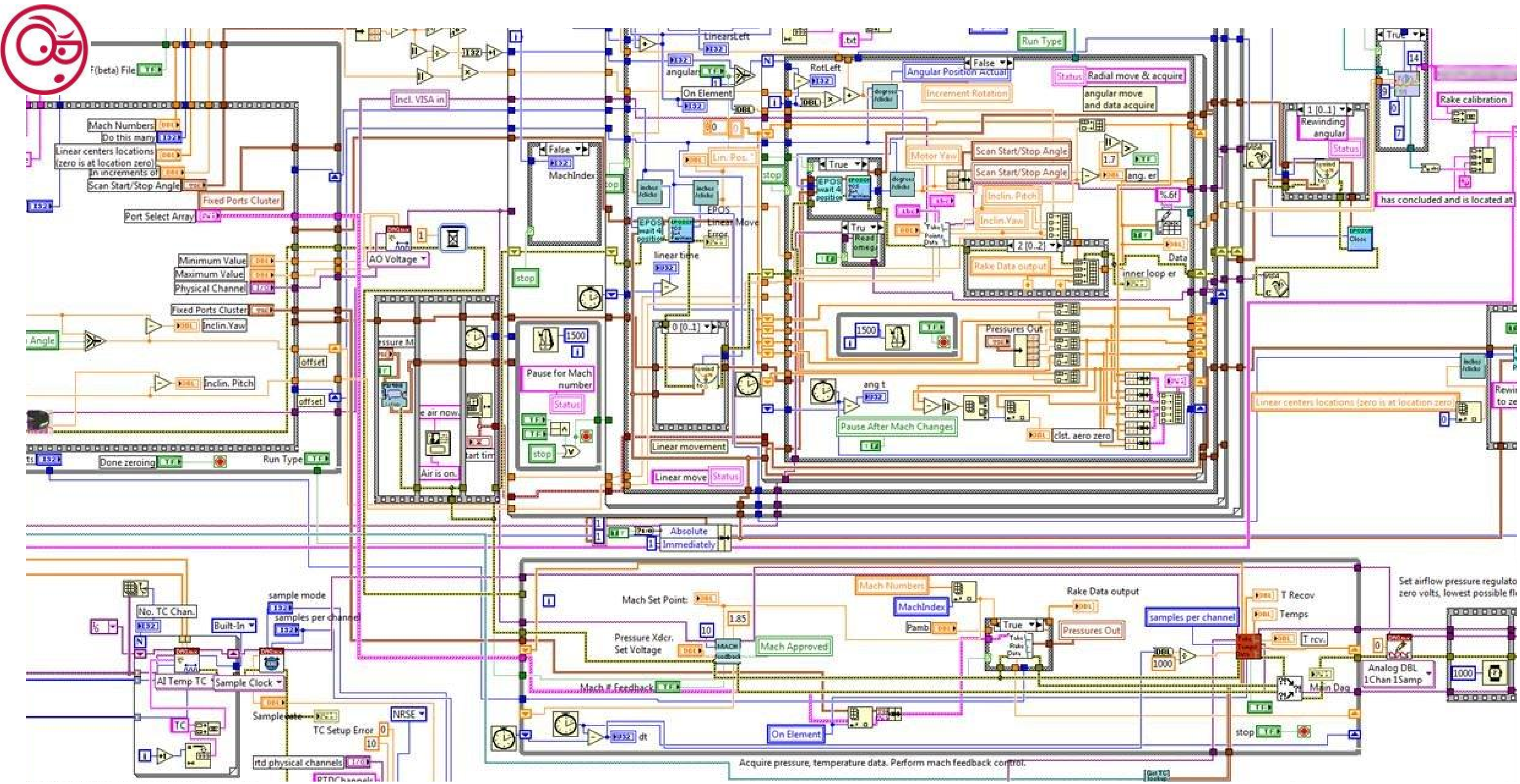
Measurement setups require a dedicated measurement script. Final user needs:

Good knowledge of the software architecture ;
Good knowledge of the development platform ;

WHAT ABOUT LabVIEW ?

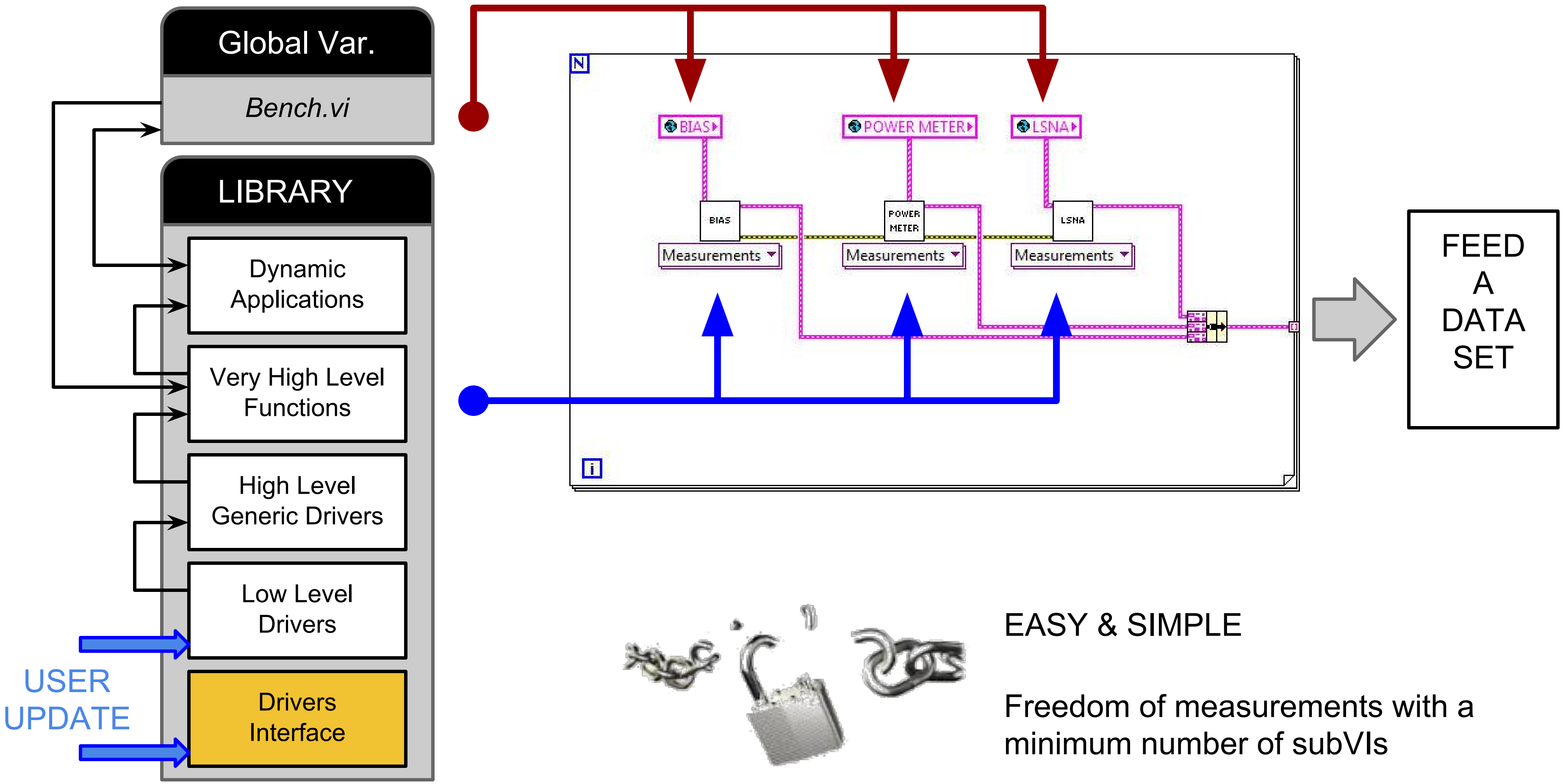
LabVIEW! Seriously?

The purpose is to provide a generic LabVIEW library to make <u>this</u> impossible!



“LabVIEW Spaghetti” coming soon in a Museum of Modern Art

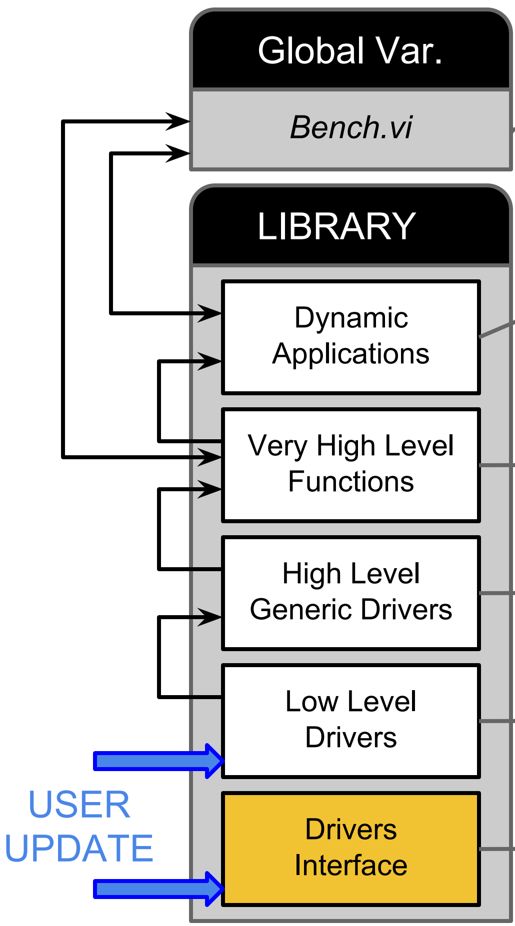
LabVIEW Open Source Instrumentation Software

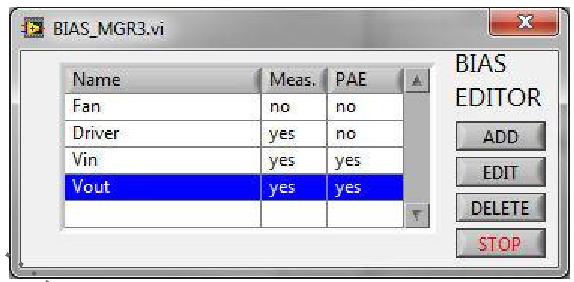


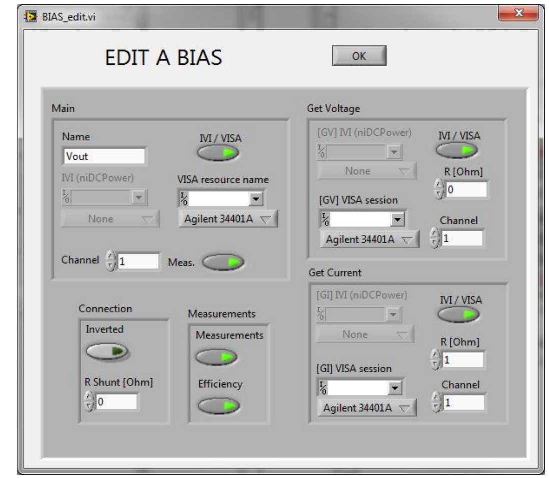
EASY & SIMPLE

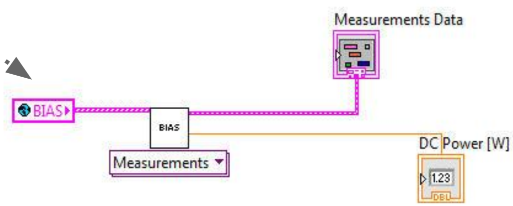
Freedom of measurements with a minimum number of subVIs

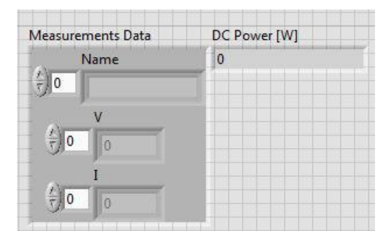
LabVIEW example with BIAS









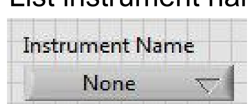


Polymorphic subVI
(input is global variable)

Polymorphic subVI
(input is *ctl)

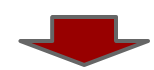
Low level functions

Type Defined File (*.ctl)
List instrument names on use in your lab



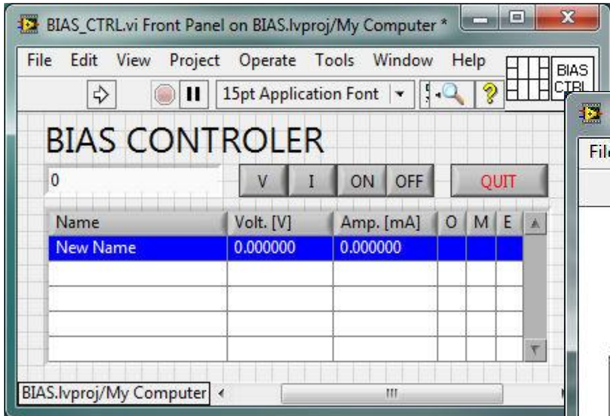
Output is a cluster of arrays:

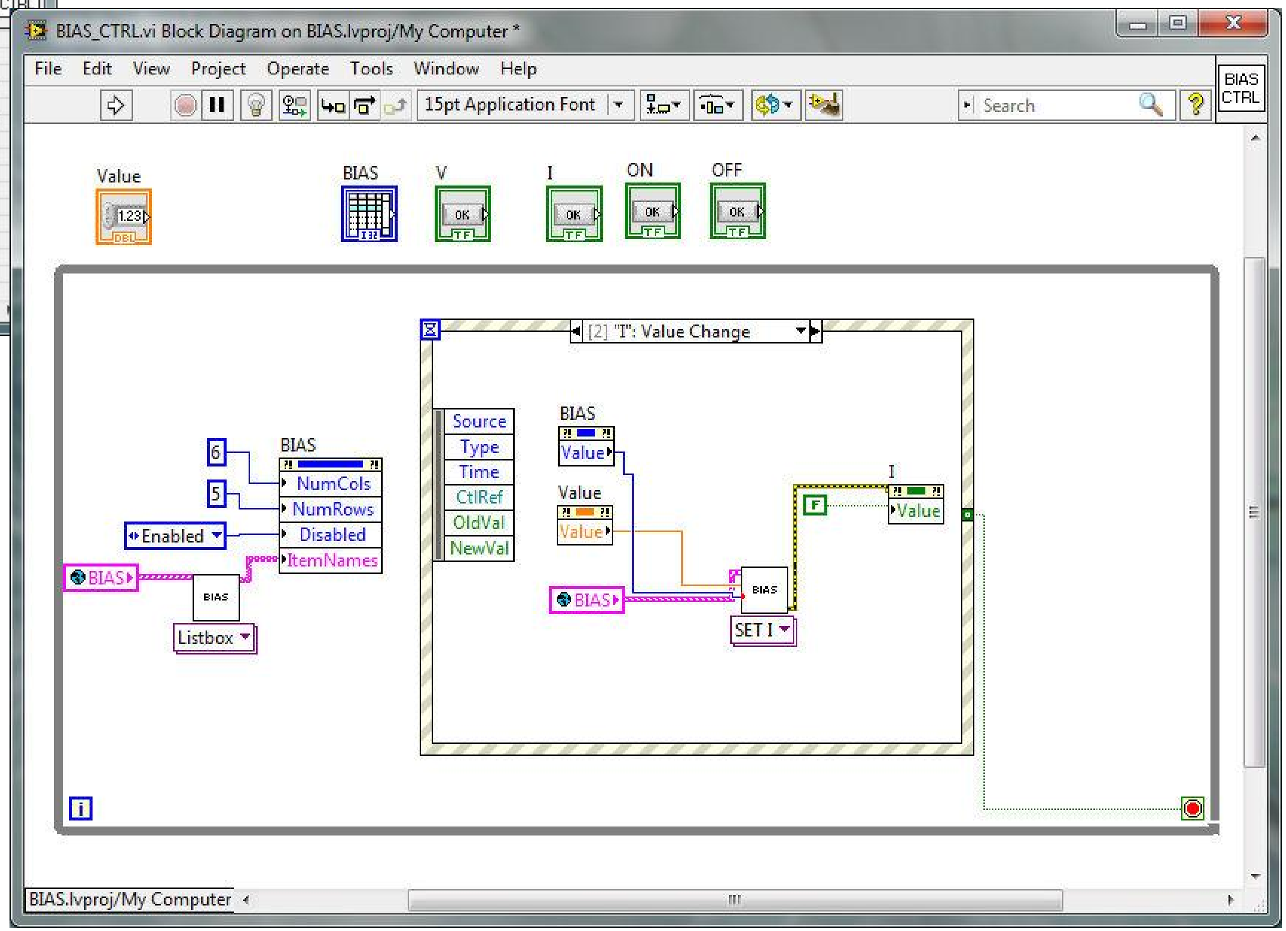
- Name ;
- V ;
- I ;



DATASET

LabVIEW example with BIAS





Source code ridiculously light with this framework

Analyzing the dataset

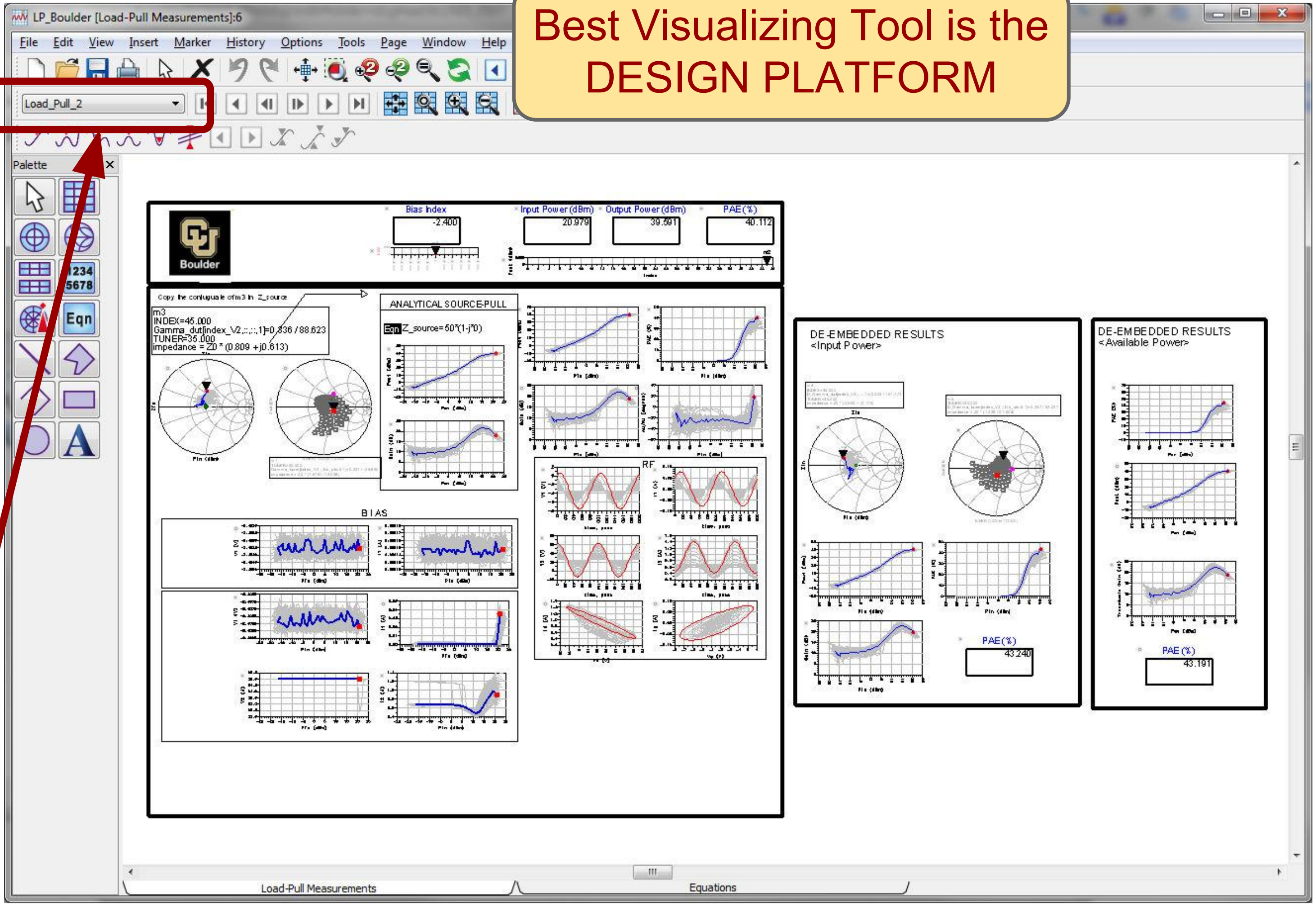
FEED A DATA SET

EXPORT DATA in ***MDIF*** *or* ***CITIFILE***

IMPORT in DATA DISPLAY tool

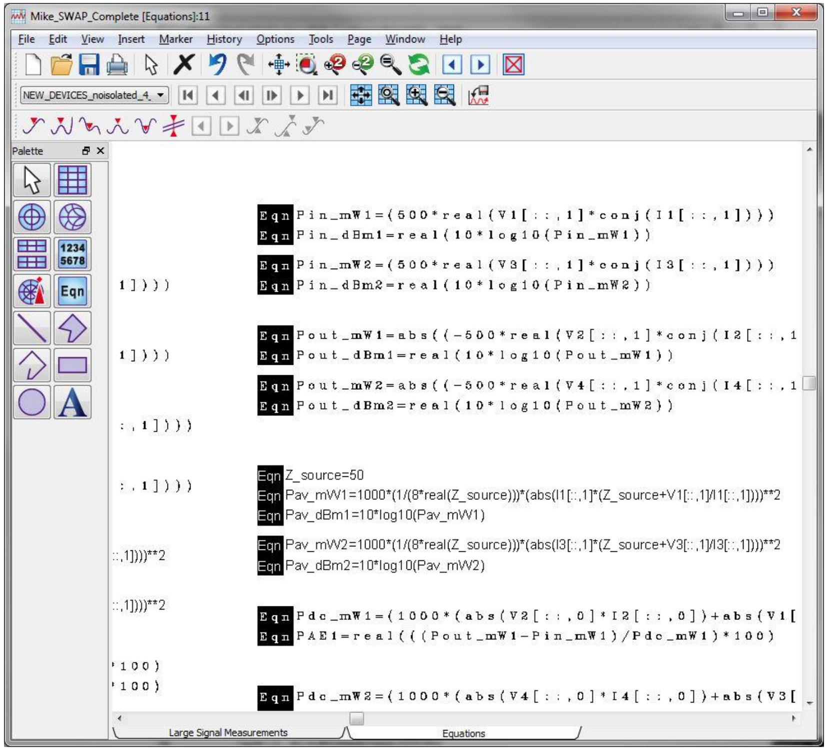
Switching datasets allow to compare easily measurements and simulations.

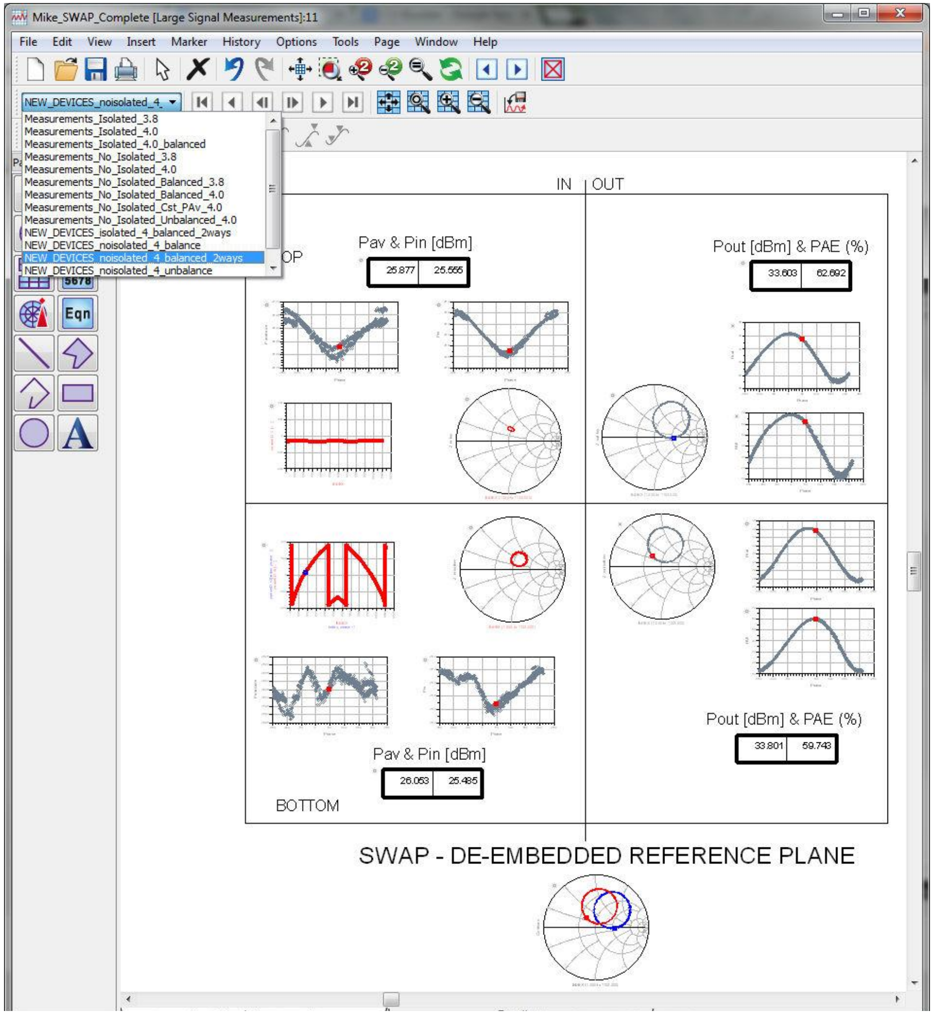
LSNA Load-Pull Measurements in Keysight ADS



Best Visualizing Tool is the DESIGN PLATFORM

Visualization Software





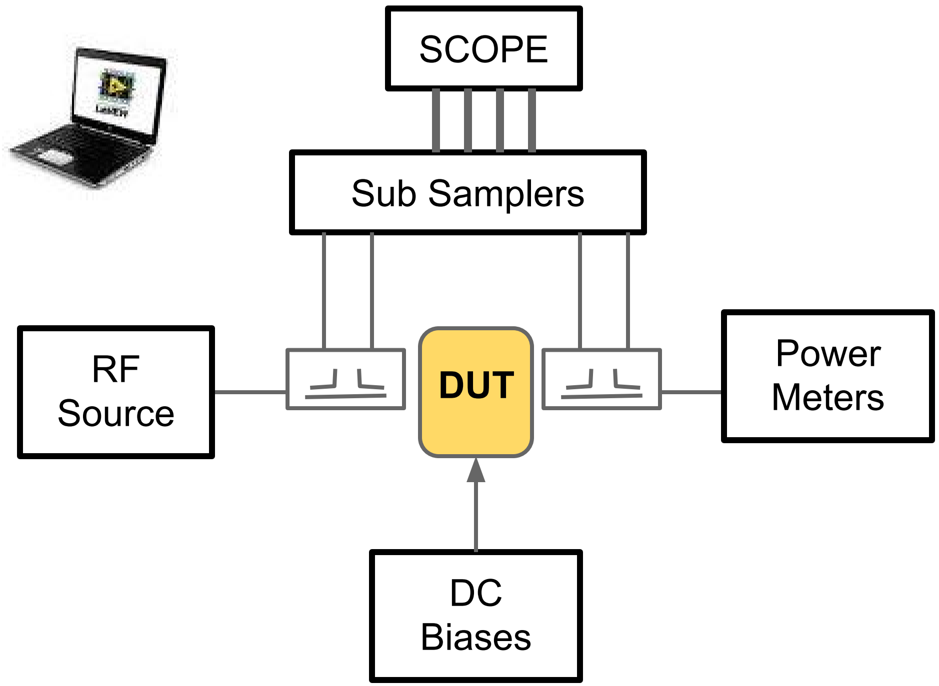
Measurement selection under Keysight ADS for Outphasing Measurements

<u>Only V and I</u> are recorded at each port.
(V and I probes for simulation)

Calculation performed in the datadisplay
(i.e. Pin, Pout, PAE, de-embedding…)

Schematic and Data Display templates may change depending of the final application.

NO LSNA ON THE MARKET?



Most resources are already in your lab… Except the sub-sampler. This element could be a sampler or a Tracking and Hold Amplifier (THA)

DO IT YOURSELF!

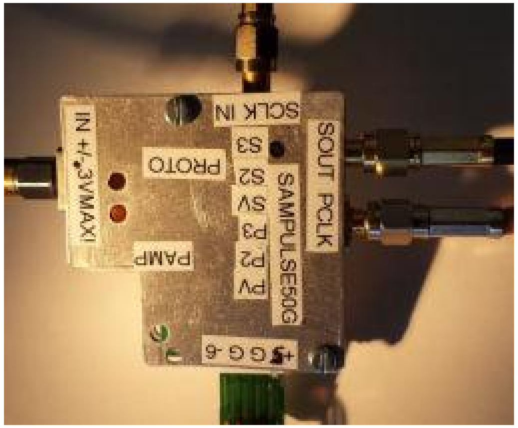
- No need for a perfect receiver
  The VNA calibration will take into account the sub-sampler transfert function
- Good isolation between channels is required
  Calibration based on the 8-error terms matrix
- Bi-directional couplers should present an acceptable directivity

S. Ahmed et al.
"4-Channel, time-domain measurement system using track and hold amplifier for the characterization and linearization of high-power amplifiers"
International Journal of Microwave and Wireless Technologies, vol.4, no 1, 2012
[Download]

Furaxa's Sub-sampler

FURAXA Ultrafast Electronics

www.furaxa.com *InP HBT Sampler IP Core*



RF Receiver Bandwidth

Maury's LSNA	**50 GHz**
VTD's SWAP X-402	**30 GHz**
This sampler	**50 GHz**

Clock Frequency

Maury's LSNA	**16-20 MHz**
VTD's SWAP X-402	**600-1200 MHz**
This sampler	**1-3000 MHz***

(*) square wave below 200 MHz

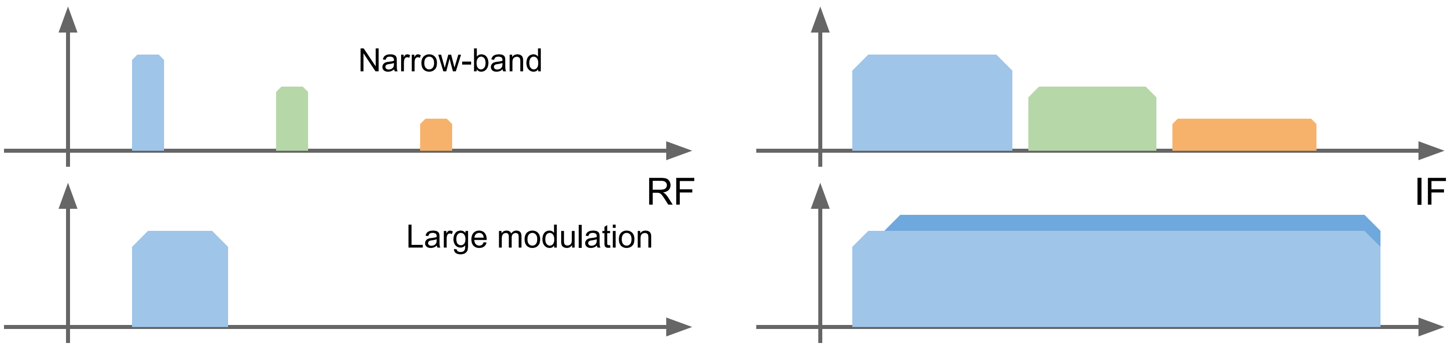
IF Receiver Bandwidth

Maury's LSNA	**20 MHz**
VTD's SWAP X-402	**100 MHz**
This sampler	**100 MHz***

(*) will be updated to 200 MHz

Modulated Signals

Flexibility on the Clock Sub-sampler frequency enable the complete RF spectrum measurements but Signal Processing necessary to unfold modulated spectrum and retrieve “Envelope Transient” consistent measured data.



Signal reconstruction require a periodic modulation (discrete spectrum).

Two possibilities for reconstruction:

- *Frequency domain*
- *Time domain (unscrambling samples)*

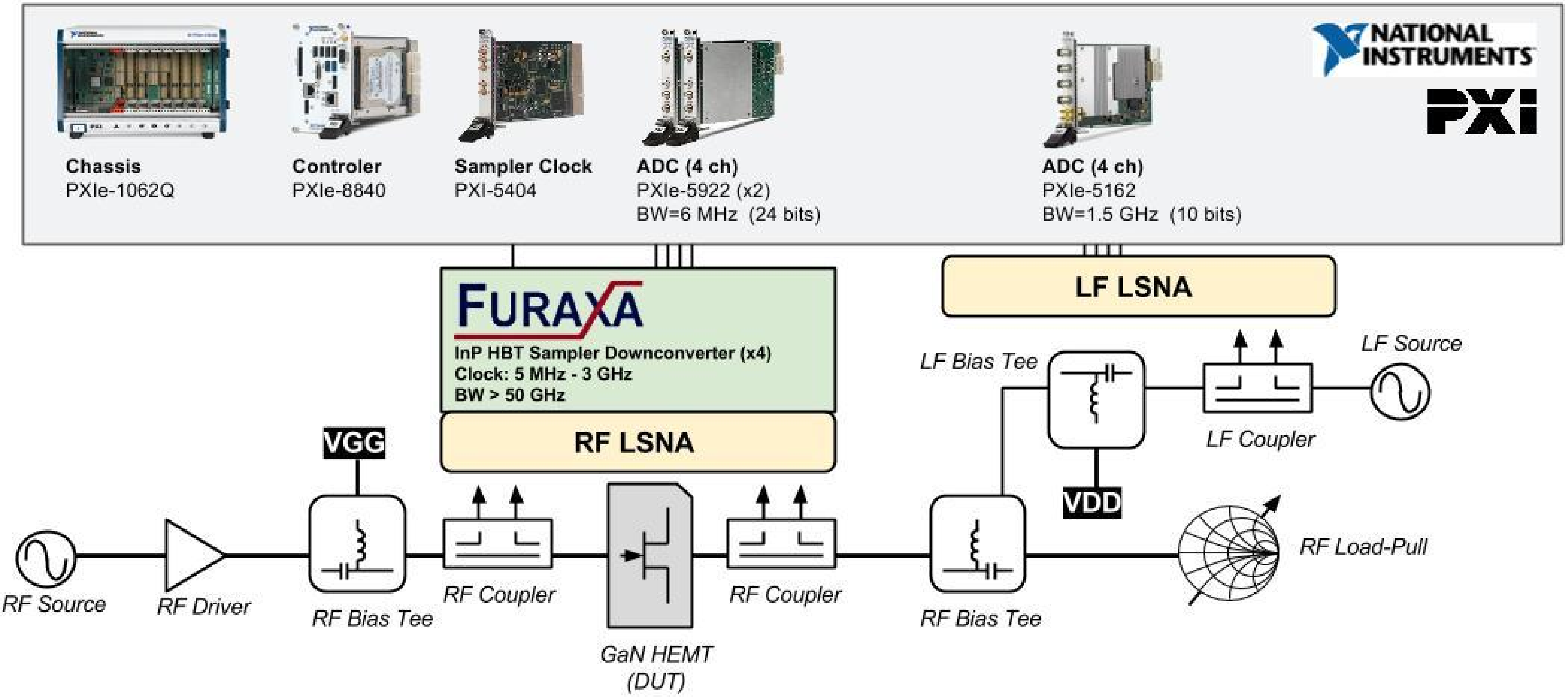
IF bandwidth limit

↓

Complete signal spectrum requires a low sampling frequency
(like standard LSNA)

M. El Yaagoubi et al.
“Time-Domain Calibrated Measurements of Wideband Multisines Using a Large-Signal Network Analyzer”
IEEE Trans. on MTT, Vol. 56, No 5, 2008
[Download]

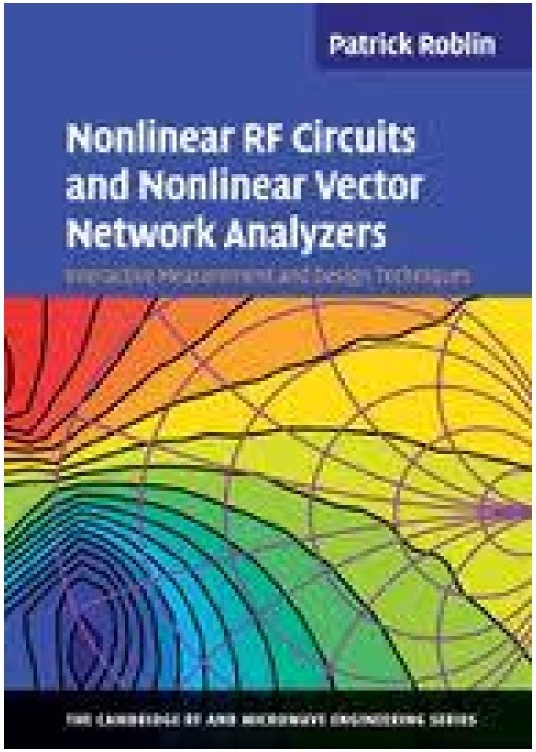
Investigations for Envelope Tracking Applications



Conclusion

- History of the LSNA from the origins (MTA, 1991) up to now.
- Applications on RF designs
- Current work at CU-Boulder on LSNA software and hardware
- Purpose is to offer a 100% LabVIEW open-source software for user measurement flexibility

This work is funded by National Instruments (Dr. Truchard) through a charitable donation. We would like to acknowledge DARPA (Dr. Greene) and ONR (Dr. Maki) for funding the initial part of this work under grant N00014-11-1-0931



Many thanks to Patrick Roblin for offering the opportunity to present this talk at NVNA users' forum

Patrick Roblin
Nonlinear RF circuits and nonlinear vector network analyzers: interactive measurement and design techniques
Cambridge University Press, 2011

Questions?

I guess you want a copy of those slides.

You can download this presentation right there:

www.microwave.fr