

# Time domain envelope characterization of power amplifiers for linear and high efficiency design solutions

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## 1 Measurement Setup

- VSA-based measurement setup
- Setup for Noise Power Ratio
- Setup for Envelope Tracking
- Calibration
- Time Domain Alignment

## 2 Noise Power Ratio

- Notch method
- Equivalent gain method
- EVM method

## 3 Envelope Tracking

- What is ET ?
- Gate and Drain dynamic laws
- Optimization criteria and results

## Introduction

## Required Energy for Basestations in 2010 in Germany



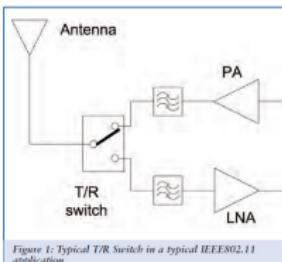
- 3300 GWh in 2010
  - This is 50% of the small Nuclear Power Plant Isar 1 (6200 GWh)
  - This is 100% of the big Water Power Plants
    - Altenwörth (1970 GWh) and Greifenstein (1720 GWh)



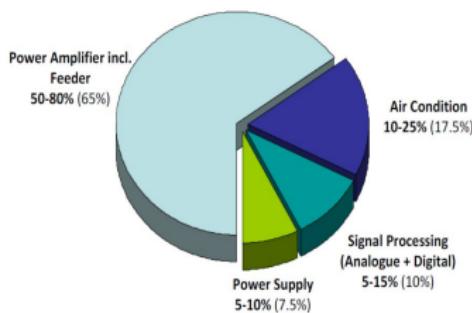
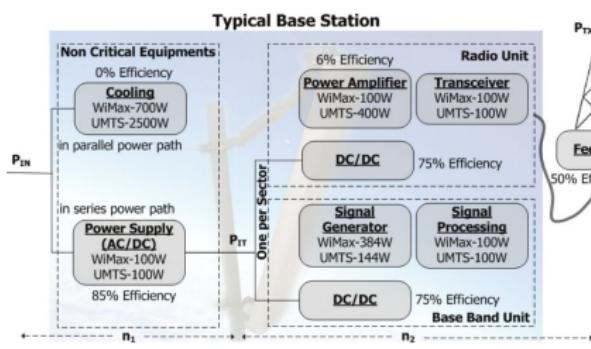
- #### ■ Urgent need for Basestations with improved efficiency

## Introduction

- Designing RF front-end

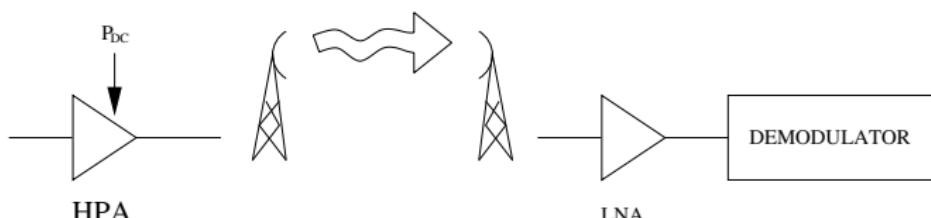


- Base-station example

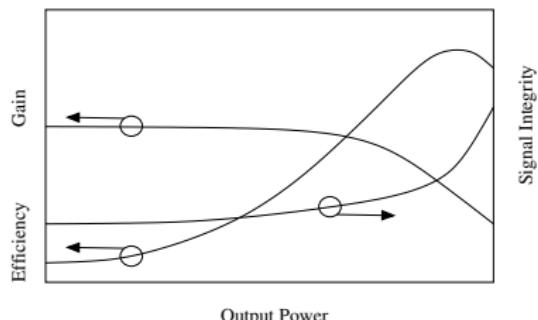


# Introduction

The framework of this talk focuses on High PA in T/R modules



The criteria to take into account are :

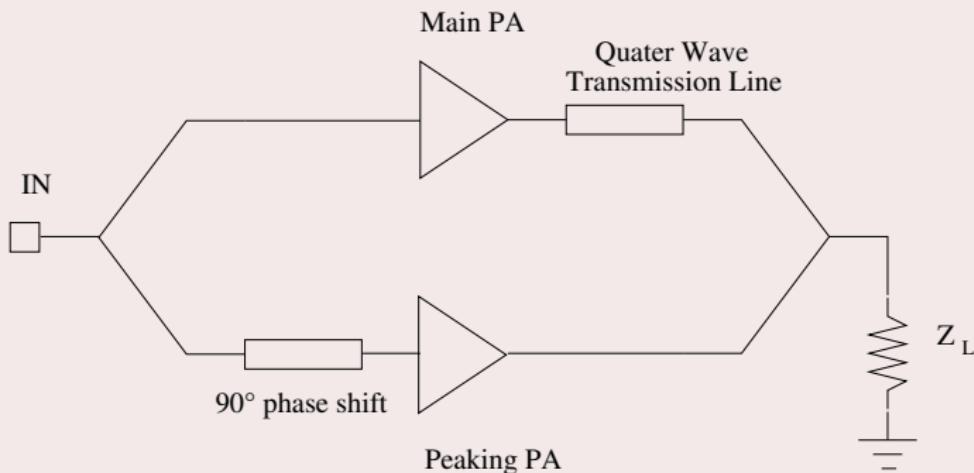


- Output Power
- Power Gain
- Efficiency
- Integrity

## Introduction

## PA workforces focus on efficiency

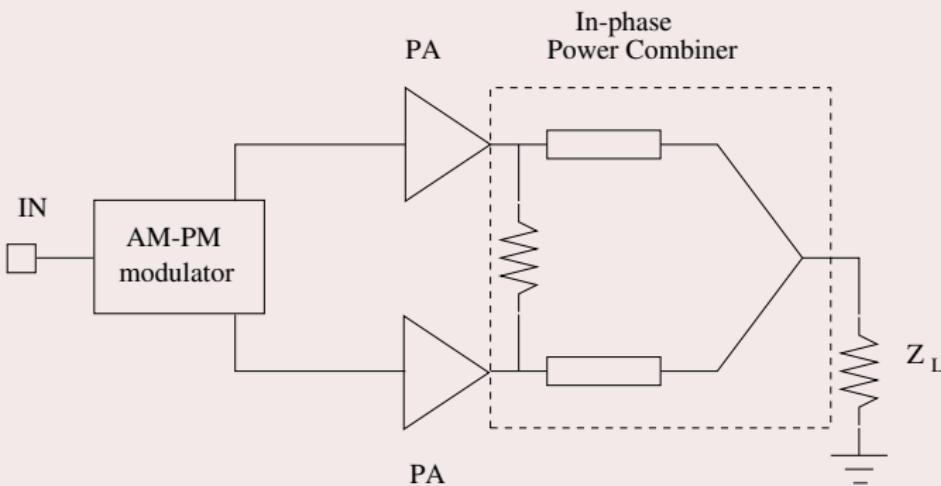
- Doherty



# Introduction

PA workforces focus on efficiency

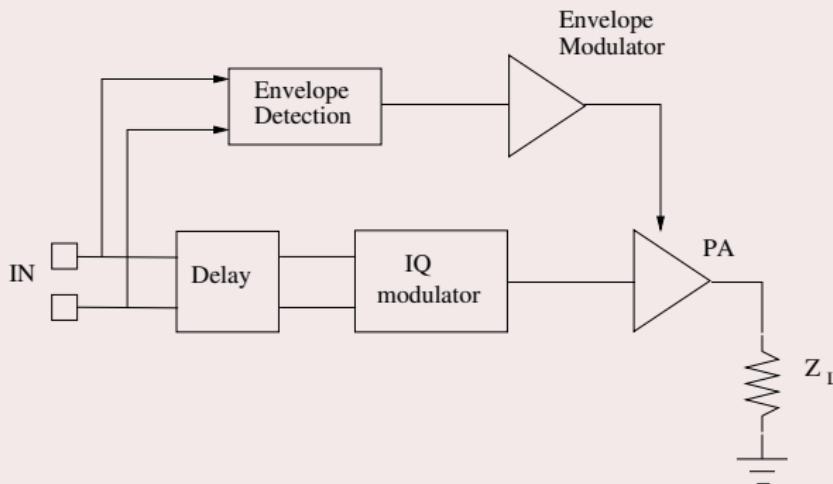
- Outphasing



# Introduction

PA workforces focus on efficiency

- Envelope Tracking



# Introduction

PA workforces focus on efficiency

Most of design flow are performed according CW characterizations and modelling.

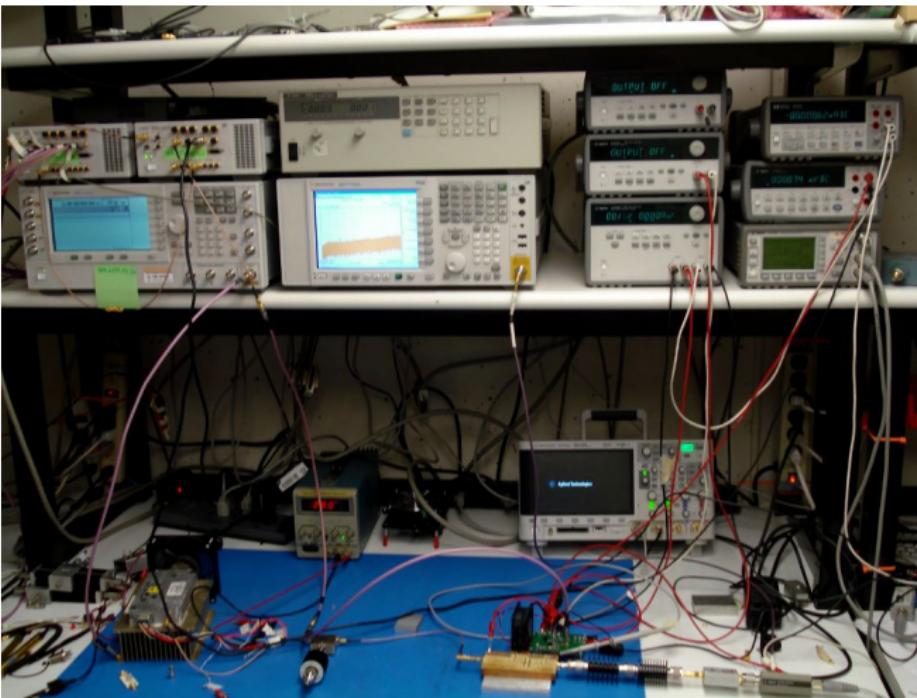
But what about the Signal Integrity at the receiver ?

- Instrumentation with modulated carriers stimulus
- Measurements dedicated on linearity criteria
- Discuss on a comparison criterion for the global TR chain

# Measurement Setup

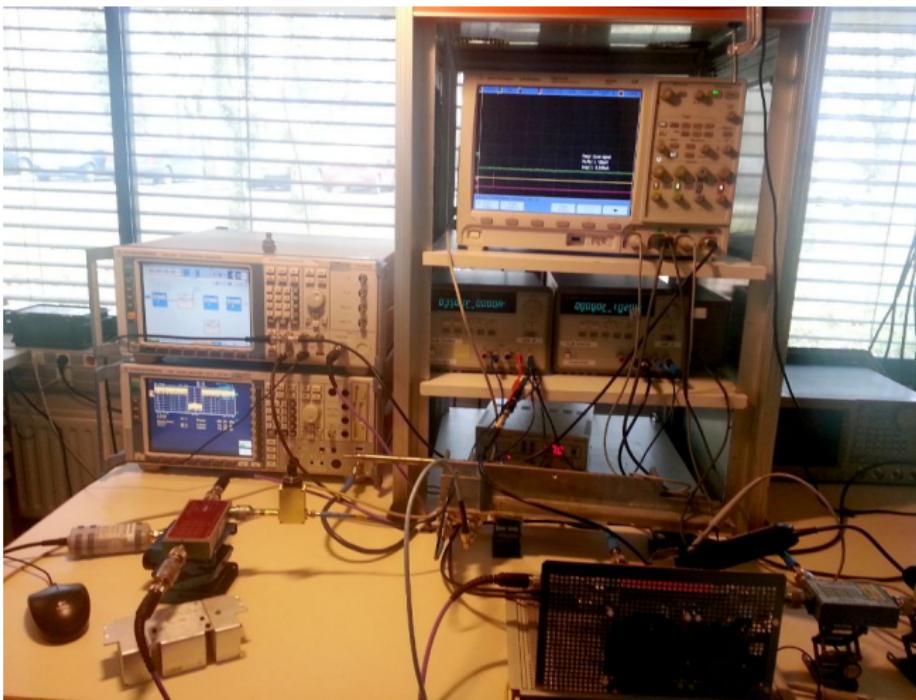
- VSA-based measurement setup
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- Setup for Envelope Tracking
- Calibration
- Time Domain Alignment

# VSA-based measurement setup



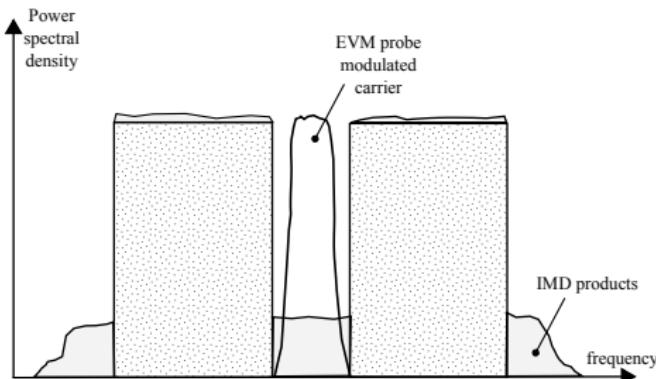
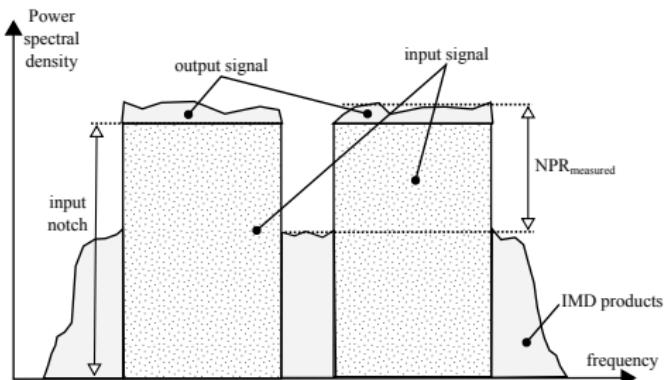
Agilent VSA-based measurement setup [4]  
(photograph courtesy of CU-Boulder)

# VSA-based measurement setup

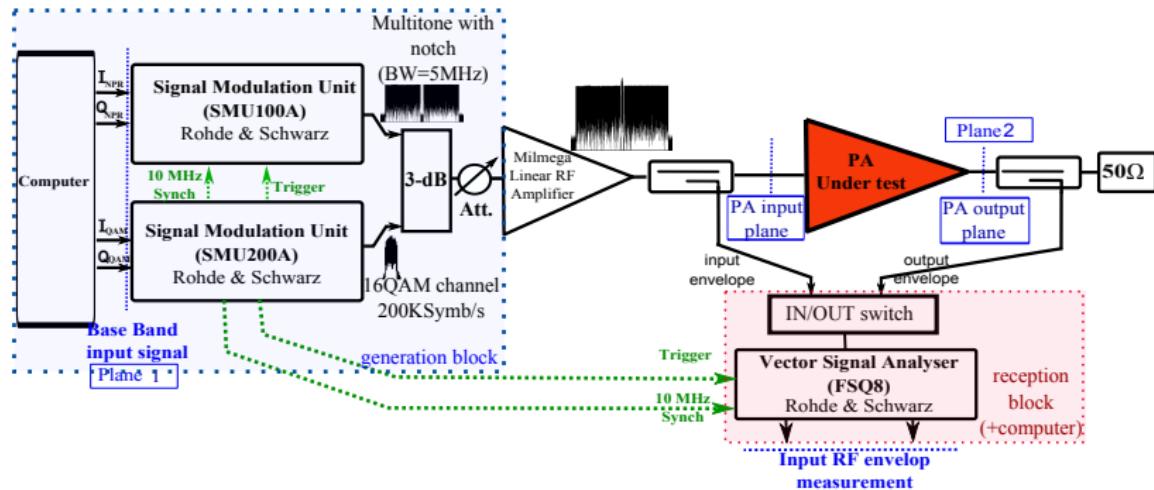


Rohde & Schwarz VSA-based measurement setup [5]  
(XLIM)

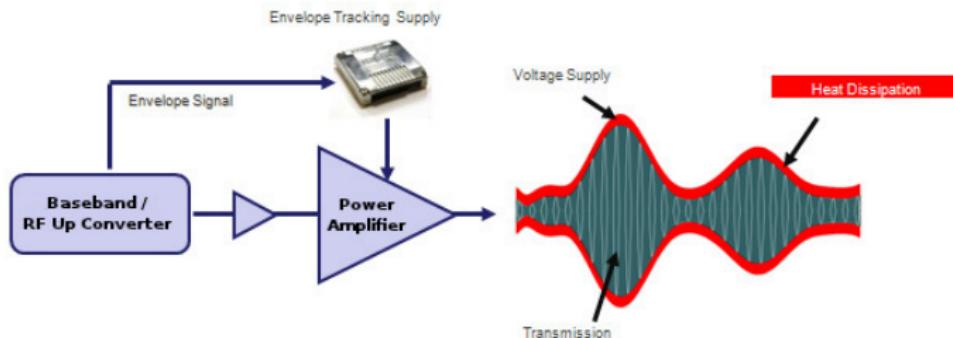
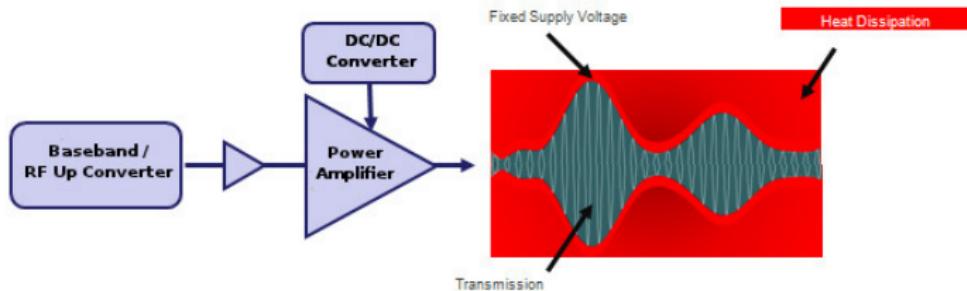
# Measurement setup for NPR : Principle [6]



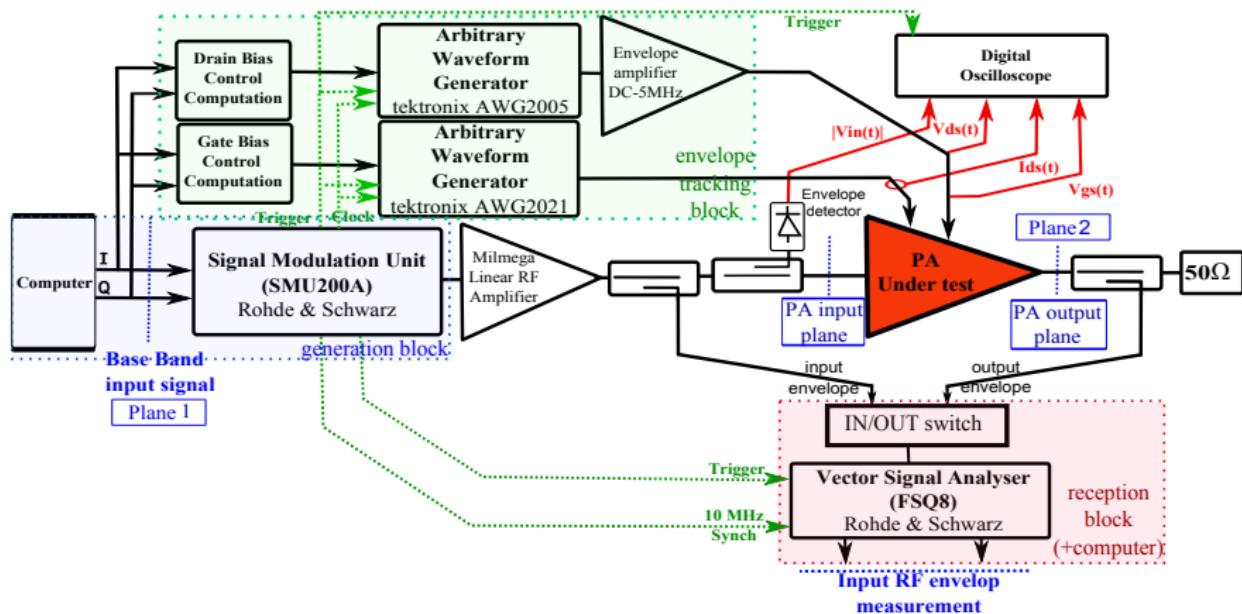
# Measurement setup for NPR : Bench



# Measurement setup for ET : Principle

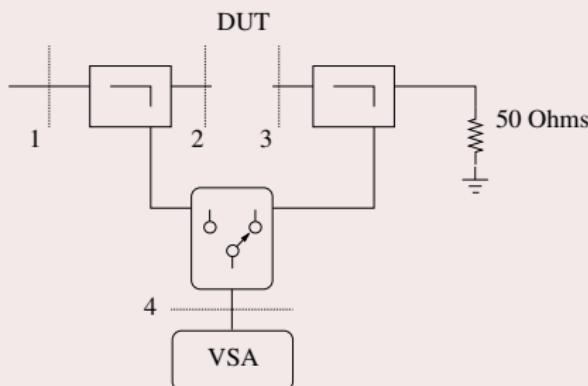


# Measurement setup for ET : Bench



# Calibration : Envelope correction

## RF path



## Input

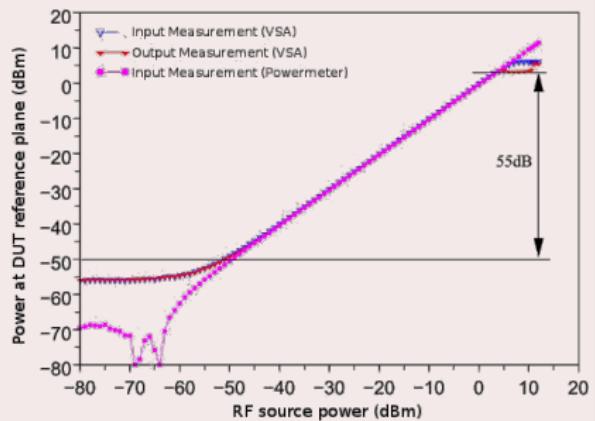
$$\tilde{X}_{DUT}(f) = \frac{S_{21}(f)}{S_{41}(f)} \cdot \tilde{X}_{MEAS}(f)$$

## Output

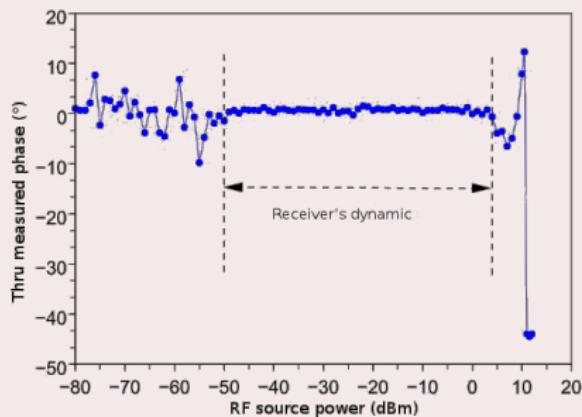
$$\tilde{X}_{DUT}(f) = \frac{1}{S_{43}(f)} \cdot \tilde{X}_{MEAS}(f)$$

# Calibration : Validation

## Power



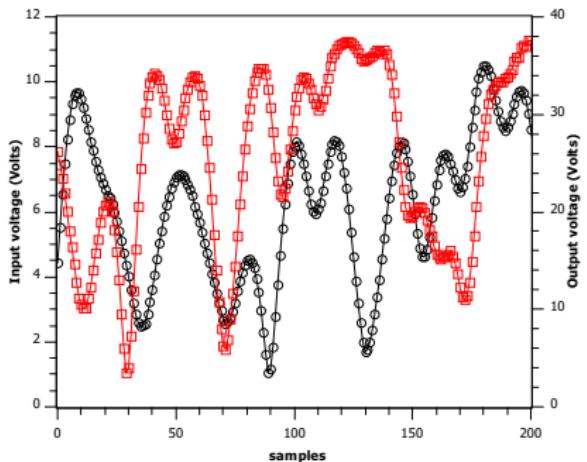
## Phase



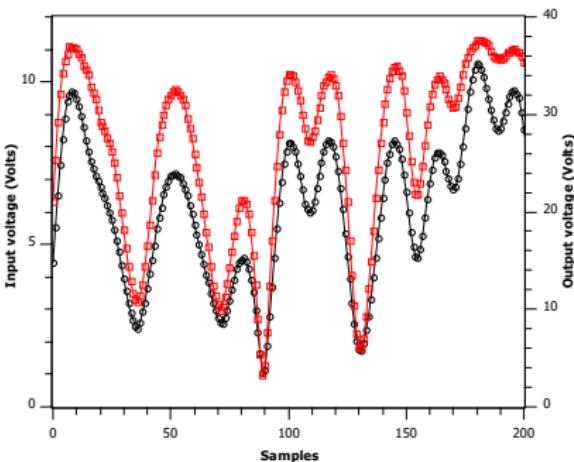
# Time Domain Alignment

- Correcting the envelope delay  $\tau$

without TDA



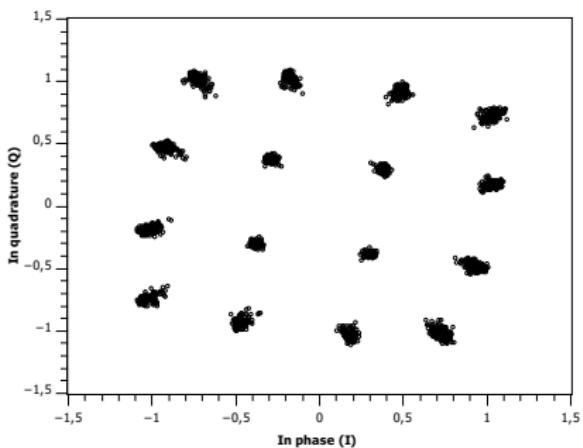
with TDA



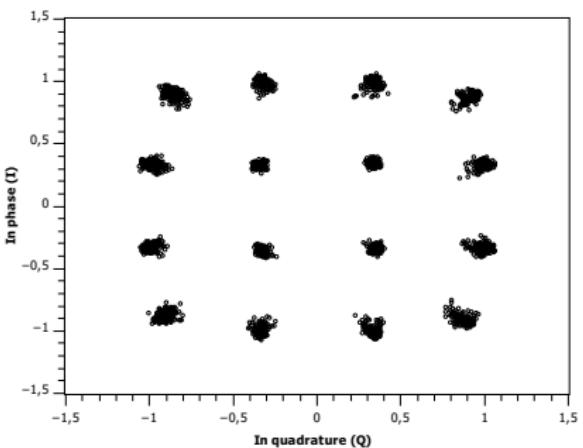
# Time Domain Alignment

- Correcting the local oscillator phase offset  $\phi_0$

without TDA



with TDA

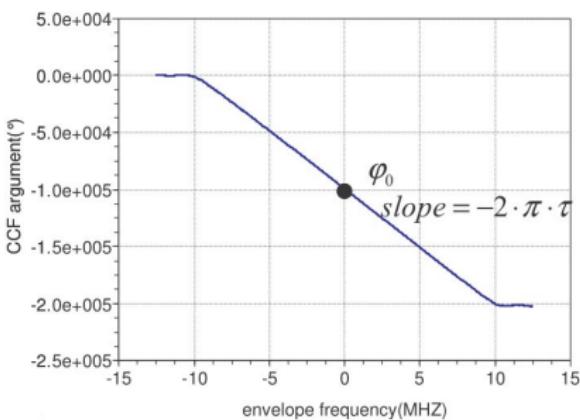


# Time Domain Alignment with crosscorrelation function [7]

$$\tilde{y}(t) = \tilde{x}(t - \tau) \cdot e^{-j \cdot \phi_0}$$

$$FFT\{\Gamma_{\tilde{y}\tilde{x}}(t)\} = \left\| \tilde{X}(f) \right\|^2 \cdot e^{j \cdot (2\pi \cdot f \cdot \tau + \phi_0)}$$

$$Arg\{FFT\{\Gamma_{\tilde{y}\tilde{x}}(t)\}\} = 2\pi \cdot f \cdot \tau + \phi_0$$

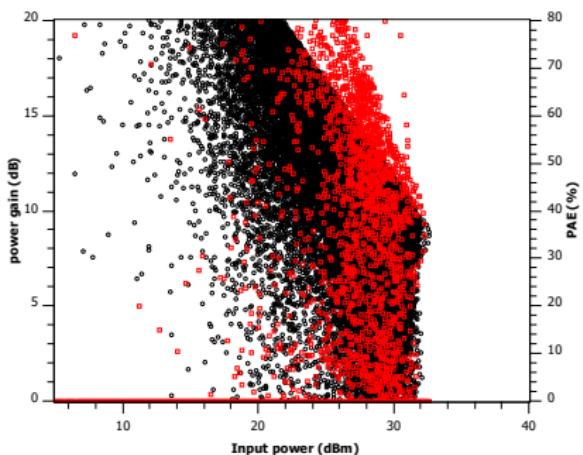


$$\tilde{X}(f) = \tilde{X}_{meas}(f) \cdot e^{j \cdot (2\pi \cdot f \cdot \tau + \phi_0)}$$

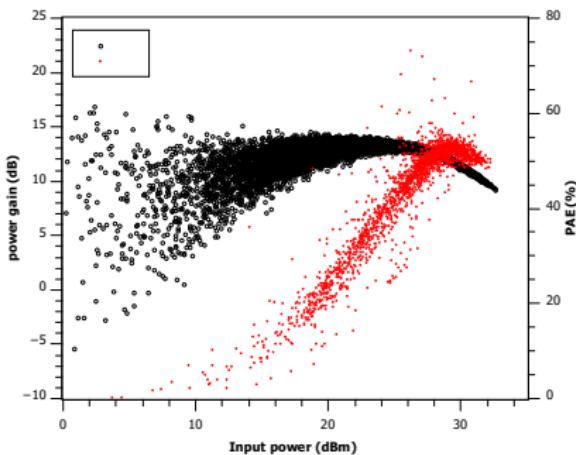
# Time Domain Alignment is necessary

- Examples on instantaneous gain and PAE

without TDA



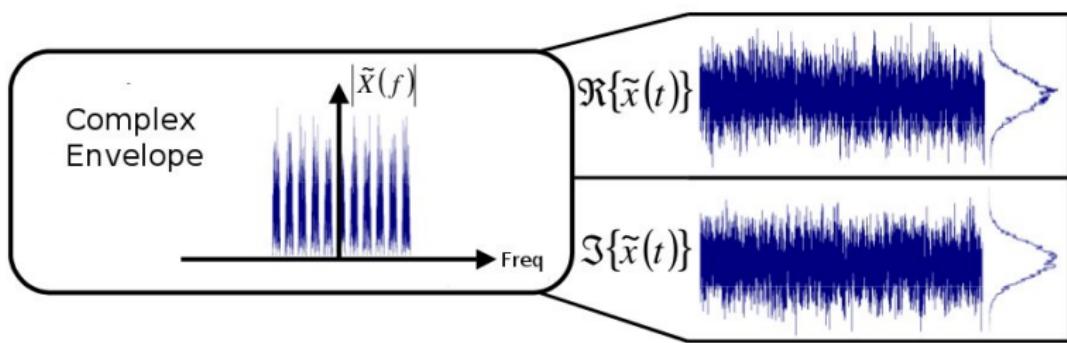
with TDA



# Noise Power Ratio

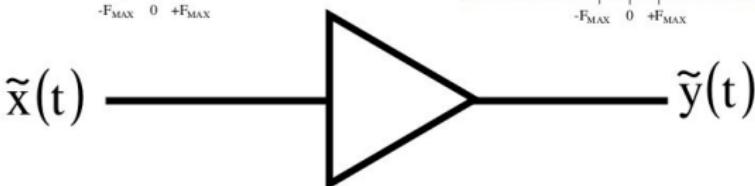
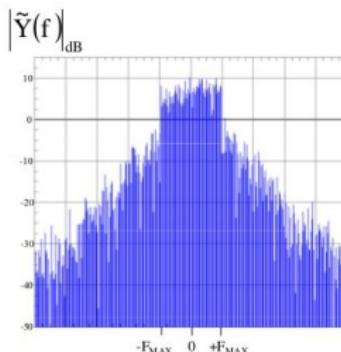
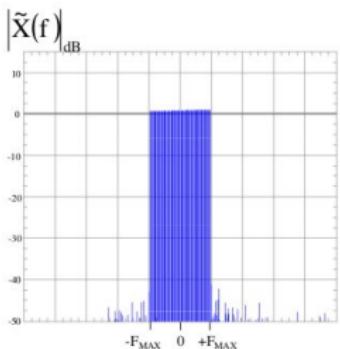
- Notch method
- Equivalent gain method
- EVM method

# Properties of multi-channel signals



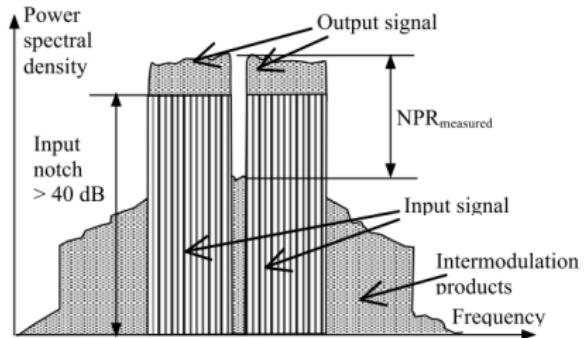
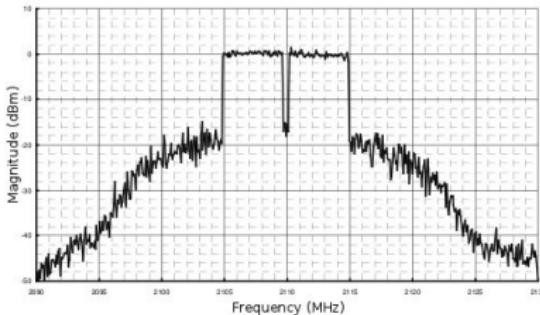
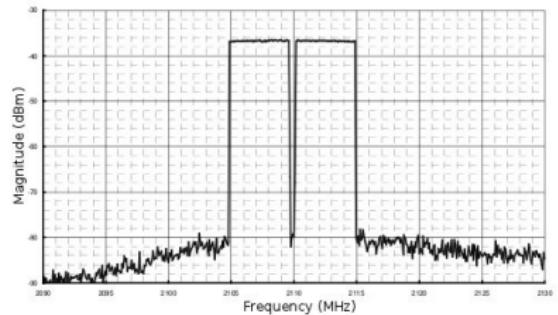
# Response of a power amplifier

One can use a band-limited gaussian noise



How to measure the Signal-to-Noise ratio ?

# The notch method [8]



$$NPR_{measured} = \frac{C+N}{N}$$
$$NPR = \frac{C}{N} = NPR_{measured} - 1$$

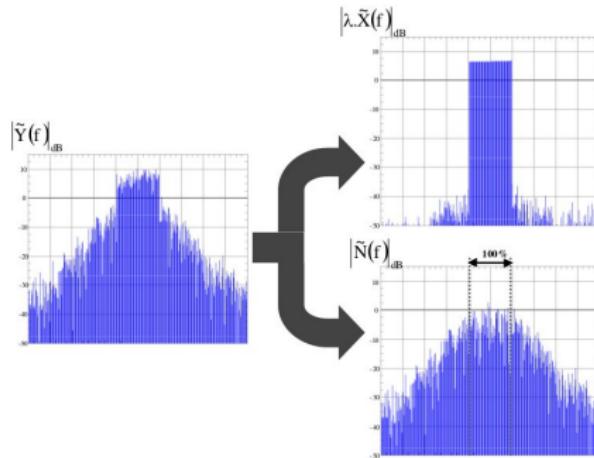
# The equivalent gain method [11]

$$\tilde{y}(t) = f_{NL}(\tilde{x}(t))$$

Bussgang theorem [9] [10]

$\tilde{x}$  is a zero-mean stationary Gaussian random signal

$$\tilde{y}(t) = \lambda \cdot \tilde{x}(t) + \tilde{n}(t)$$



# The equivalent gain method [11]

$$\lambda = \frac{R_{\tilde{x}\tilde{y}}}{R_{\tilde{x}\tilde{x}}} = \frac{E[\tilde{y}(t)\tilde{x}^*(t)]}{E[\tilde{x}(t)\tilde{x}^*(t)]}$$

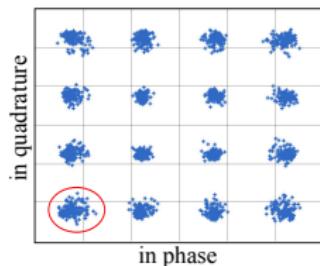
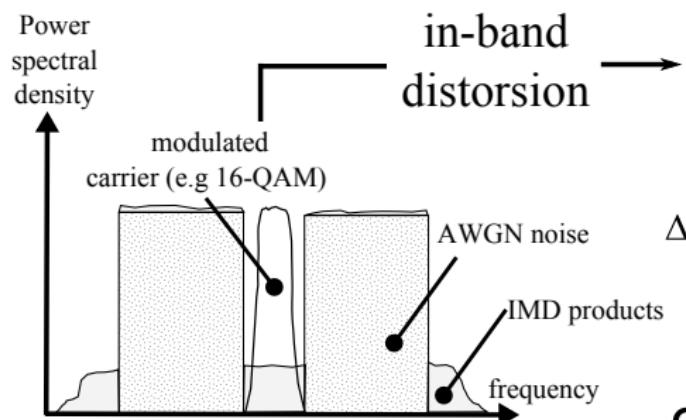
$$NPR = \frac{C}{N} = \frac{E[(\tilde{y}(t) - \tilde{n}(t))(\tilde{y}(t) - \tilde{n}(t))^*]}{E[\tilde{n}(t)\tilde{n}^*(t)]}$$

with

$$\tilde{n}(t) = \tilde{y}(t) - \lambda \cdot \tilde{x}(t)$$

$$NPR|_{dB} = 10 \log_{10} \left( \frac{\sum_{f_i \in \Delta} \|\lambda \cdot X(f_i)\|^2}{\sum_{f_i \in \Delta} \|Y(f_i) - \lambda \cdot X(f_i)\|^2} \right)$$

# The EVM method

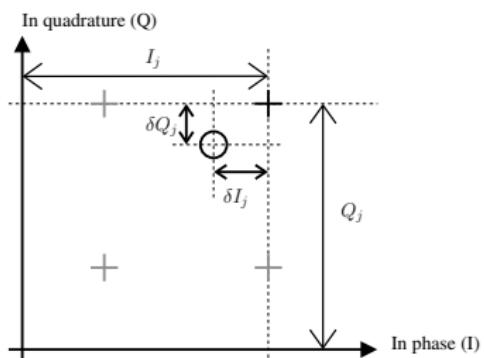


$\Delta_i$  is equal to zero



$\sigma$  is due to the in-band uncorrelated part of IMD (AWGN noise)

# The EVM method

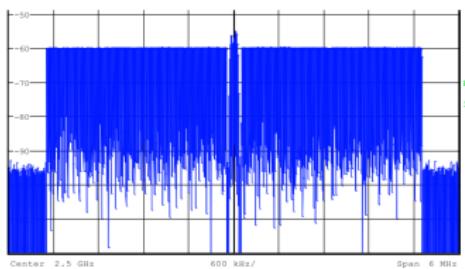


$$MER = \sqrt{\frac{\sum_{j=1}^N (I_j^2 + Q_j^2)}{\sum_{j=1}^N (\delta I_j^2 + \delta Q_j^2)}}$$
$$EVM = \sqrt{\frac{\frac{1}{N} \sum_{j=1}^N (\delta I_j^2 + \delta Q_j^2)}{V_{max}^2}}$$

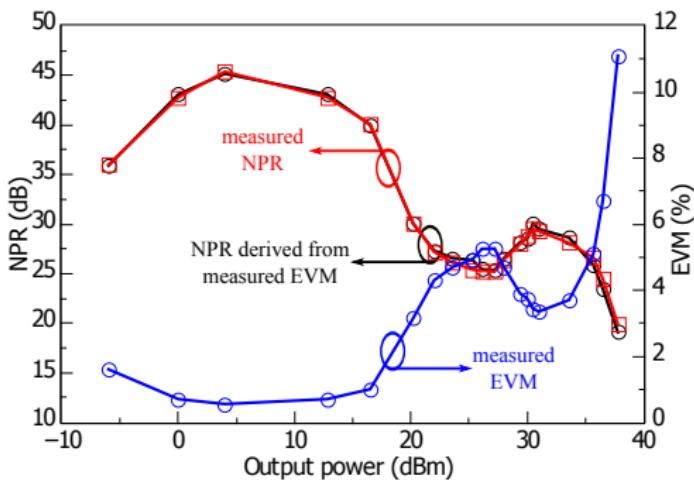
$$\frac{C}{N} = MER^2 = \left( \frac{1}{EVM \times V} \right)^2 \text{ with } V = \frac{V_{max}}{V_{rms}}$$

$$NPR|_{dB} = 20 \log_{10} (EVM \times V) - 10 \log_{10} (R)$$

# The EVM method



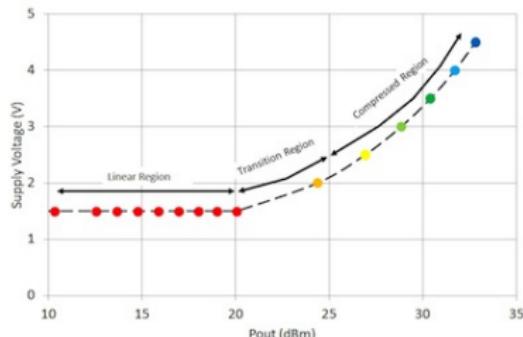
Modulation format	V
BPSK	1
QPSK	1
16-QAM	1.341
32-QAM	1.303
64-QAM	1.527



# Envelope Tracking

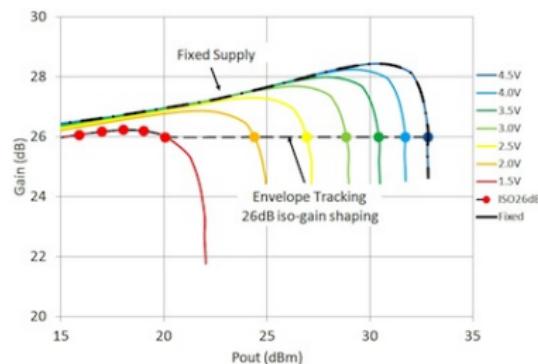
- What is ET ?
- Gate and Drain dynamic law
- Optimization criteria and results

# What is Envelope Tracking?



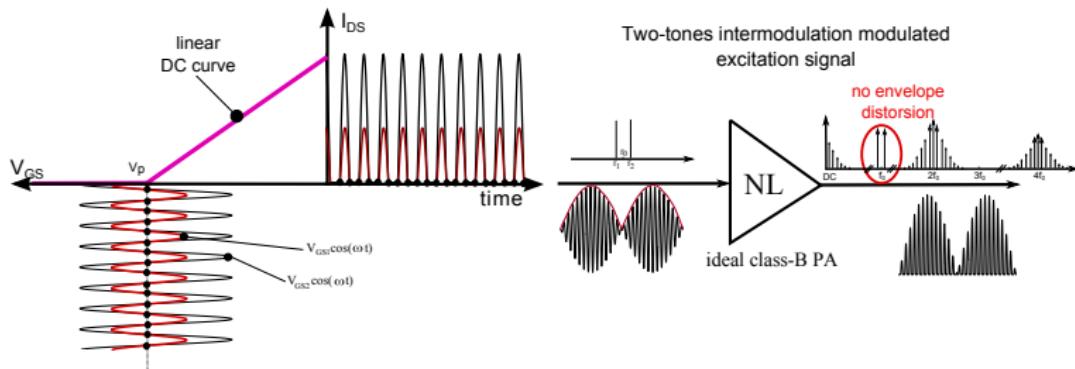
A CW drain bias law is tuned by recording AM-to-AM profiles under different  $VDS_O$  conditions.

The resulting ET PA shows a constant envelope power gain while ensuring high efficiency due to the compression operation.



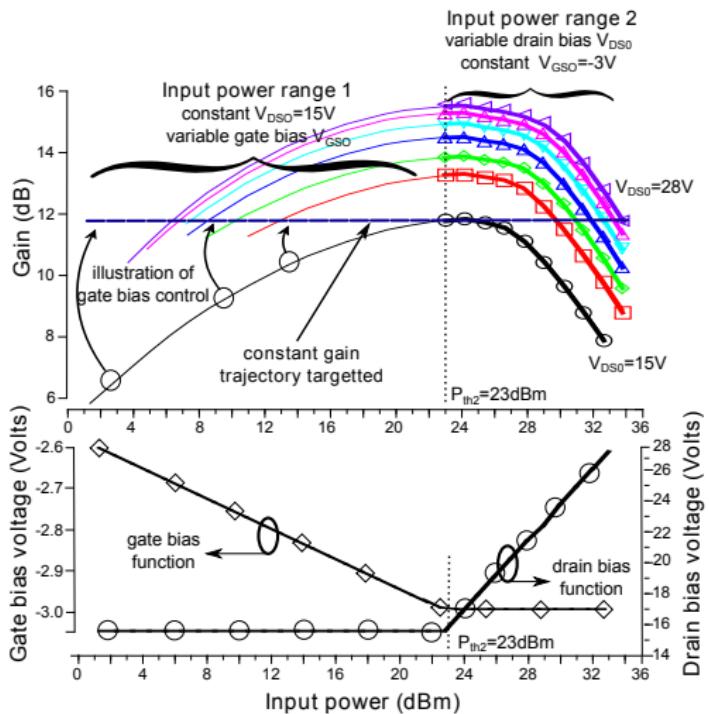
<http://www.nujira.com/>

# Proposed combined gate and drain ET on Class-B PA



GaN  $I_{DS}$  ( $V_{GS}$ ) profile tends to be linear above the pinch-off point class B theoretically offers good in-band linearity since there is no conduction angle modulation depending on input signal amplitude.

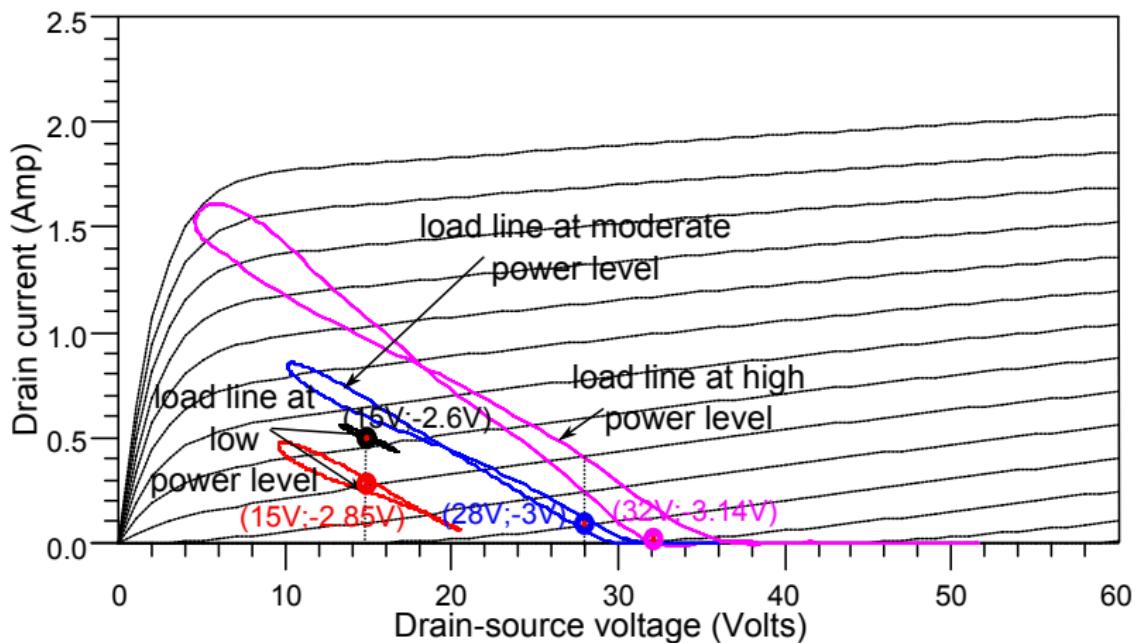
# Principle to target a constant gain for a class-B PA



Both  $V_{DSO}$  and  $V_{GSO}$  are varied to ensure constant gain. Input power range 1 corresponds to a Gate-ET PA biased under  $VDD=15V$ . The range 2 leads to have a class-B drain-ET PA.

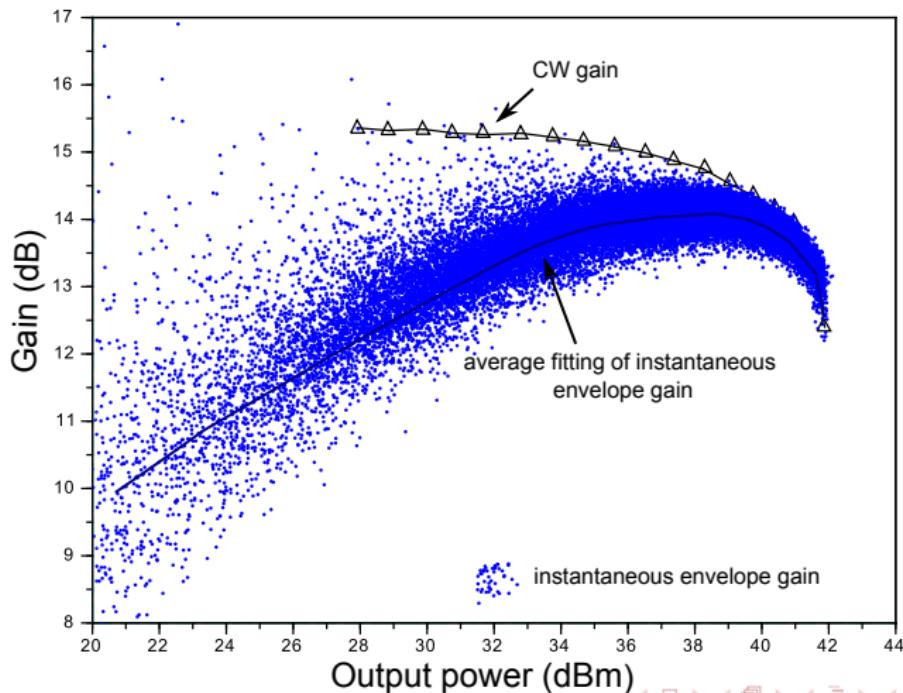
The corresponding biases functions are clearly separated which leads to have a more simple approach.

# Dynamic load-lines with gate and drain ET



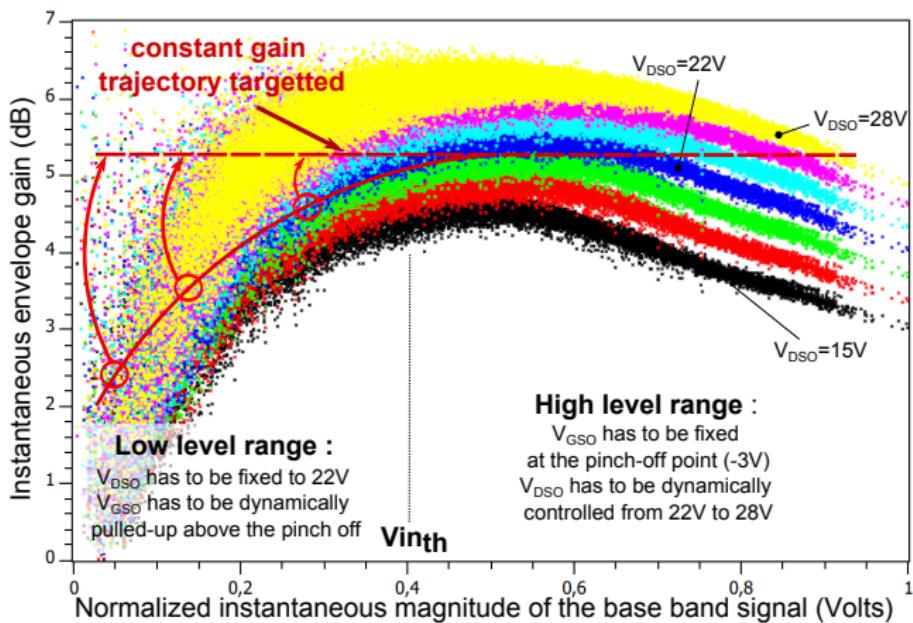
# Gate and drain bias trajectories extraction

AM-AM measurements of a CREE CGH27015-TB for a CW and a 16QAM (1 MSymb) at 2.5 GHz.

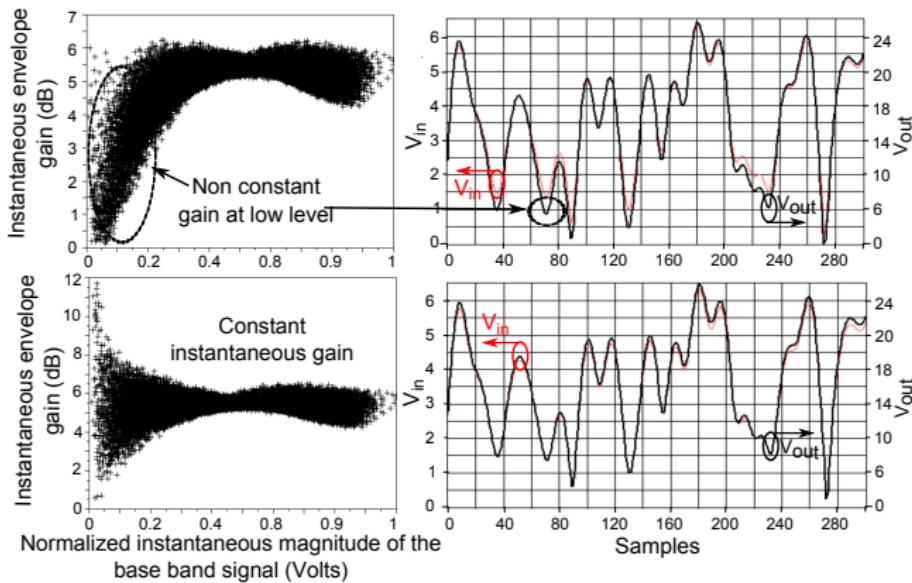


# Multi-bias dynamic AM-AM measurements

Measured AM-to-AM profiles with the useful digital modulated signal (16-QAM signal) under the 15V-28V  $V_{DS0}$  range and for a class-B operating point.

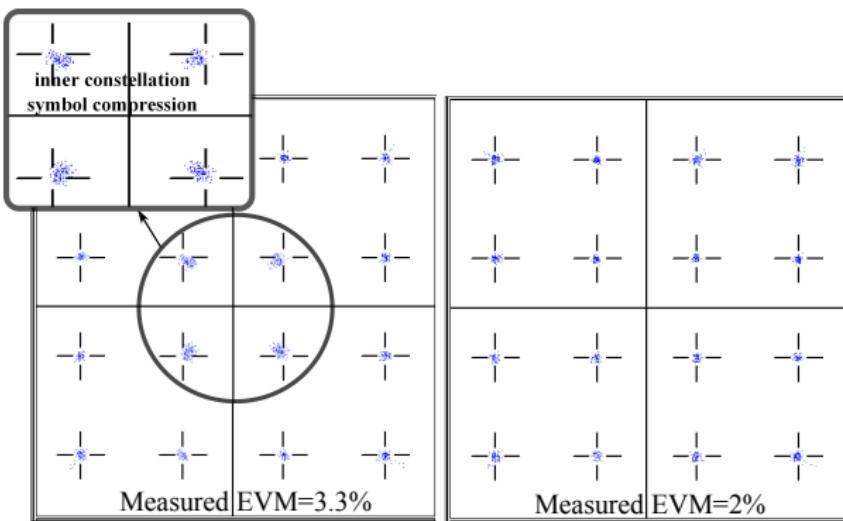


# Experimental optimization on the output voltage envelope



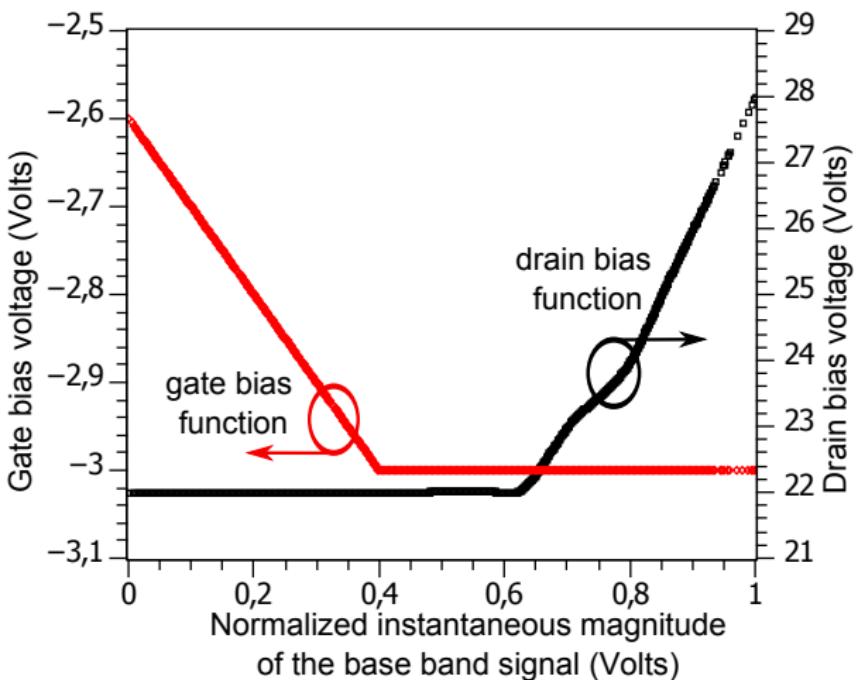
Visual criteria : dynamic AM-to-AM profile along with input/output envelopes. At the PA planes, maximally flatness profile is reached.

# Experimental optimization on EVM

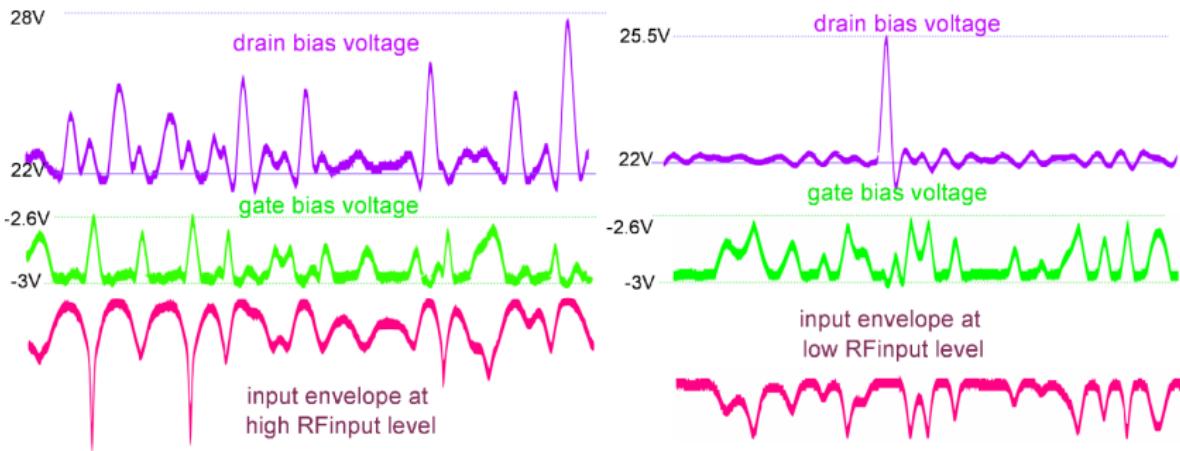


Second visual criteria : EVM measurement performed on the demodulated signal at the PA output plane.

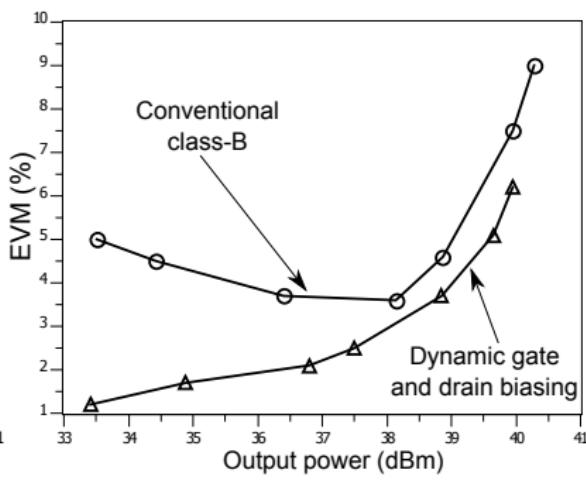
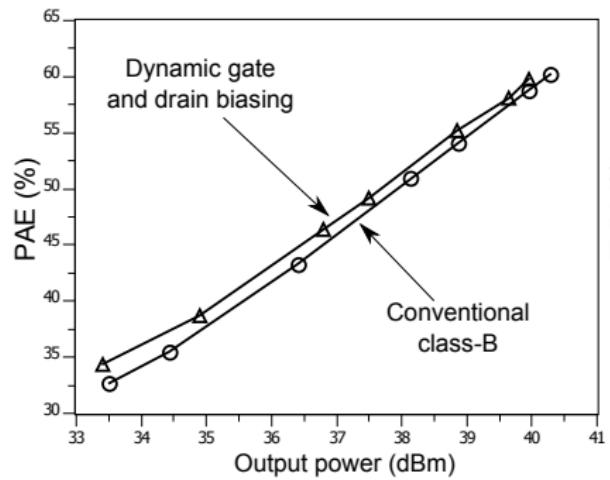
# Extracted gate and drain biases functions



# Scope captures of the biasing temporal waveforms



# Comparison between conventional class-B and our dynamic gate and drain biased PA



# Conclusion

- Why modulated signals bench are so important ?
- Application on NPR
- Application on ET

# References |

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- [2] G. Koutias and P. Demestichas. A review of energy efficiency in telecommunication networks. *Journal TELFOR*, November 2010.
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- [4] H. Jang, A. Zai, T. Reveyrand, P. Roblin, Z. Popović, and D.E. Root. Simulation and measurement-based x-parameter models for power amplifiers with envelope tracking. In *IEEE MTT-S Digest, IMS 2013, TU3F-1, Seattle, WA, June 2013.*, pages 1–4.
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- [6] J. Sombrin. On the formal identity of EVM and NPR measurement methods : Conditions for identity of error vector magnitude and noise power ratio. In *European Microwave Conference (EuMC)*, pages 337–340, Manchester, UK, 2011.
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## References II

- [9] Julian J. Bussgang. Crosscorrelation functions of amplitude-distorted gaussian signals. Technical report, Massachusetts Institute of Technology, 1952.
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- [11] S.-W. Chen, W. Panton, and R. Gilmore. Effects of nonlinear distortion on CDMA communication systems. *IEEE Transactions on Microwave Theory and Techniques*, 44(12) :2743–2750, 1996.