Digital Pre-distortion Measurement for HF High Power Amplifier

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Agilent Technologies, Inc.

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Agenda

1. Power Amplifier Fundamentals

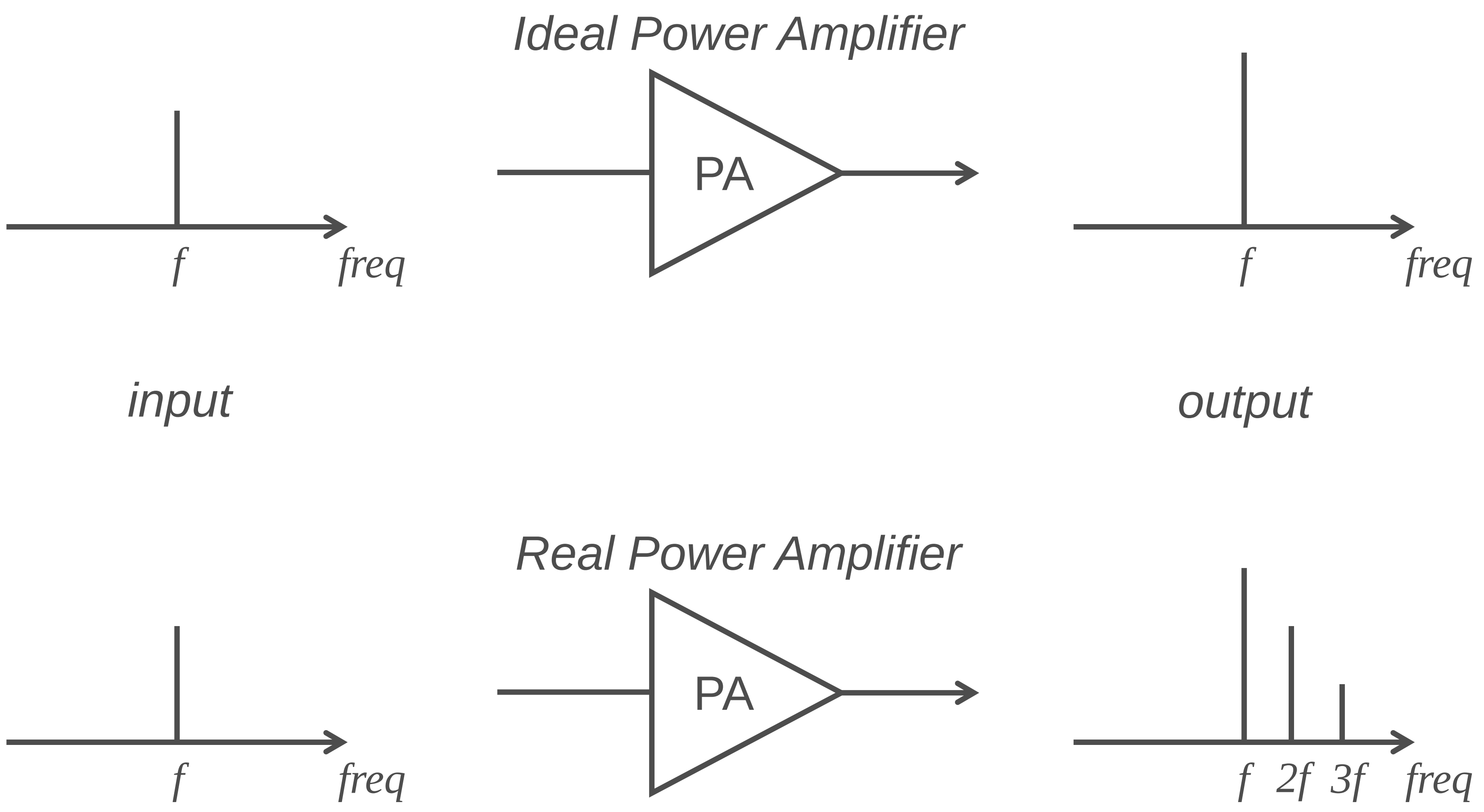
2. Digital Pre-Distortion (DPD) Concepts

3. Digital Pre-Distortion Algorithm

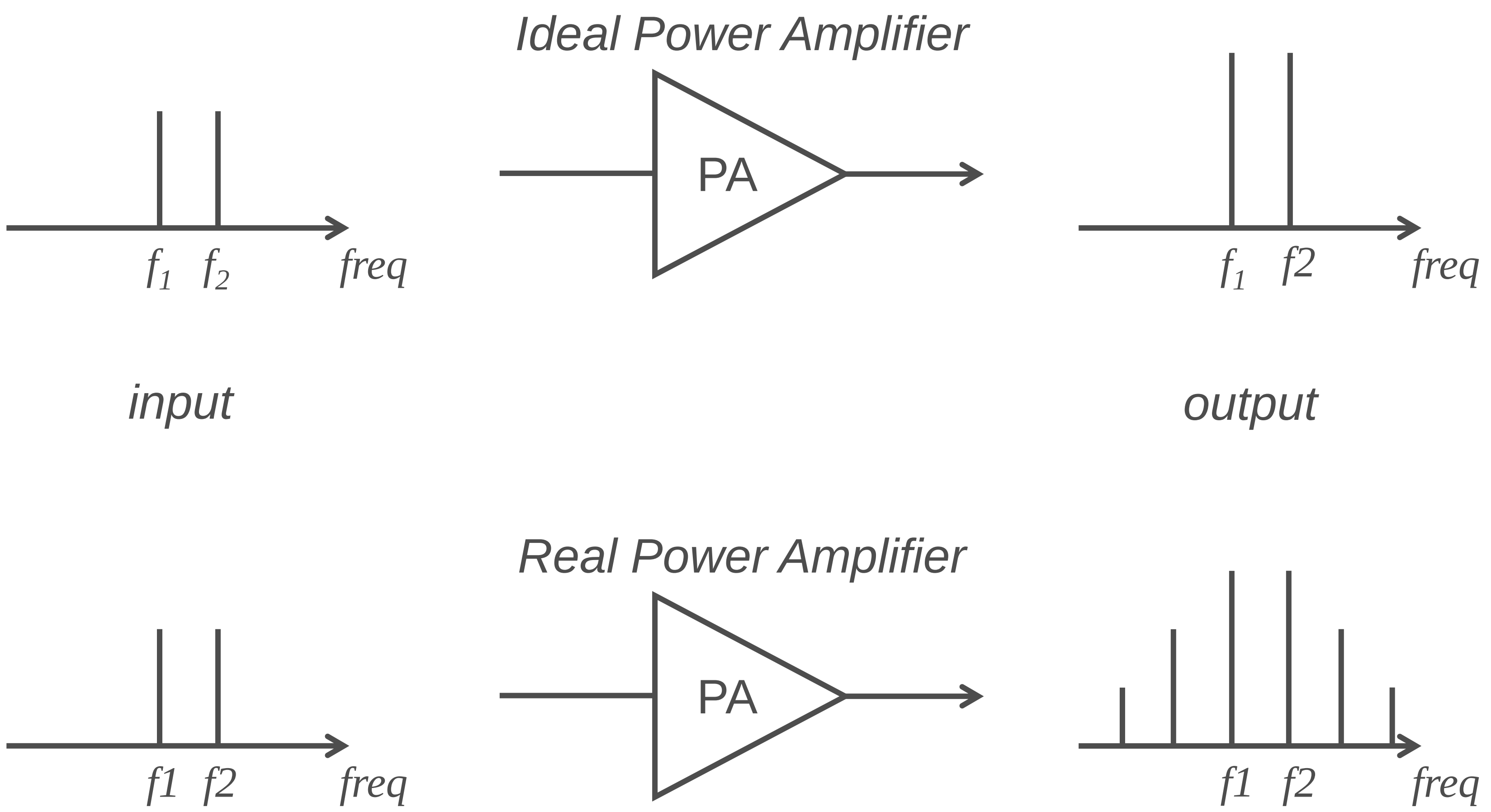
4. DPD verification with Agilent Hardware

5. Summary

The Single Tone scenario



The Two-Tones scenario



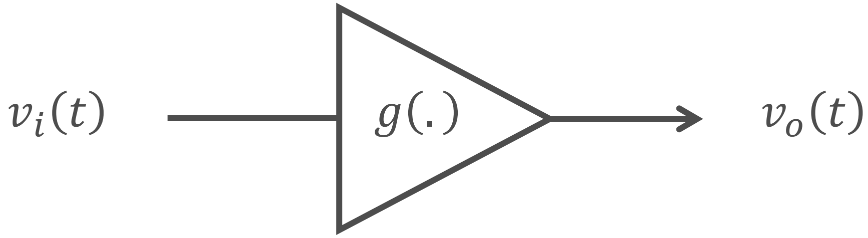
Polynomial Expression of a PA Model

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:

$$y = a_1 x + a_2 x^2 + a_3 x^3$$

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 $v_o(t)$



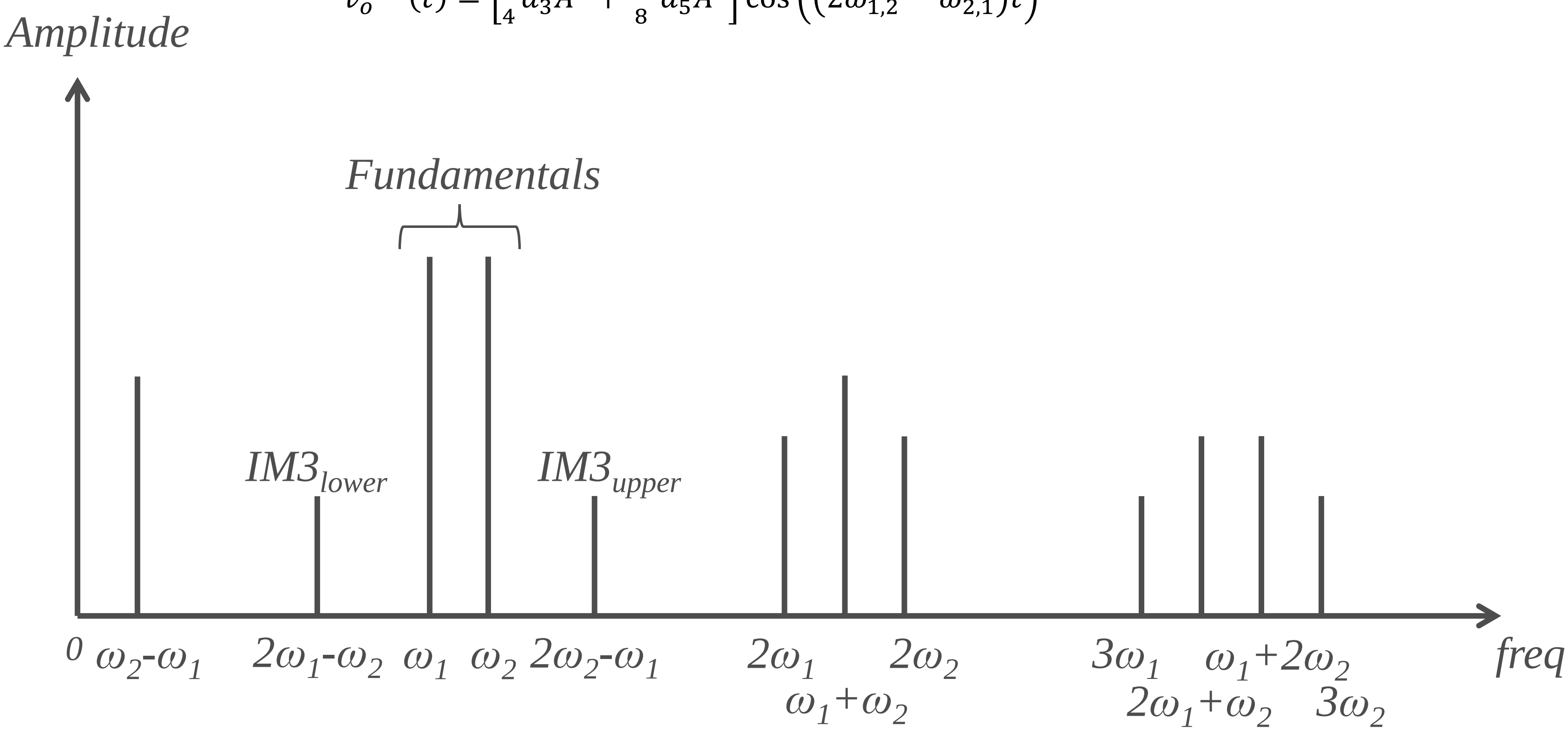
$$v_o(t) = g.v_i(t)$$

Intermodulation in a Nonlinear Power Amplifier *

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

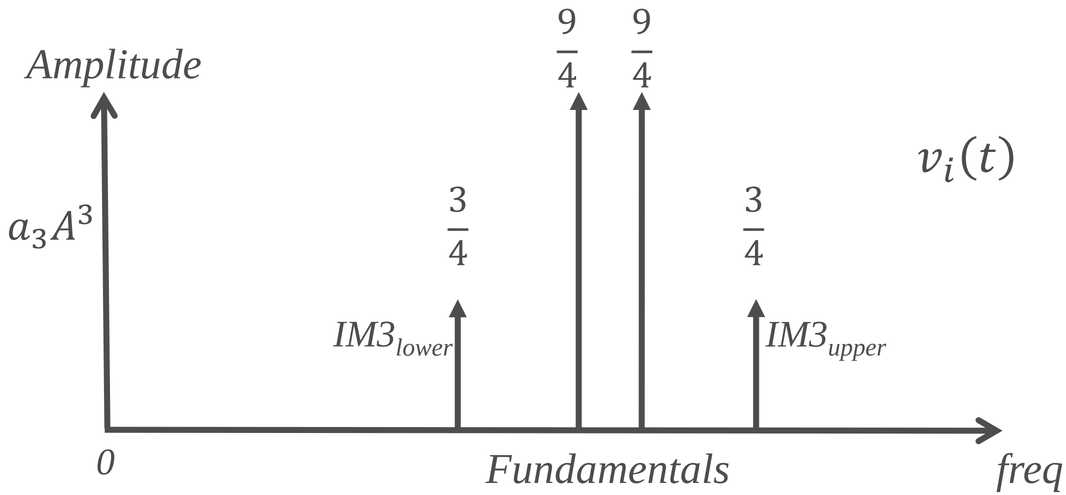
$$v_o^{IM1}(t) = \left[a_1 A + \frac{9}{4} a_3 A^3 + \frac{25}{4} a_5 A^5\right] \cos(\omega_{1,2} t)$$

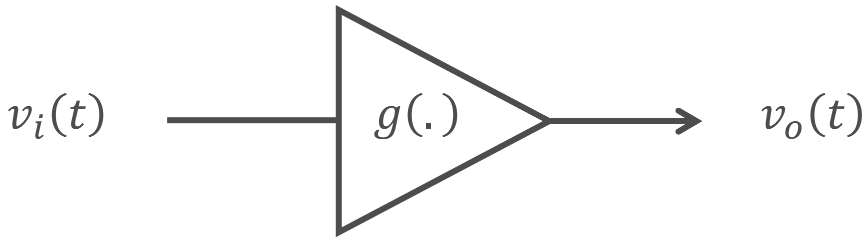
$$v_o^{IM3}(t) = \left[\frac{3}{4} a_3 A^3 + \frac{25}{8} a_5 A^5\right] \cos\left((2\omega_{1,2} - \omega_{2,1})t\right)$$



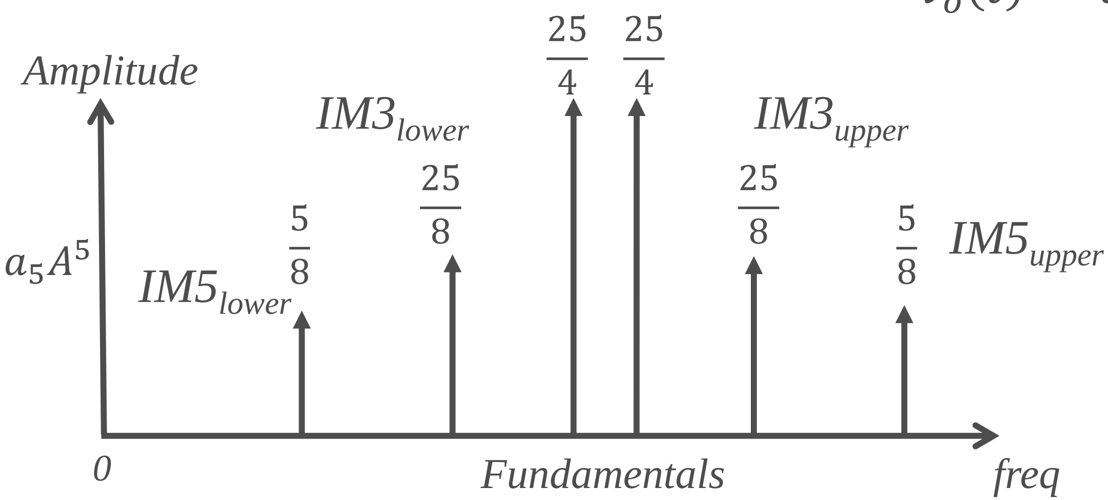
*** this is a memoryless system**

Intermodulation in a Nonlinear, Memoryless PA





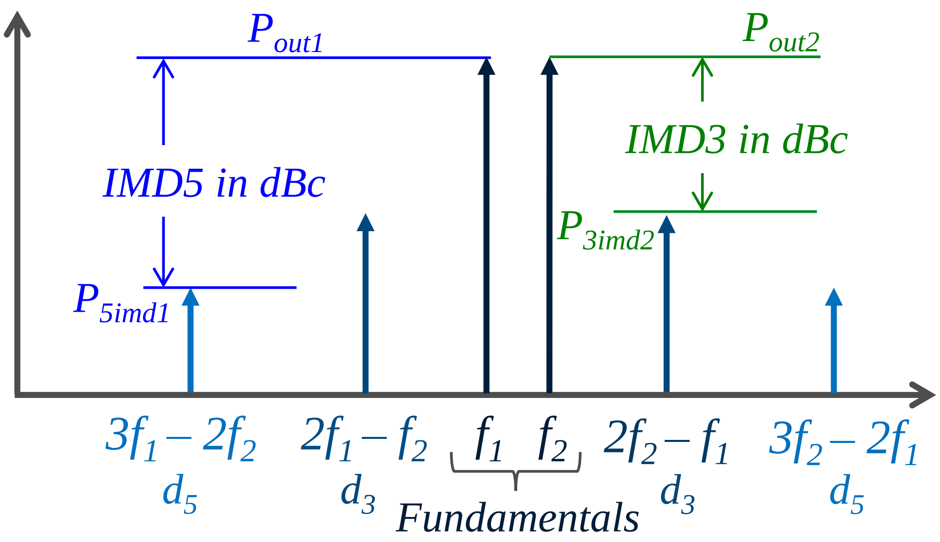
$$v_o(t) = a_1v_i(t) + a_3v_i^{3}(t) + a_5v_i^{5}(t)$$



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:



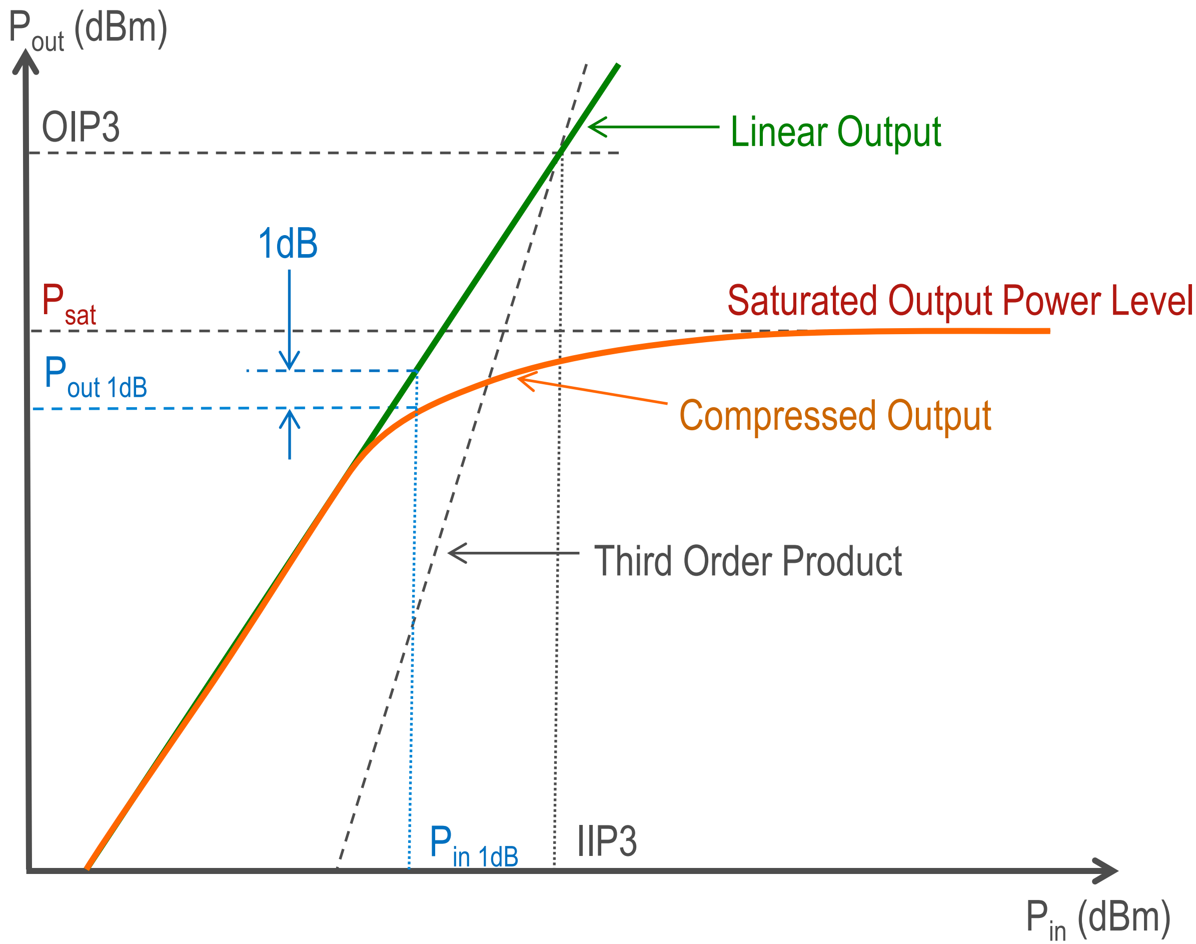
$f_{1,2}$ = fundamental
$2f_{1,2}$ = second harmonic (square law)
$3f_{1,2}$ = third harmonic (third order)

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 $f_{1,2}$

$$IMD3 = P3_{imd} - Pout$$
$$IMD5 = P5_{imd} - Pout$$

The Third Order Intercept Point (IP3/TOI)

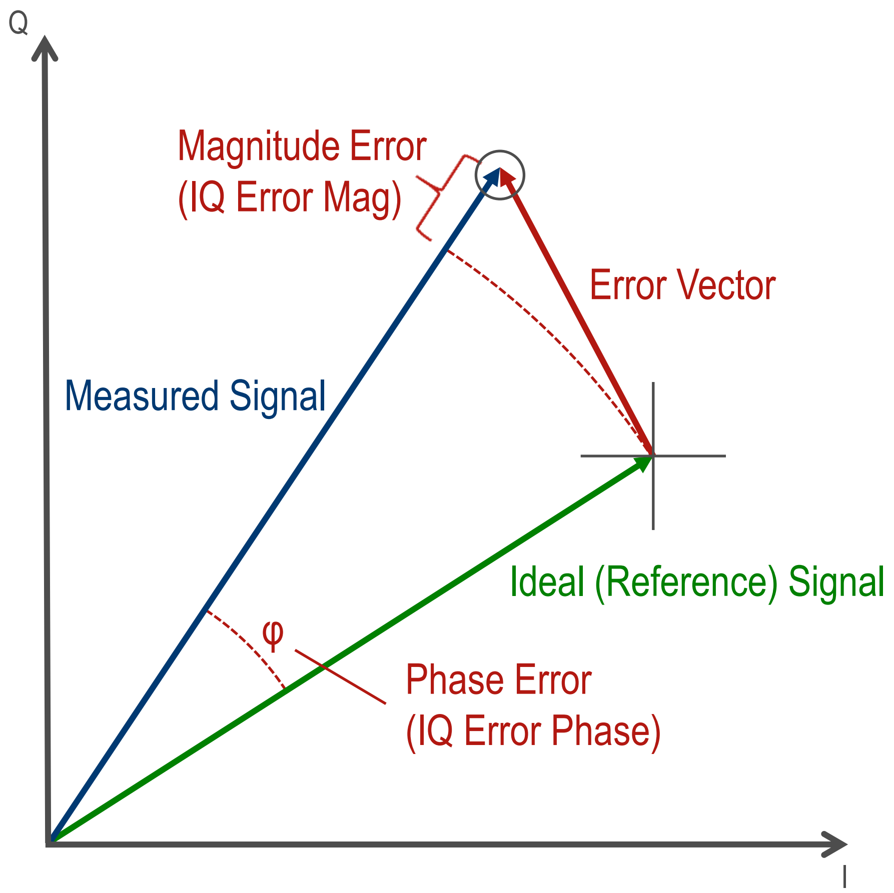


$$IIP3\ (dBm) = P_{in}\ (dBm) + 0.5 \cdot IMD3\ (dBc)$$

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

Adjacent Channel Leakage Ratio (ACLR)

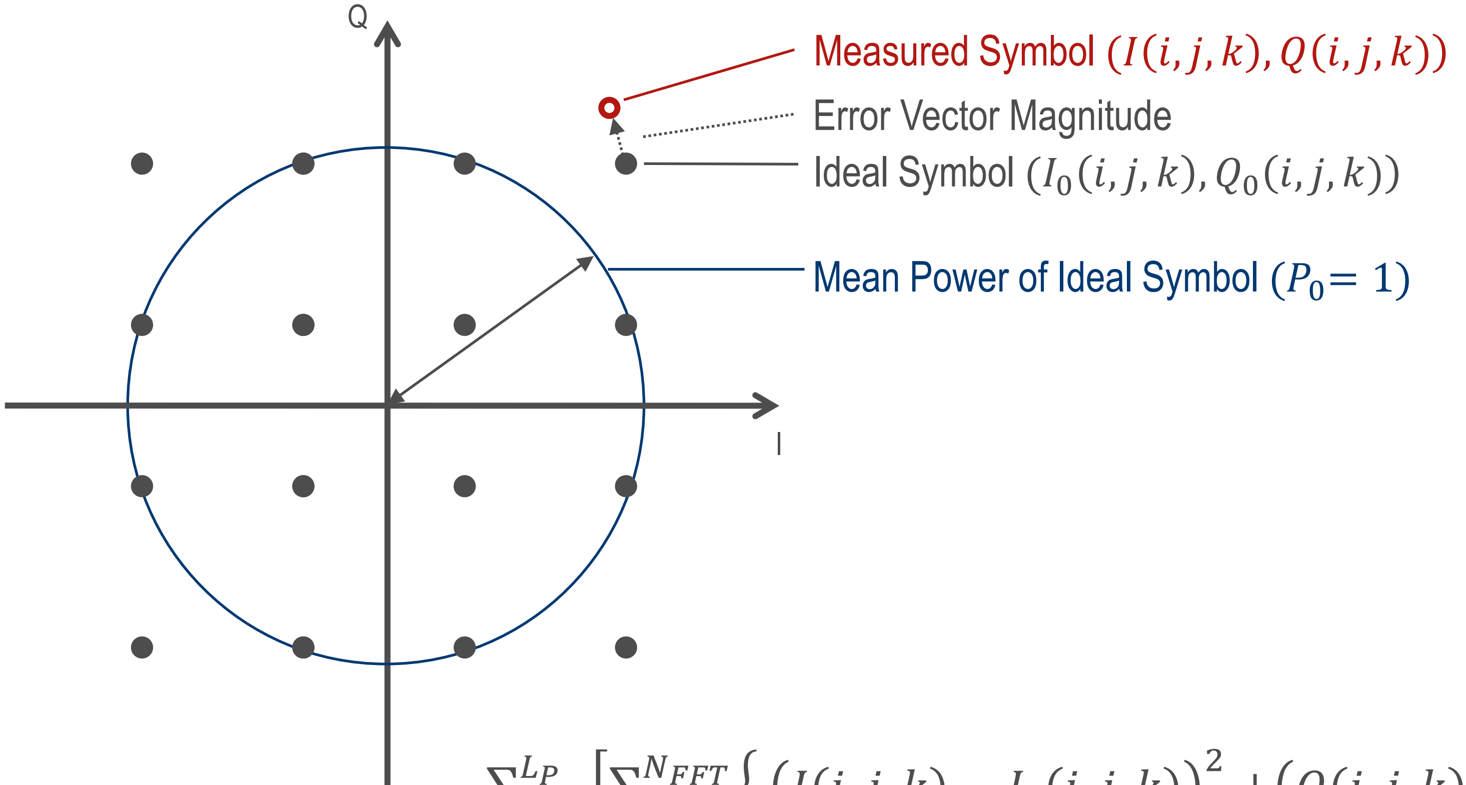
Error Vector Magnitude (EVM)



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.



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

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.

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Digital Predistortion (DPD) Principles

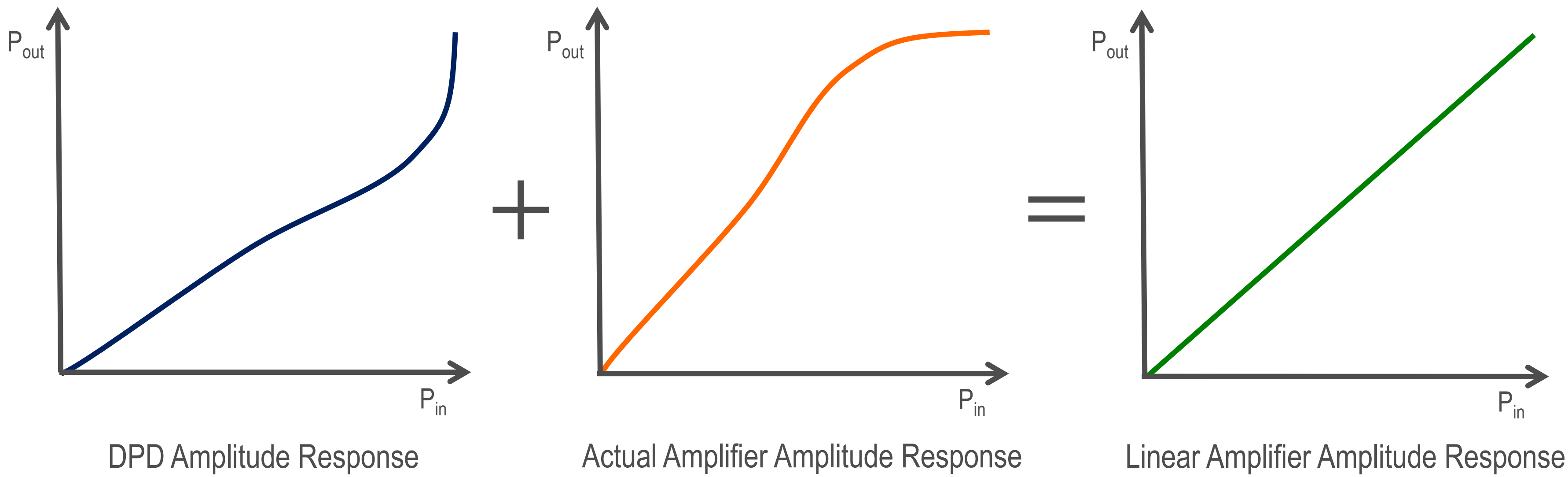
The need for Power Amplifier linearization and efficiency is very important for today's designers.

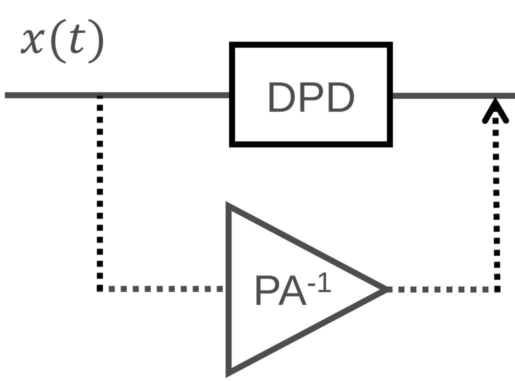
Digital Pre-Distortion has become a critical component of the design process to satisfy this need, as this technique preconditions the signal before the PA to compensate for its non-linear transfer characteristics.

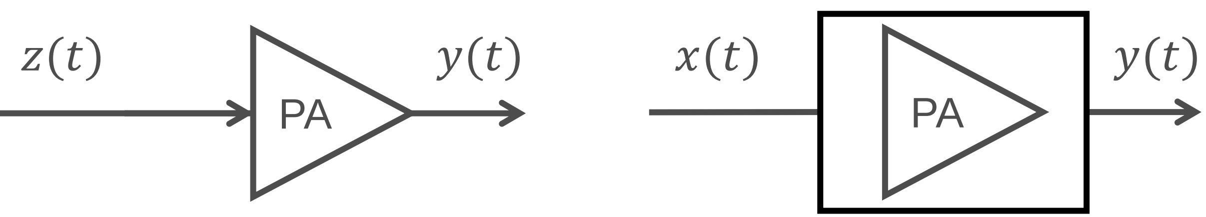
By enabling it to operate in its high power-added efficiency (PAE) region near saturation, it produces a more linear, higher output power radio, without significant signal distortion.

Digital Predistortion Principles

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

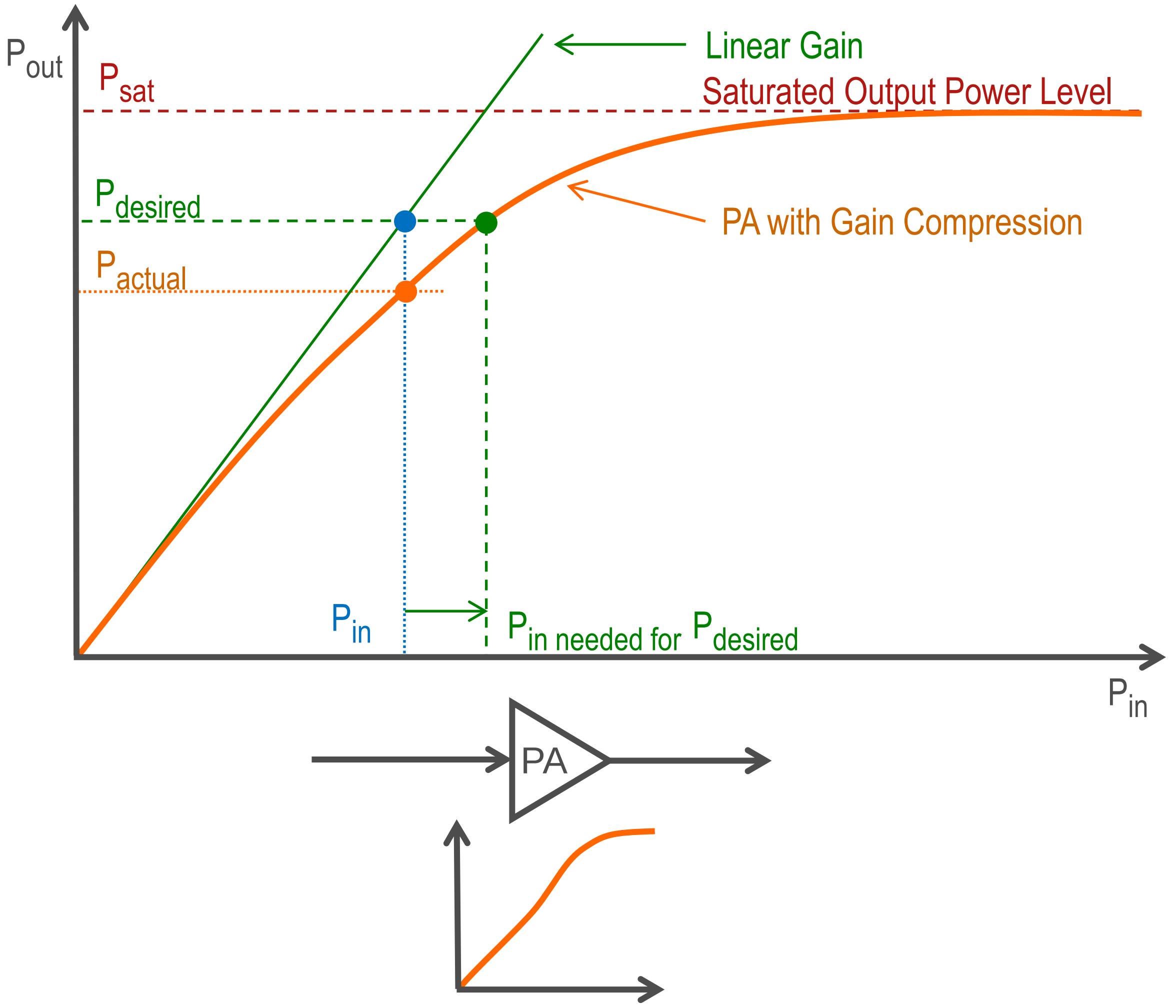




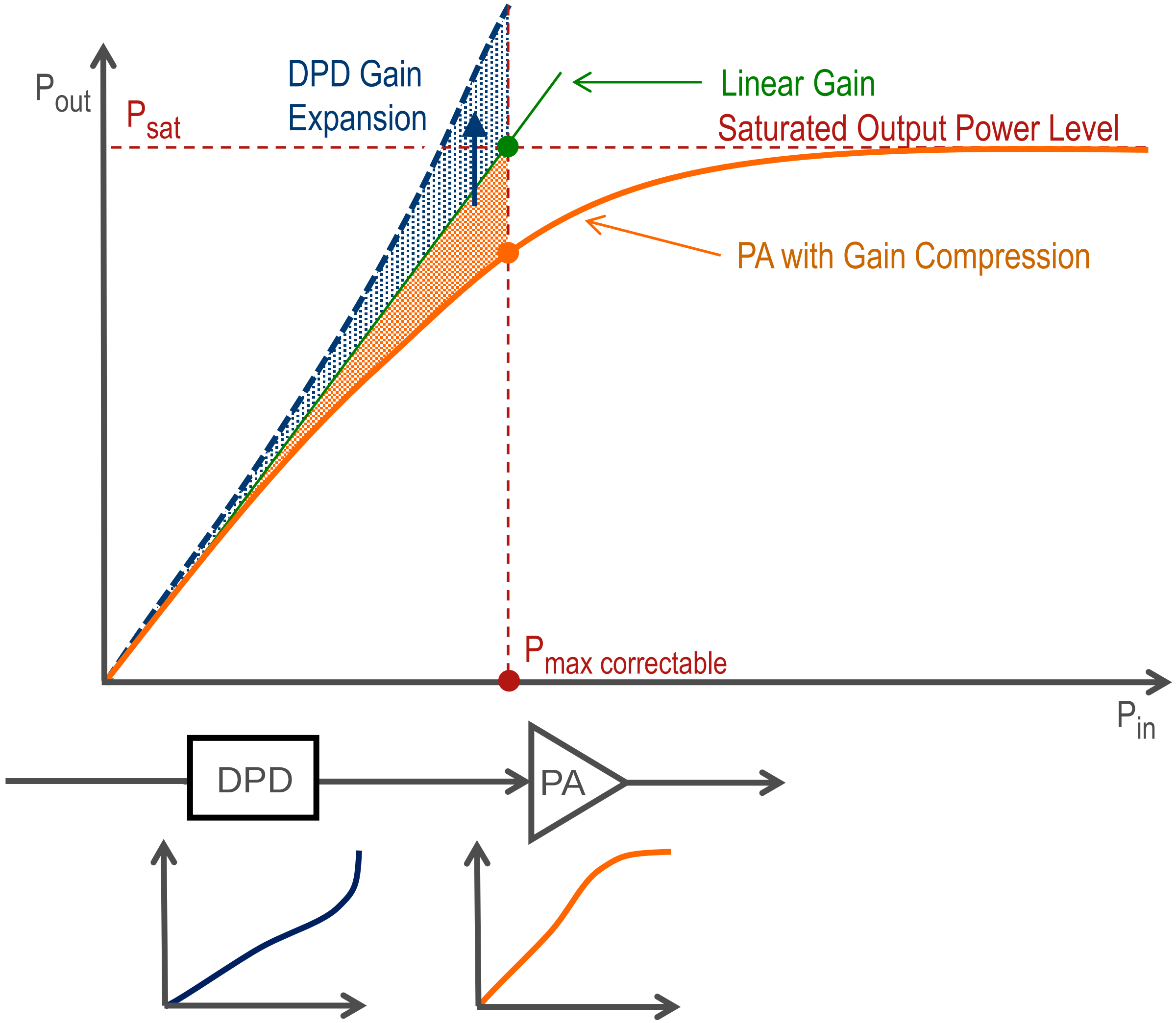


We can see the need to accurately characterize the amplifier behaviour is required to deploy DPD successfully

DPD Principles: The Compressing PA

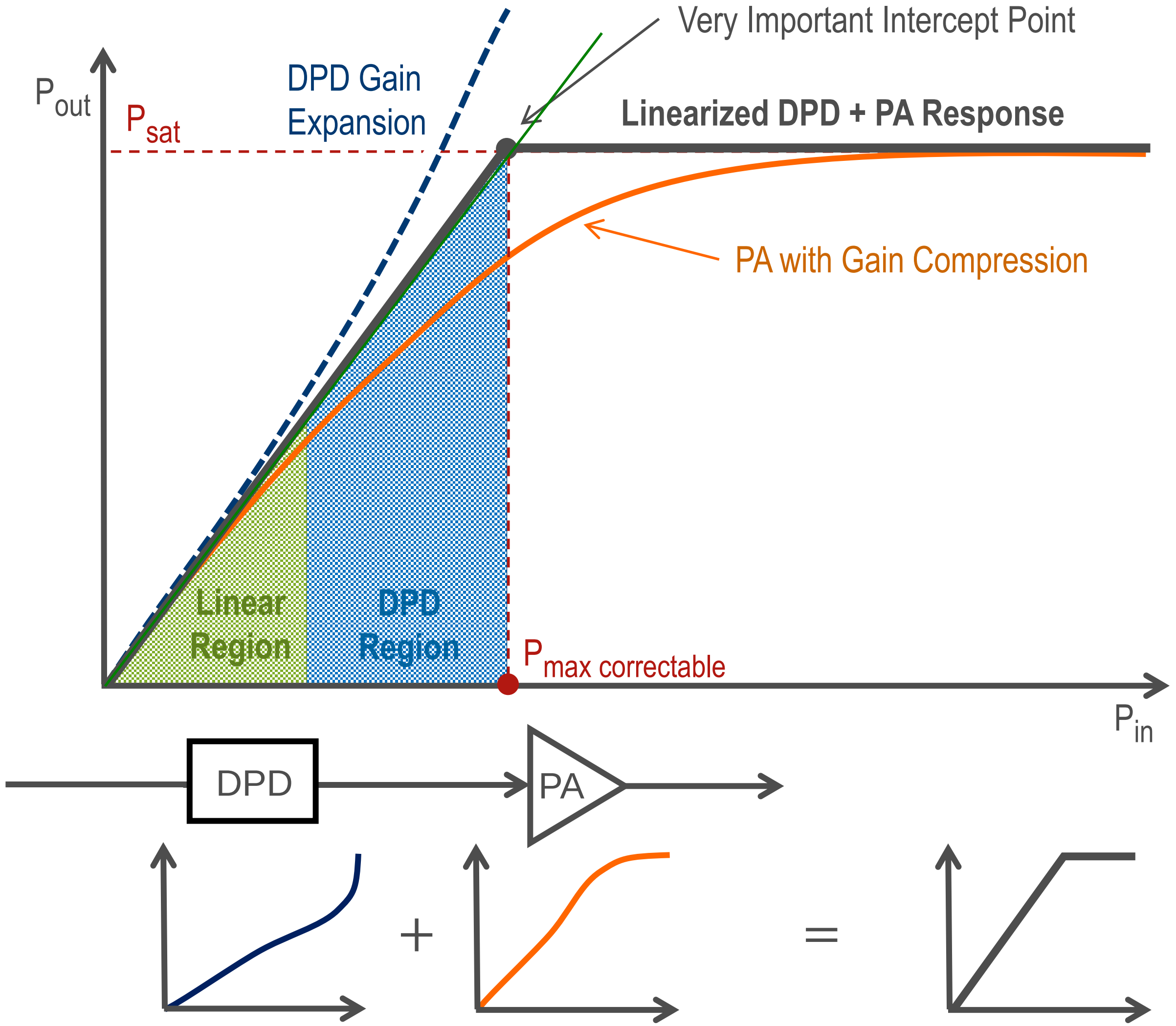


DPD Principles: Pre-Expansion



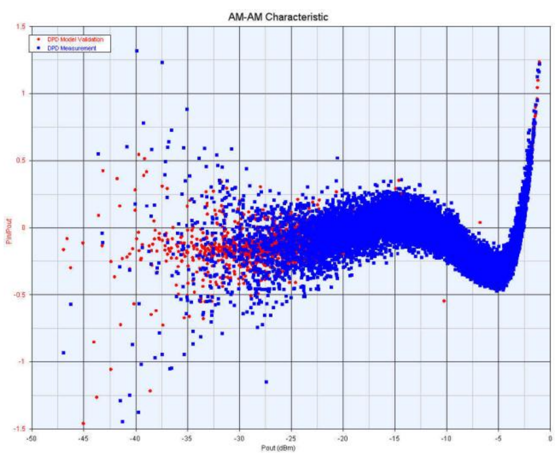
SLIDE 18

DPD Principles: Linearized Results

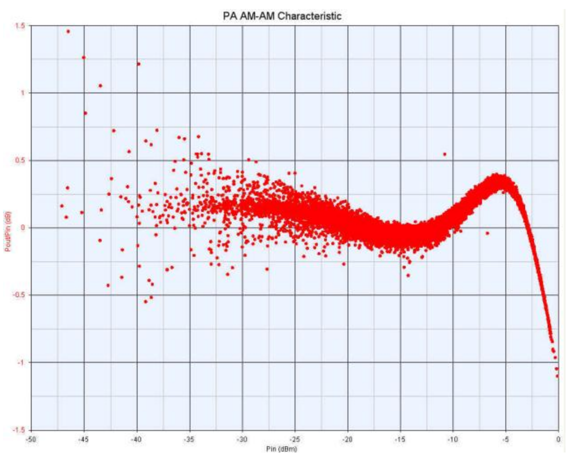


AM-AM Effects: Change in Gain vs Power Levels

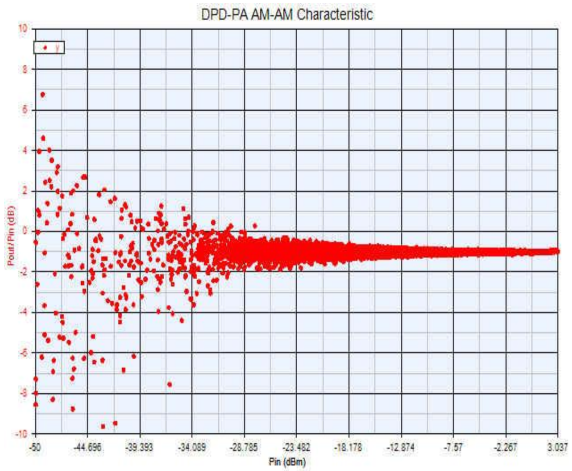
Pre-Distorter AM-to-AM

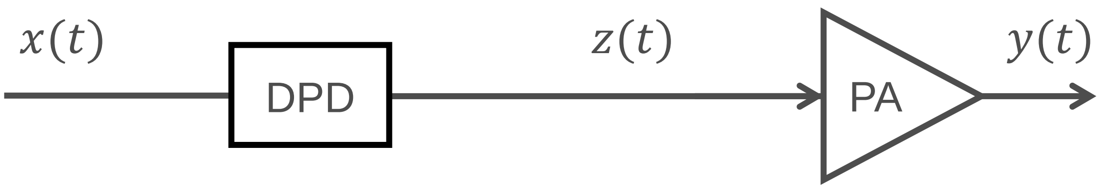


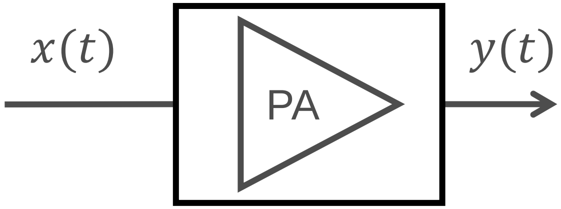
Power Amp AM-to-AM



DPD + PA AM-to-AM







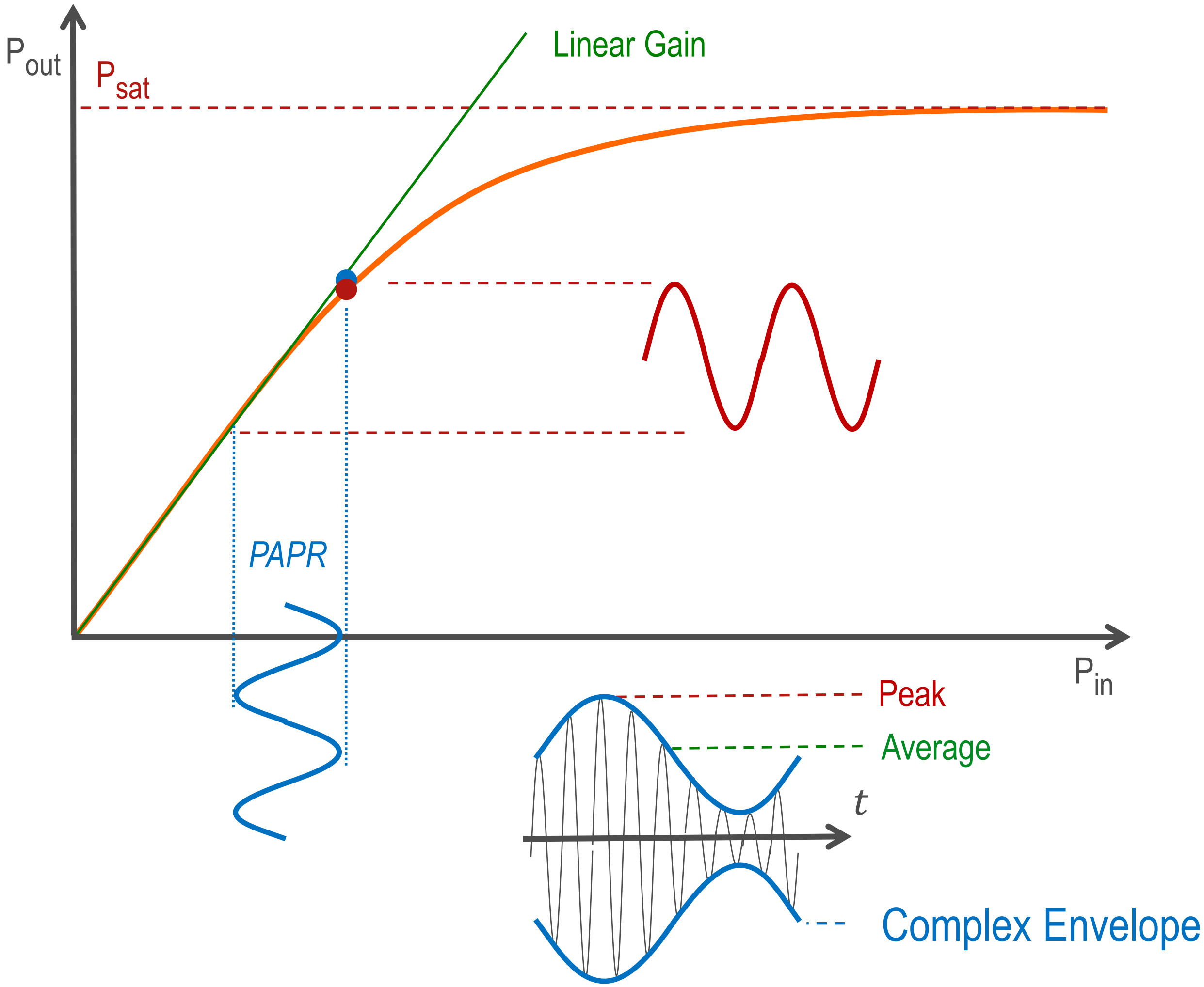
Some Key Definitions for this Class:

- **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…

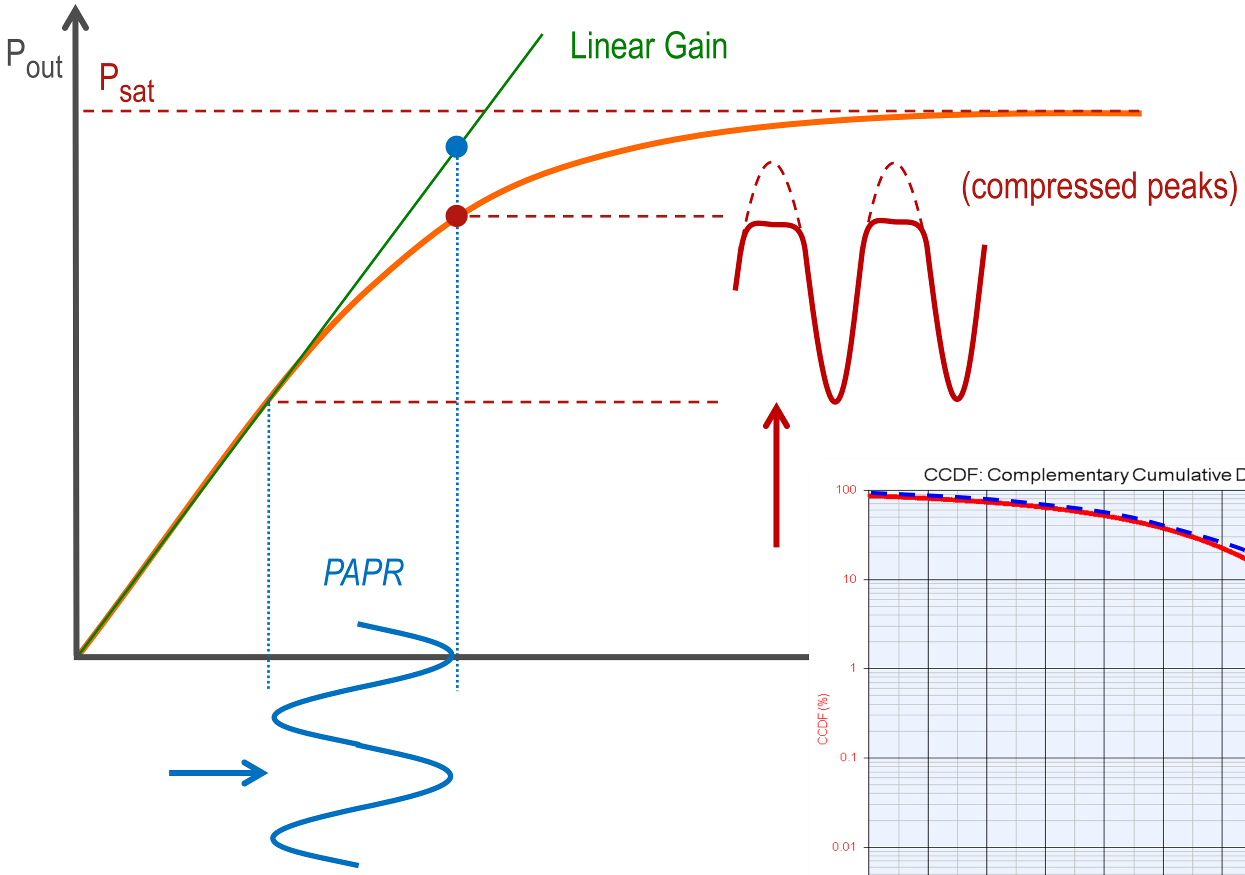
DPD Principles: Time Varying Envelope

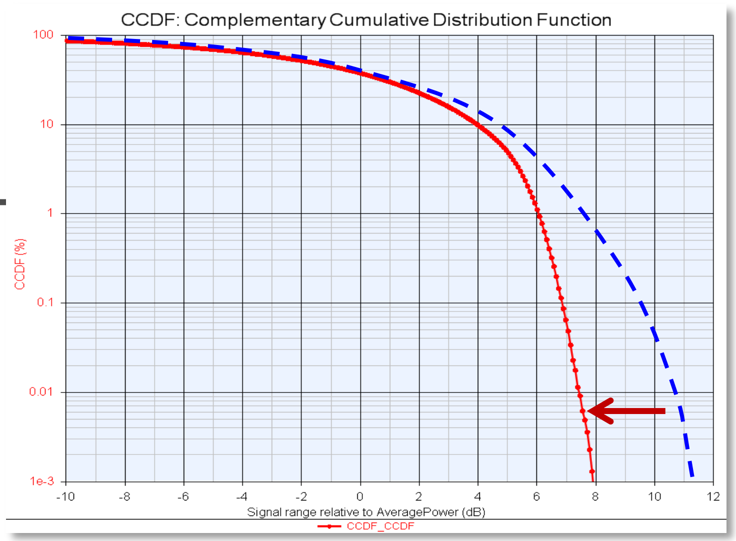
Linear Operation



DPD Principles: Time Varying Envelope

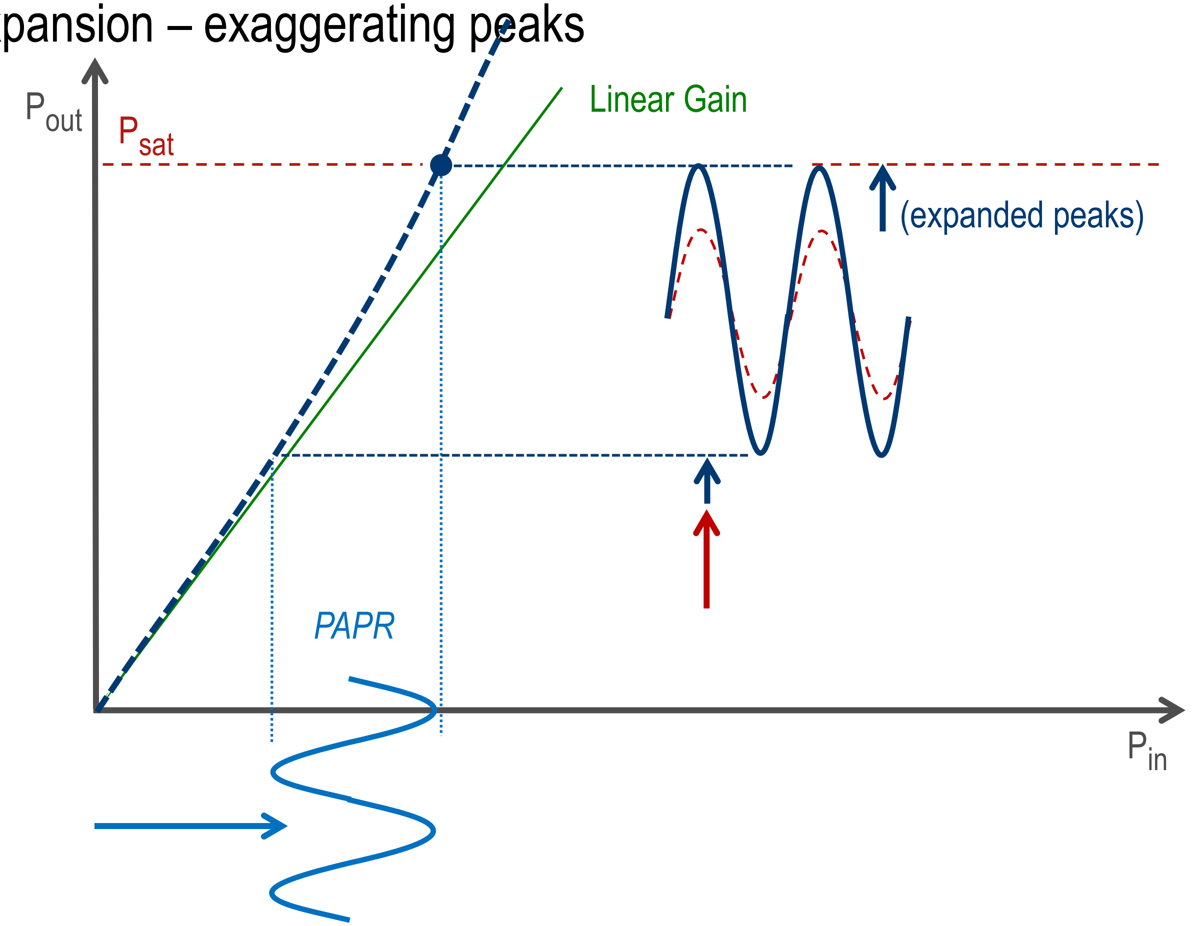
Nonlinear Operation – Peaks are Compressed



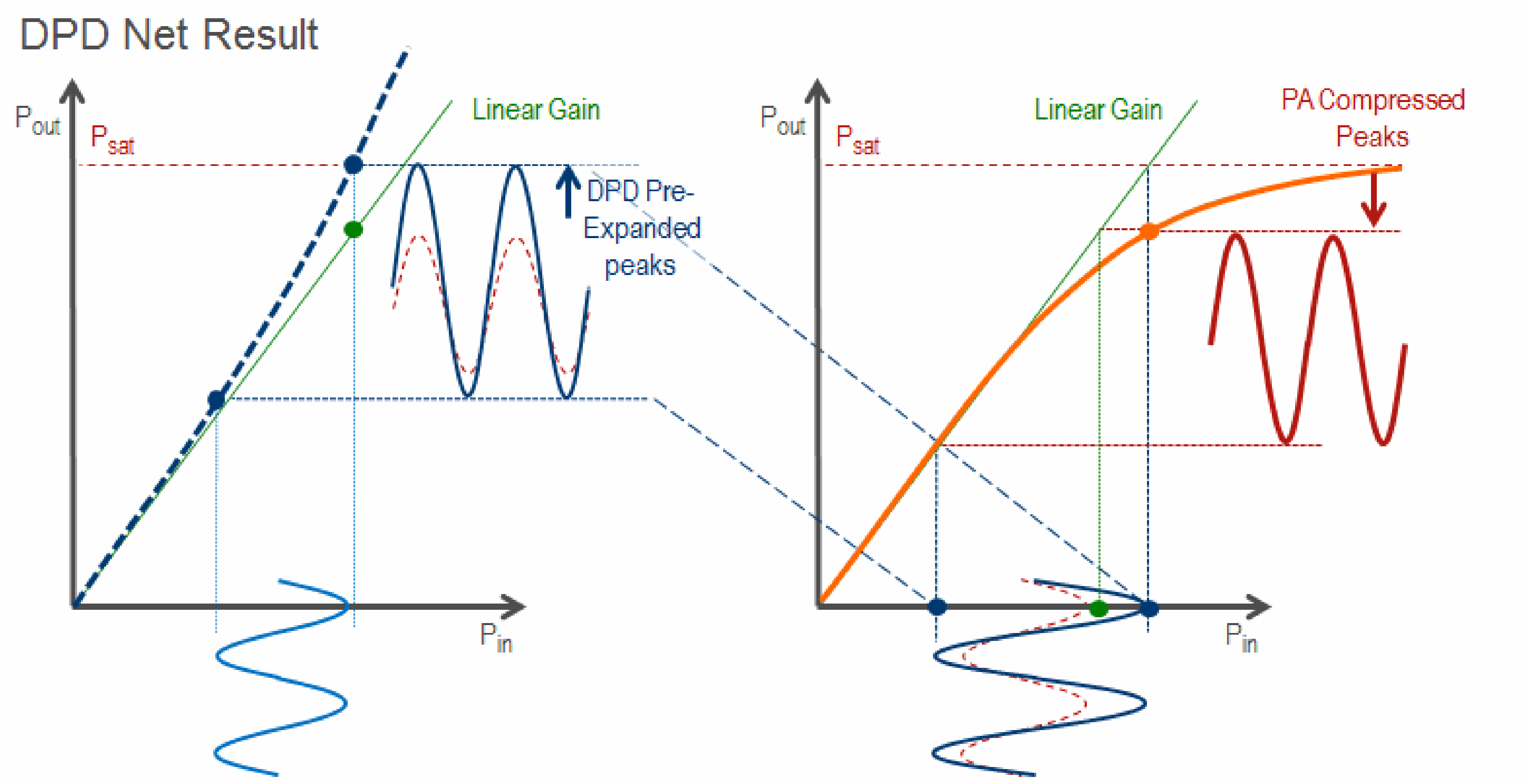


DPD Principles: Time Varying Envelope

DPD Pre-Expansion – exaggerating peaks



DPD Principles: Time Varying Envelope



Baseband Digital Pre-Distortion

RF Power Amplification

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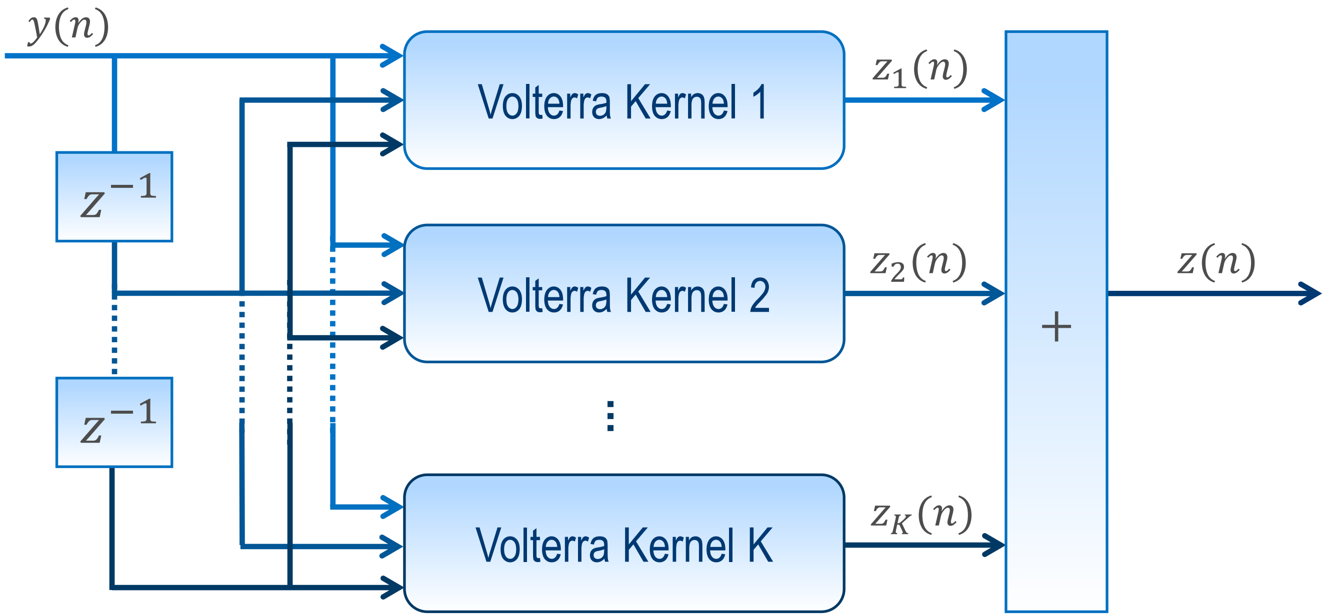
The Volterra Model

The Volterra series predistorted can be described by

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

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:

$$z(n) = \sum_{m_1=0}^{Q} h_1(m_1) y(n-m_1)$$

$$+ \sum_{m_1=0}^{Q} \sum_{m_2=0}^{Q} h_2(m_1,m_2) y(n-m_1) y(n-m_2)$$

$$+ \sum_{m_1=0}^{Q} \sum_{m_2=0}^{Q} \sum_{m_3=0}^{Q} h_3(m_1,m_2,m_3)\, y(n-m_1) y(n-m_2) y(n-m_3)$$

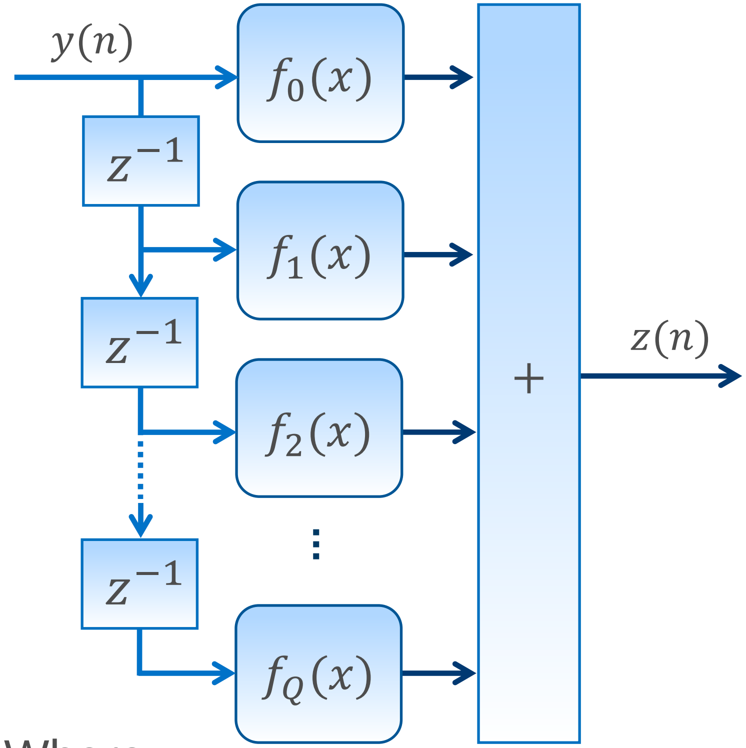
$$+ \cdots$$

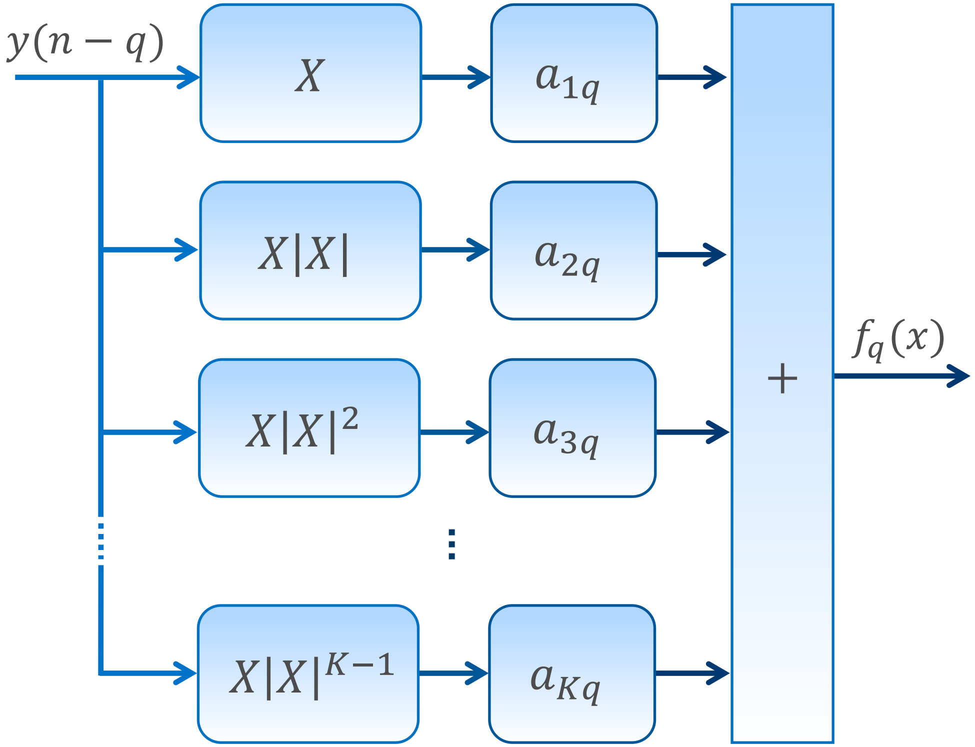
Where:
Q is the memory order and
m_1, m_2, m_3 is the memory depth:

$h_1(m_1)$	First-order Volterra Model
$h_2(m_1, m_2)$	Second-order Volterra Model
$h_3(m_1, m_2, m_3)$	Third-order Volterra Model

Memory Polynomial Model

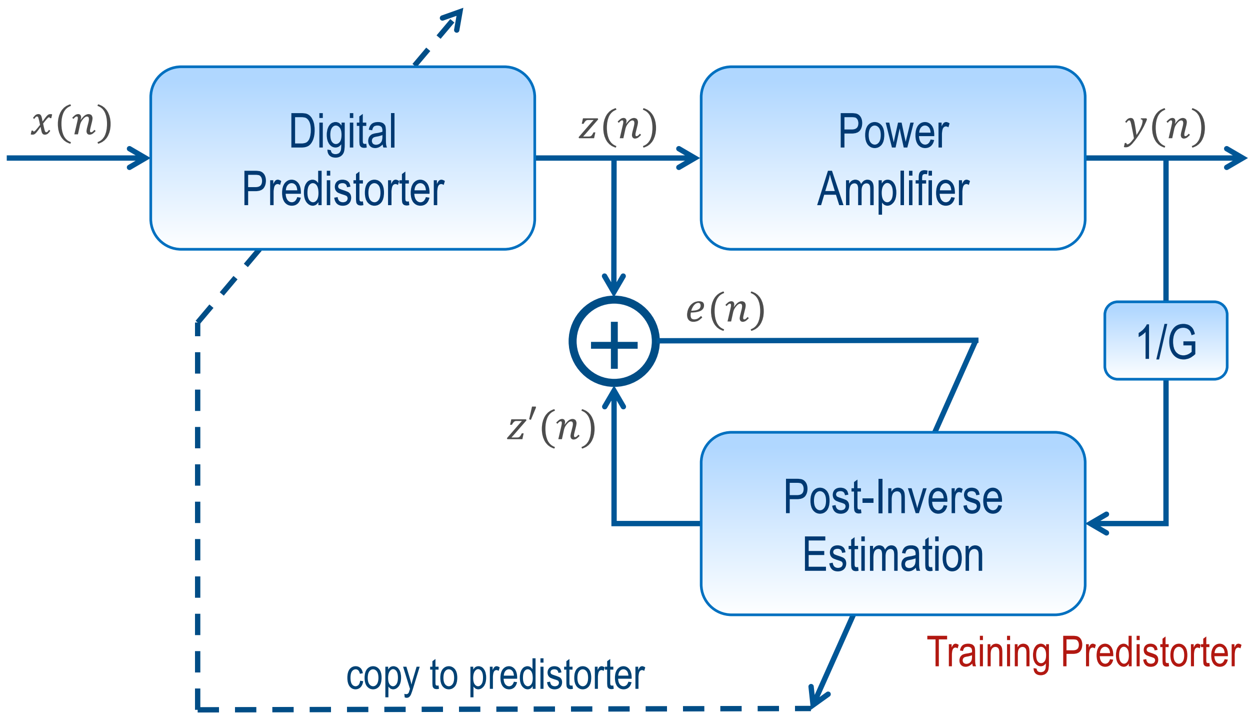
$$z(n) = \sum_{k=1}^{K} \sum_{q=0}^{Q} a_{kq} y(n-q)\,|y(n-q)|^{k-1}$$





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.

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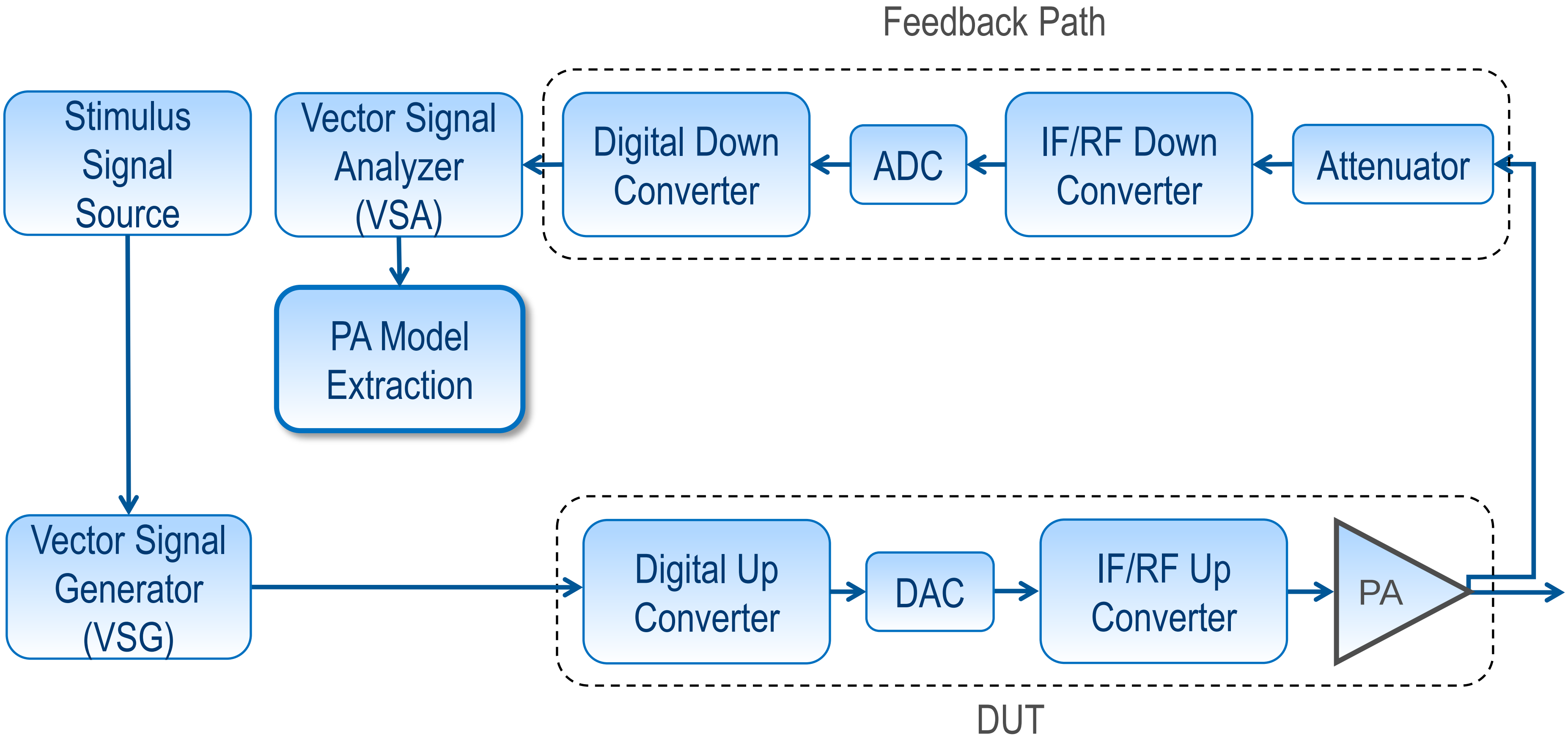
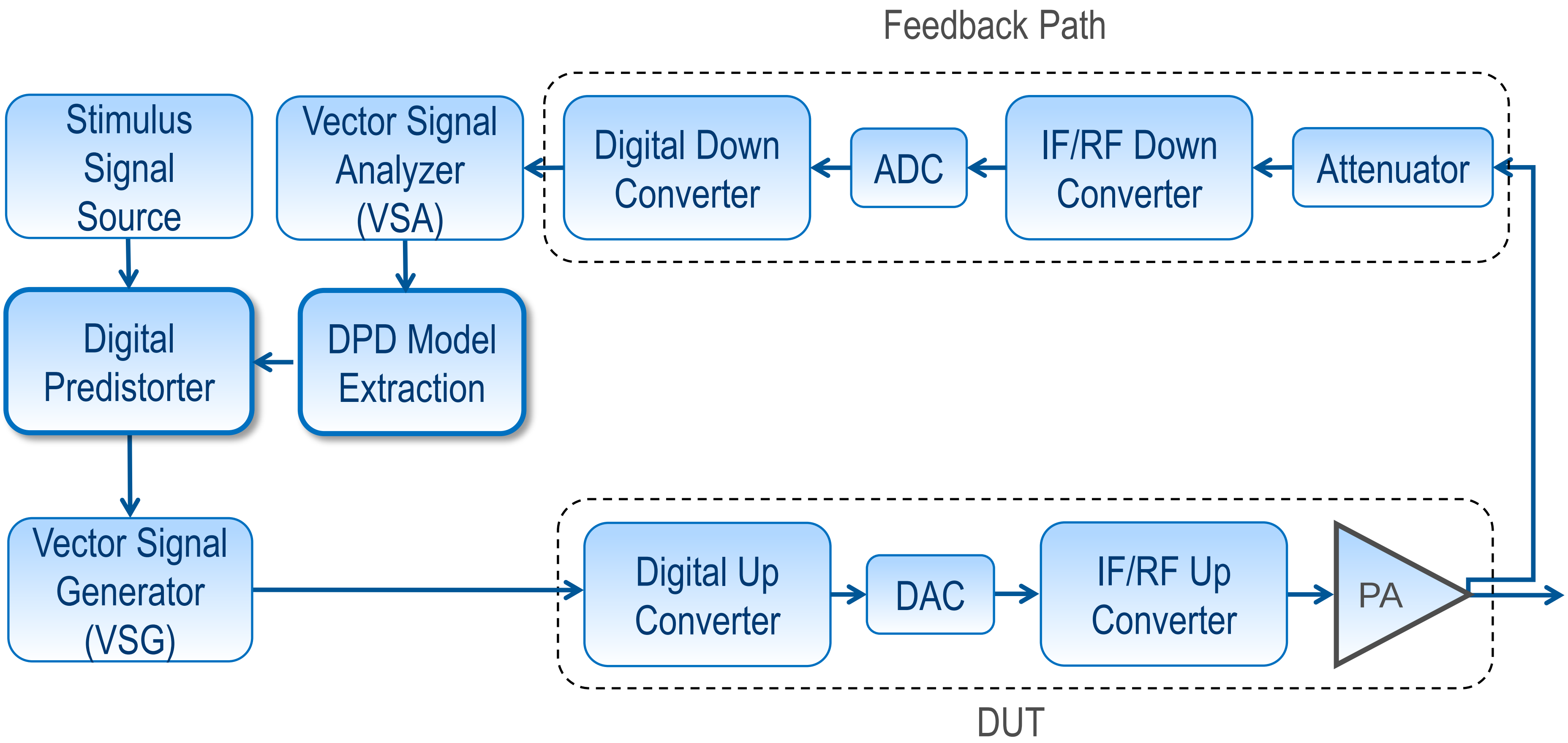
PA Modeling Verification System



DPD Verification System



The Steps Required for Successful DPD

The SystemVue DPD flow is a 5 step process

1 Create DPD Stimulus

Step 1 is to generate stimulus waveform (such as LTE, LTE-A, 802.11ac or multi-standard radio).

2 Capture PA Response

Step 2 is to measure the RF PA input and RF PA output, as independent physical measurements

3 Extract DPD Model

Step 3 is to extract DPD model. This step also needs synchronization, delay adjustment etc.

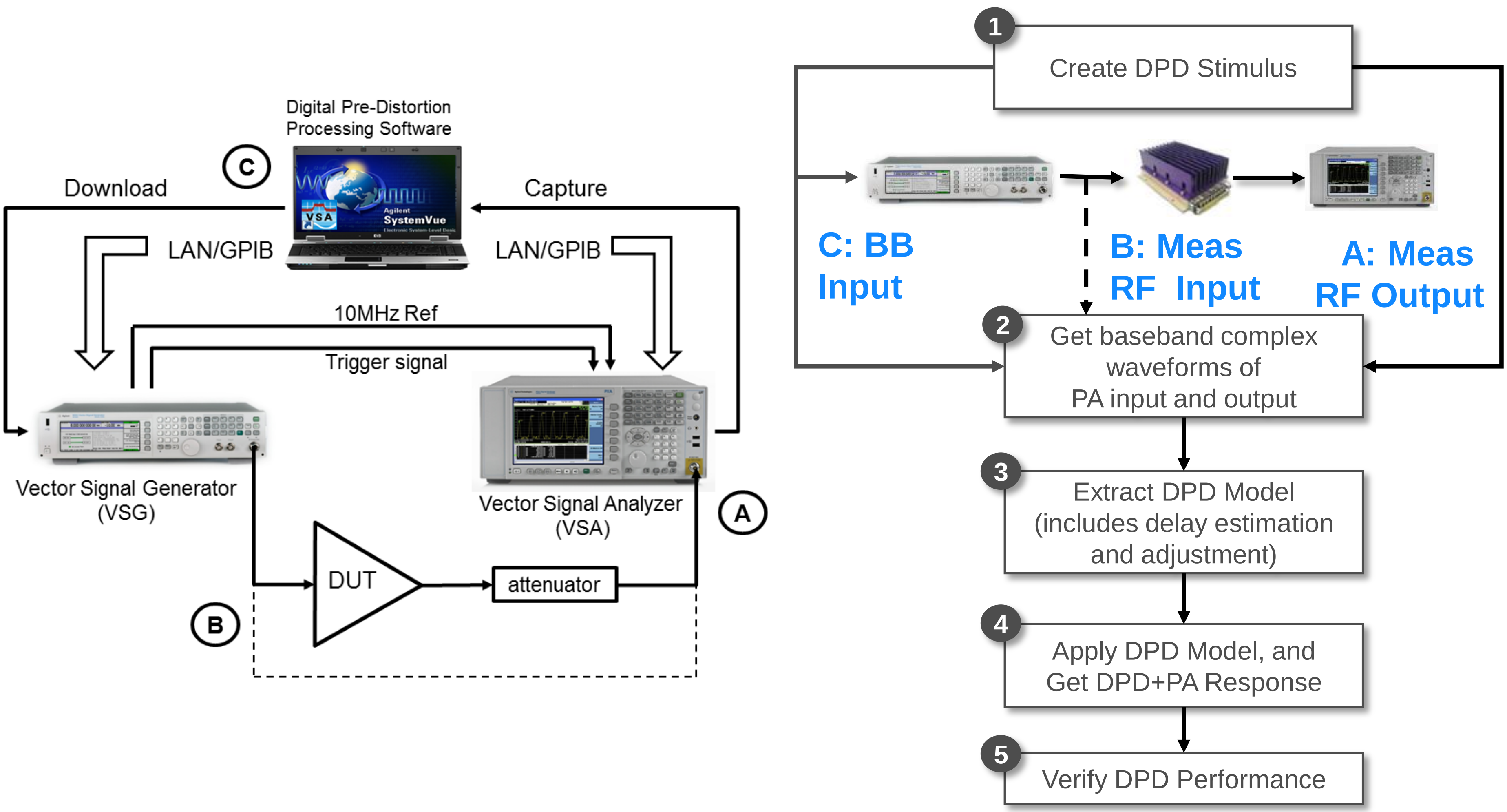
4 Capture DPD + PA Response

Step 4 is to apply DPD model, and capture DPD + PA response

5 Verify DPD + PA Response

Step 5 is to verify the full DPD system performance

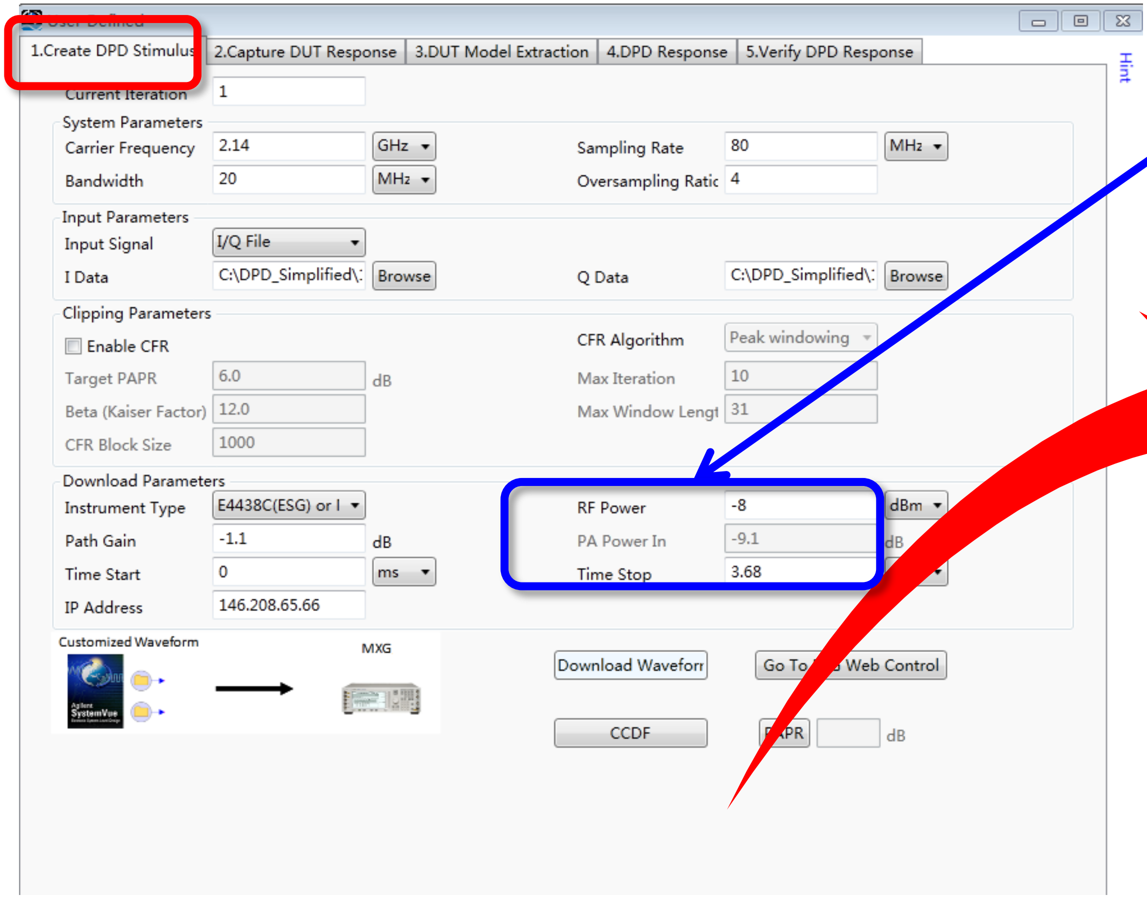
Agilent DPD Verification Platform



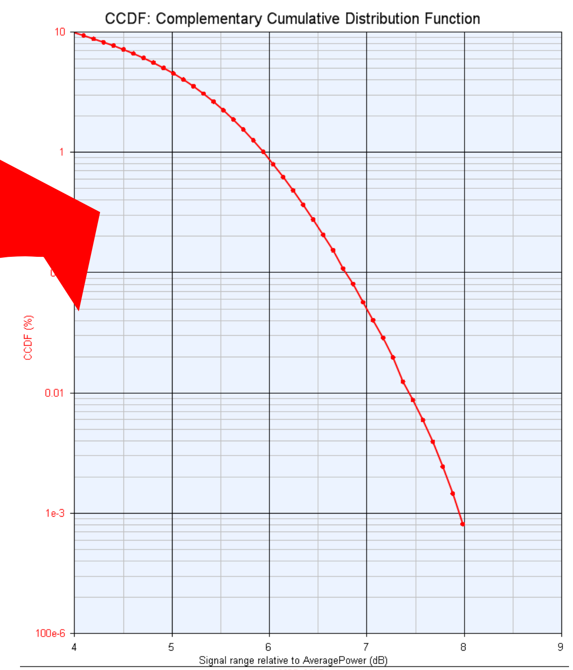
SystemVue DPD Modeling Flow

Step 1. Create DPD stimulus waveform

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



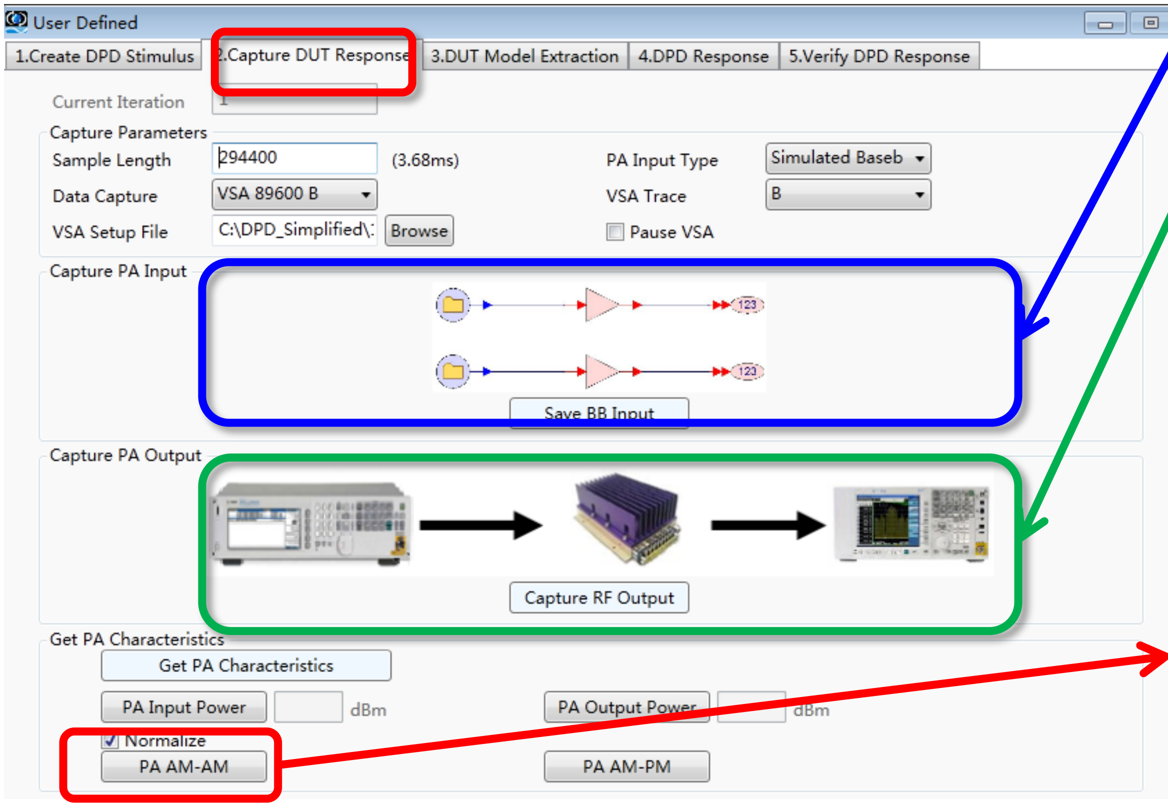
The download **power** and length of the waveform can also be set.



SystemVue DPD Modeling Flow

Step 2. Capture PA response

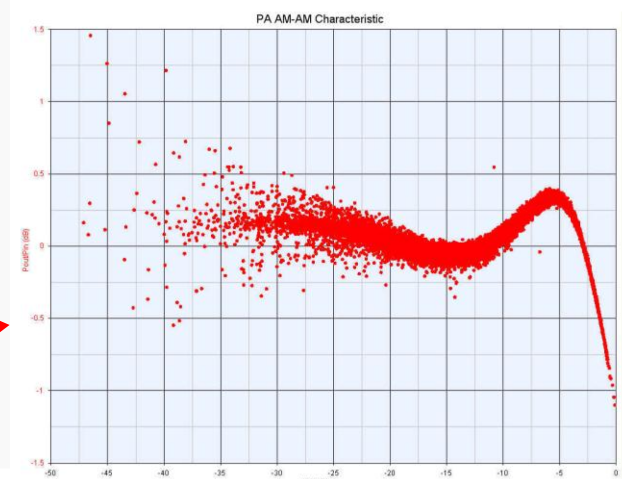
- Get both PA input and output and save them in files
- Can use Agilent VSA89600 software or Command Expert to capture waveform from VSA.
- Show PA AM-AM and AM-PM.



THRU : Save RF PA input or baseband simulation PA input

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

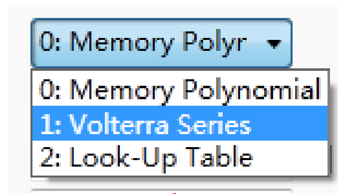
The measured I/Q files are stored and used in following steps.

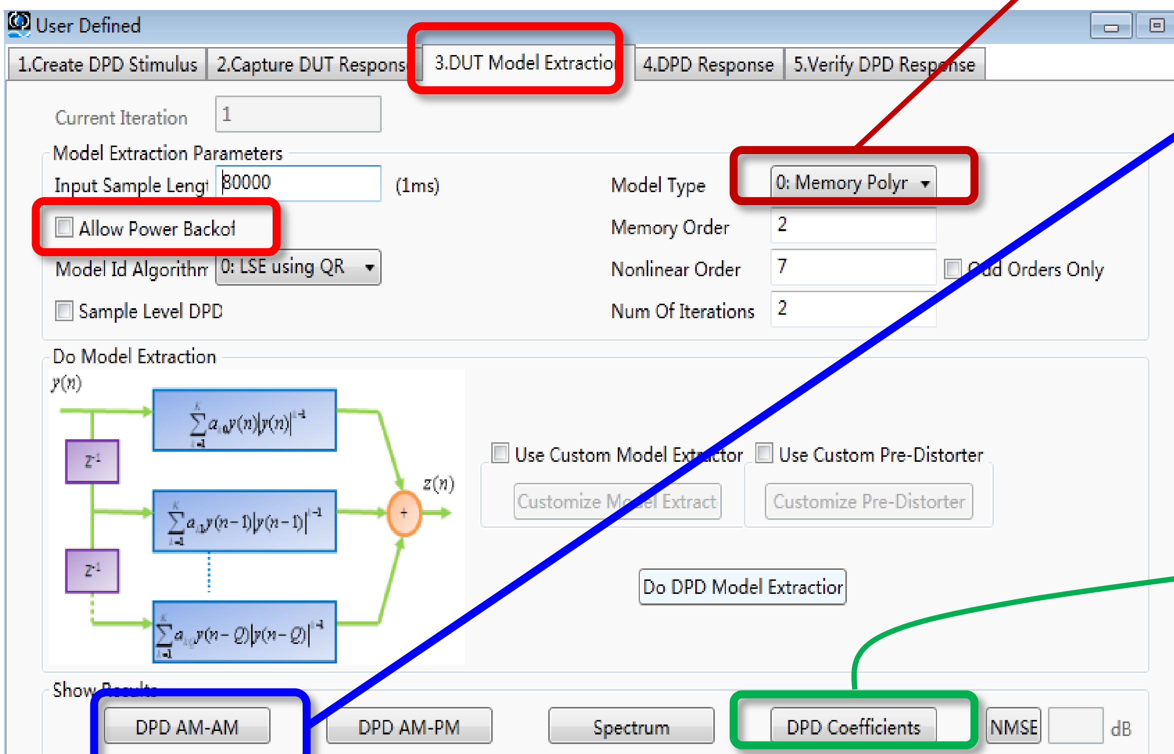


SystemVue DPD Modeling Flow

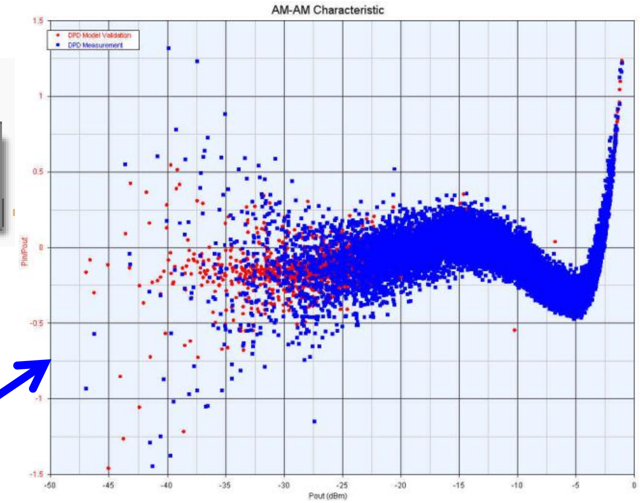
Step 3. DPD Model Extraction

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





DPD AM-to-AM Characteristic

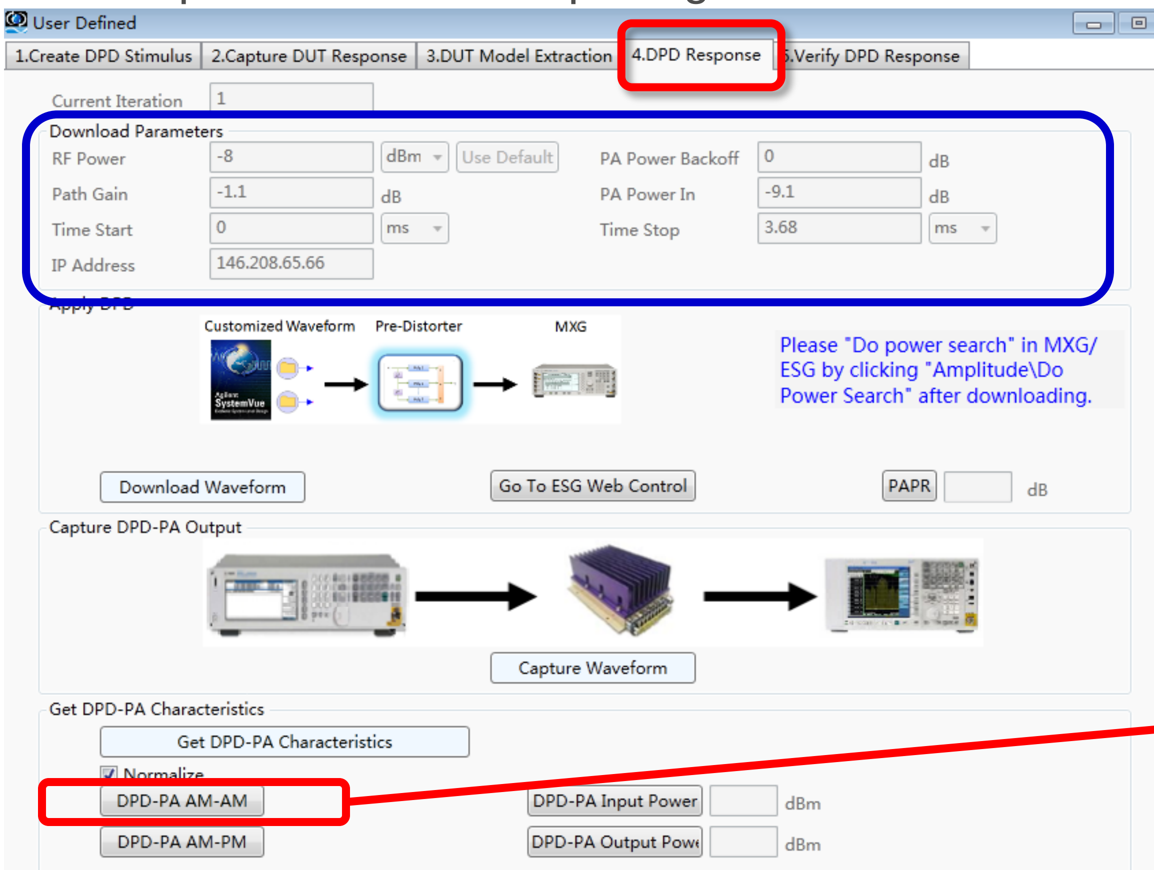


Real	Imaginary
24.272984	54.663756
-29.017471	-58.294568
12.197462	21.366817
-2.018507	-2.897401
0.425925	0.900555
10.991139	18.097705
-14.291582	-22.202843
6.505712	9.560252
-1.196895	-1.656454
0.069031	0.086404

SystemVue DPD Modeling Flow

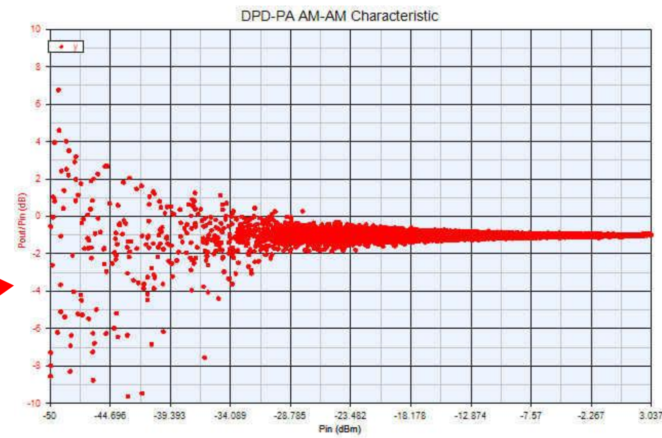
Step 4. Capture DPD+PA Response

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



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..

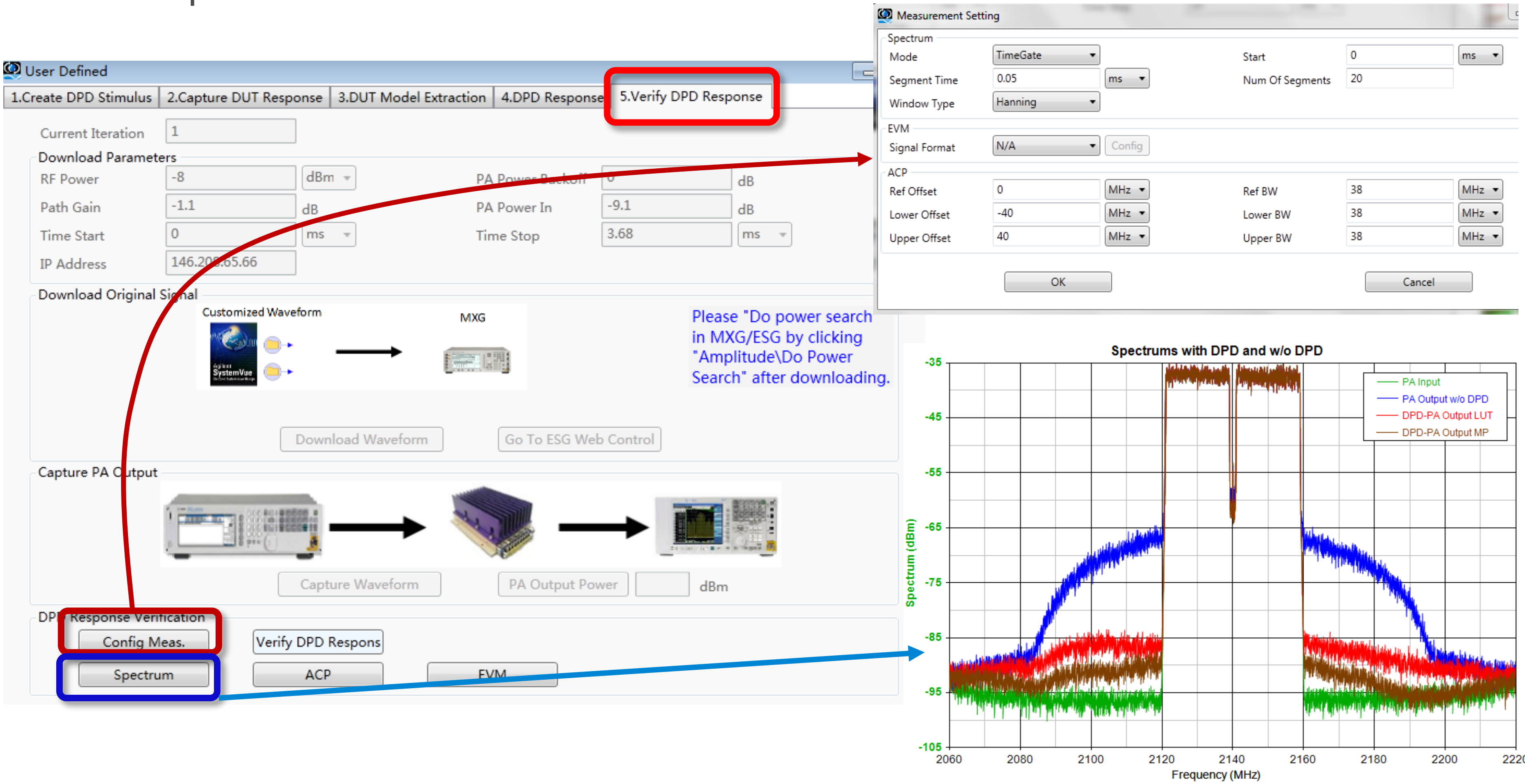
DPD+PA AM-to-AM Characteristic



SystemVue DPD Modeling Flow

Step 5. Verify DPD+PA response

- Compare results with DPD and without DPD.



Summary

Problem statement

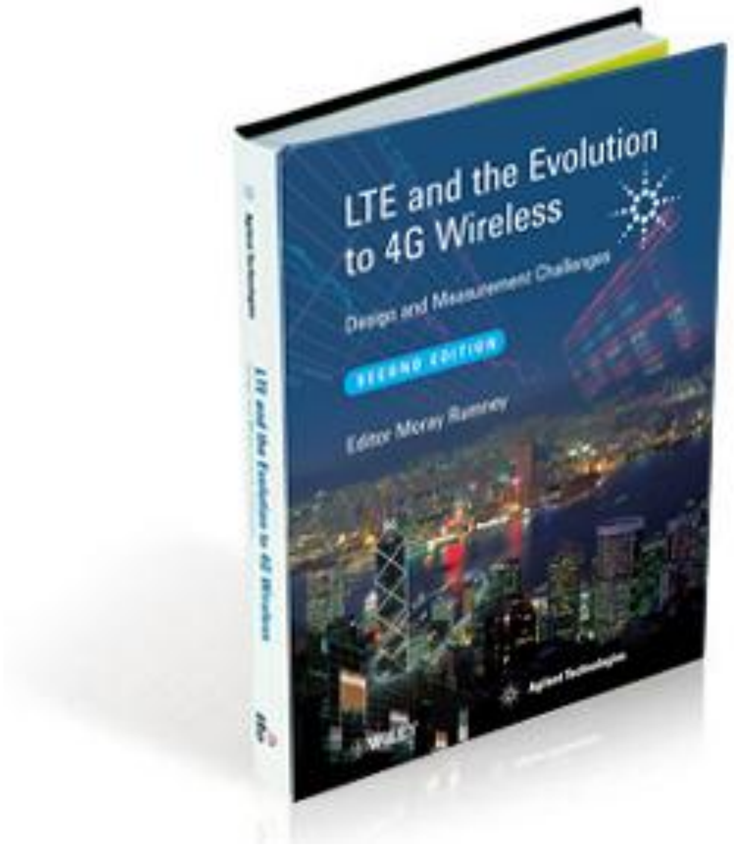
HF high power amplifier measurement needs tomeasure IMD3 and IMD5. It’s a big challenge to pass IMD3 and IMD5 measurement.

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

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SystemVue

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