



Digital Pre-distortion Measurement for HF High Power Amplifier



Presented by: Jinbiao Xu
Agilent Technologies, Inc.

Anticipate — Accelerate — Achieve

Agenda

1. Power Amplifier Fundamentals

2. Digital Pre-Distortion (DPD) Concepts

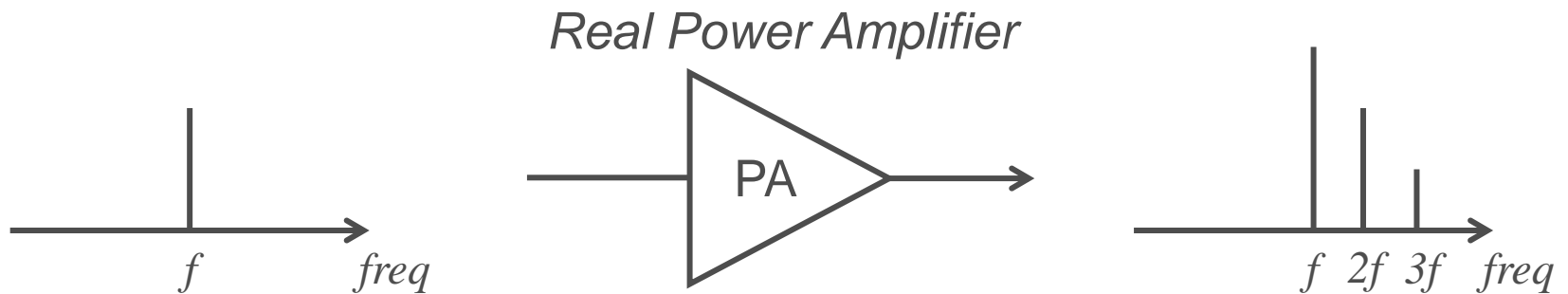
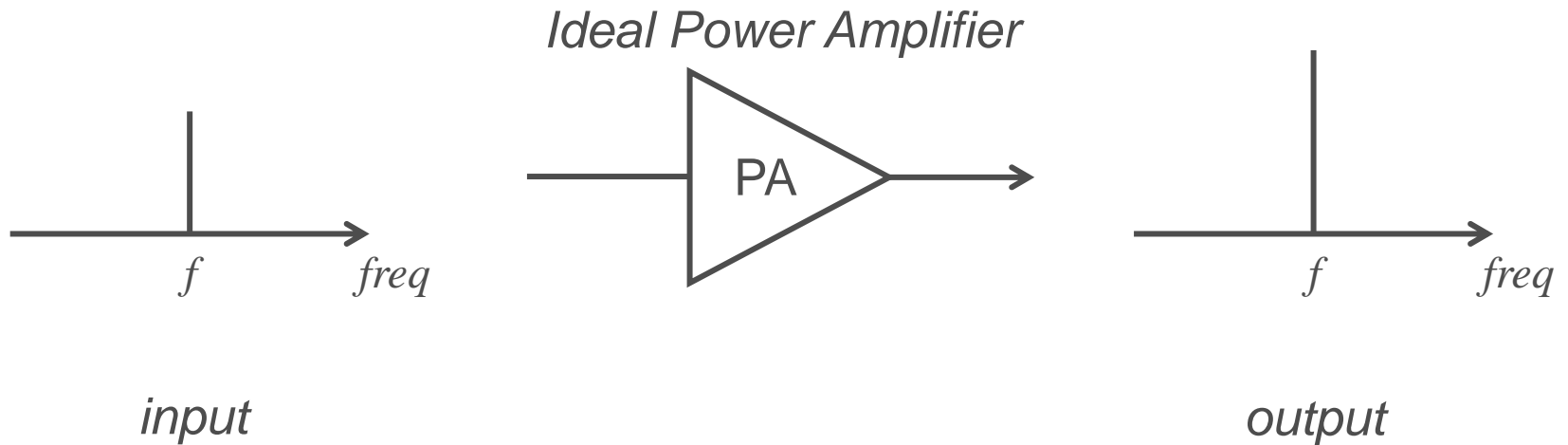
3. Digital Pre-Distortion Algorithm

4. DPD verification with Agilent Hardware

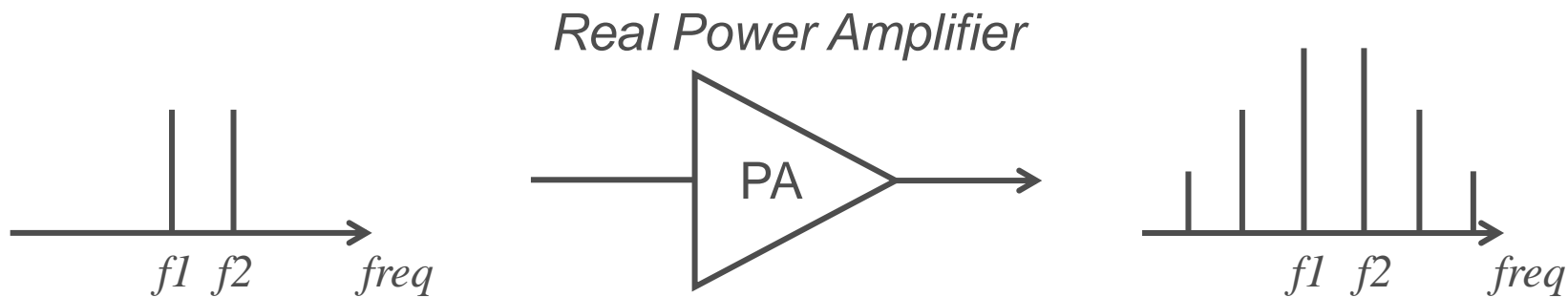
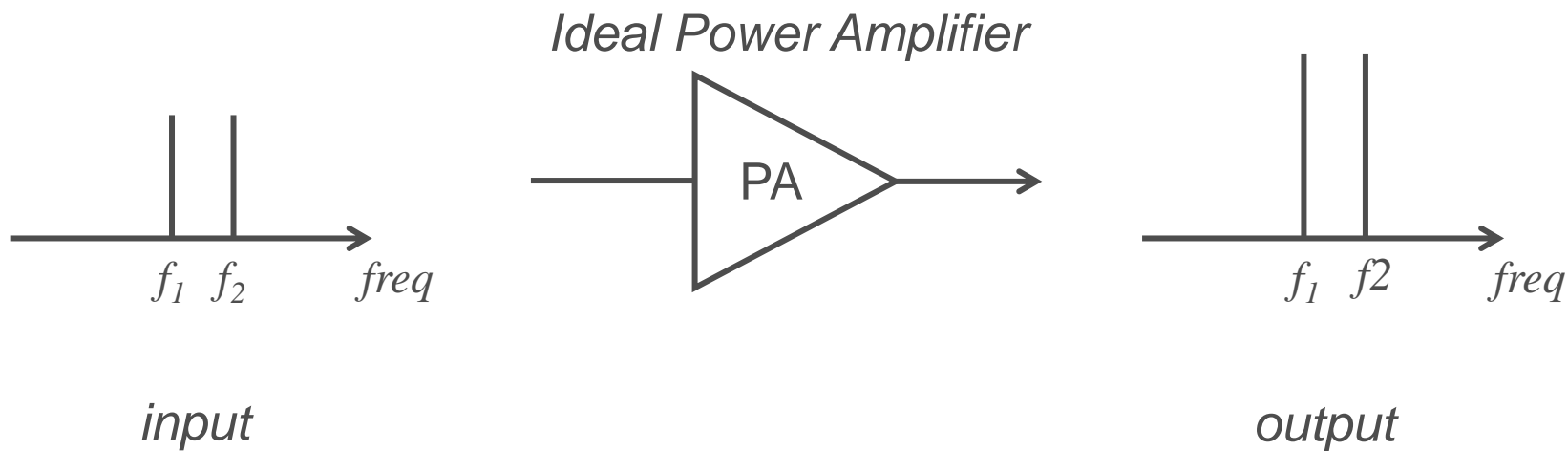
5. Summary



The Single Tone scenario



The Two-Tones scenario



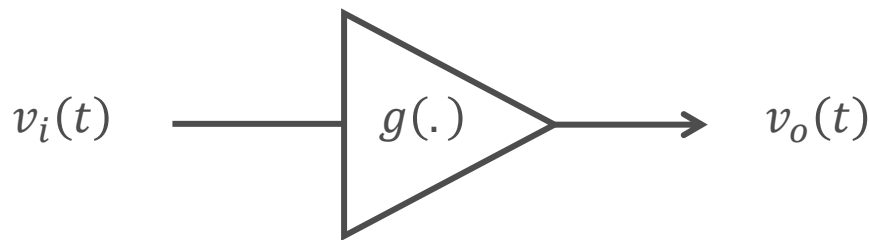
Polynomial Expression of a PA Model

To accurately represent the nonlinearity of a Power Amplifier, we can use a polynomial expression. As an example, to describe a 3rd order system the output can be expressed with the following equation:

$$y = a_1x + a_2x^2 + a_3x^3$$

Where a_1 is the linear, small signal gain, a_2 and a_3 are the gain constants for the quadratic and cubic nonlinearities, respectively.

If we assume our Power Amplifier has gain g , we can consider a relationship between the input signal $v_i(t)$ and output signal $v_o(t)$



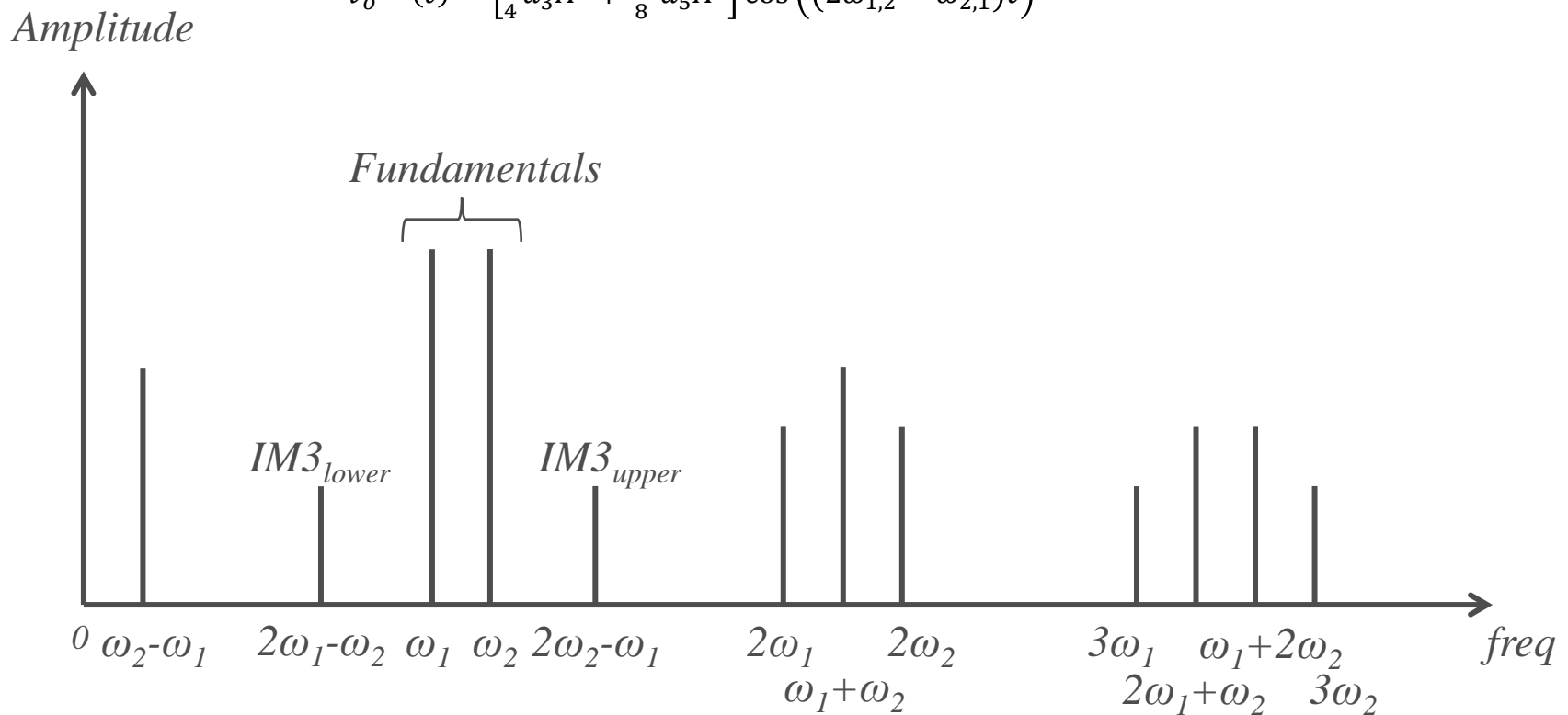
$$v_o(t) = g \cdot v_i(t)$$

Intermodulation in a Nonlinear Power Amplifier *

Let us now consider a two tone input to our PA system:

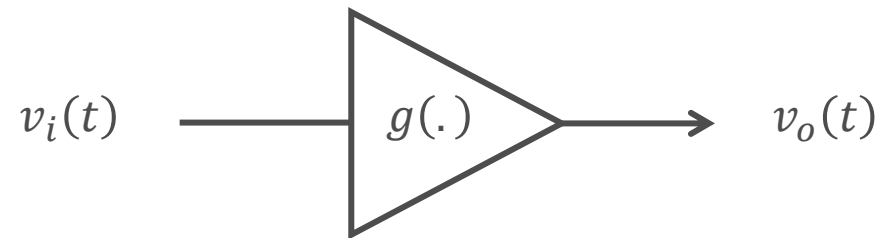
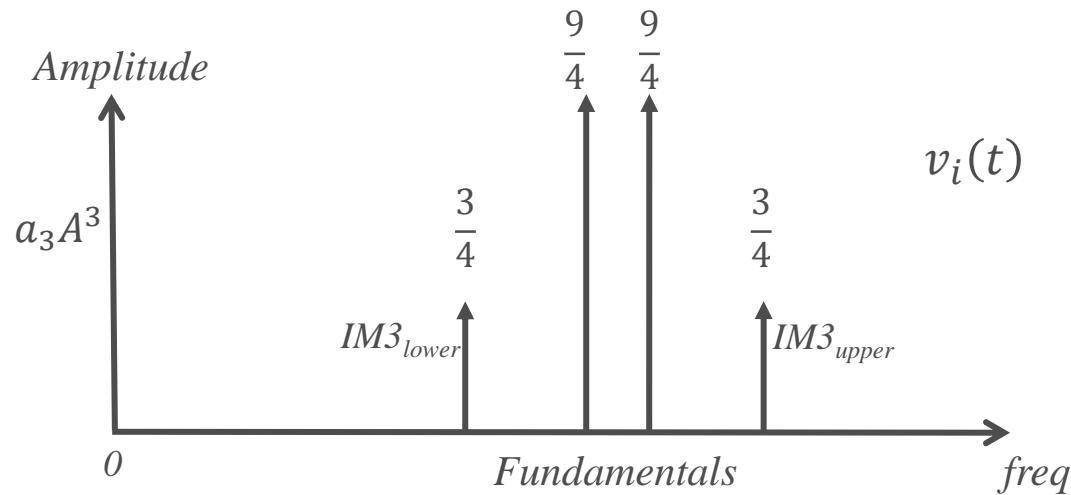
$$v_o^{IM1}(t) = \left[a_1 A + \frac{9}{4} a_3 A^3 + \frac{25}{4} a_5 A^5 \right] \cos(\omega_{1,2} t)$$

$$v_o^{IM3}(t) = \left[\frac{3}{4} a_3 A^3 + \frac{25}{8} a_5 A^5 \right] \cos((2\omega_{1,2} - \omega_{2,1})t)$$

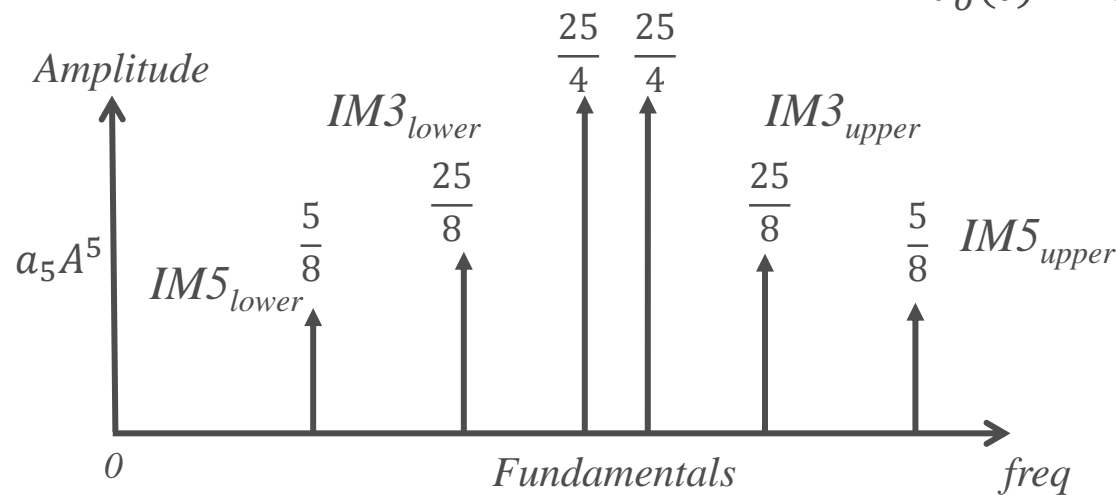


*** this is a memoryless system**

Intermodulation in a Nonlinear, Memoryless PA



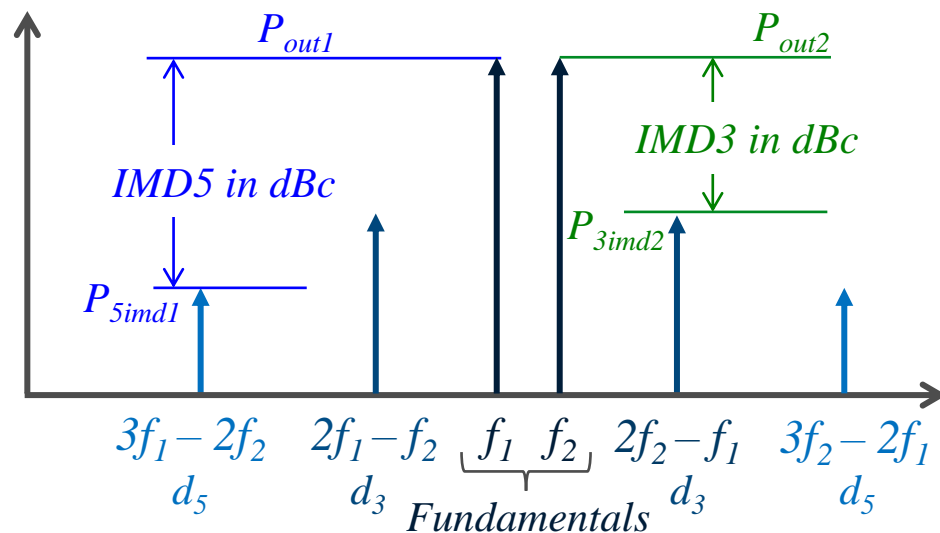
$$v_o(t) = a_1 v_i(t) + a_3 v_i^3(t) + a_5 v_i^5(t)$$



As only odd-order nonlinearities will generate in-band distortion products, we can eliminate the quadratic non-linearity from the polynomial representation of the PA.

Intermodulation Distortion (IMD) Products

Now we will take a closer look at the unwanted intermodulation products from our two tone example:



$f_{1,2}$ = fundamental
 $2f_{1,2}$ = second harmonic (square law)
 $3f_{1,2}$ = third harmonic (third order)

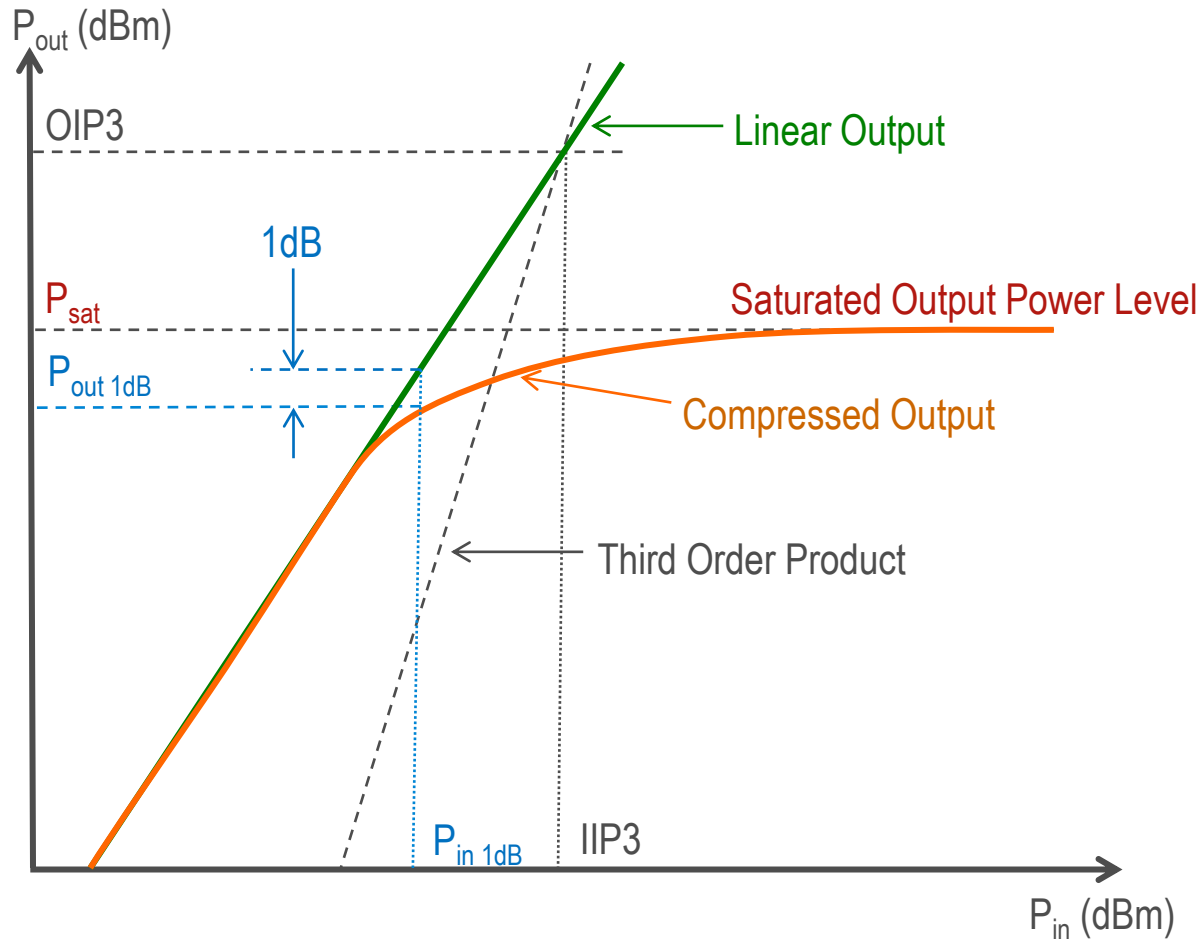
d_3 = third order IMD product
 d_5 = fifth order IMD product

IMD is usually expressed in “dBc”, dB relative to carriers, in this case $f_{1,2}$ or $f_{1,2}$

$$IMD3 = P_{3imd} - P_{out}$$

$$IMD5 = P_{5imd} - P_{out}$$

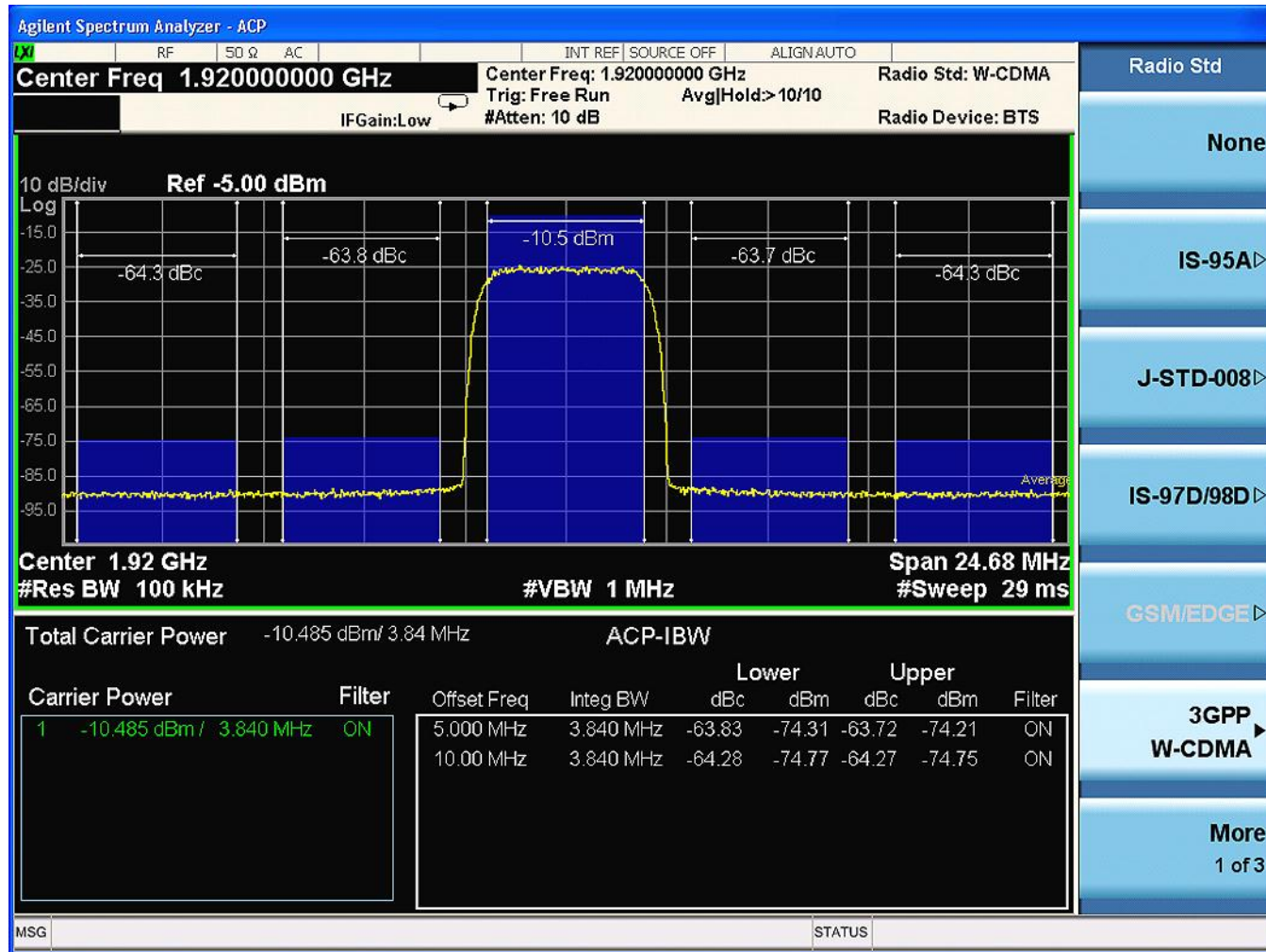
The Third Order Intercept Point (IP3/TOI)



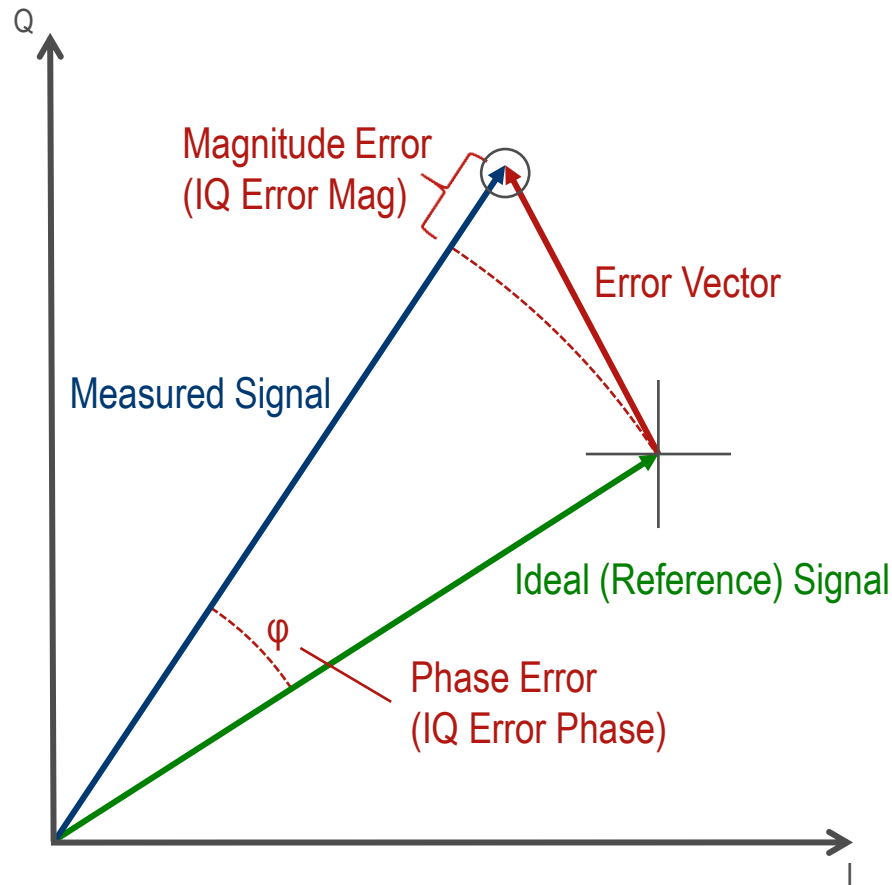
$$IIP3\ (dBm) = P_{in}\ (dBm) + 0.5 \cdot IMD3\ (dBc)$$

$$OIP3\ (dBm) = P_{out}\ (dBm) + 0.5 \cdot IMD3\ (dBc) = IIP3 + G$$

Adjacent Channel Leakage Ratio (ACLR)



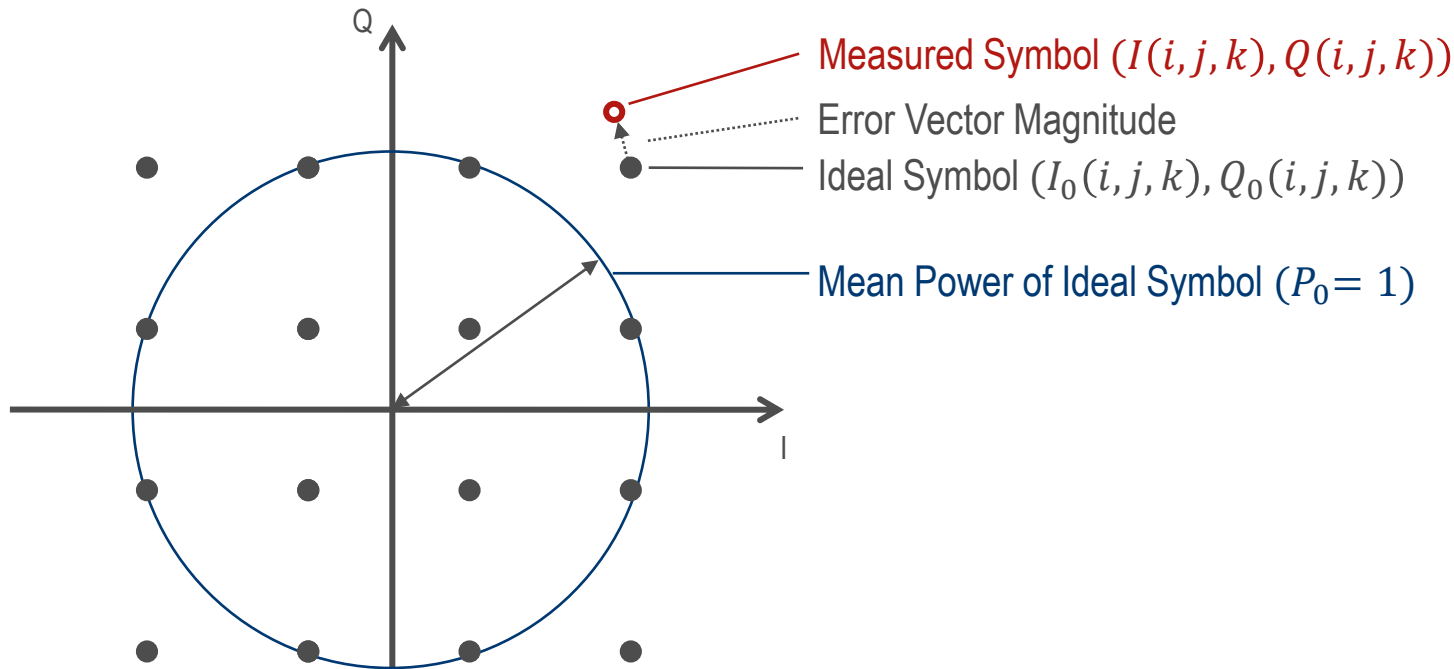
Error Vector Magnitude (EVM)



The EVM measurement provides us with great insight into the performance of digitally modulated signals. With proper use, these measurements can help pinpoint what degradation is present in a signal, and furthermore, help identifying their sources.

The EVM Measurement

EVM is a measurement of Transmitted Modulation Accuracy. It yields the vector difference between the ideal and actual measured test vector.



$$Error_{RMS} = \frac{\sum_{i=1}^{N_f} \frac{\sum_{j=1}^{L_P} \left[\sum_{k=1}^{N_{FFT}} \left\{ (I(i, j, k) - I_0(i, j, k))^2 + (Q(i, j, k) - Q_0(i, j, k))^2 \right\} \right]}{P_0 \cdot L_P \cdot N_{FFT}}}{N_f}$$

Power Amplifier Measurement Metrics

CW (Two-Tones)

- Output power
- Gain compression curve
- **IMD3/IMD5**
- IP3/TO1

This paper is for Two-Tones DPD measurement.
The objective is to decrease IMD3/IMD5 distortion and allow PA passes through measurement.

Modulation Waveform

- ACPR
- EVM

Some specifications defines Power Amplifier measurement metrics such as IMD3/IMD5 for CW as well as ACPR and EVM for modulated signal.

Only all these measurement metrics, the PA can meet specification and deliver to marketing.

Digital Pre-distortion techniques can help to pass above PA measurement metrics.



Agenda

1. Power Amplifier Fundamentals

2. Digital Pre-Distortion (DPD) Concepts

3. Digital Pre-Distortion Algorithm

4. DPD verification with Agilent Hardware

5. Summary



Digital Predistortion (DPD) Principles

The need for Power Amplifier linearization and efficiency is very important for today's designers.

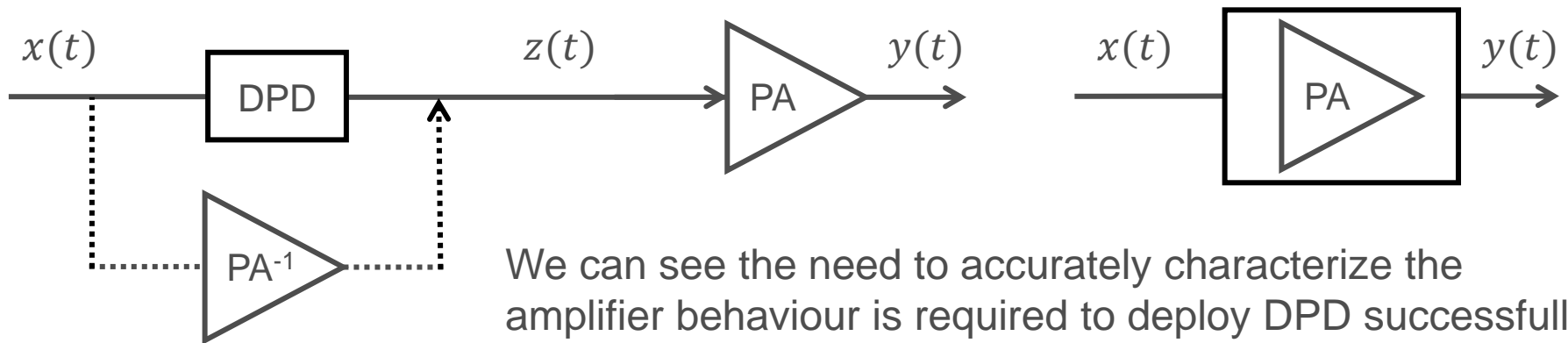
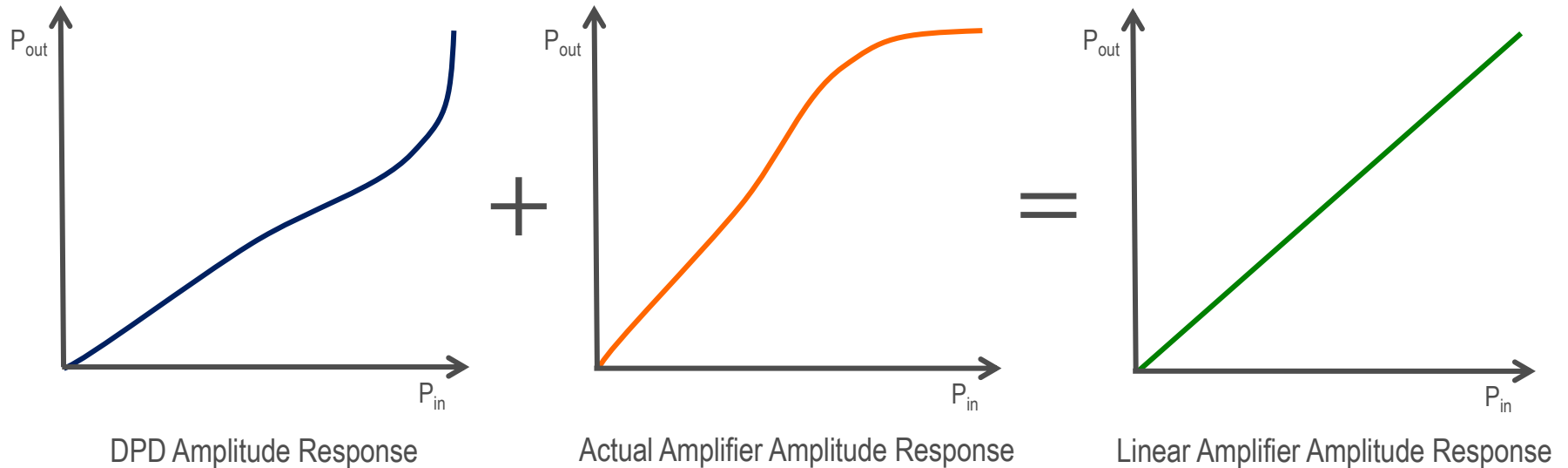
Digital Pre-Distortion has become a critical component of the design process to satisfy this need, as this technique preconditions the signal before the PA to compensate for its non-linear transfer characteristics.

By enabling it to operate in its high power-added efficiency (PAE) region near saturation, it produces a more linear, higher output power radio, without significant signal distortion.

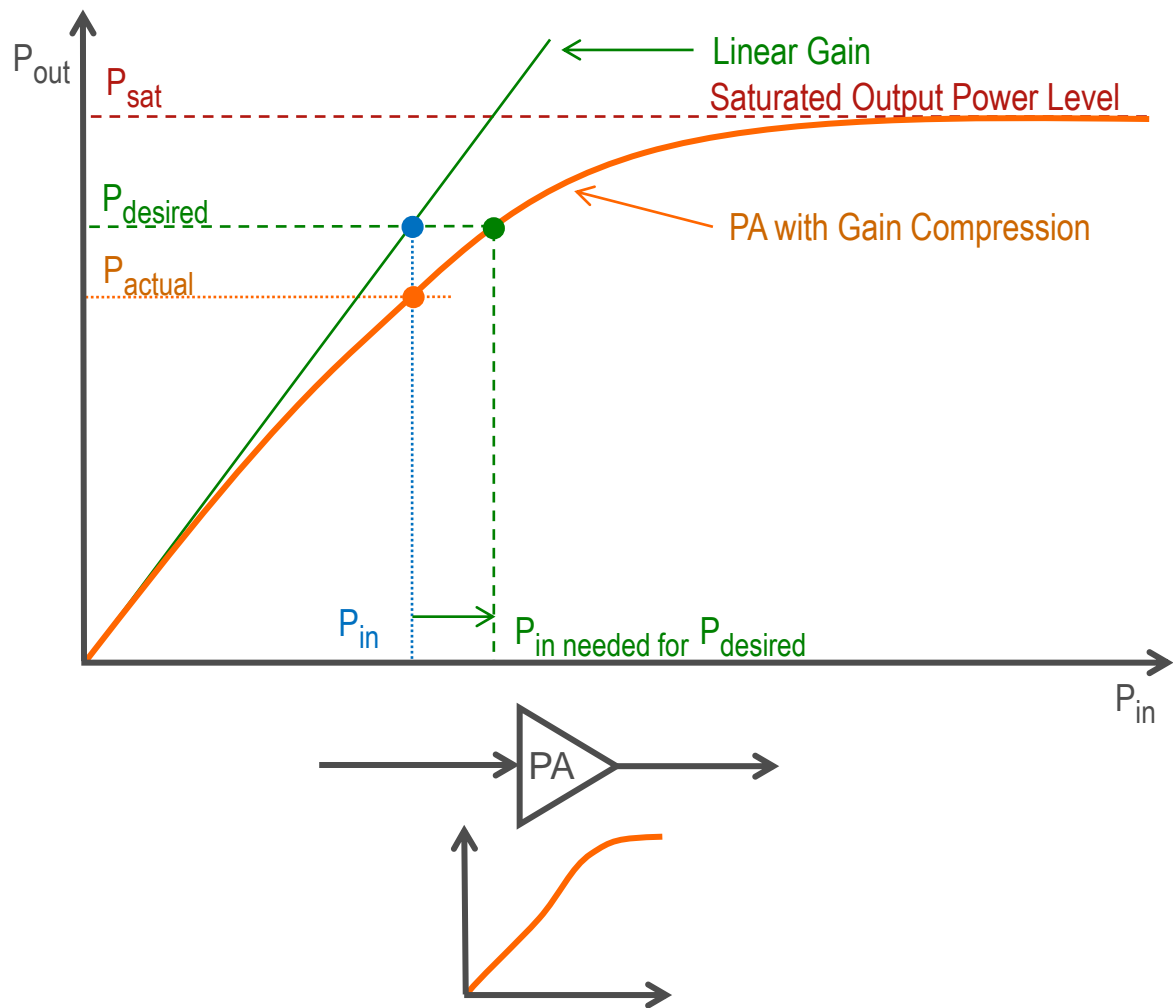


Digital Predistortion Principles

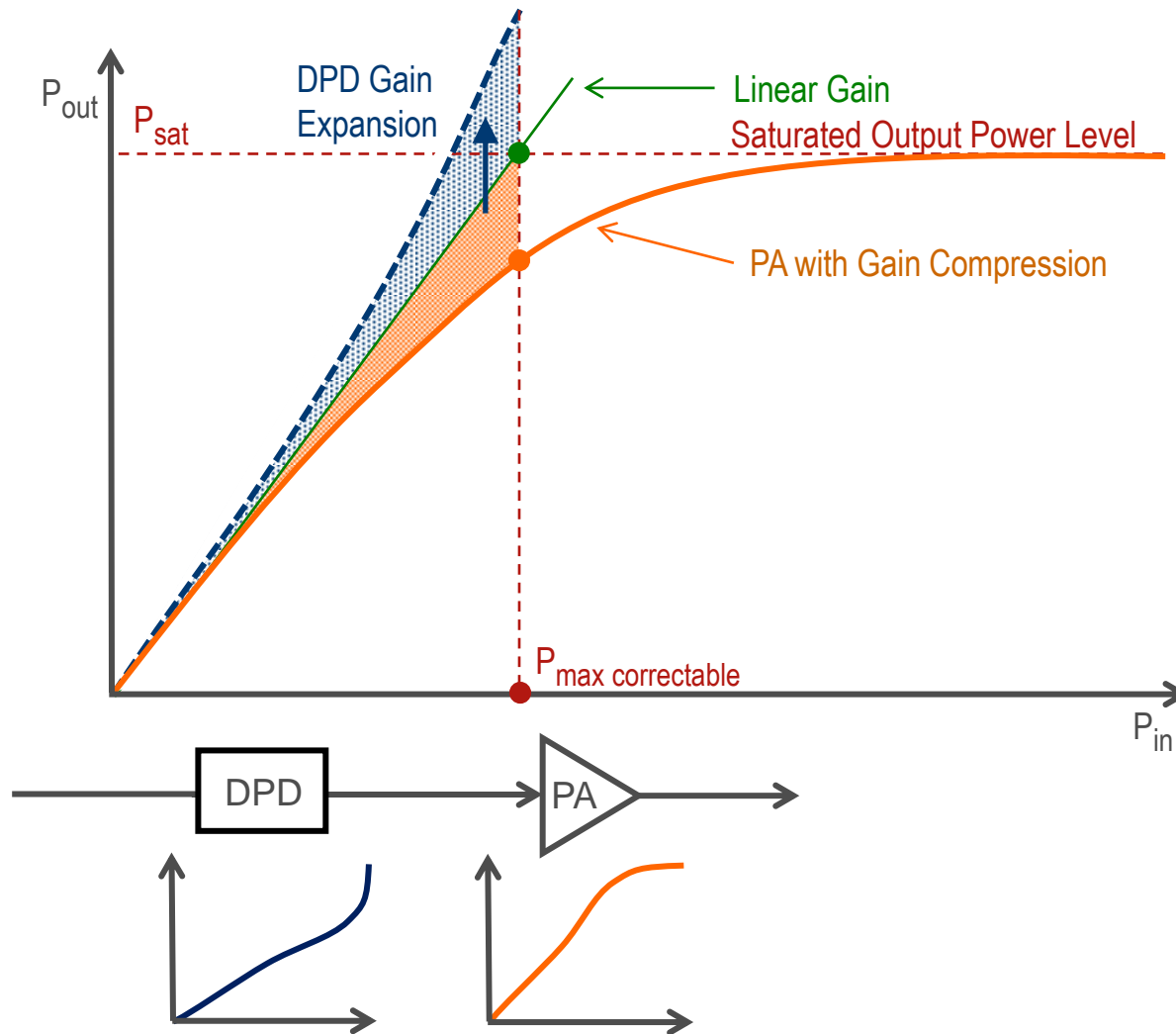
So, how do we correct the amplifier's nonlinearity?



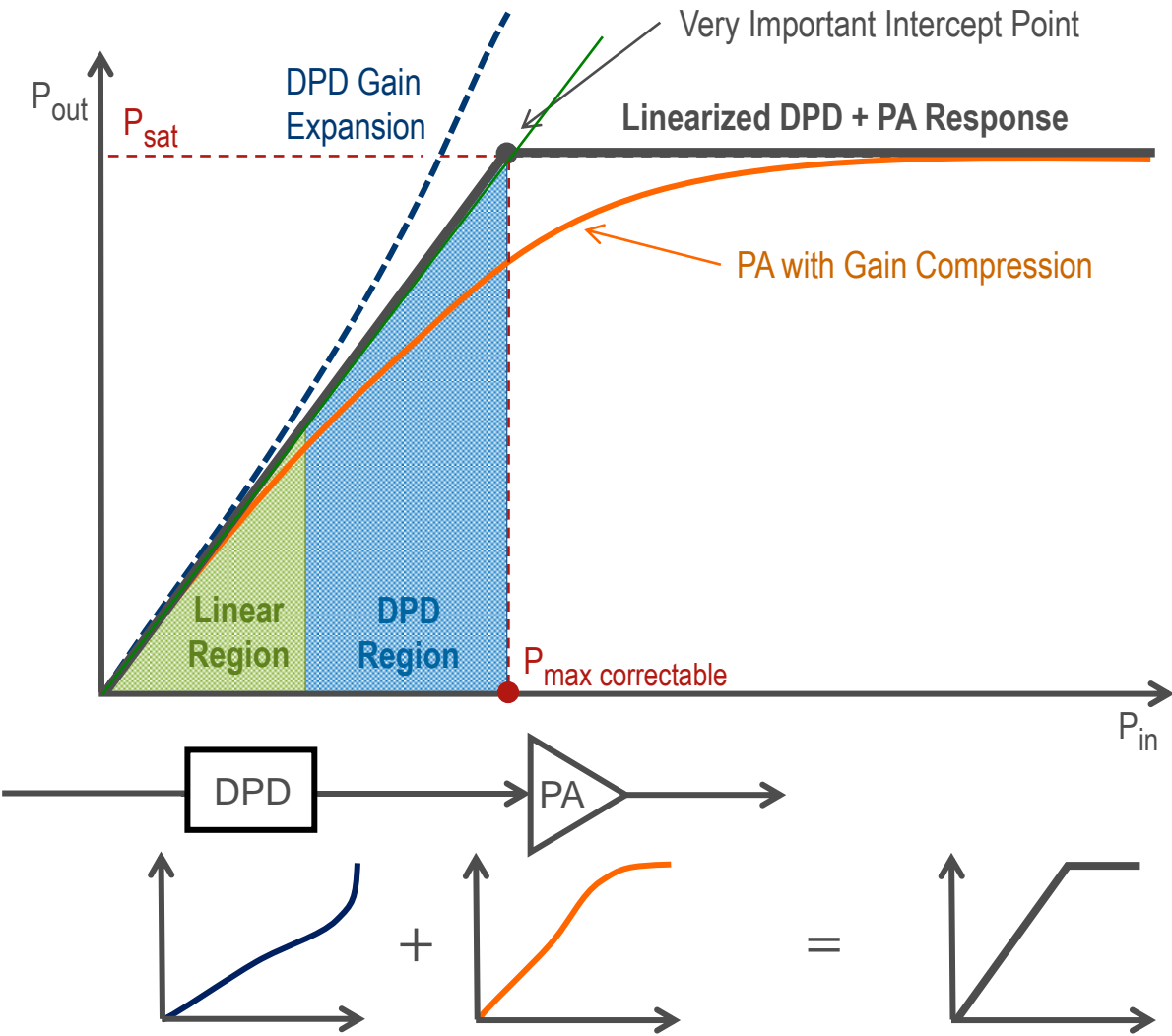
DPD Principles: The Compressing PA



DPD Principles: Pre-Expansion

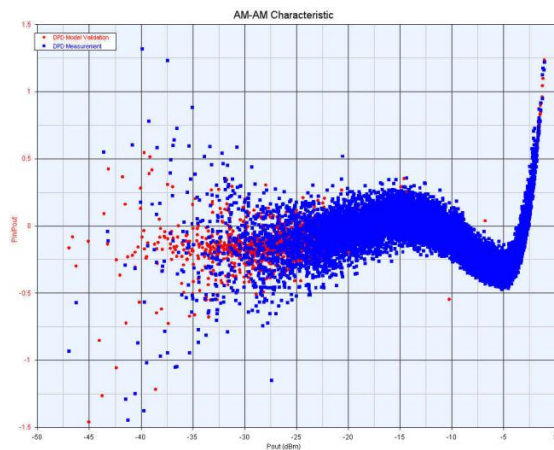


DPD Principles: Linearized Results

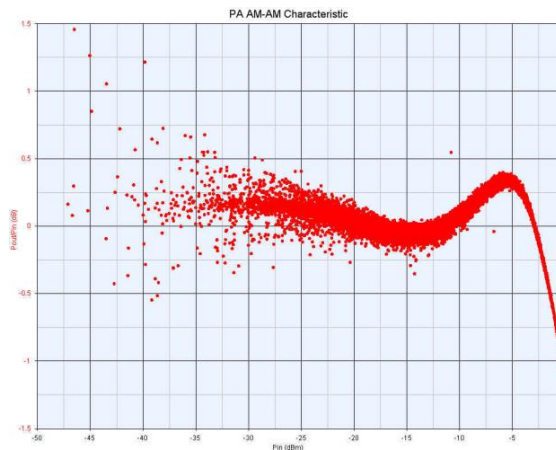


AM-AM Effects: Change in Gain vs Power Levels

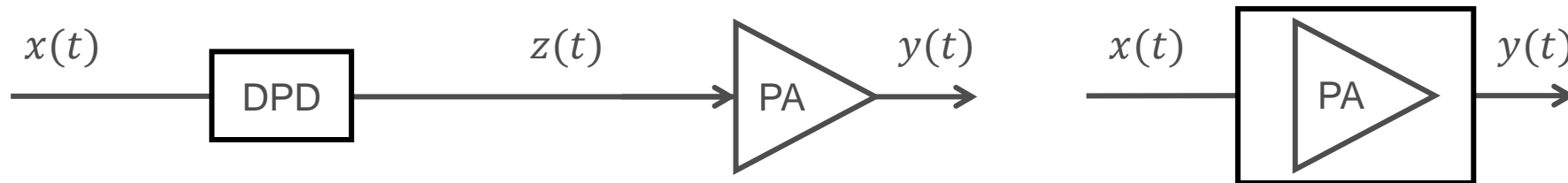
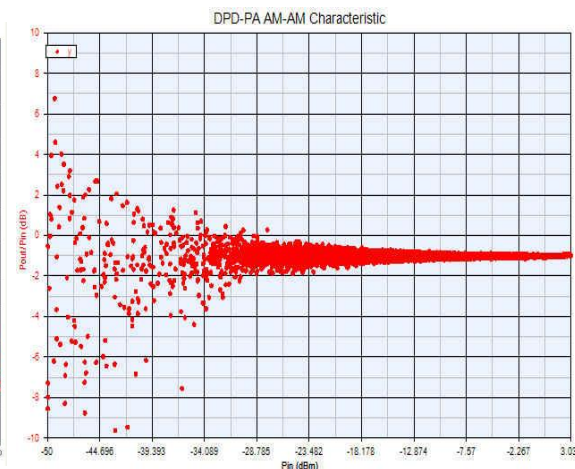
Pre-Distorter AM-to-AM



Power Amp AM-to-AM



DPD + PA AM-to-AM

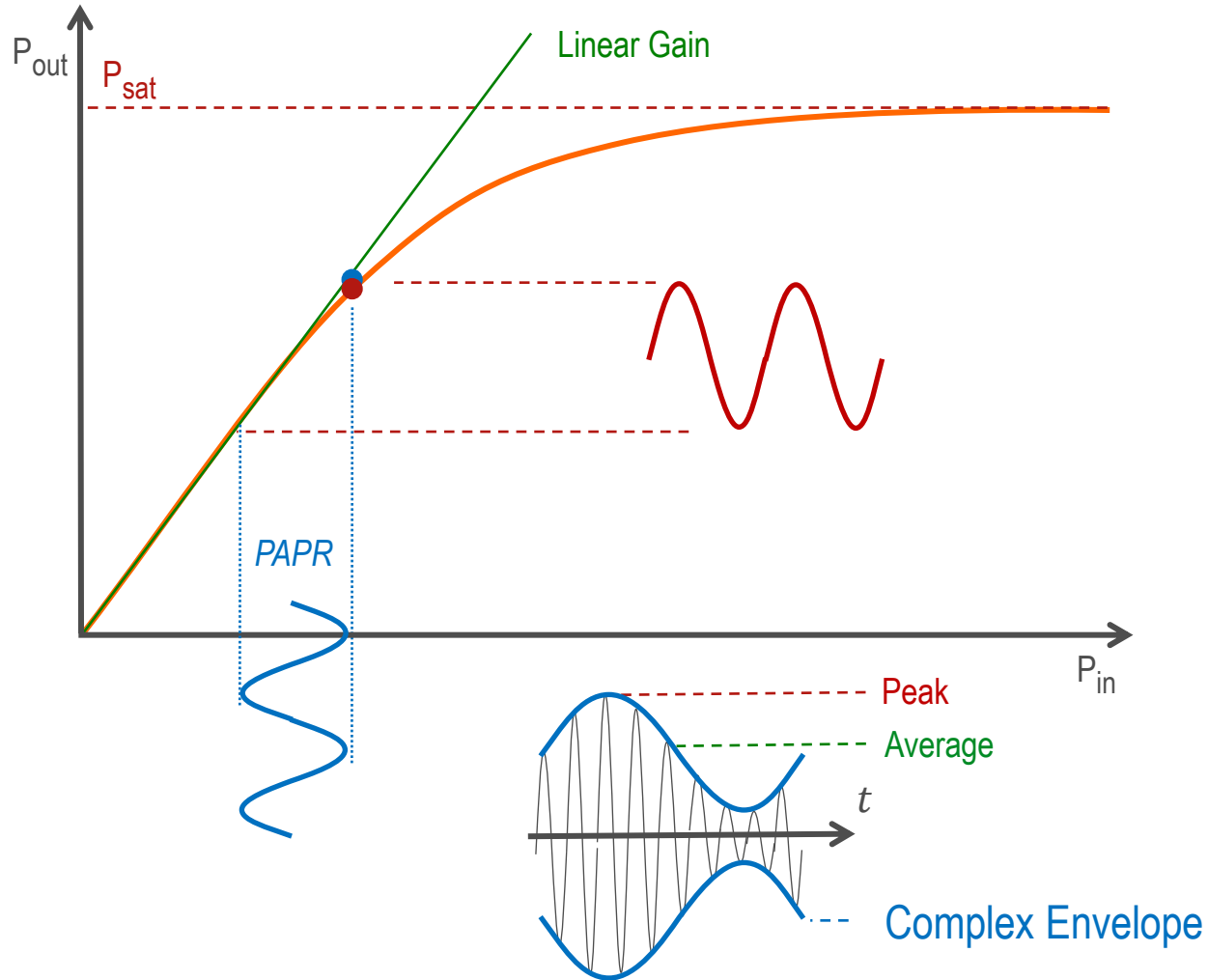


Some Key Definitions for this Class:

- **AM-AM:** Change in Gain vs. Power level, compared to small-signal ($dB(S21)$)
- **AM-PM:** Change in Transmission Phase, compared to small-signal ($phase(S21)$)
- **CCDF:** Percentage of time a particular amplitude level spends above avg power
Let's look at origins of the CCDF in detail...

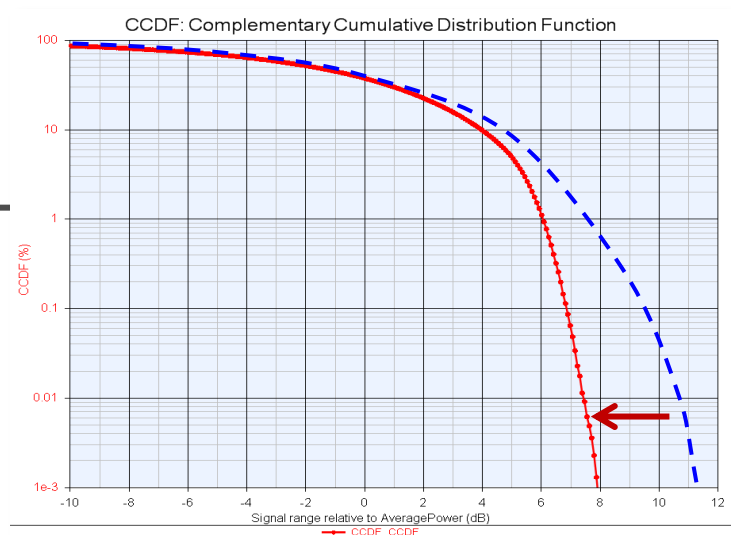
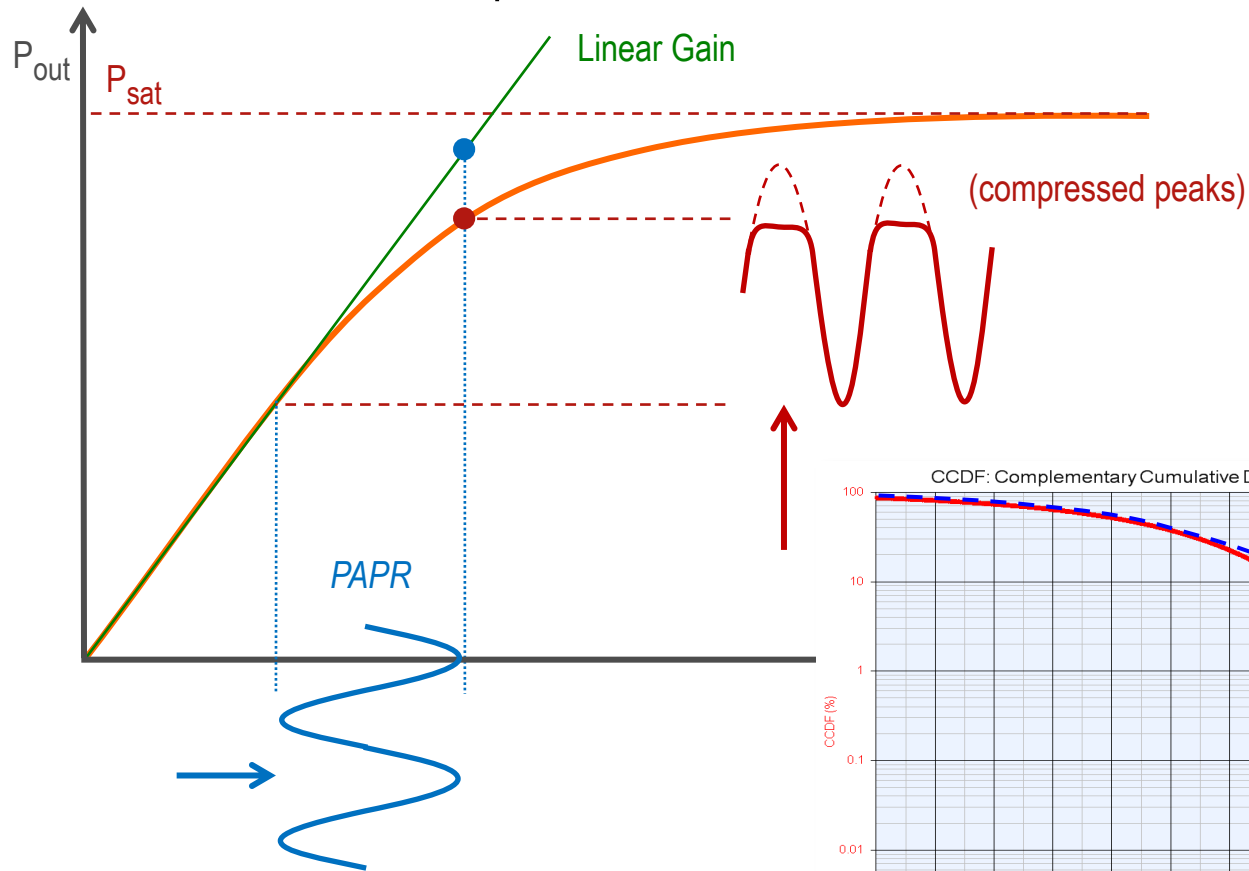
DPD Principles: Time Varying Envelope

Linear Operation



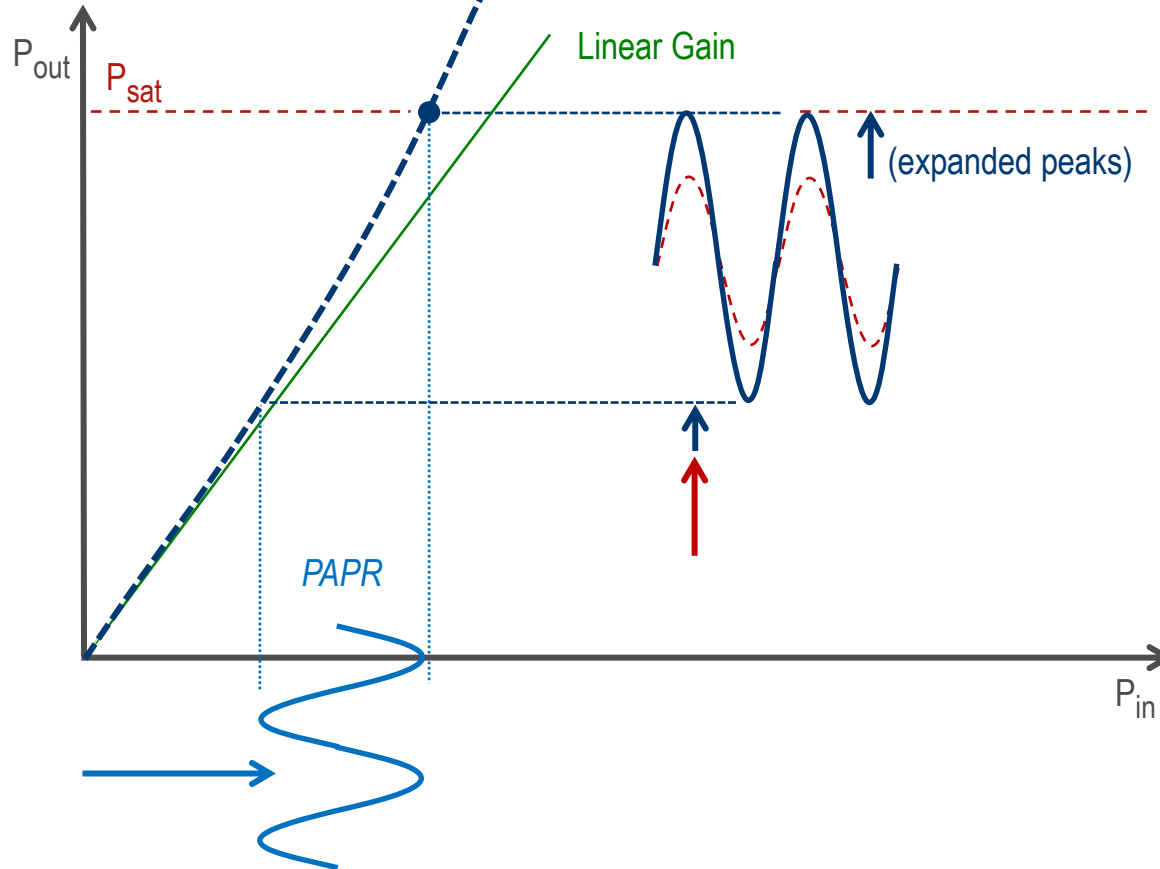
DPD Principles: Time Varying Envelope

Nonlinear Operation – Peaks are Compressed



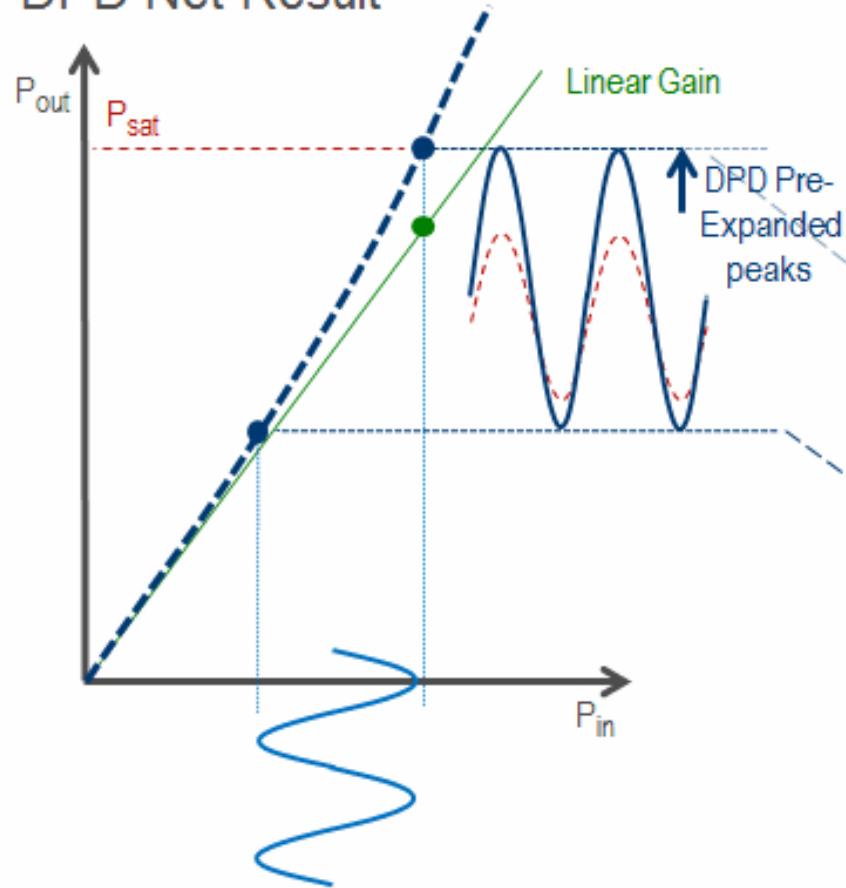
DPD Principles: Time Varying Envelope

DPD Pre-Expansion – exaggerating peaks

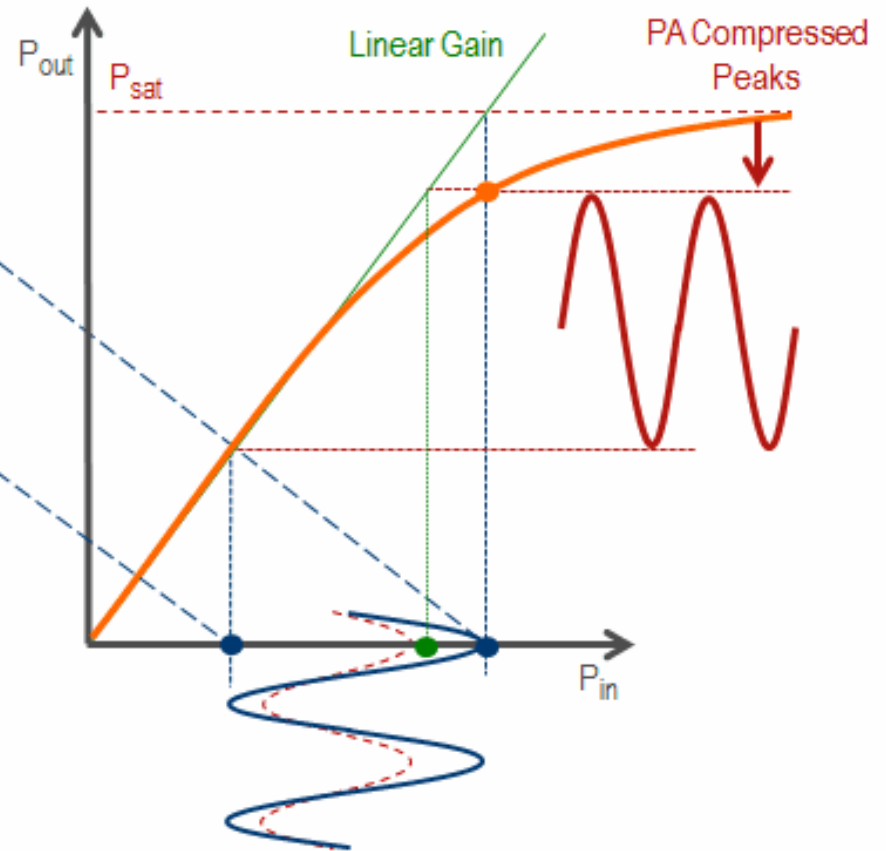


DPD Principles: Time Varying Envelope

DPD Net Result



Baseband Digital Pre-Distortion



RF Power Amplification

Agenda

1. Power Amplifier Fundamentals
2. Digital Pre-Distortion (DPD) Concepts
3. Digital Pre-Distortion Algorithm
4. DPD verification with Agilent Hardware
5. Summary

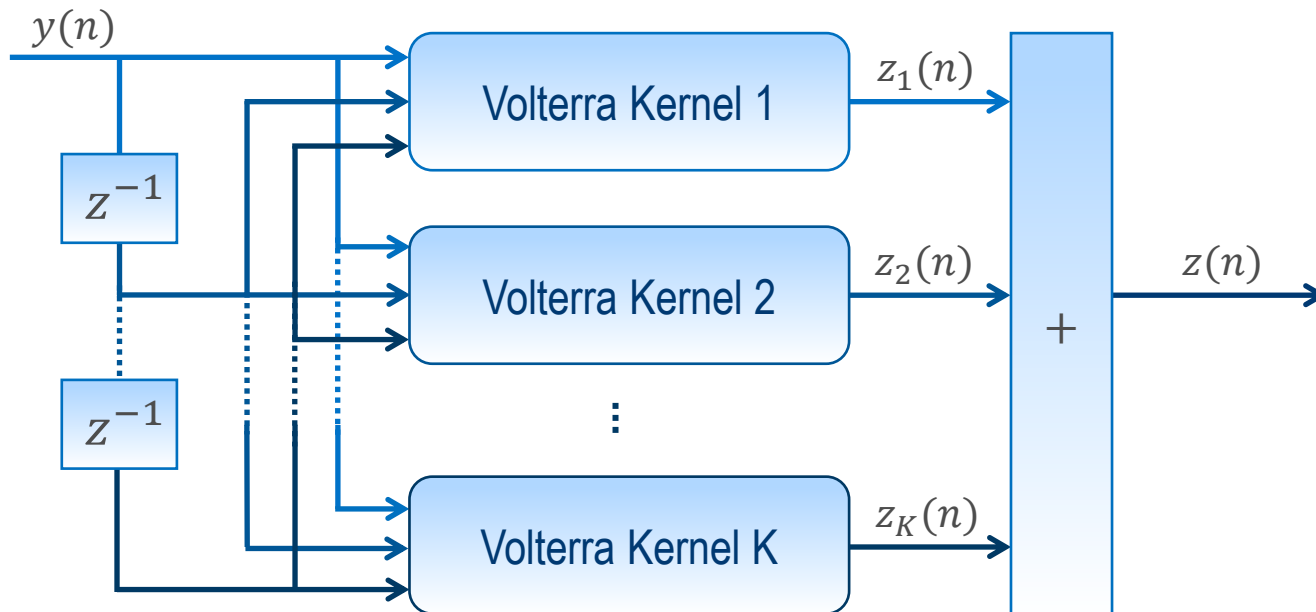


The Volterra Model

The Volterra series predistorted can be described by

$$z(n) = \sum_{k=1}^K z_k(n), \text{ where } z_k(n) = \sum_{m_1=0}^Q \dots \sum_{m_k=0}^Q h_k(m_1, \dots, m_k) \prod_{l=1}^k y(n - m_l)$$

Which is a 2-dimensional summation of power series & past time envelope responses



Volterra Model (3rd Order)

For a 3rd order example, we can write $z(n)$ as follows:

$$\begin{aligned} z(n) = & \sum_{m_1=0}^Q h_1(m_1) y(n - m_1) \\ & + \sum_{m_1=0}^Q \sum_{m_2=0}^Q h_2(m_1, m_2) y(n - m_1) y(n - m_2) \\ & + \sum_{m_1=0}^Q \sum_{m_2=0}^Q \sum_{m_3=0}^Q h_3(m_1, m_2, m_3) y(n - m_1) y(n - m_2) y(n - m_3) \\ & + \dots \end{aligned}$$

Where:

Q is the memory order and

m_1, m_2, m_3 is the memory depth:

$h_1(m_1)$

$h_2(m_1, m_2)$

$h_3(m_1, m_2, m_3)$

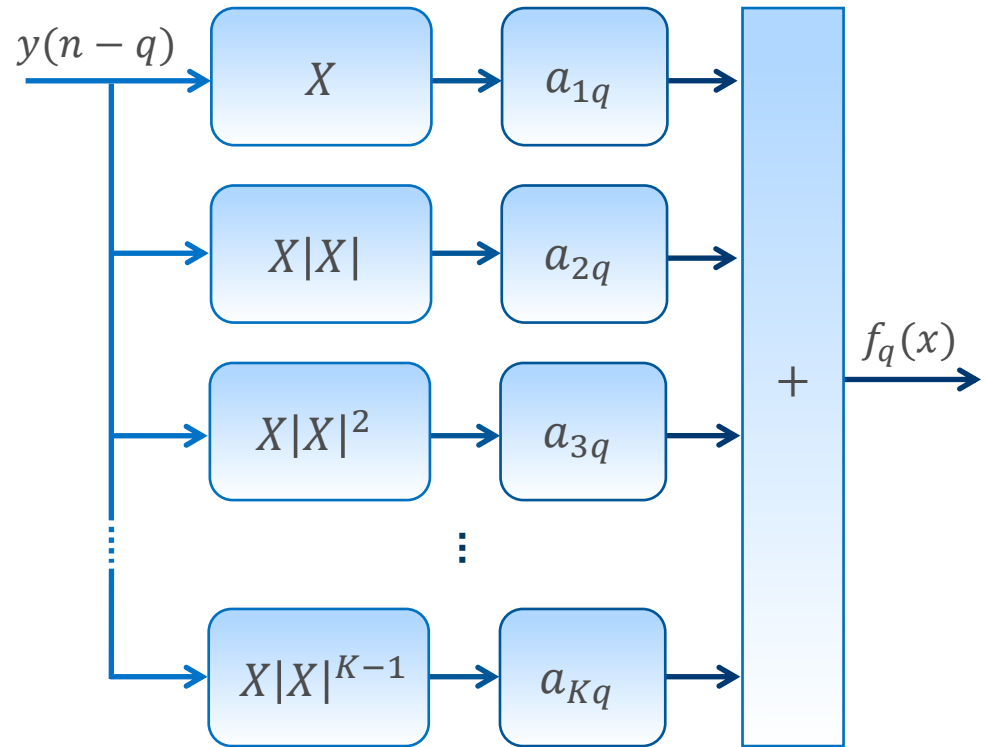
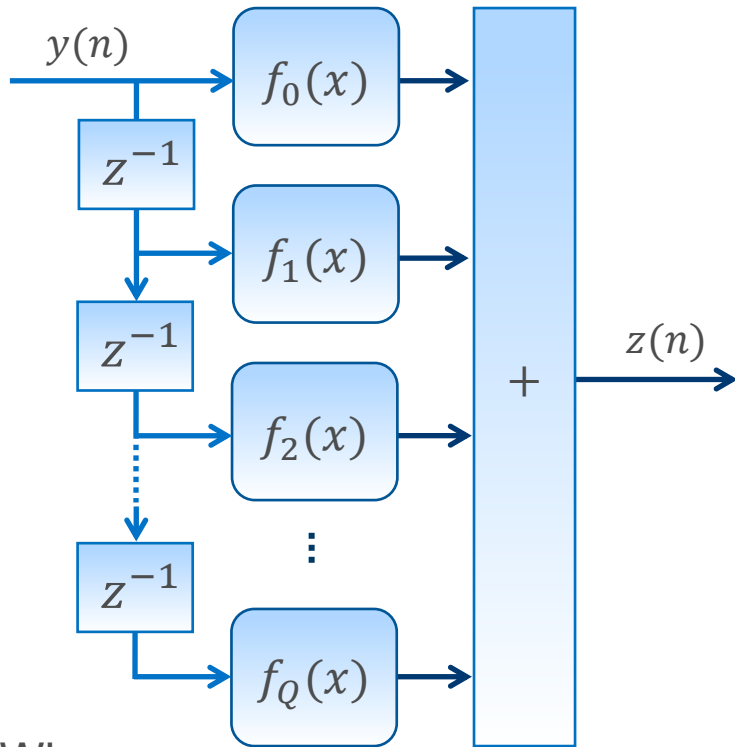
First-order Volterra Model

Second-order Volterra Model

Third-order Volterra Model

Memory Polynomial Model

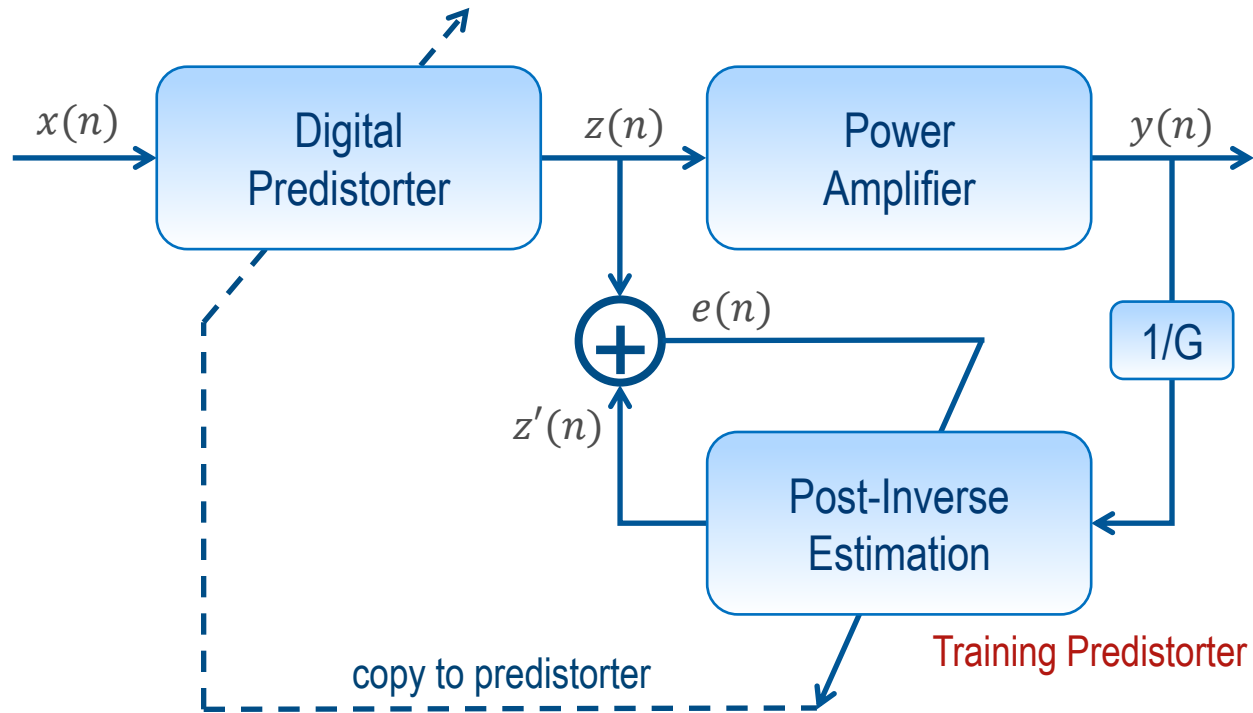
$$z(n) = \sum_{k=1}^K \sum_{q=0}^Q a_{kq} y(n-q) |y(n-q)|^{k-1}$$



Where:

Q is the memory order and
 K is the nonlinear order

Indirect Learning Architecture



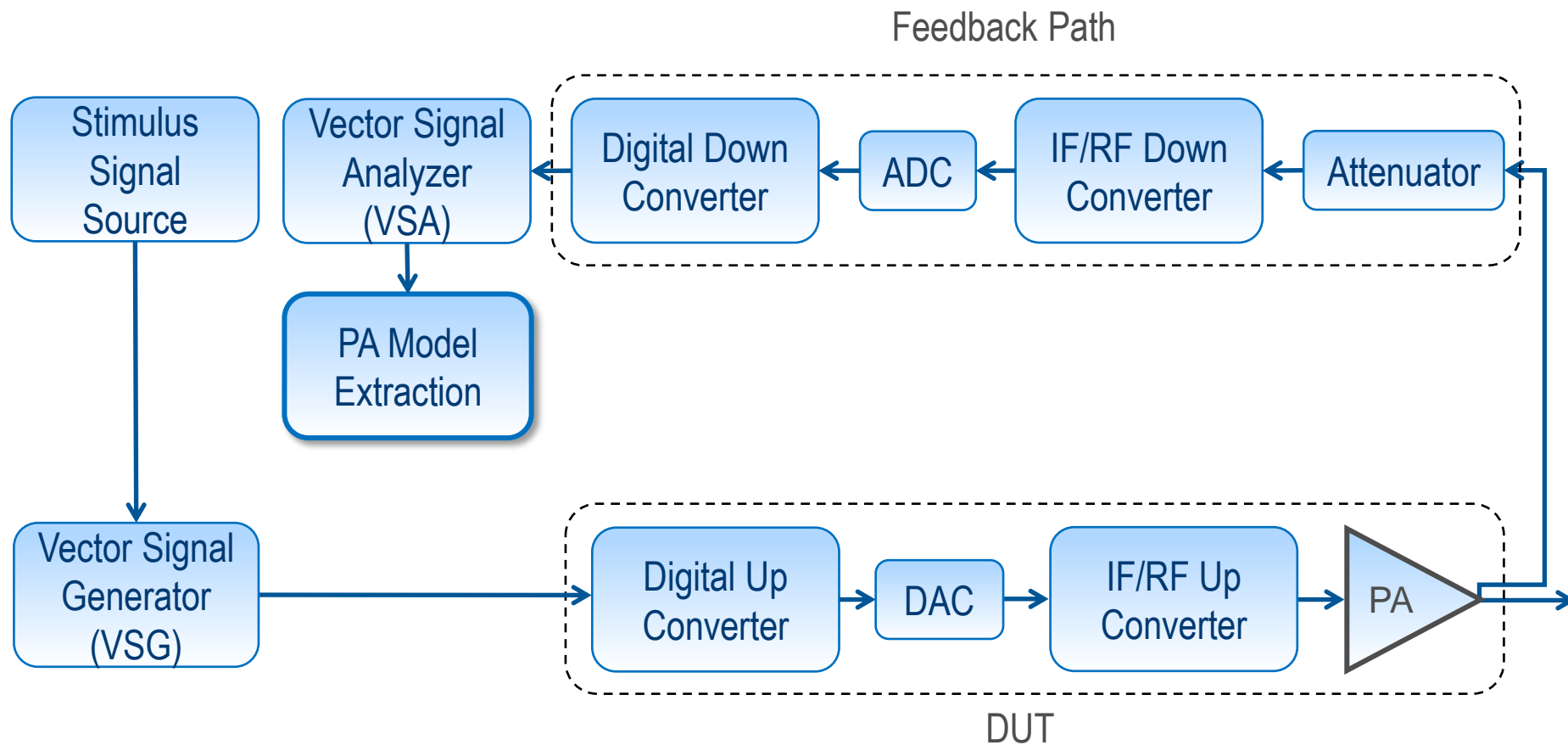
The indirect learning is a the open-loop architecture and the use of least square (LS) algorithm. The indirect learning scheme is widely implemented as it eliminates the requirement for building a closed-loop real time system, which dramatically reduces the complexity.

Agenda

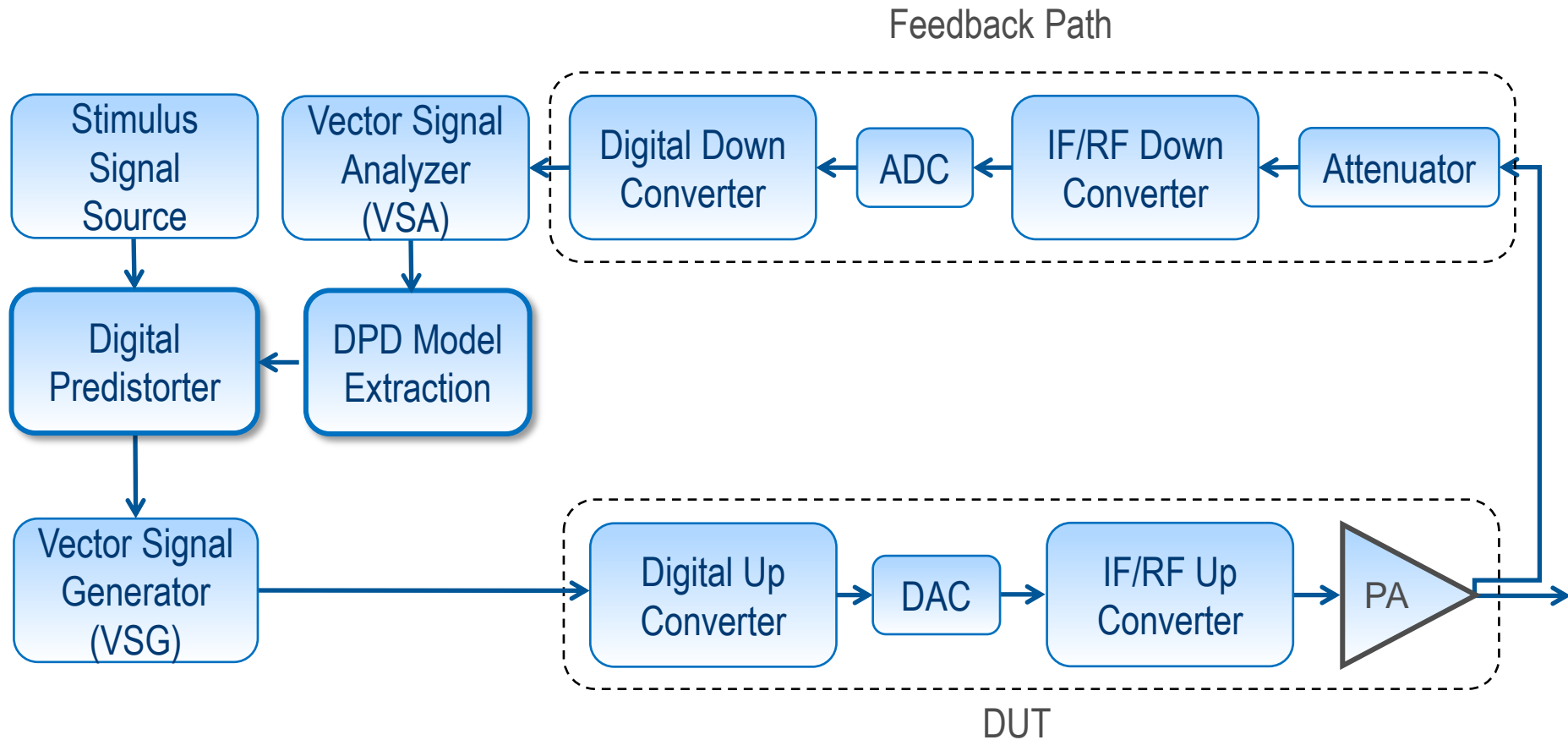
1. Power Amplifier Fundamentals
2. Digital Pre-Distortion (DPD) Concepts
3. Digital Pre-Distortion Algorithm
4. DPD verification with Agilent Hardware
5. Summary



PA Modeling Verification System

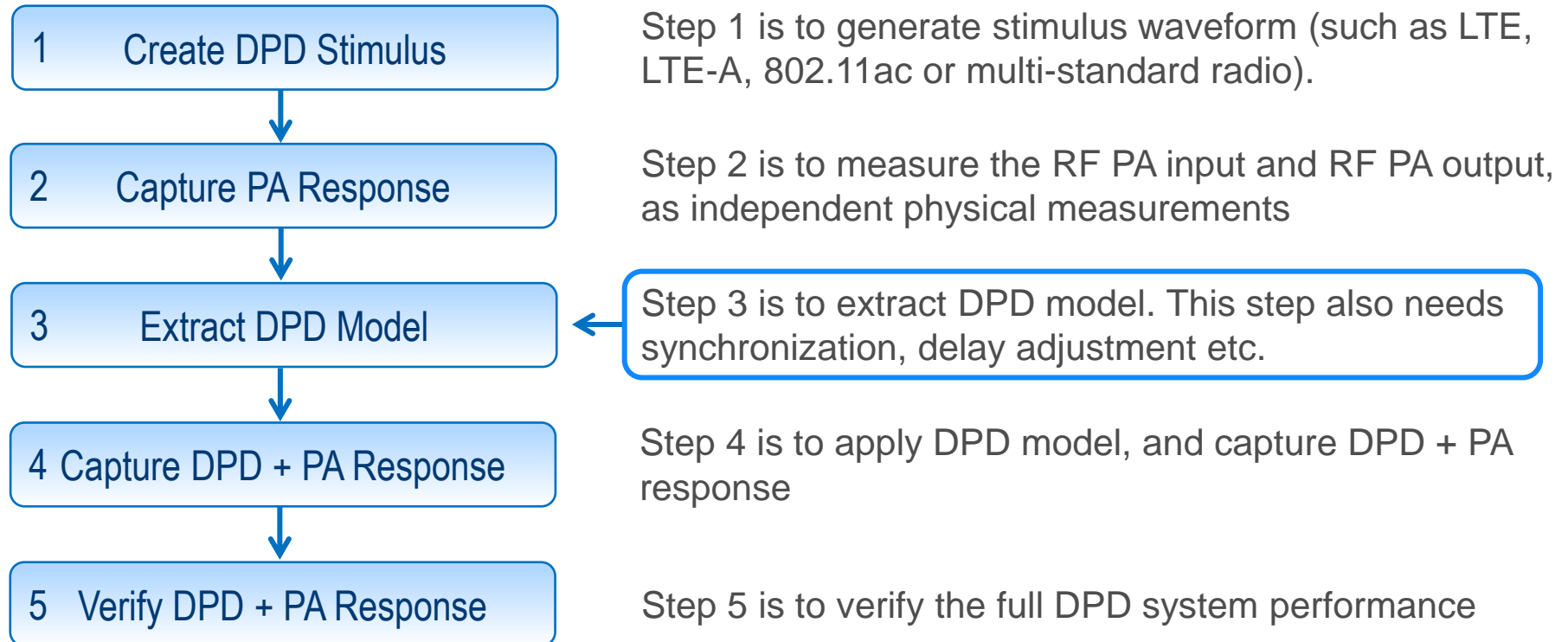


DPD Verification System

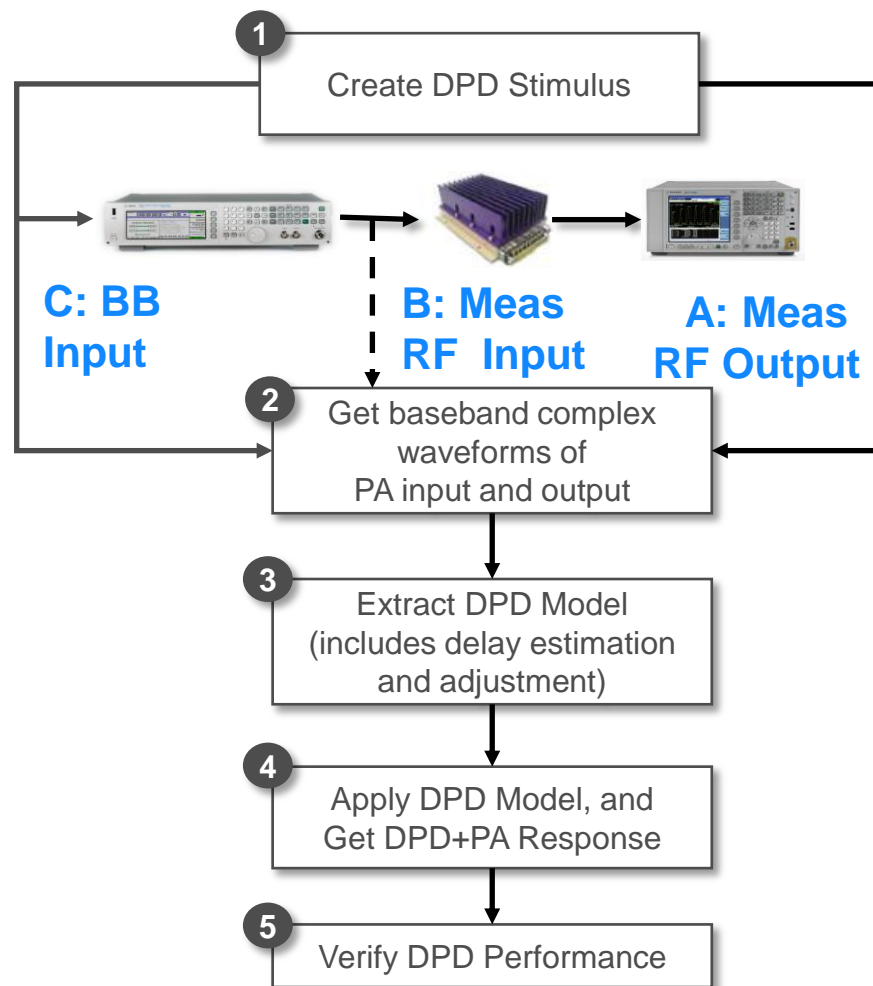
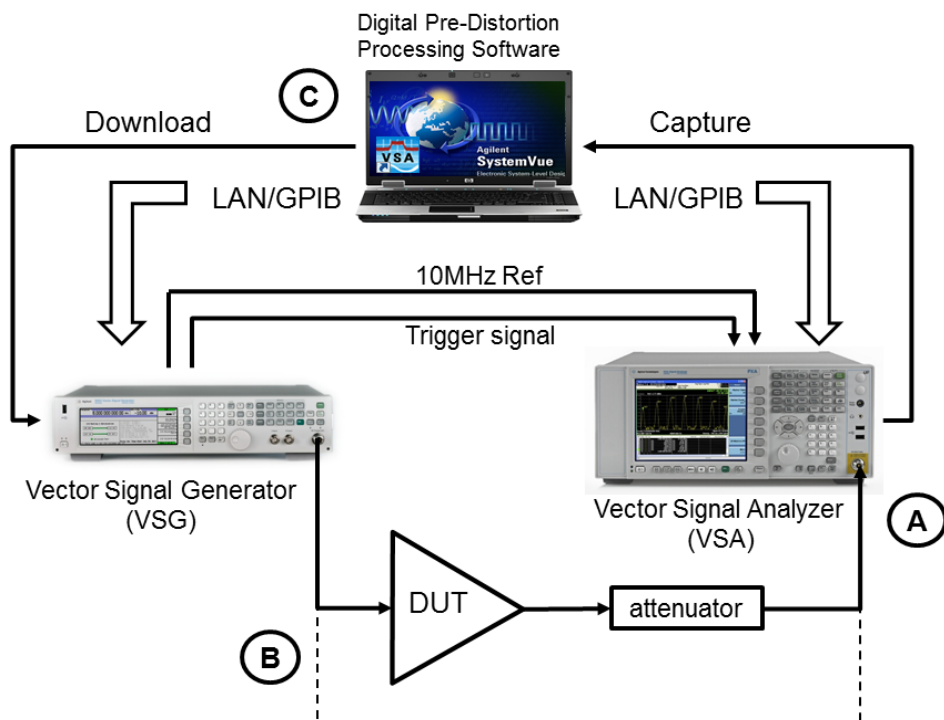


The Steps Required for Successful DPD

The **SystemVue DPD flow** is a 5 step process



Agilent DPD Verification Platform



SystemVue DPD Modeling Flow

Step 1. Create DPD stimulus waveform

- Custom waveform: I/Q ACSII file, Signal Studio file, .sdf file format.
- LTE/LTE-A DL/UL, 11ac

1.Create DPD Stimulus 2.Capture DUT Response 3.DUT Model Extraction 4.DPD Response 5.Verify DPD Response

Current Iteration: 1

System Parameters

Carrier Frequency: 2.14 GHz

Bandwidth: 20 MHz

Sampling Rate: 80 MHz

Oversampling Ratio: 4

Input Parameters

Input Signal: I/Q File

I Data: C:\DPD_Simplified\ Browse

Q Data: C:\DPD_Simplified\ Browse

Clipping Parameters

Enable CFR: ☐

Target PAPR: 6.0 dB

Beta (Kaiser Factor): 12.0

CFR Block Size: 1000

CFR Algorithm: Peak windowing

Max Iteration: 10

Max Window Length: 31

Download Parameters

Instrument Type: E4438C(ESG) or I

Path Gain: -1.1 dB

Time Start: 0 ms

IP Address: 146.208.65.66

RF Power: -8 dBm

PA Power In: -9.1 dB

Time Stop: 3.68 ms

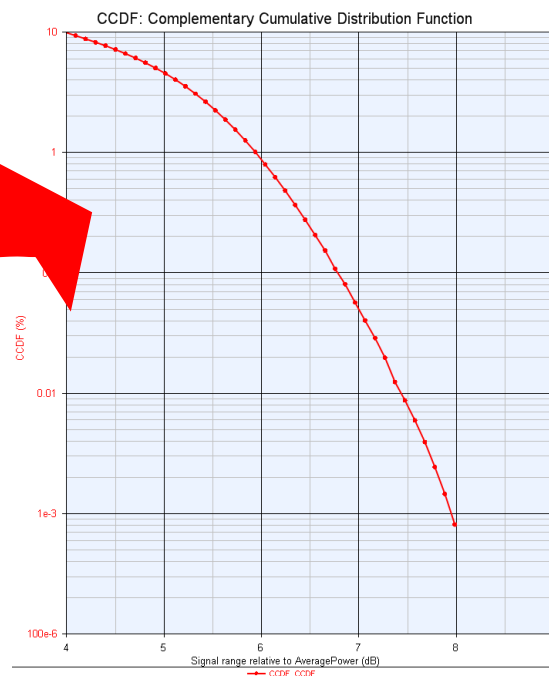
Download Waveform

Go To Web Control

CCDF

PAPR: dB

The download **power** and length of the waveform can also be set.



SystemVue DPD Modeling Flow

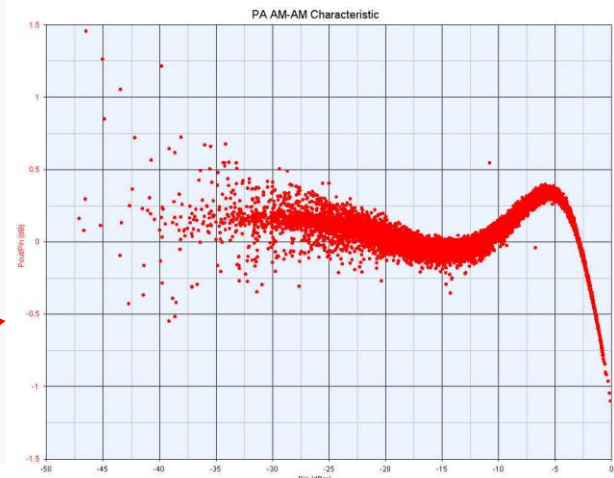
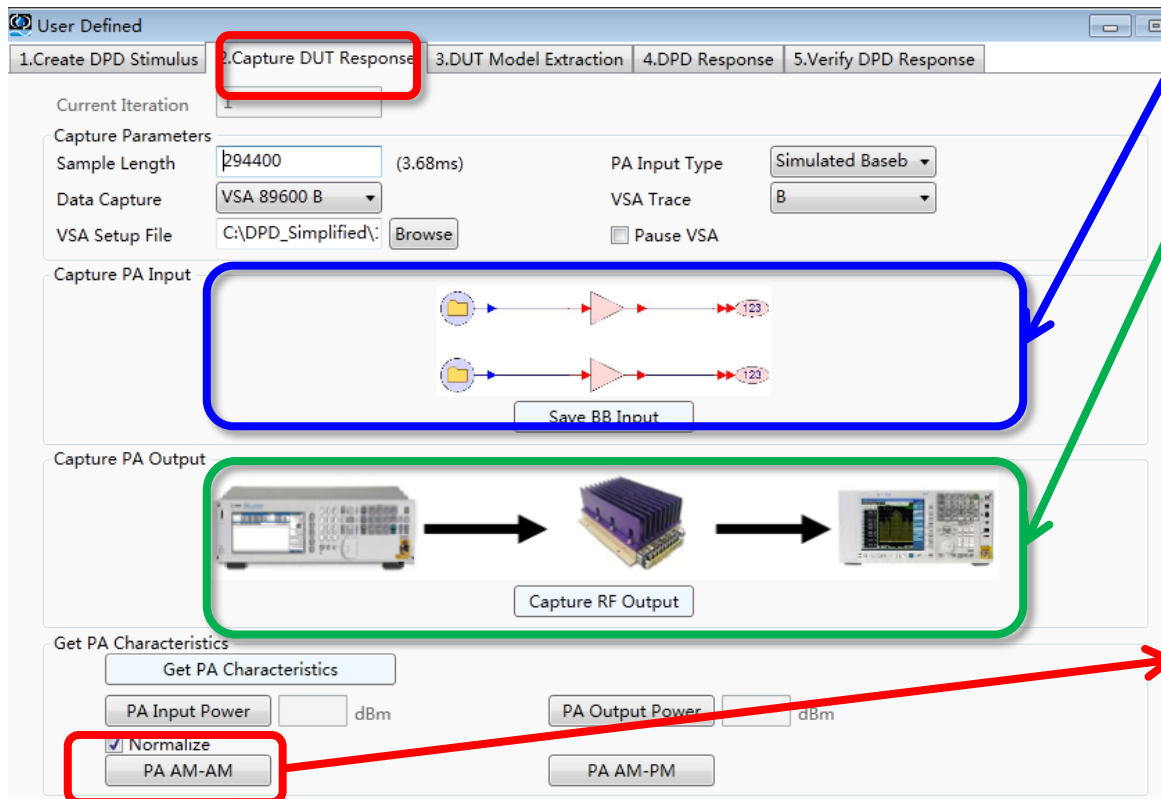
Step 2. Capture PA response

- Get both PA input and output and save them in files
- Can use Agilent VSA89600 software or Command Expert to capture waveform from VSA.
- Show PA AM-AM and AM-PM.

THRU : Save RF PA input or baseband simulation PA input

DUT: Connect the VSG to the PA, Save RF PA output

The measured I/Q files are stored and used in following steps.



SystemVue DPD Modeling Flow

Step 3. DPD Model Extraction

- Provide Memory Polynomial, Volterra and LUT algorithm.
- Support Iterative DPD
- Provide DPD algorithm with power back off and without power back off.

User Defined

1.Create DPD Stimulus 2.Capture DUT Response 3.DUT Model Extraction 4.DPD Response 5.Verify DPD Response

Current Iteration 1

Model Extraction Parameters

Input Sample Length: 80000 (1ms)

☒ Allow Power Backoff

Model Id Algorithm: 0: LSE using QR

☐ Sample Level DPD

Model Type: 0: Memory Polyr

Memory Order: 2

Nonlinear Order: 7

Num Of Iterations: 2

Do Model Extraction

$y(n)$

z^{-1}

$z(n)$

$\sum_{k=0}^K a_k y(n-k) |y(n-k)|^{-1}$

$\sum_{k=0}^K a_k y(n-1-k) |y(n-1-k)|^{-1}$

$\sum_{k=0}^K a_k y(n-2-k) |y(n-2-k)|^{-1}$

$z(n)$

☐ Use Custom Model Extractor ☐ Use Custom Pre-Distorter

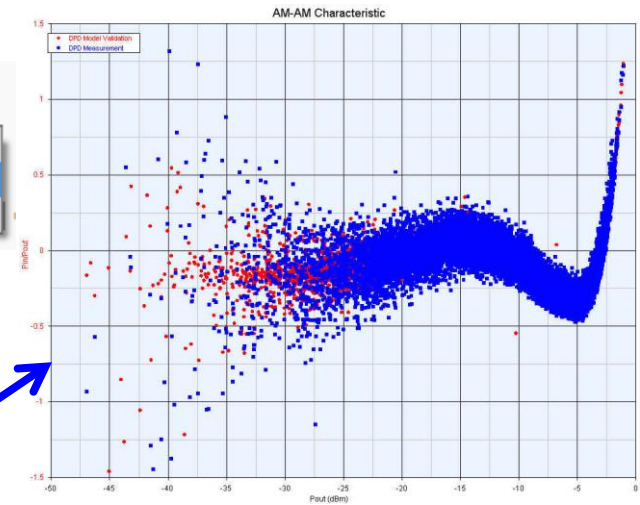
Customize Model Extract Customize Pre-Distorter

Do DPD Model Extractor

Show Results

DPD AM-AM DPD AM-PM Spectrum DPD Coefficients NMSE dB

DPD AM-to-AM Characteristic



Real

Imaginary

24.272984	54.663756
-29.017471	-58.294568
12.197462	21.366817
-2.018507	-2.897401
0.425925	0.900555
10.991139	18.097705
-14.291582	-22.202843
6.505712	9.560252
-1.196895	-1.656454
0.069031	0.086404

SystemVue DPD Modeling Flow

Step 4. Capture DPD+PA Response

- Generate pre-distorted waveform and download it into VSG.
- Capture DPD+PA output signal from VSA

The screenshot shows the 'User Defined' configuration window for Step 4, '4.DPD Response'. The 'Download Parameters' section is highlighted with a blue box and contains the following fields:

Parameter	Value	Unit
RF Power	-8	dBm
Path Gain	-1.1	dB
Time Start	0	ms
IP Address	146.208.65.66	
PA Power Backoff	0	dB
PA Power In	-9.1	dB
Time Stop	3.68	ms

Below the parameters, there is a diagram showing the signal flow: Customized Waveform → Pre-Distorter → MXG. A text box next to it says: 'Please "Do power search" in MXG/ESG by clicking "Amplitude/Do Power Search" after downloading.'

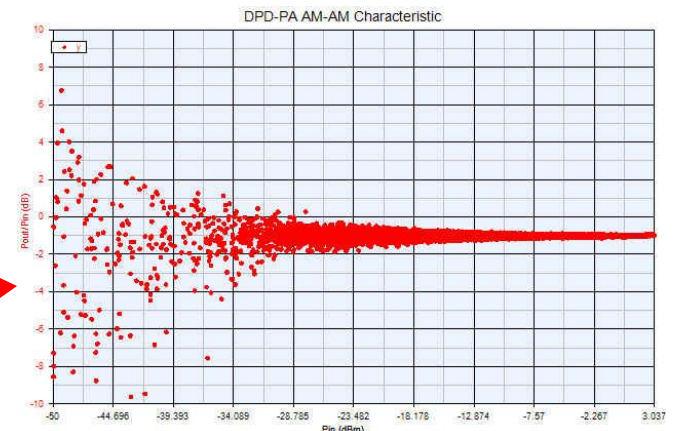
There are buttons for 'Download Waveform', 'Go To ESG Web Control', and 'PAPR' (set to 0 dB).

The 'Capture DPD-PA Output' section shows a diagram of a VSA, a PA, and a VSA. A 'Capture Waveform' button is located below the diagram.

The 'Get DPD-PA Characteristics' section has a 'Get DPD-PA Characteristics' button and a 'Normalize' checkbox. Below these are three buttons: 'DPD-PA AM-AM' (highlighted with a red box), 'DPD-PA AM-PM', and 'DPD-PA Input Power' (set to 0 dBm). There is also a 'DPD-PA Output Power' field set to 0 dBm.

This downloading parameters is controlled by "Allow Power Backoff" panel in Step 3. The RF power must be same as Step1 if grayed when w/o power back off..

DPD+PA AM-to-AM Characteristic



SystemVue DPD Modeling Flow

Step 5. Verify DPD+PA response

- Compare results with DPD and without DPD.

User Defined

1.Create DPD Stimulus 2.Capture DUT Response 3.DUT Model Extraction 4.DPD Response 5.Verify DPD Response

Current Iteration 1

Download Parameters

RF Power -8 dBm PA Power Backoff 0 dB

Path Gain -1.1 dB PA Power In -9.1 dB

Time Start 0 ms Time Stop 3.68 ms

IP Address 146.208.65.66

Download Original Signal

Customized Waveform → MXG

Download Waveform Go To ESG Web Control

Capture PA Output

Capture Waveform PA Output Power dBm

DPD Response Verification

Config Meas. Verify DPD Respons

Spectrum ACP EVM

Please "Do power search in MXG/ESG by clicking "Amplitude\Do Power Search" after downloading.

Measurement Setting

Spectrum

Mode TimeGate Start 0 ms

Segment Time 0.05 ms Num Of Segments 20

Window Type Hanning

EVM

Signal Format N/A Config

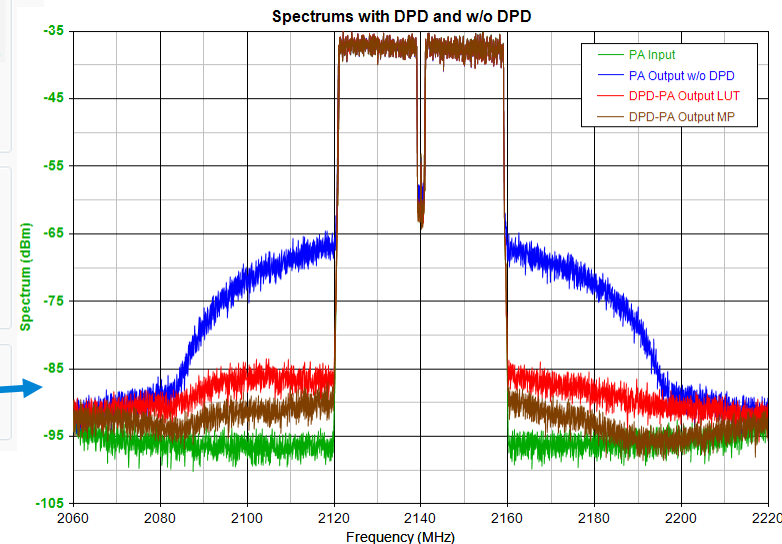
ACP

Ref Offset 0 MHz Ref BW 38 MHz

Lower Offset -40 MHz Lower BW 38 MHz

Upper Offset 40 MHz Upper BW 38 MHz

OK Cancel



Summary

Problem statement

HF high power amplifier measurement needs to measure IMD3 and IMD5. It's a big challenge to pass IMD3 and IMD5 measurement.

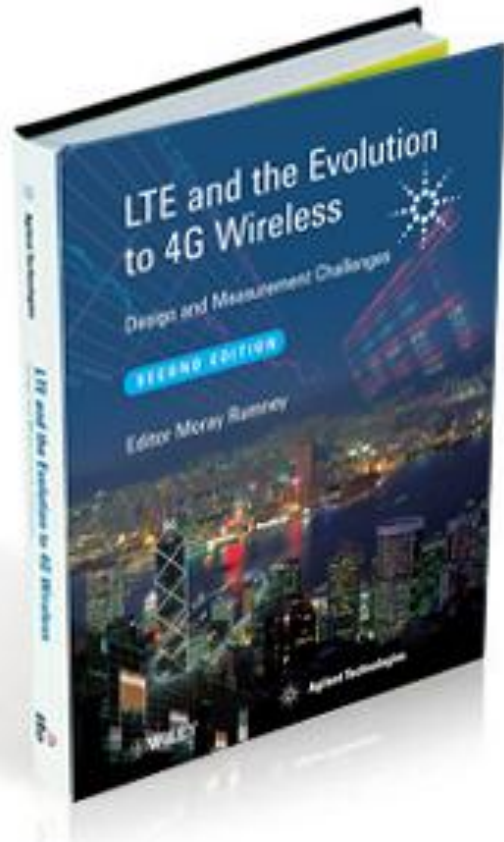
Solution approaches

- Digital Pre-Distortion (DPD) can decrease IMD3 and IMD5 to help to pass HF PA IMD3/IMD5 measurements.
- SystemVue offers a practical DPD modeling flow to do DPD measurement.



Agilent LTE/LTE-Advanced textbook

Discusses many of the DPD concepts shown today



NEW FOR 2nd Edition

SystemVue applications featured in this book

- LTE-Advanced (3GPP Releases 8-12)
- MIMO channel/Over-the-Air testing
- Multi-Standard Radio (MSR)
- DPD, Crest Factor Reduction
- Integration of Design & Test

<http://www.agilent.com/find/LTEbook>

ISBN 978-1-1199-6257-1 (Wiley & Sons)



“Digital Pre-distortion Measurement for HF High Power Amplifier”

THANK YOU

W1716 Digital Pre-Distortion

Web - www.agilent.com/find/eesof-systemvue-dpd-builder

App Note - <http://cp.literature.agilent.com/litweb/pdf/5990-6534EN.pdf>

App Note - <http://cp.literature.agilent.com/litweb/pdf/5990-7818EN.pdf>

App Note - <http://cp.literature.agilent.com/litweb/pdf/5990-8883EN.pdf>

SystemVue

www.agilent.com/find/eesof-systemvue

www.agilent.com/find/eesof-systemvue-videos

www.agilent.com/find/eesof-systemvue-evaluation

Or, contact your regional Agilent resource

www.agilent.com/find/eesof-contact

