Welcome

DPD for Everyone and by Everyone

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Sr. Member IEEE

Agenda

About Digital Pre-Distortion (DPD)

DPD challenges for 4G/wideband systems

Design a PA that is more linearizable

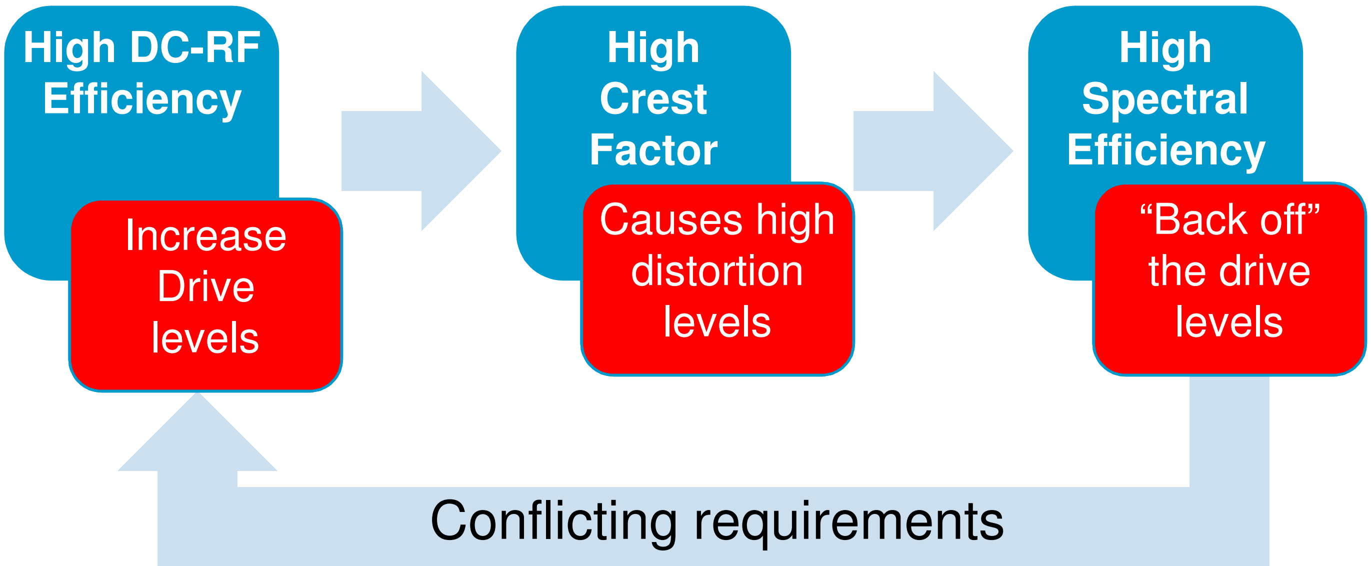
Understand the limits of the DPD algorithm

Practical implementation

Some Results

Q&A

Problem Statement



How to handle signals with high Crest Factor, while driving the PA to operate with high PAE, while also having low signal distortion?

Solution Approach

CFR

High DC-RF Efficiency

Increase Drive levels

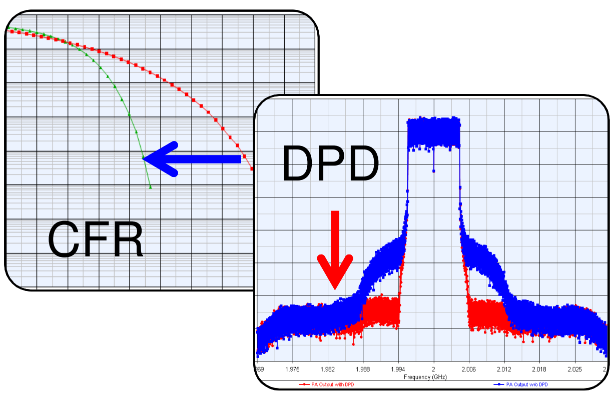
High Crest

Causes high distortion levels

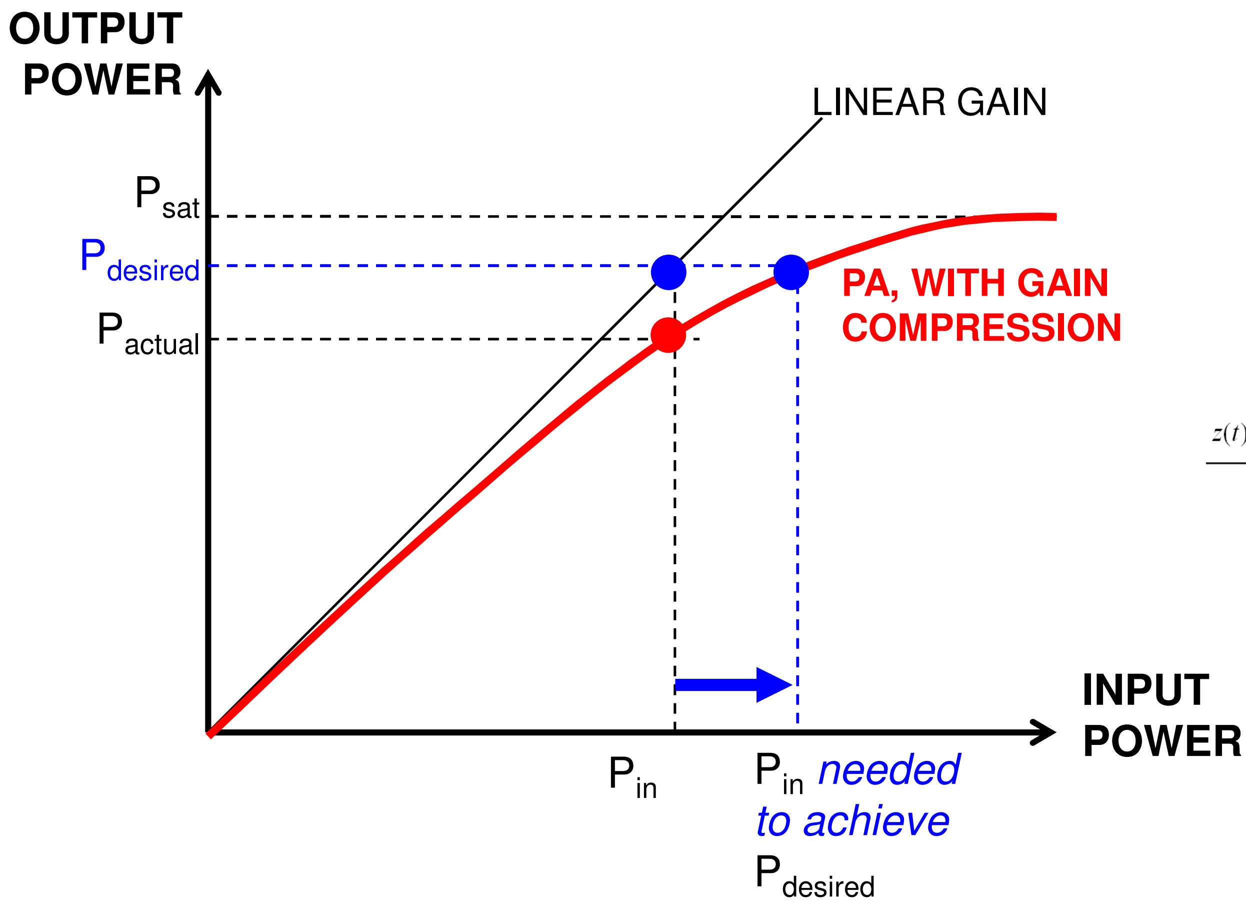
DPD

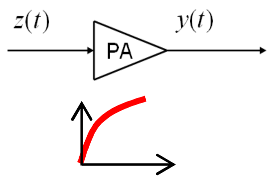
High Spectral Efficiency

Higher Throughput rates for subscribers

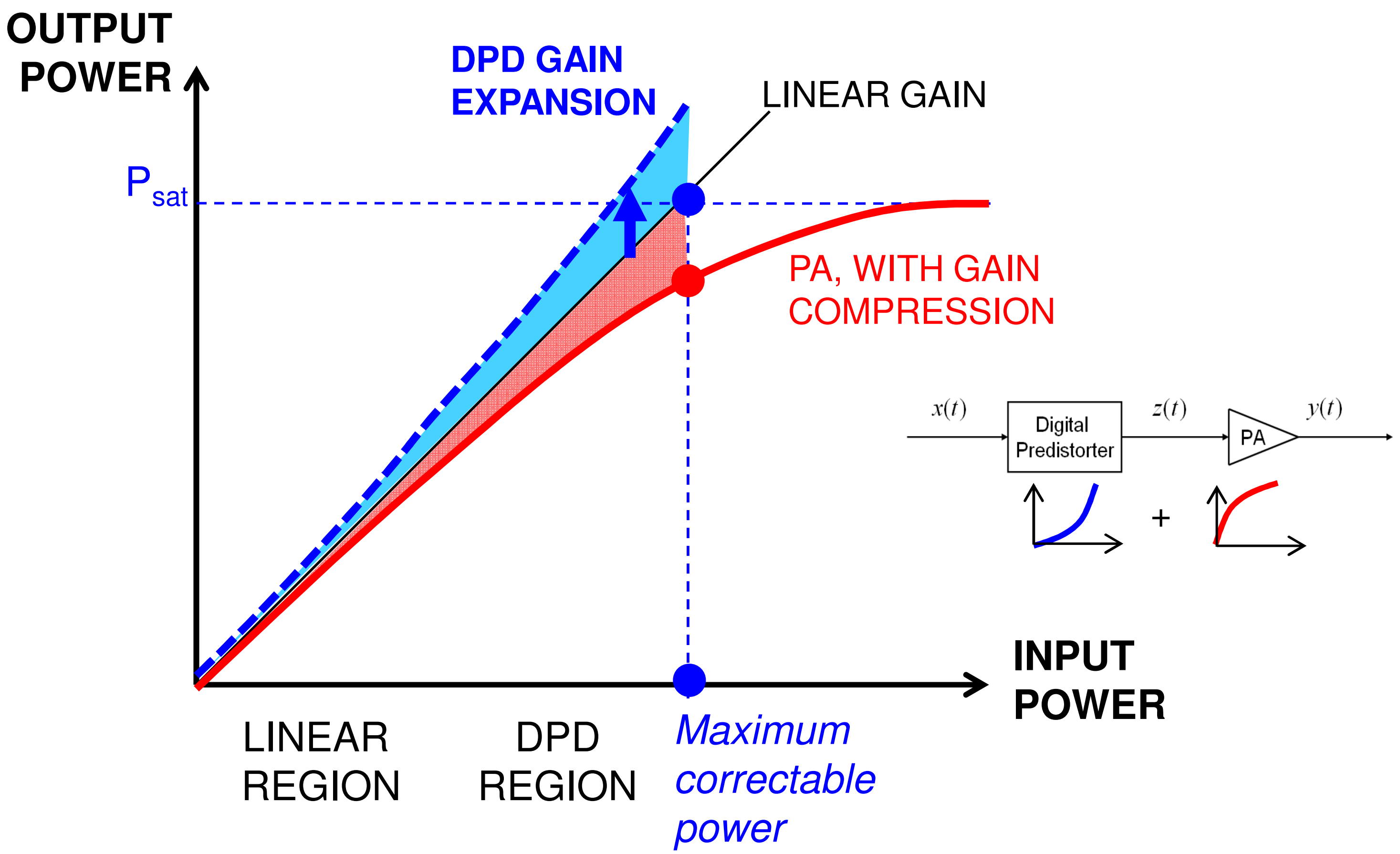


Digital Pre-distortion Principles – Compressing PA

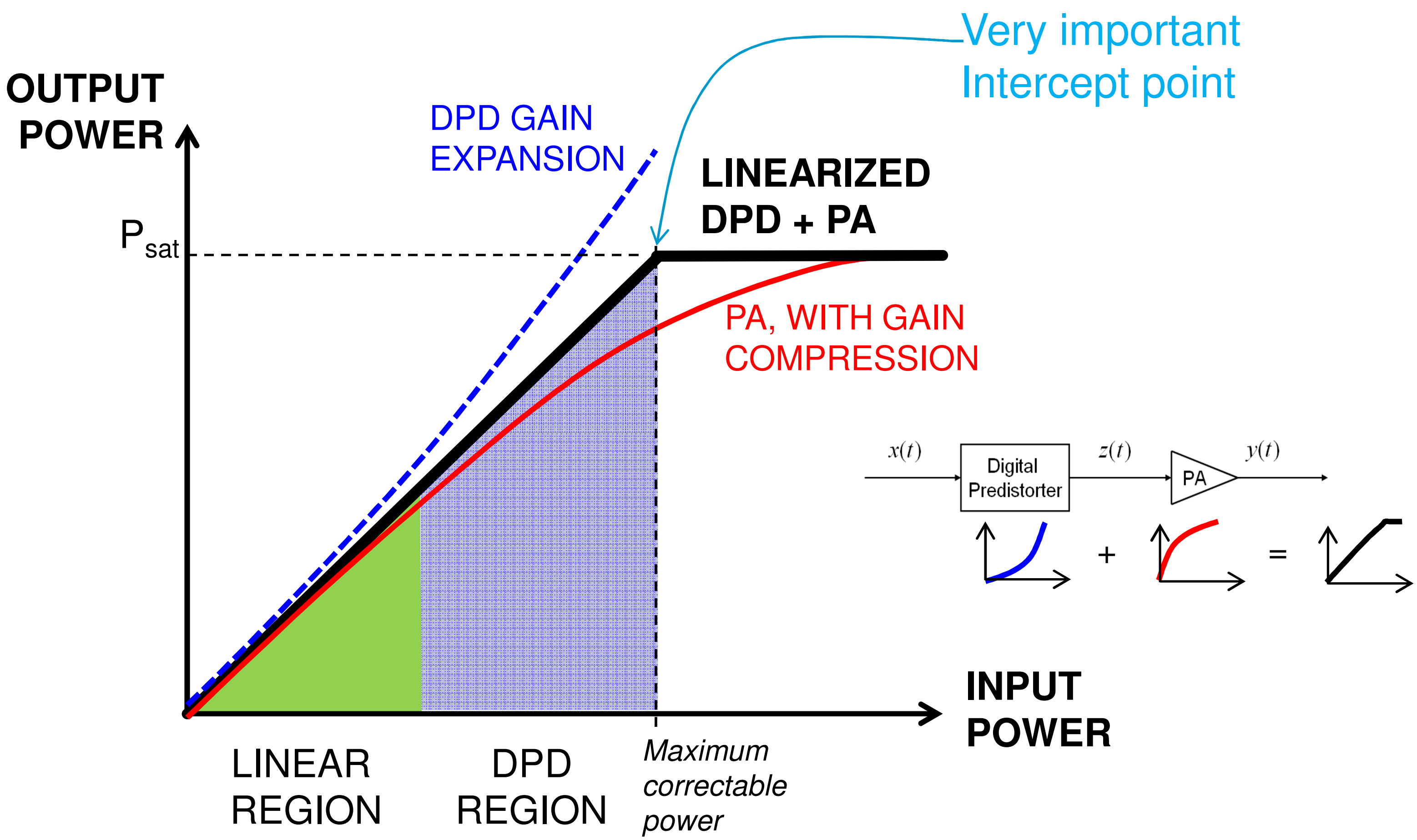




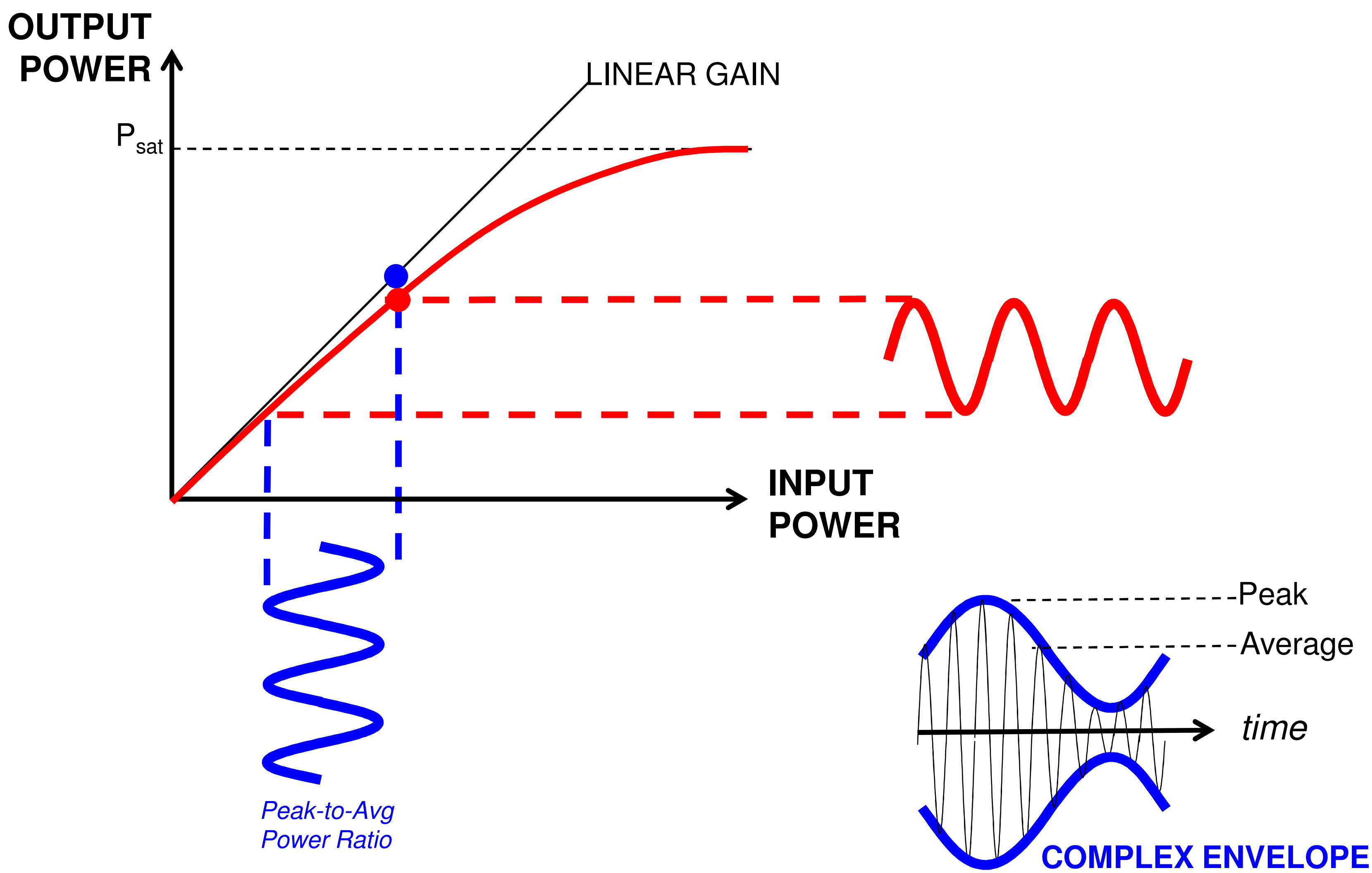
Digital Pre-distortion Principles – Pre-expansion



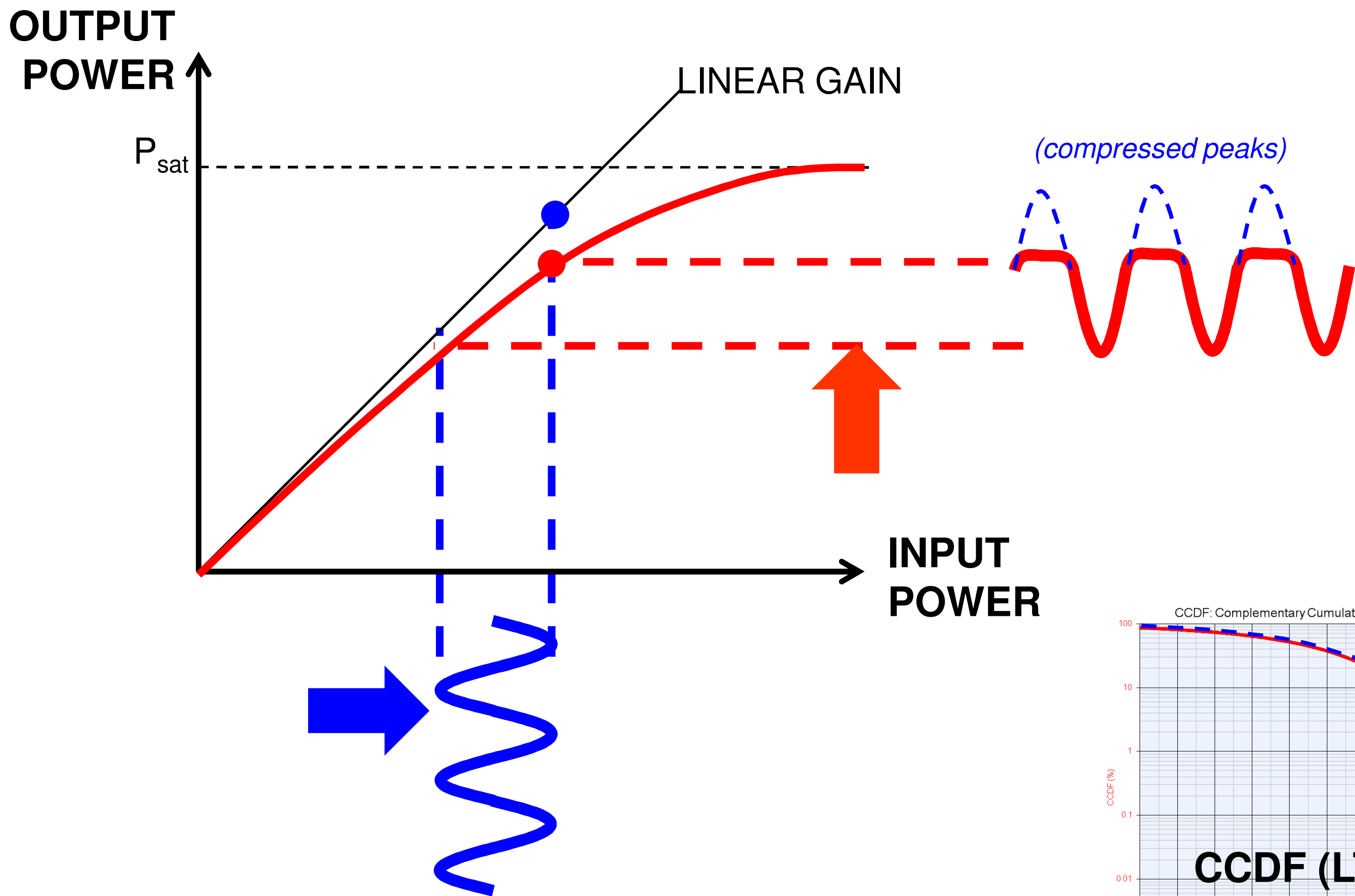
Digital Pre-distortion Principles – Linearized Result

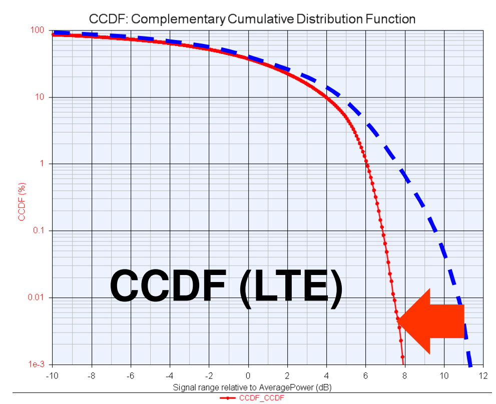


Linear Operation with Time-varying Envelope

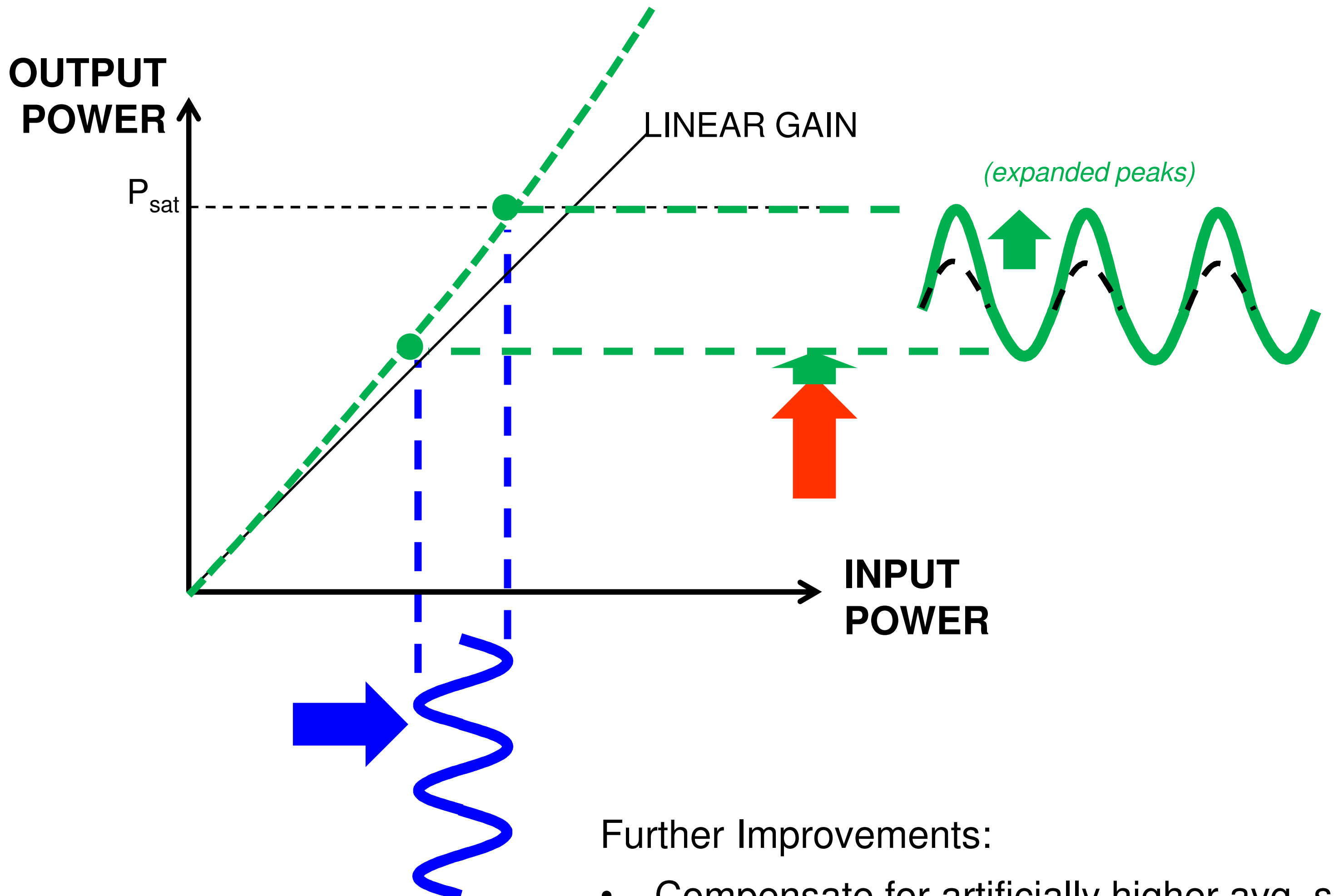


Nonlinear Operation – Peaks are Compressed





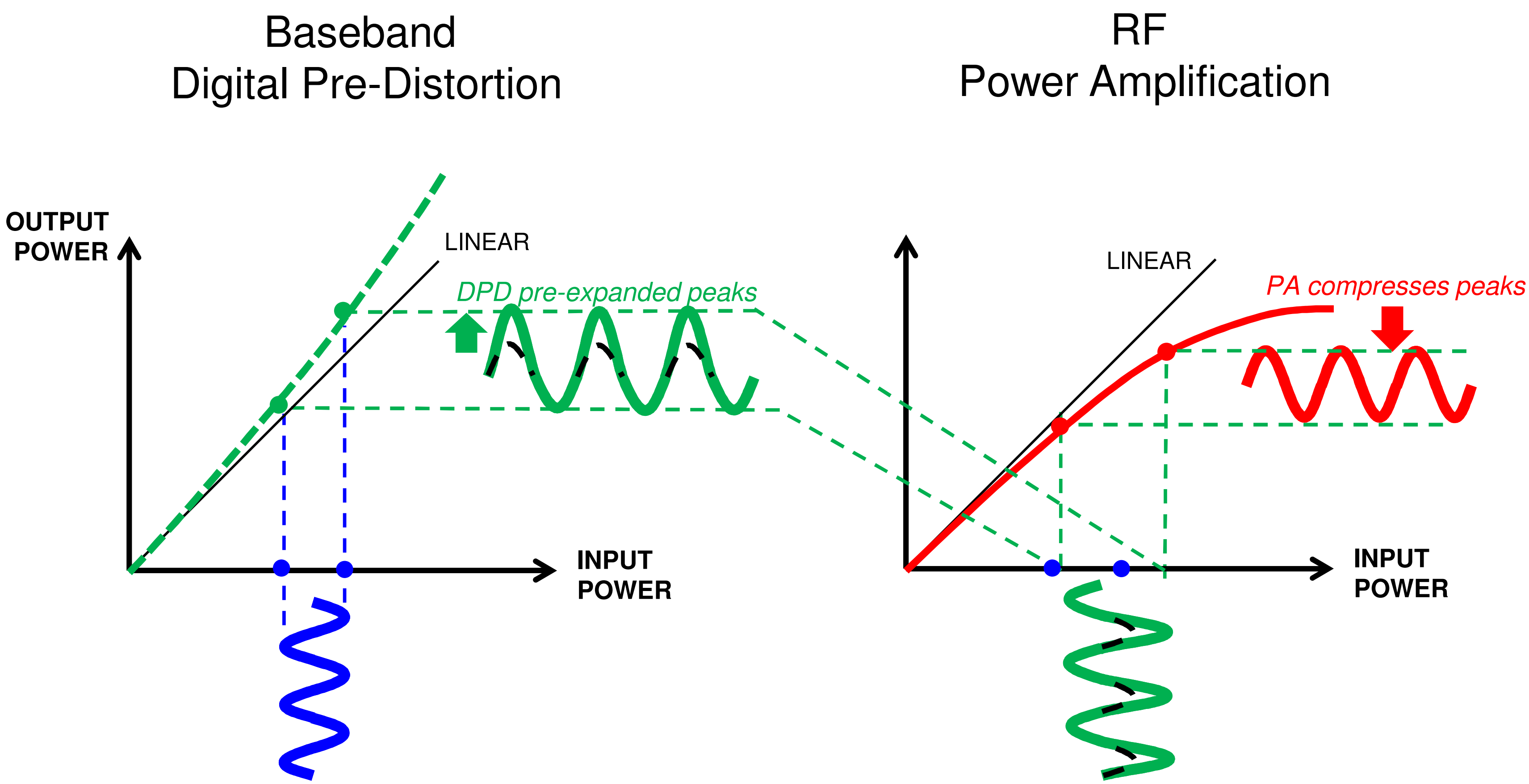
DPD Pre-Expansion – Peaks are Exaggerated



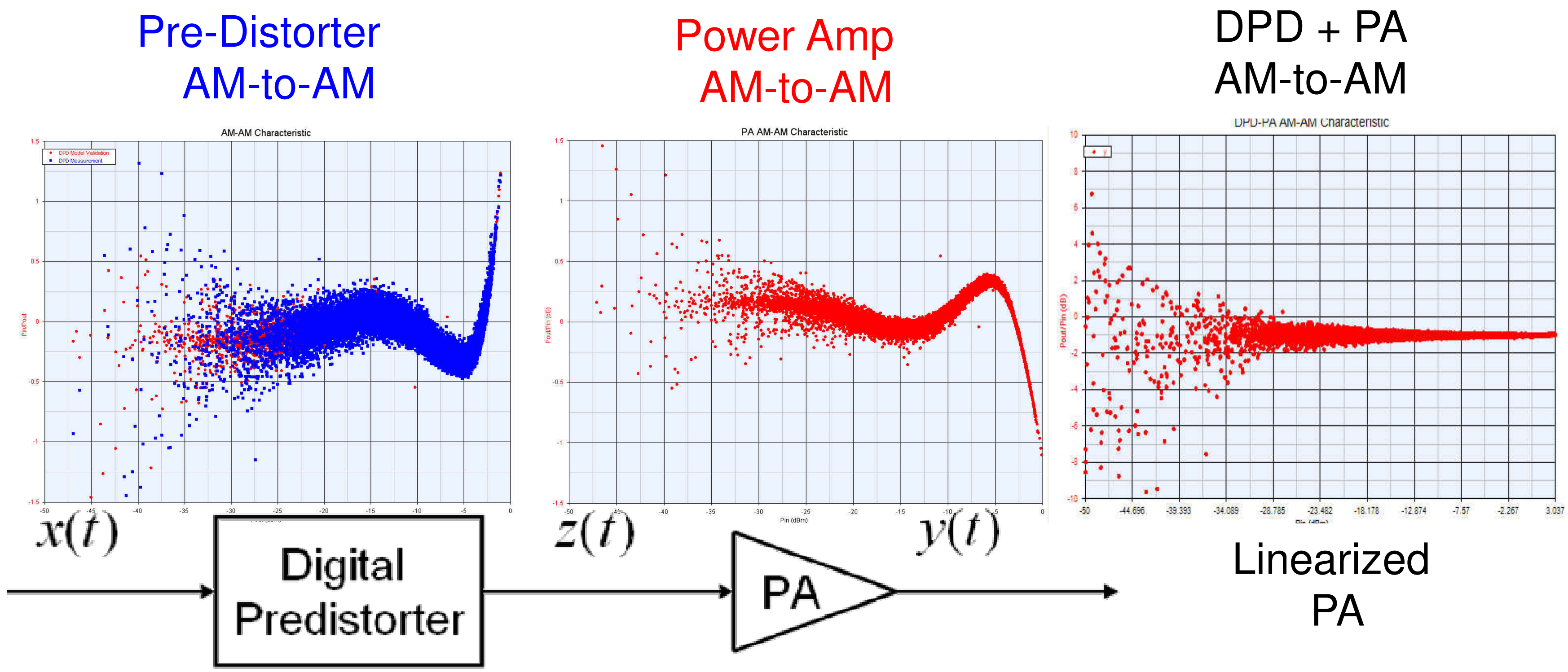
Further Improvements:

- Compensate for artificially higher avg. signal power
- Condition signal w/Crest Factor Reduction (CFR)

DPD Net Result: *Linear Gain of Complex-valued RF Carrier Envelope Over a Specific Range of Power Levels*



AM-AM Effects (Change in Gain vs. Power level)

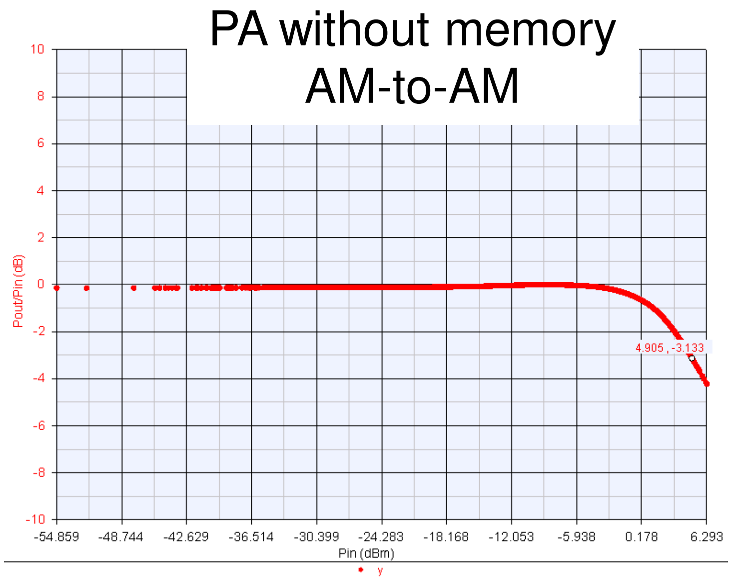


Definitions

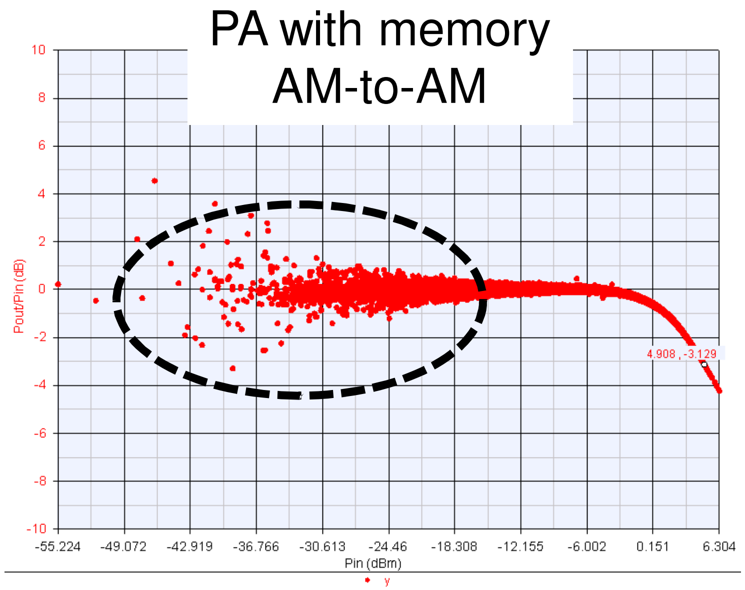
- **AM-AM** : Change in Gain vs. Power level, compared to small-signal *(dB(S21))*
- **AM-PM** : Change in Transmission Phase, compared to small-signal *(phase(S21))*
- **CCDF**: Percentage of time a particular amplitude level spends above avg power

Additional issues: Memory Effects

Output is Dependent on Previous History: "Path Dependence"



Output waveform has an instantaneous 1:1 correspondence in time with input waveform



Output waveform depends on previous values

What Does a DPD Look Like? (Volterra Model)

Volterra series pre-distorter can be described by

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

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

$$z(n) = h_0 + \sum_{m_1=0}^{Q} h_1(m_1) y(n - m_1) + \sum_{m_1=0}^{Q} \sum_{m_2=0}^{Q} h_2(m_1, m_2) y(n - m_1) y(n - m_2) + \ldots$$

A memory polynomial pre-distorter uses the diagonal kernels of the Volterra series and can be viewed as a generalization of the Hammerstein pre-distorter. It is constructed using the indirect learning architecture, thereby eliminating the need for a model assumption and parameter estimation of the power amplifier. Compared to the Hammerstein pre-distorter, the memory polynomial predistorter has slightly more terms, but it is much more robust and its parameters can be easily estimated using a least-squares algorithm.

A full Volterra produces a huge computational load. People usually simplify it into:

- Wiener model
- Hammerstein model
- Wiener-Hammerstein model
- Memory polynomial model

Memory Polynomial Model

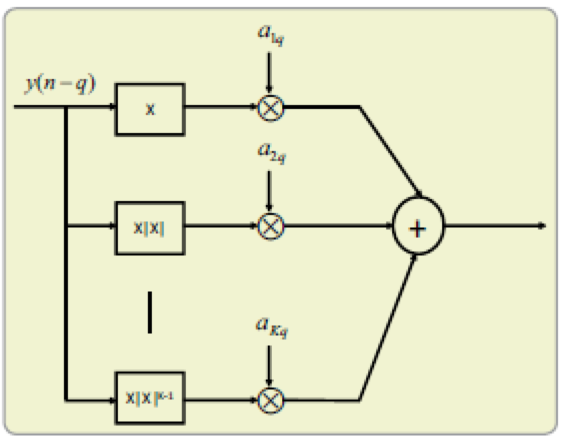
If only diagonal terms are kept in Volterra model, Volterra model becomes memory polynomial model.

$$z(n)=\sum_{k=1}^{K}\sum_{q=0}^{Q}a_{kq}\,y(n-q)\left|y(n-q)\right|^{k-1} \quad \text{--- 4}$$

,where, K is Nonlinearity order and Q is Memory length

If *Q=0, the structure in the equation degenerates to a memoryless polynomial.* Since the model in equation 4 is linear with respect to its coefficients, the predistorter coefficients *akq can be directly obtained using a least-squares algorithm* by defining a new sequence:

$$u_{kq}(n)=\frac{y(n-q)}{G}\left|\frac{y(n-q)}{G}\right|^{k-1}$$



At convergence, we should have

$$z=Ua$$

where

$$z=[z(0),z(1),\ldots,z(N-1)]^T$$

$$U=[u_{10},\cdots,u_{K0},\cdots,u_{1Q},\cdots,u_{KQ}],$$

$$u_{kq}=[u_{kq}(0),u_{kq}(1),\cdots,u_{kq}(N-1)]^T,$$

$$a=[a_{10},\cdots,a_{K0},\cdots,a_{1Q},\cdots,a_{KQ}]^T.$$

The least-squares solution for (6) is

$$\hat{a}=(U^HU)^{-1}U^Hz$$

where $(U)^H$ denotes the complex conjugate transpose matrix.

L. Ding, G. T. Zhou, D. R. Morgan, Z. Ma, J. S. Kenney, J. Kim, and C. R. Giardina, "Memory polynomial predistorter based on the indirect learning architecture," in *Proc. of GLOBECOM*, Taipei, Taiwan, 2002, vol. 1, pp. 967–971.

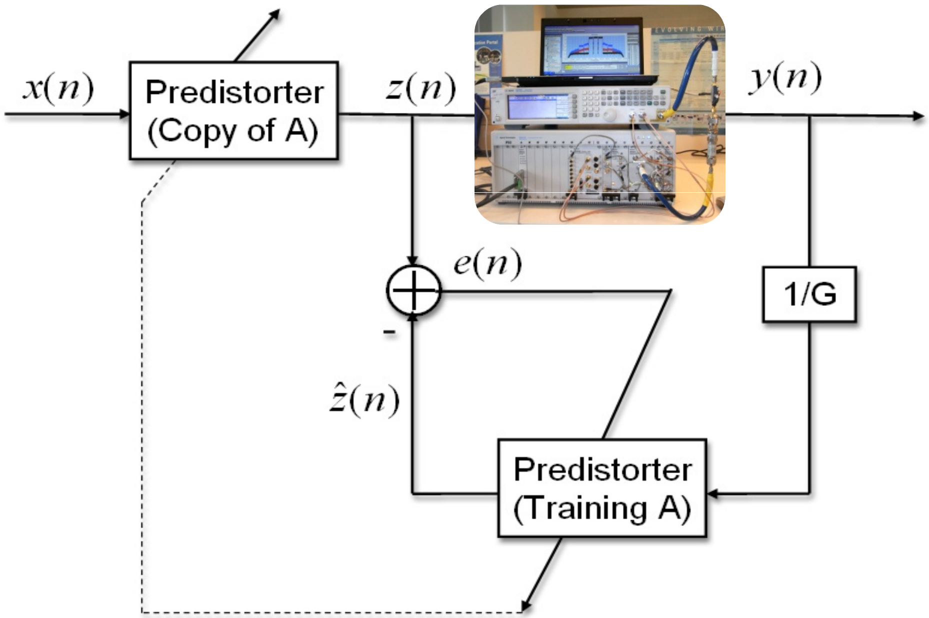
DPD Principles – Memory Polynomial Model

How is it done in practice?

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

Where

- K is Nonlinearity order
- Q is Memory length



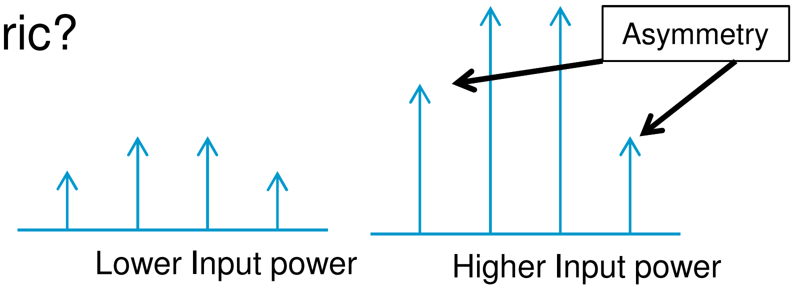
DPD Principles – Memory Polynomial Model

How do we select K (nonlinear order) and Q (memory length)?

- K is perhaps more tangible. When do you say "this amplifier is pretty nonlinear?"
- Q There are no golden rules yet. Mostly set up by experience.

What is memory? Is there a metric?

Asymmetry in intermod products
Indicates memory.



"the unlinearized IMD total power normalized to the IMD power obtained after optimum static linearization"[1]
Is some times used as a metric for memory.

[1] João Paulo Martins et.al. IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 54, NO. 12, DECEMBER 2006

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About Digital Pre-Distortion (DPD)

DPD challenges for 4G/wideband systems

Design a PA that is more linearizable

Understand the limits of the DPD algorithm

Practical implementation

Some Results

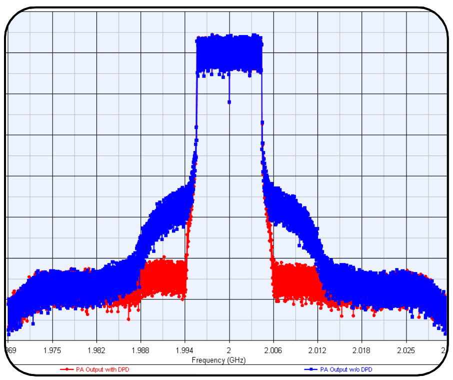
Q&A

DPD Challenges for 4G/Wideband Systems

Wider Bandwidth

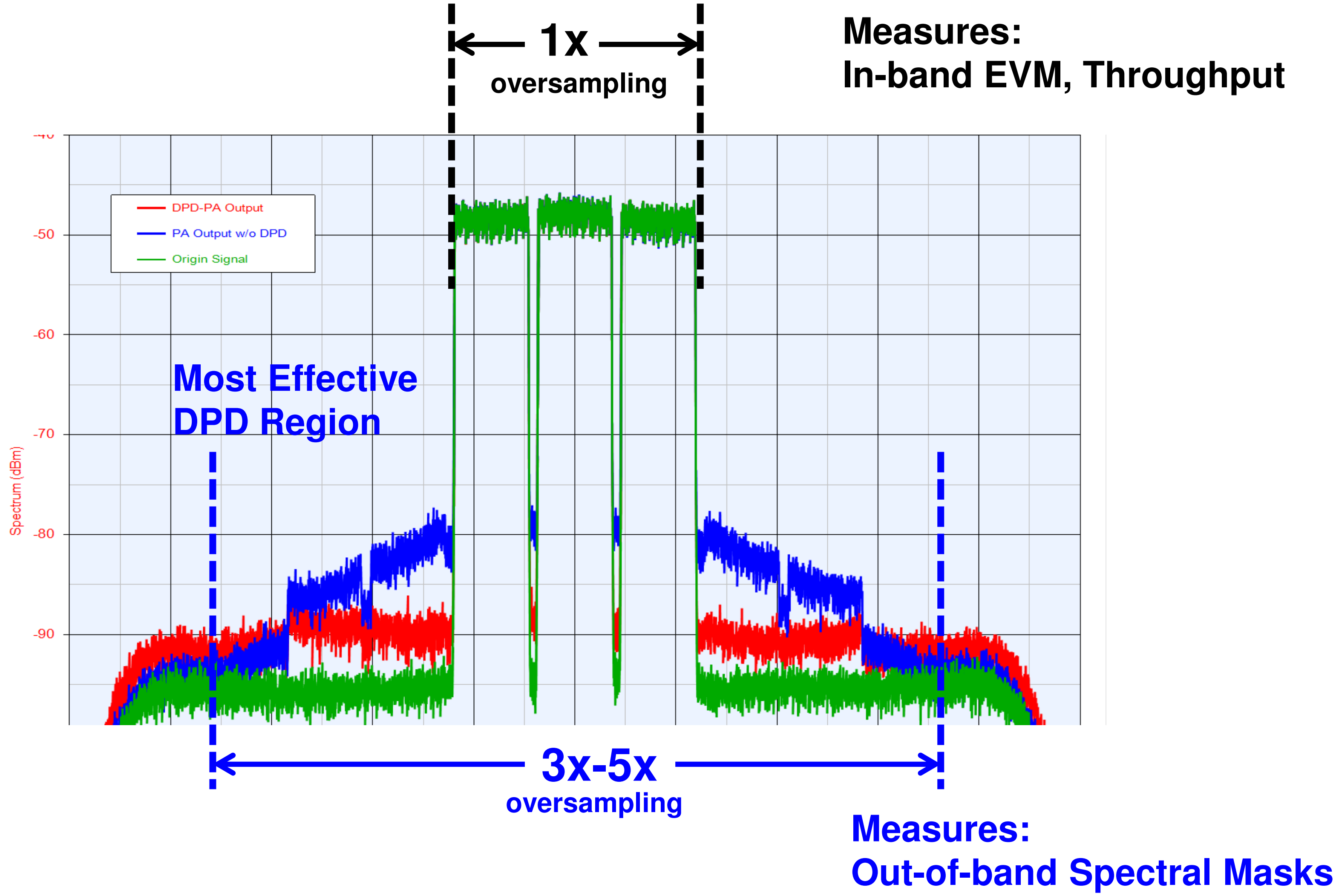
Higher Crest Factor

Rapidly changing environment



- LTE-Advanced (100MHz) and 802.11ac (160MHz) are physically 5x-8x wider than previous generation
- Oversampling increases this bandwidth an additional 3x-5x
- Drives wider ADC/DAC, data rates, test equipment, & more
- Requires powerful embedded processors : DSP/FPGA/ASIC

Oversampling Increases the Measurement BW

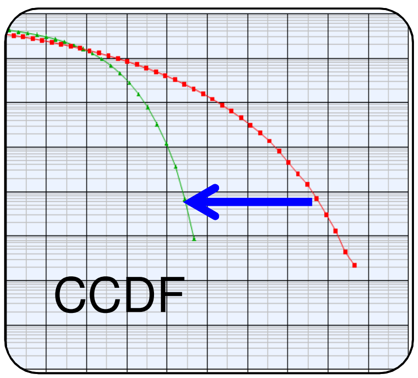


DPD Challenges for 4G/Wideband Systems

Wider Bandwidth

Higher Crest Factor

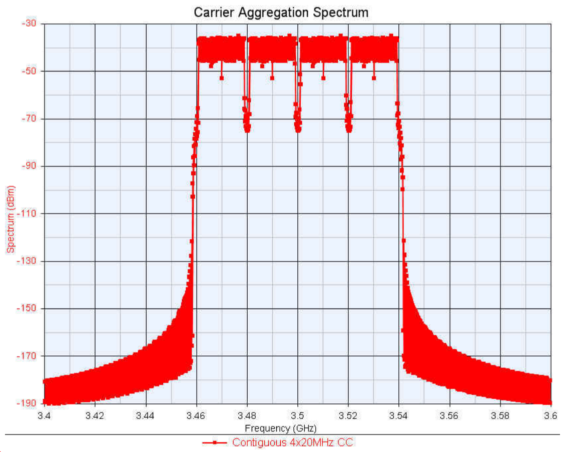
Rapidly changing environment



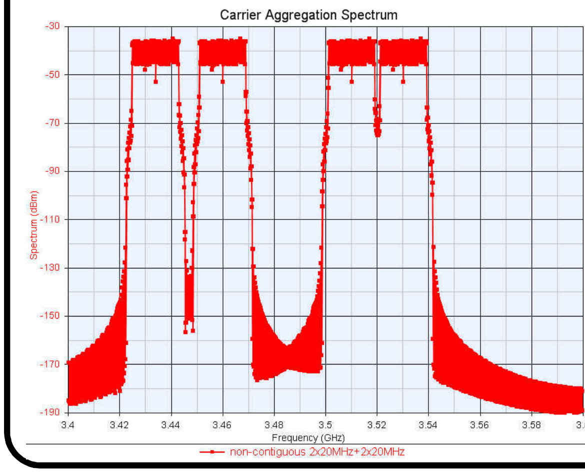
- Carrier aggregation increases PAPR (drives Efficiency down)
- Need to have compatibility with 3G signals.
- Highly-configurable signals (time-varying RBs) can lead to worst-case RF scenarios
- People apply Crest Factor Reduction differently….
  ….how to estimate the effect of CFR on your PA if *someone else* is doing the DSP?

The Effect of Carrier Aggregation on PAPR

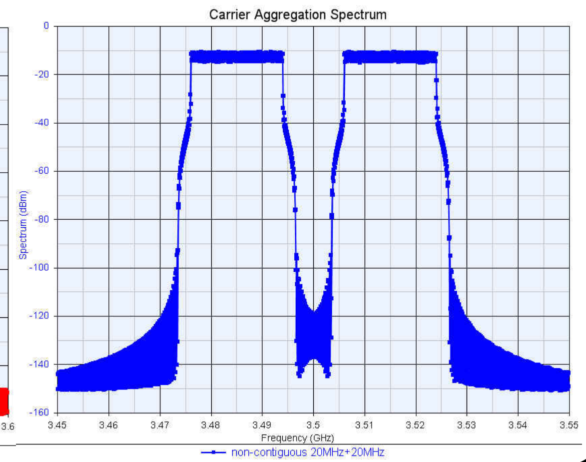
CA Scenario 1 FDD DL



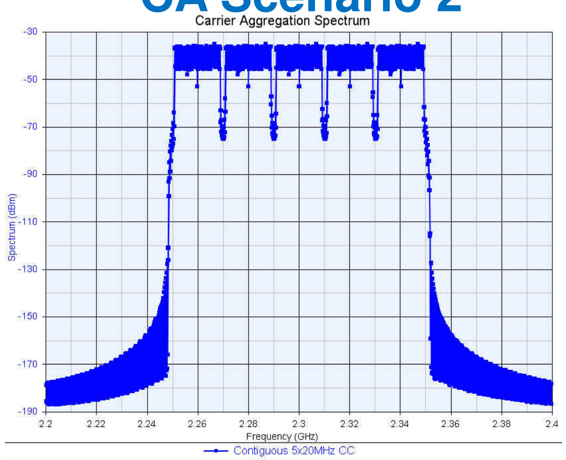
CA Scenario 4 FDD DL



CA Scenario 4 FDD UL



CA Scenario 2



Carrier Agg. Scenario	Link Type	Configuration	PAPR of single CC, *before* aggregation	PAPR with CCs, *after* aggregation
Scenario 1	FDD DL	4x20 MHz CCs	8.45 dB	**9.98 dB**
Scenario 2	TDD DL	5x20 MHz CCs	9.17 dB	**11.71 dB**
Scenario 4	FDD DL	2x20+2x20MHz	8.38 dB	**9.58 dB**
	FDD UL	20 + 20MHz	5.79 dB	**6.86 dB**

DPD Challenges for 4G/Wideband Systems

Wider Bandwidth

Higher Crest Factor

Rapidly changing environment

- LTE-Advanced, 802.11ac, and other Standards still changing
- IP issues: interoperability of signals, algorithms, channels, coded performance
- Closed DPD IP (no control)
- Availability of commercial DPD solutions
- Ecosystem & vendor re-alignments
- BB/RF hardware platform neutrality for local spectral variations, vendors, standards

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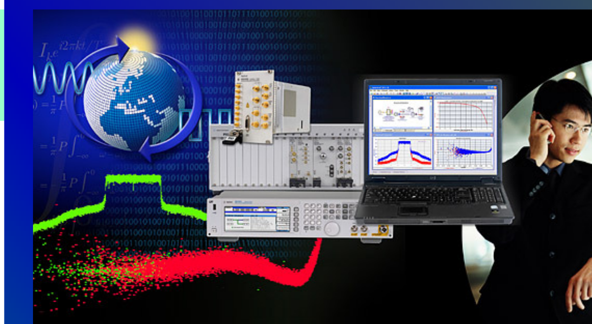


PA Linearizability

- “I have a PA, but I do not know how linearizable it is.”
- “I can not give an accurate model of my PA”
  - That captures non-linearity
  - Memory effects, short term and long term
  - Frequency response and
  - Noise
- “How do I exercise my degrees of freedom of my design?”
- “What technology/techniques are there for good PA modeling?”

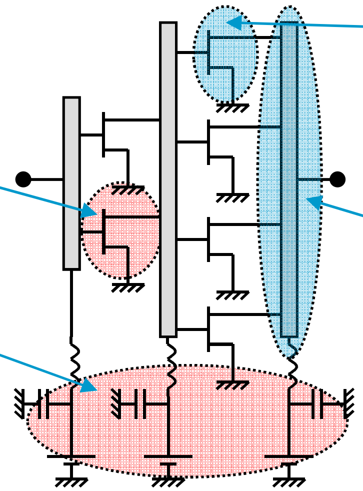
Let us review:

1. Memory effects and
2. PA modeling

Manifestations of Memory Effects in Circuits

Some examples

- Thermal effects
- Trapping effects



- Transistors (transit time)
- Biasing circuits
- AGC loops
- DC offset correction
- Matching networks (group delay)
- Band filtering

Long time-constant memory ~µs to ms

Short time-constant memory ~ns

Baseband Memory Effects

Nonlinear Coupling

In band Memory Effects

PA Linearizability

- PA modeling involves creating behavioral models:

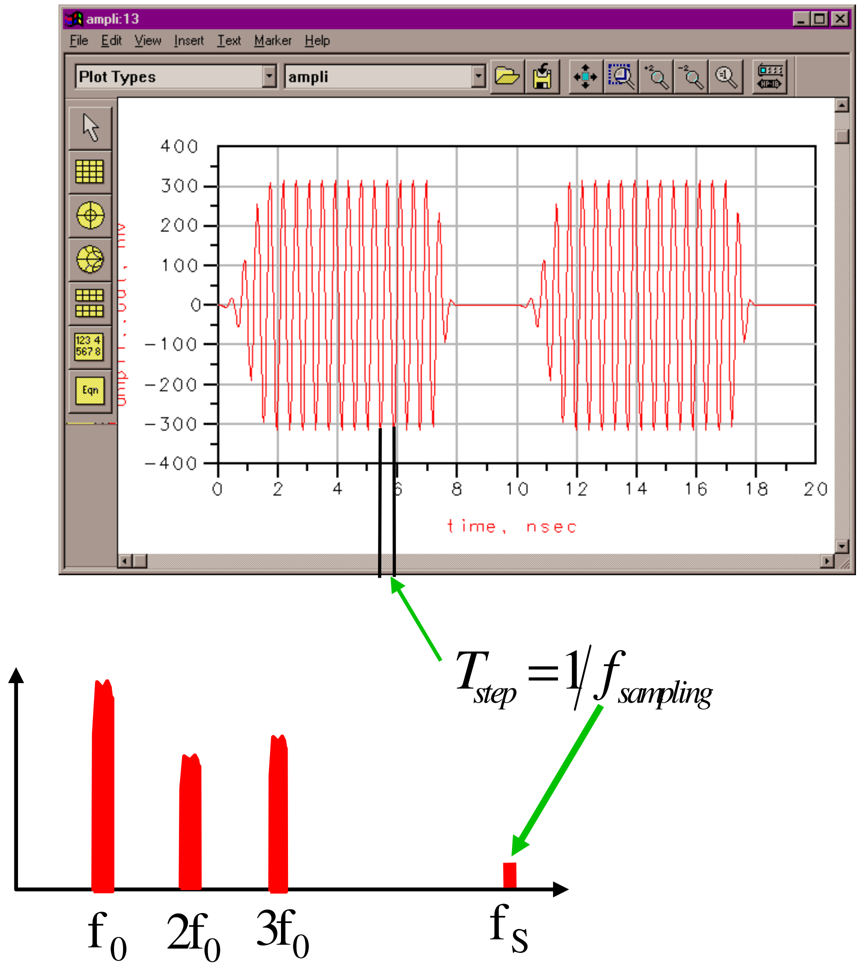
  Power-dependent S-parameters
  X-parameters current
  Static Polynomial
  Hammerstein
  Parallel Hammerstein
  Volterra
  Radial Bassis-function neural Network

- All the above have either limitations or work for certain signals or too complex.

- Best two alternatives:
  - Fast Circuit Envelope (FCE) model -- limited to RFIC world (and not covered in this presentation).
  - Direct co-simulation – avoid intermediate modeling altogether!

Time Domain Simulation

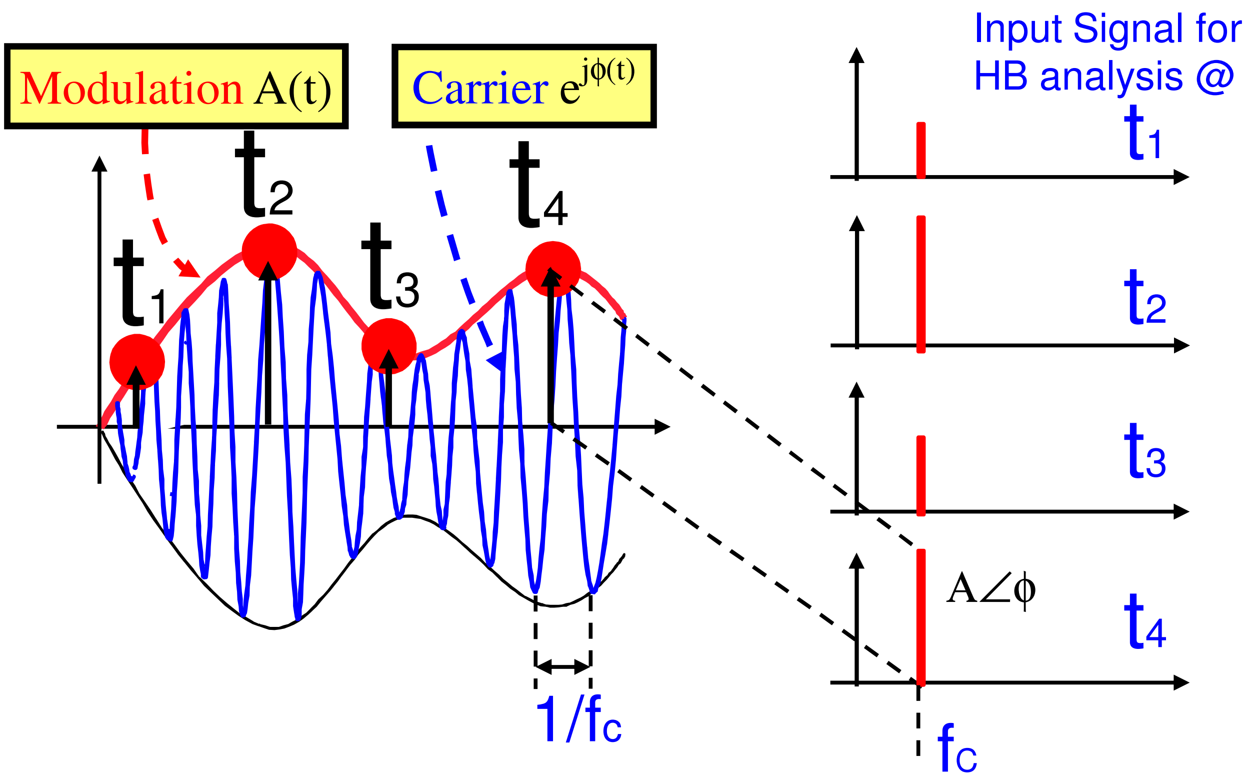
- Must sample the carrier frequency over at least one period of the modulation signal
  - Very small time steps
  - Long simulation time
  - Don't know if settled
- To display spectrum must compute FFT of large number of sample points
  - Long computation
- No frequency-domain models (microstrip, S-parameters, etc.)



Circuit Envelope Technique

Step 1 - Transform input signal

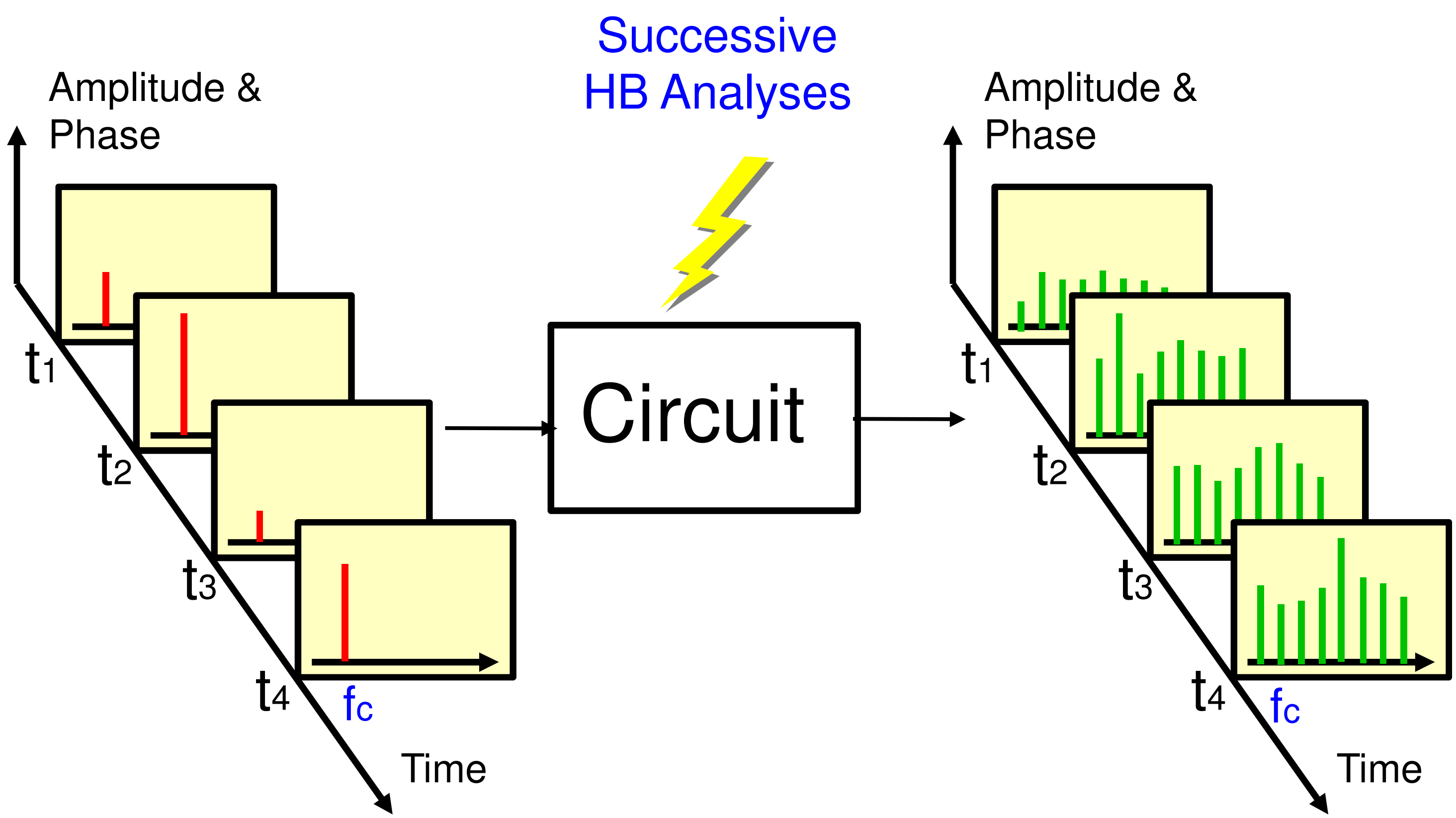
Each modulated signal can be represented as a carrier modulated by an envelope - $A(t) * e^{jf(t)}$



The values of amplitude and phase of the sampled envelope are used as input signals for Harmonic Balance analyses

Circuit Envelope Technique

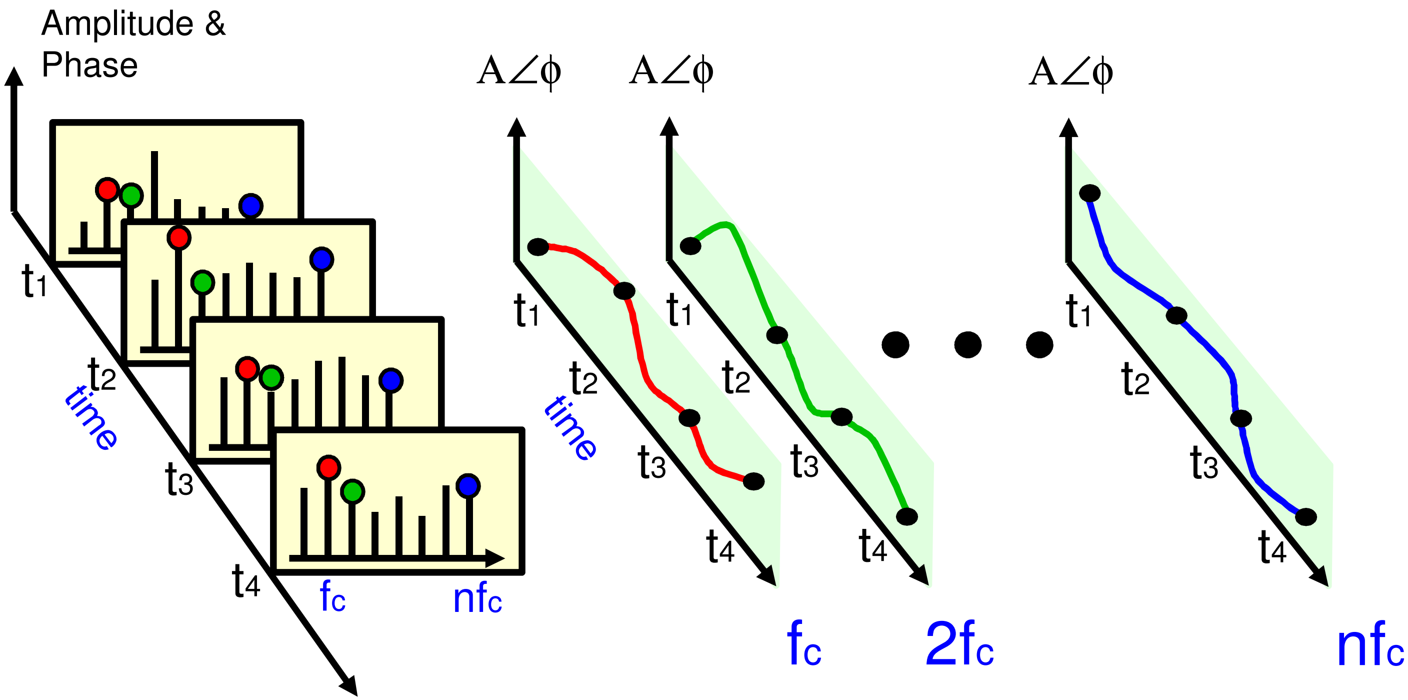
Step 2 - Frequency Domain Analysis



An Harmonic Balance analysis is performed at each time step. This process creates a succession of spectra that characterize the response of the circuit at the different time steps.

Circuit Envelope Technique

Step 3 - Time domain Analysis

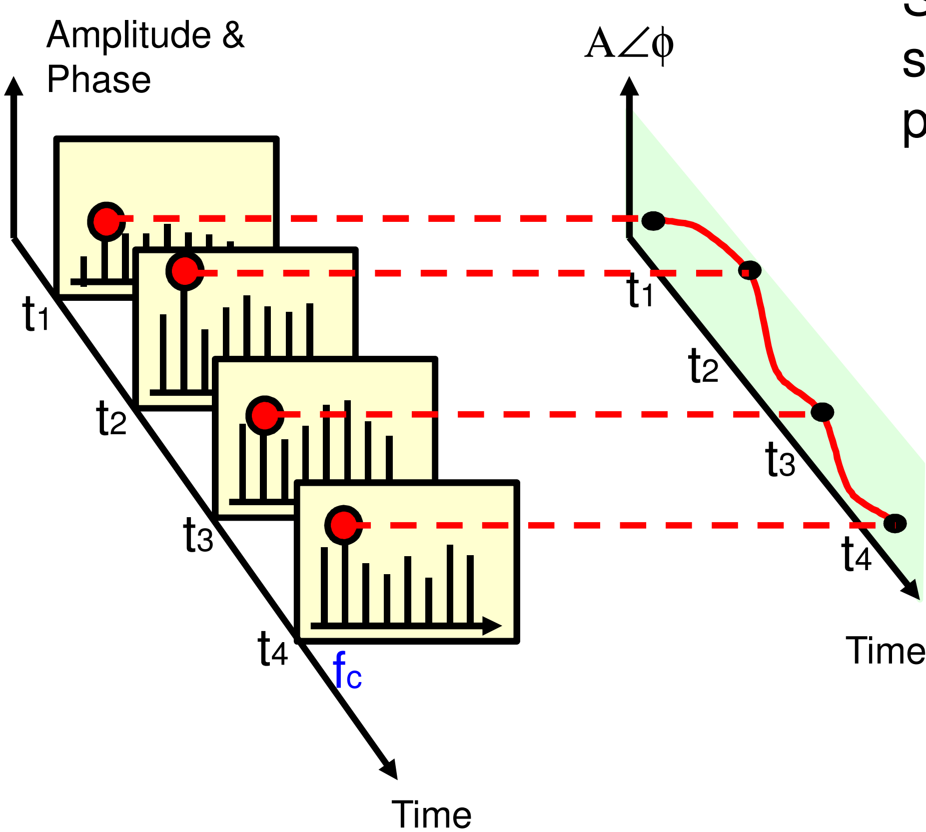


Circuit Envelope provides a complete non steady-state solution of the circuit through a Fourier series with time-varying coefficients

$$v(t) = real\left[\sum_{k=0}^{N} V_k(t)\, e^{j\omega_k t}\right]$$

Circuit Envelope Technique

Extracting Information From Time Domain Data

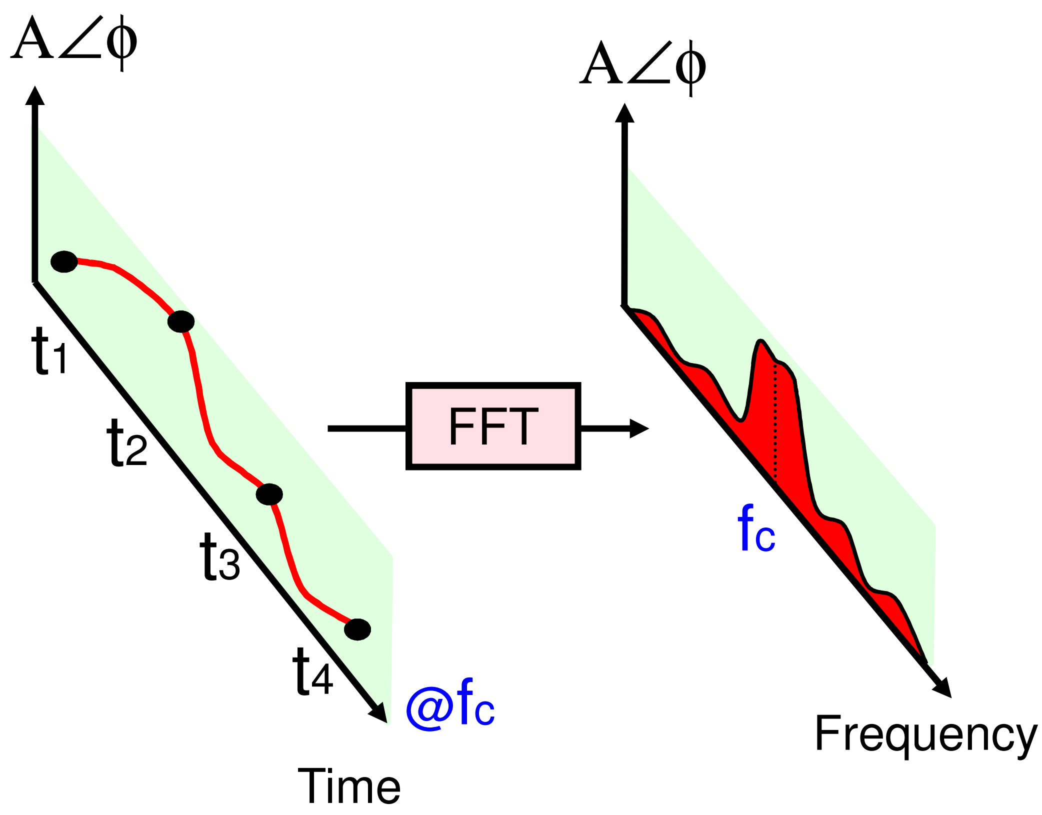


Selecting the desired harmonic spectral line (fc in this case), it is possible to analyze:

- Amplitude vs. Time
  - Oscillator start up
  - Pulsed RF response
  - AGC transients
- Phase (ϕ) vs. Time (τ)
  - VCO instantaneous frequency ($\delta\phi/\delta\tau$), PLL lock time
- Amplitude & phase vs. time
  - Constellation plots
  - EVM, BER

Circuit Envelope Technique

Extracting Information From Frequency Domain Data



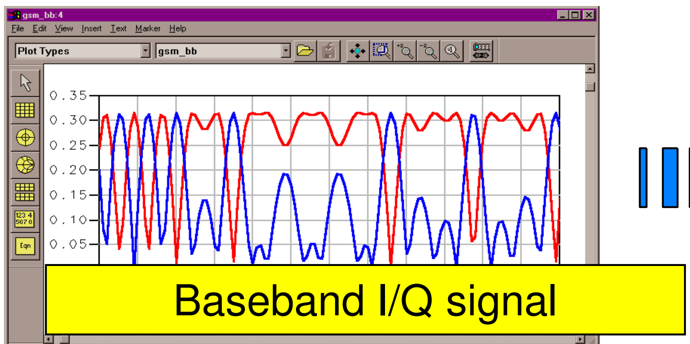
By applying FFT to the selected time-varying spectral line it is possible to analyze:

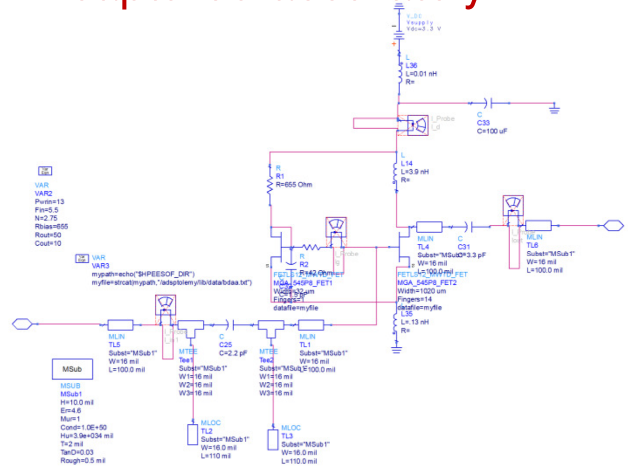
- Adjacent Channel Power Ratio (ACPR)
- Noise Power Ratio (NPR)
- Power added efficiency
- Reference frequency feed through in PLL
- Mixer intermods:
  - 3rd, 5th, 7th, 9th etc.

PA Modeling: A Direct Co-simulation Approach

Instead of modeling
– use the circuit directly!

Memory effects and non-linearity captured accurately





DPD Builder

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How to optimize the DPD algorithm?

DPD + Behavioral
- Potentially ignores memory effects and may not give best results

DPD + HW Amplifier
- How do we know the measurement set up is not the limiting factor?

DPD + Actual circuit simulation
- Opportunity to optimize circuit as well as the DPD algorithm concurrently

DPD (fixed point) + Actual circuit simulation
- Tells how much realistic efficiency is achieved that takes the DPD HW current consumption also.

Next --- Some Results

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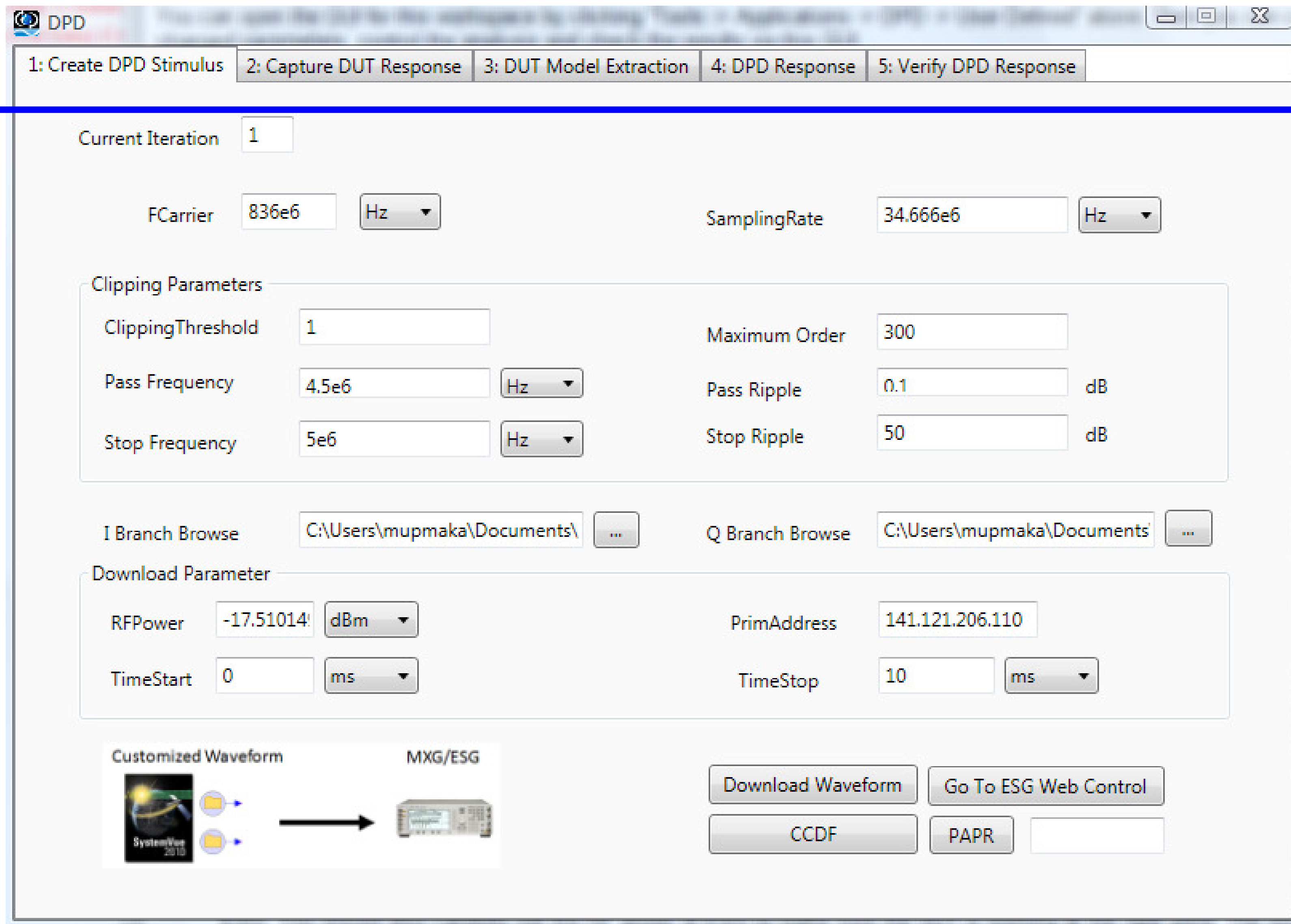
Step by step to do DPD on a HW amplifier
Presentation & Demonstration

Five Easy Steps! But lot of details



Before you start DPD builder

1. Know the signal
2. Know your Power amplifier
3. Know the instruments
   A. Signal Source
   B. Signal Analyzer
4. Cable losses
5. DC bias source

Know CCDF of your signal

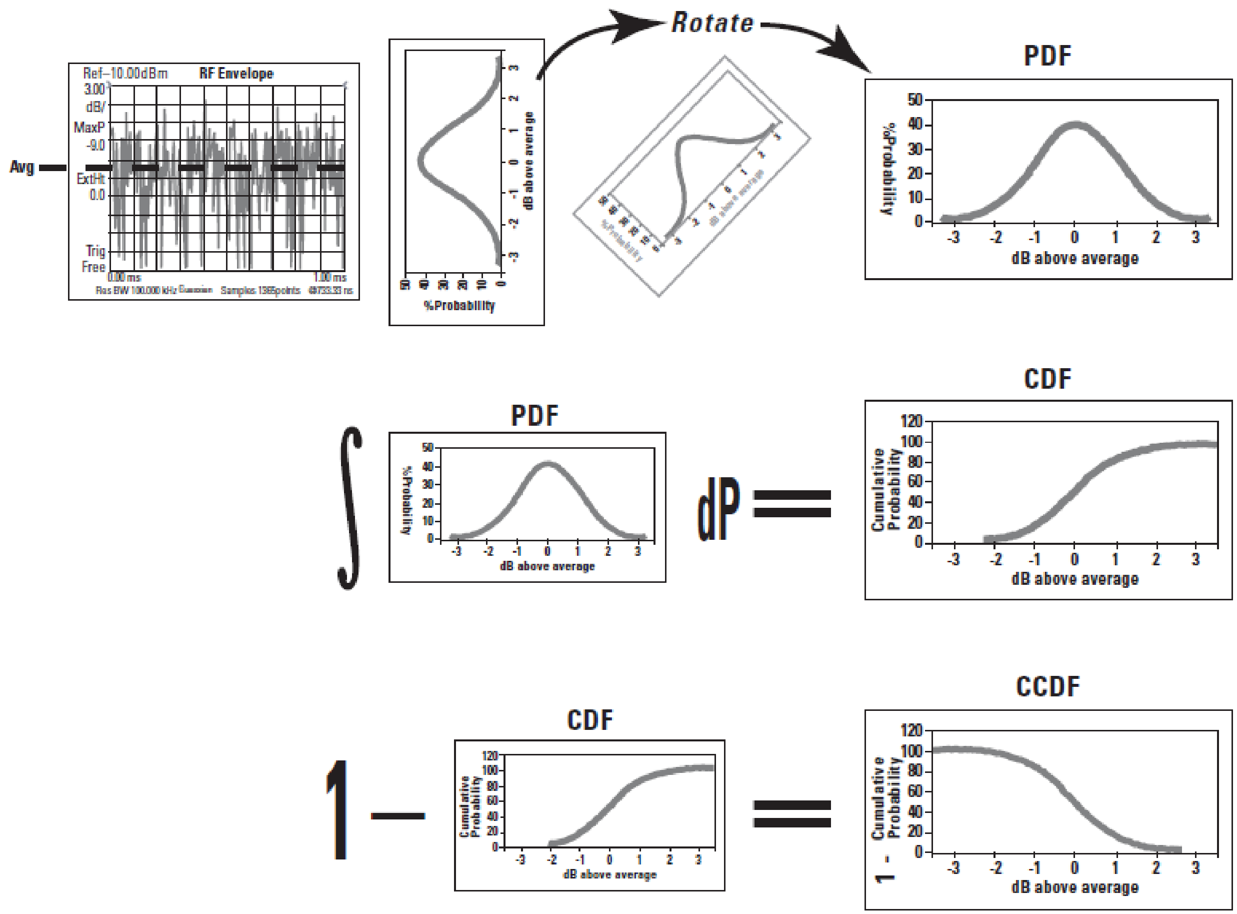
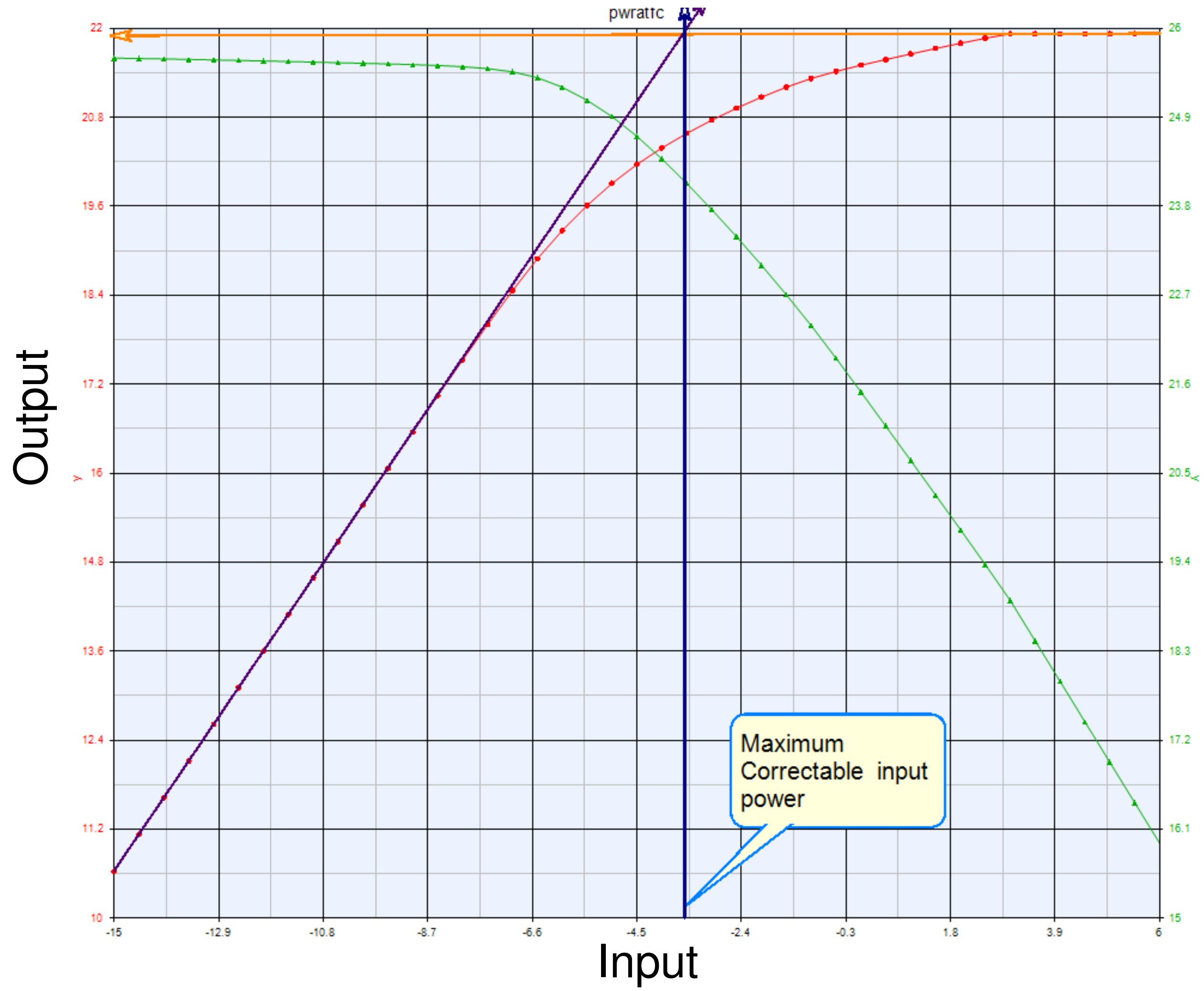


Figure 2: Mathematical origin of CCDF

Know your Amplifier
Gain and Gain compression

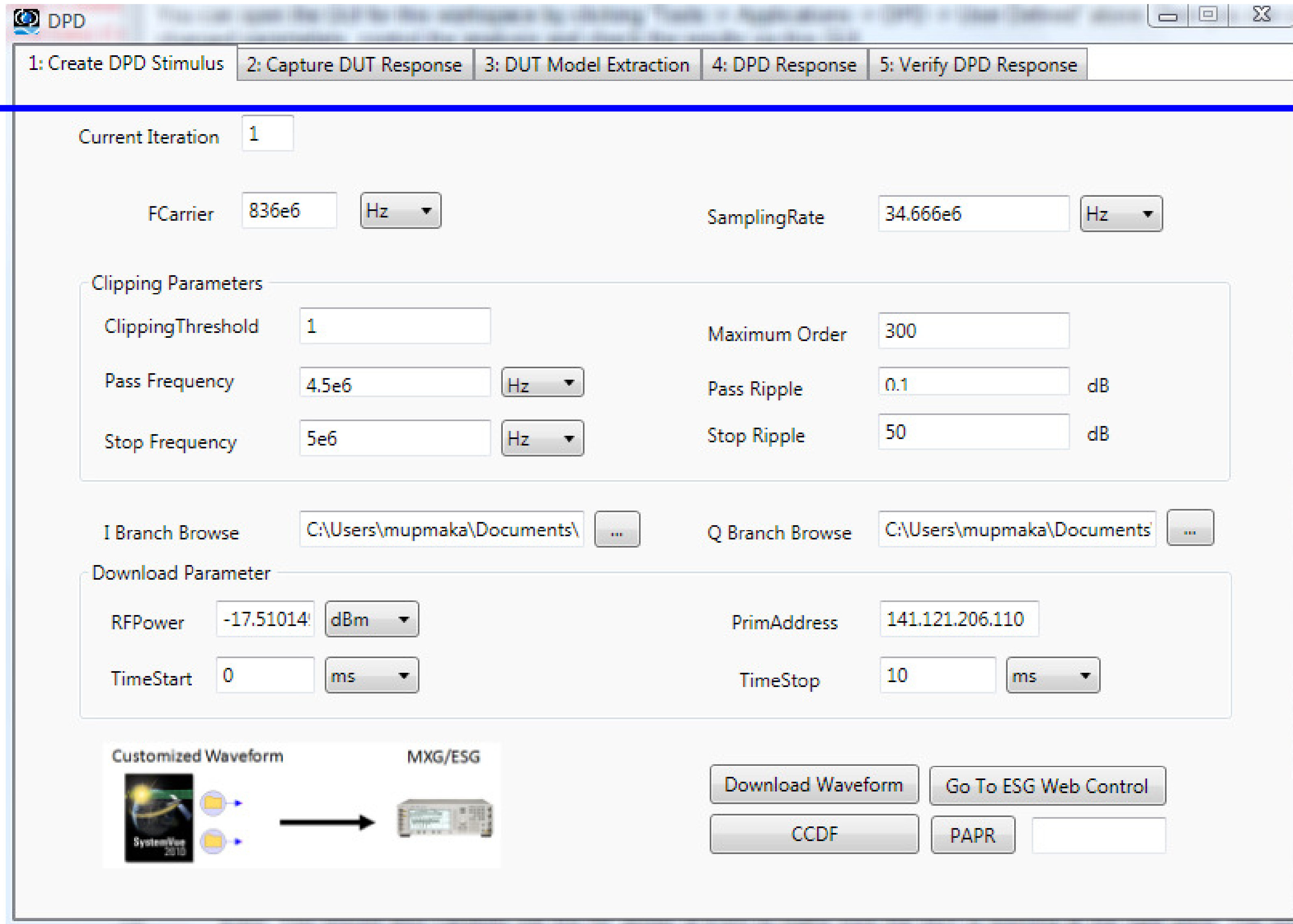


Agilent Technologies

Before you stat DPD builder

1. Know the signal
2. Know your Power amplifier
3. Know the instruments
   A. Signal Source
   B. Signal Analyzer
4. Cable losses
5. DC bias source
6. VSA (89600) software.

Five Easy Steps! But lot of details

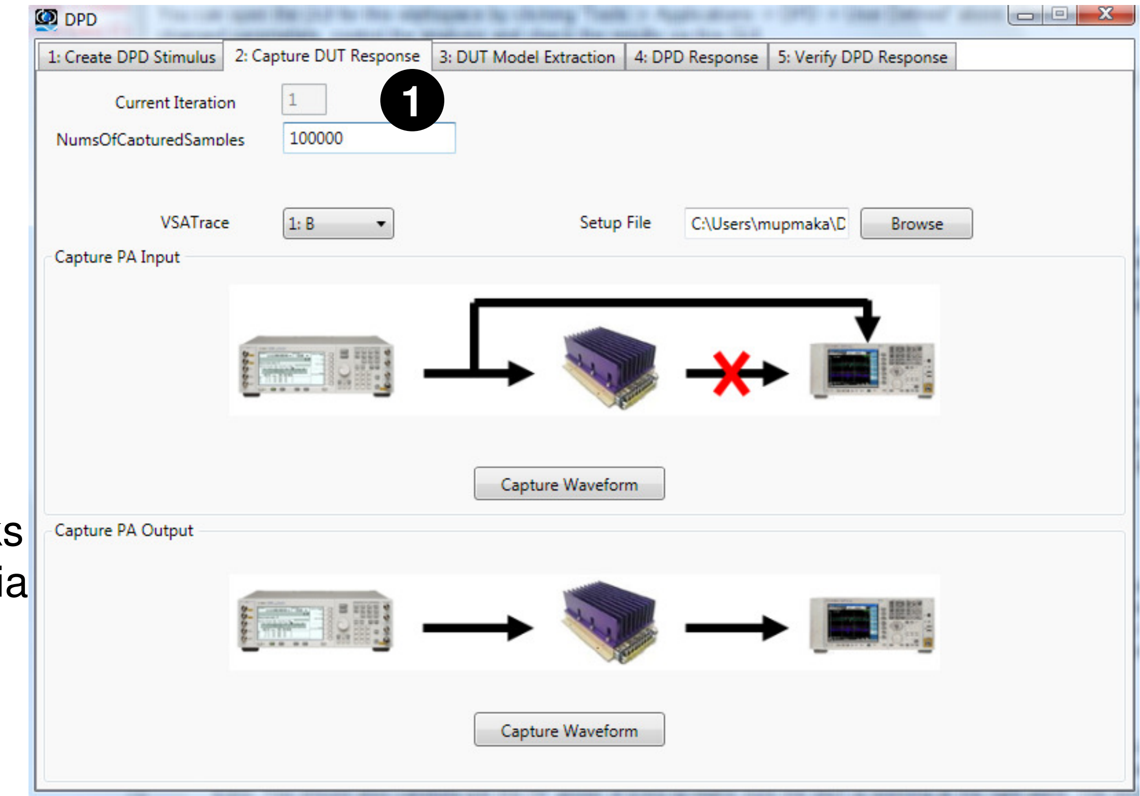


Capture: configure the measurement samples

Iteration-1

❶
Configure the number of samples to capture.

Whereas SystemVue talks *directly* to the ESG/MXG, it talks to the Analyzer via the 89600 VSA software.



Do you have enough time points for a statistically valid extraction?

Before you go any further, the VSA software must be able to make a standalone hardware measurement. Once VSA configured, then SystemVue's task is very simple. It just talks to the VSA, and anything the VSA can control.

Capture the PA output waveform

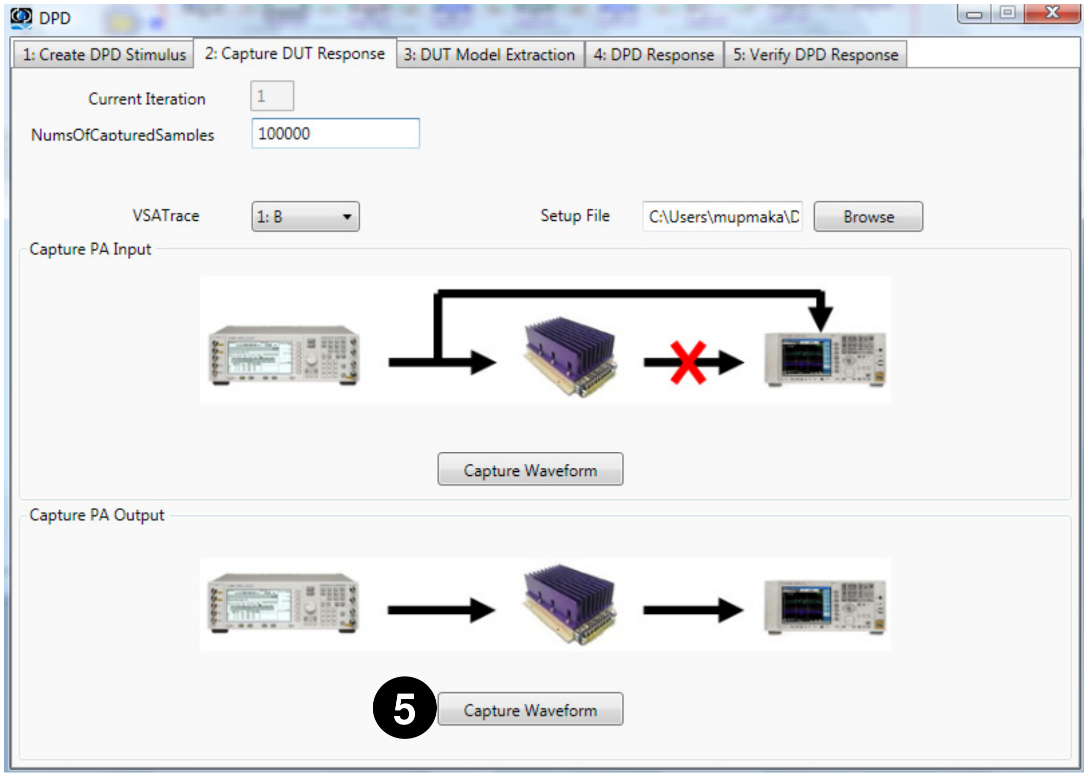
Iteration-1

5

Connect the PA into the measurement system.

Do a quick local measurement with the VSA to make sure that your PA is really operating.

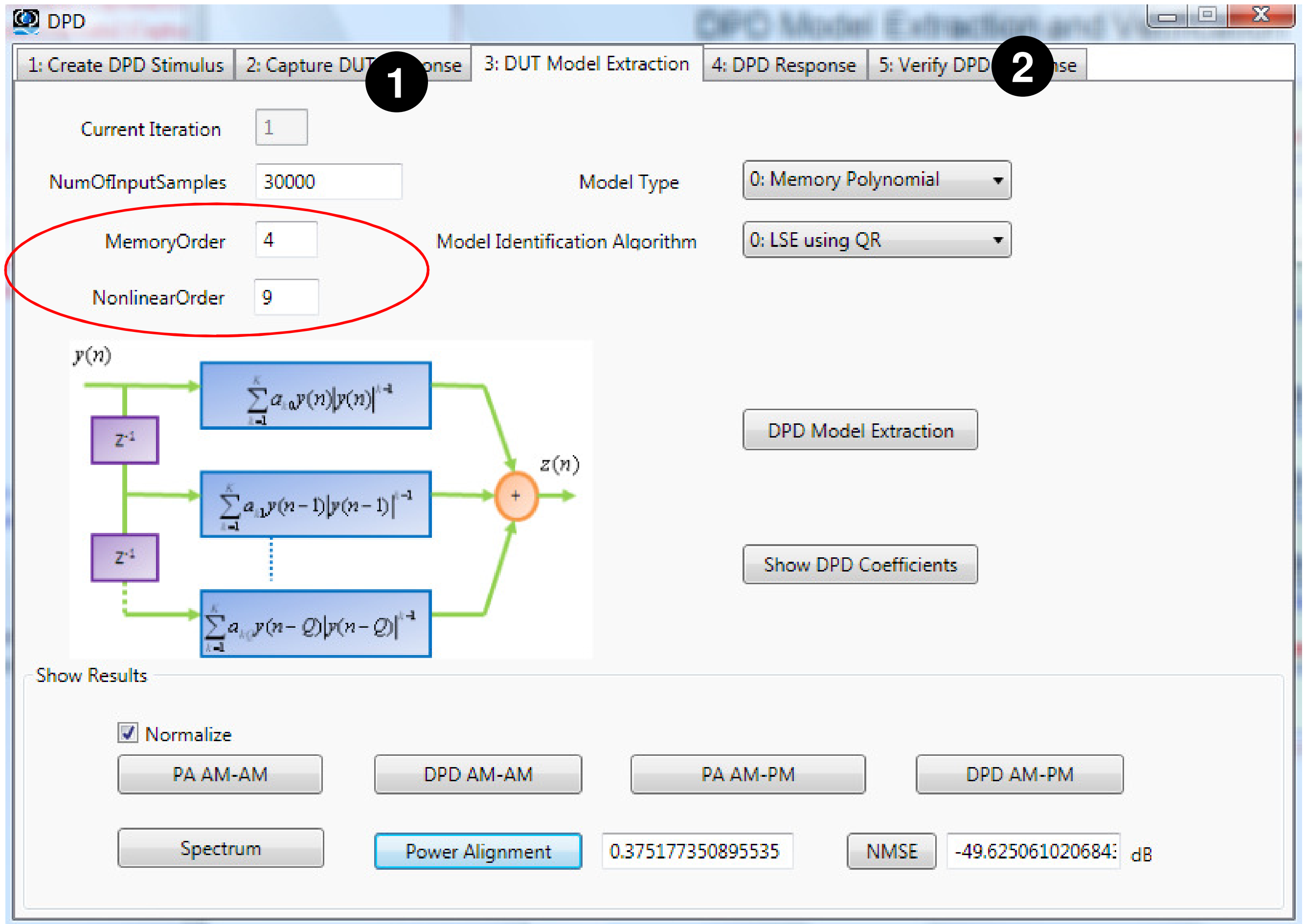
Verify the true output power using the "Integrated BW Markers"



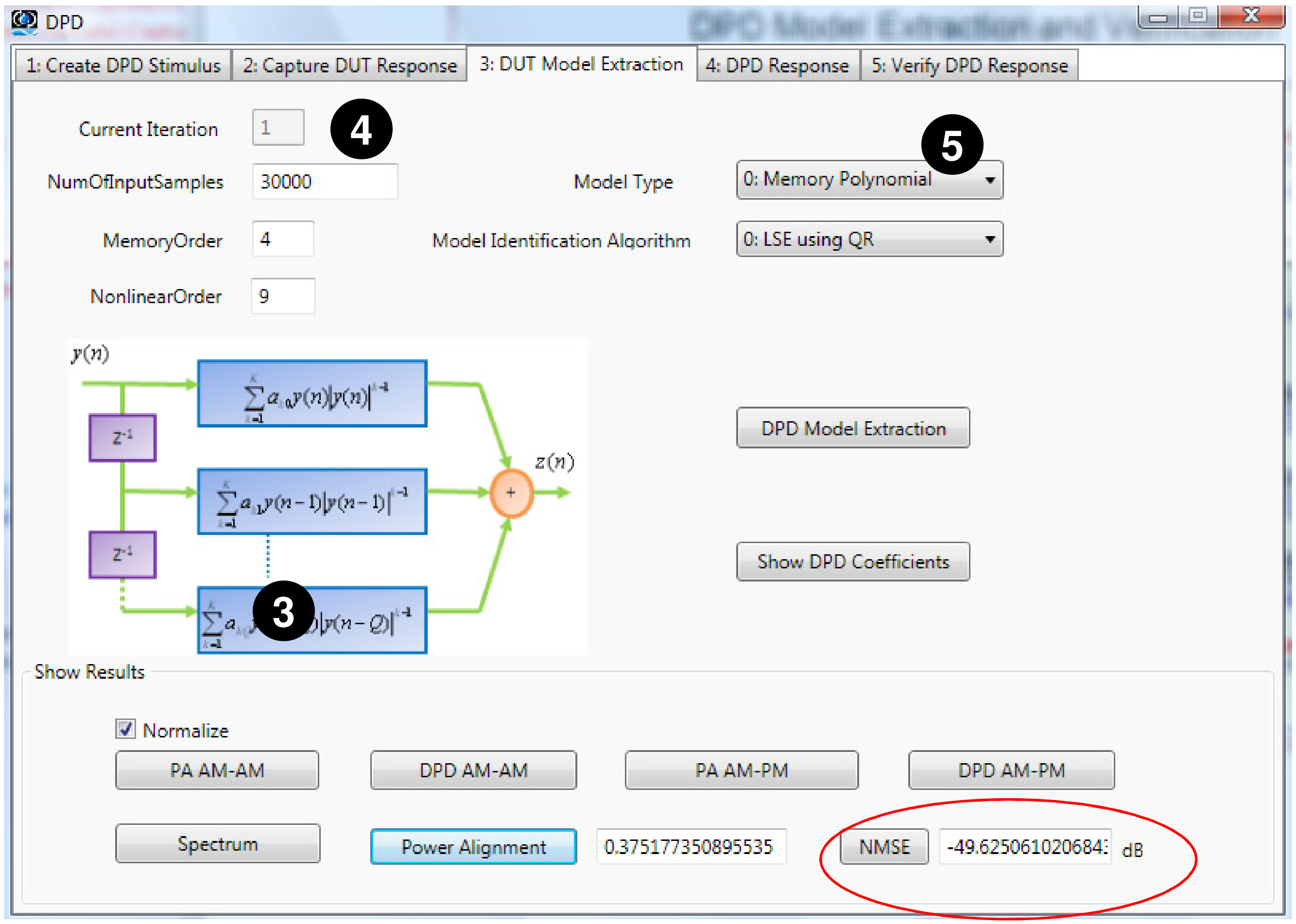
5 FILES STORED:
Step2_PAOutputdata_Imag_Iter1.txt
Step2_PAOutputdata_Real_Iter1.txt

IMPORTANT
Make sure that you have enough attenuation on the spectrum analyzer to prevent the PA from overloading the receiver front end.

Iteration-1

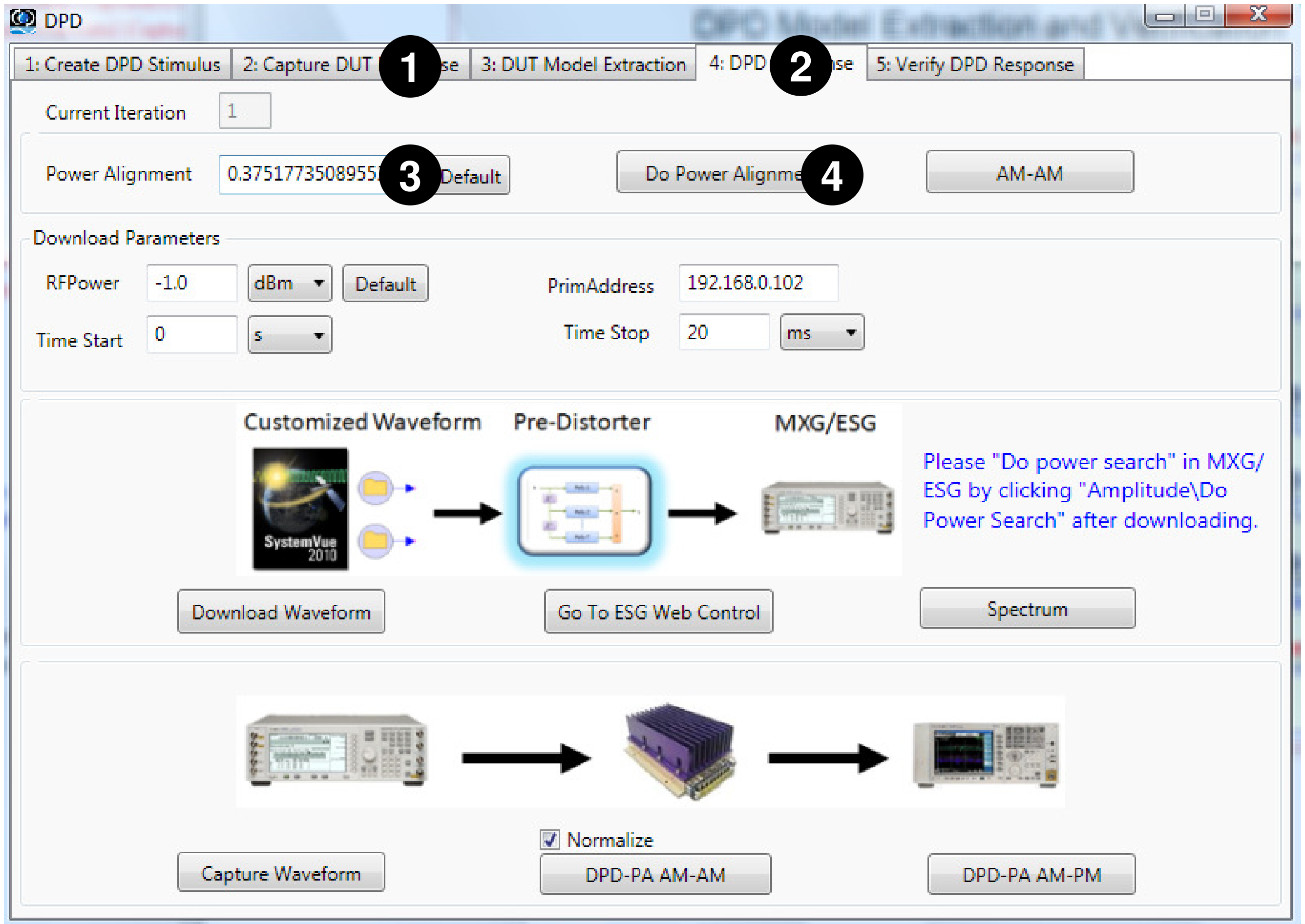

DPD
1: Create DPD Stimulus
2: Capture DUT
onse
3: DUT Model Extraction
4: DPD Response
5: Verify DPD
nse
1
2
Current Iteration
1
NumOfInputSamples
30000
Model Type
0: Memory Polynomial
MemoryOrder
4
Model Identification Algorithm
0: LSE using QR
NonlinearOrder
9
y(n)
z(n)
DPD Model Extraction
Show DPD Coefficients
Show Results
Normalize
PA AM-AM
DPD AM-AM
PA AM-PM
DPD AM-PM
Spectrum
Power Alignment
0.375177350895535
NMSE
-49.625061020684
dB

Iteration-1

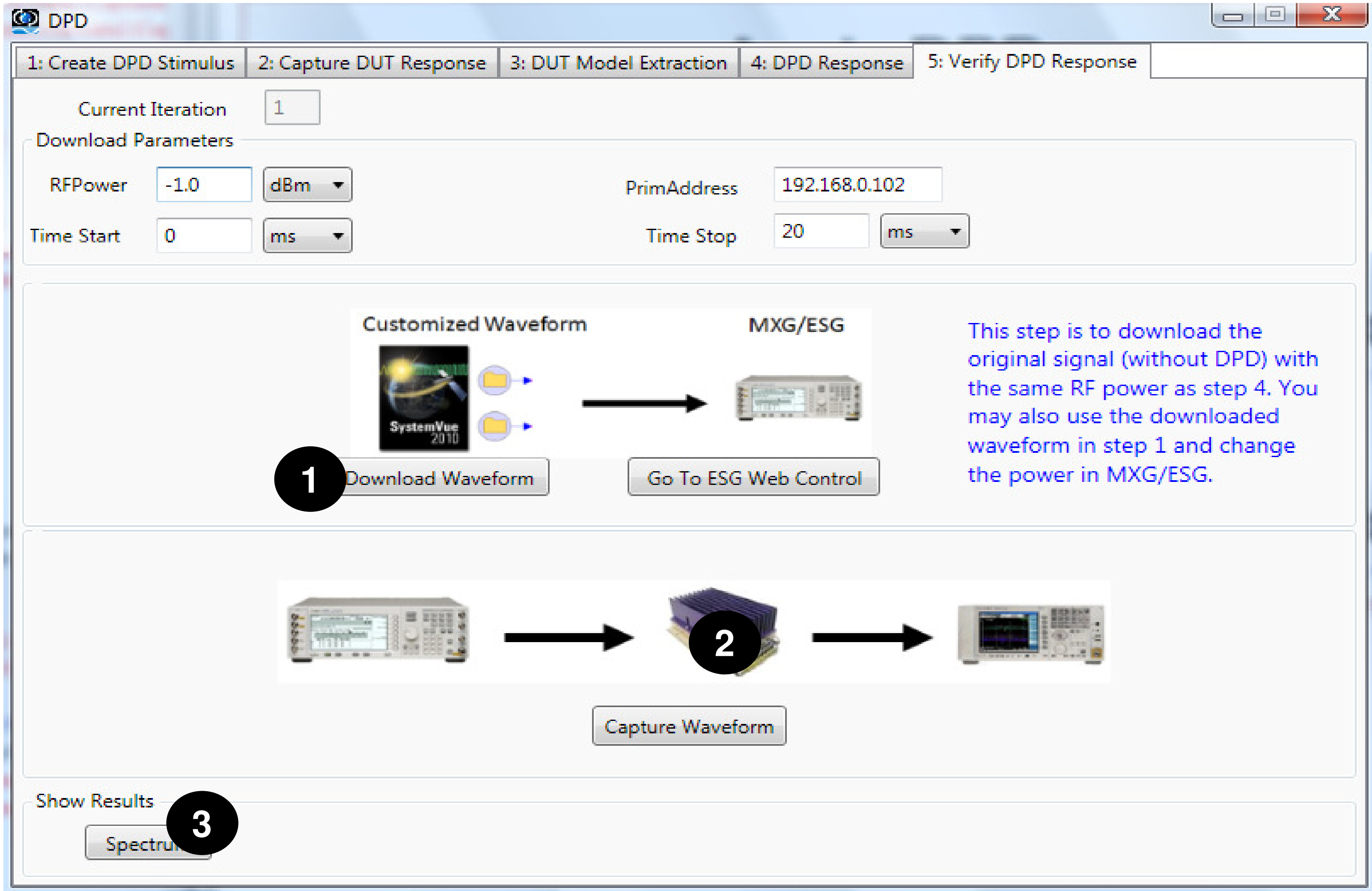


DPD
1: Create DPD Stimulus
2: Capture DUT Response
3: DUT Model Extraction
4: DPD Response
5: Verify DPD Response
Current Iteration
1
4
NumOfInputSamples
30000
Model Type
0: Memory Polynomial
5
MemoryOrder
4
Model Identification Algorithm
0: LSE using QR
NonlinearOrder
9
y(n)
z(n)
3
DPD Model Extraction
Show DPD Coefficients
Show Results
Normalize
PA AM-AM
DPD AM-AM
PA AM-PM
DPD AM-PM
Spectrum
Power Alignment
0.375177350895535
NMSE
-49.625061020684
dB

Iteration-1


DPD
1: Create DPD Stimulus
2: Capture DUT
se
3: DUT Model Extraction
4: DPD
se
5: Verify DPD Response
1
2
3
4
Current Iteration
1
Power Alignment
0.37517735089551
Default
Do Power Alignme
AM-AM
Download Parameters
RFPower
-1.0
dBm
Default
PrimAddress
192.168.0.102
Time Start
0
s
Time Stop
20
ms
Customized Waveform
Pre-Distorter
MXG/ESG
SystemVue 2010
Please "Do power search" in MXG/ ESG by clicking "Amplitude\Do Power Search" after downloading.
Download Waveform
Go To ESG Web Control
Spectrum
Normalize
Capture Waveform
DPD-PA AM-AM
DPD-PA AM-PM

End--Iteration 1



Ideally the DPD spectrum should coincide with the original signal spectrum excepting a gain difference. If the DPD has not improved the out put spectrum then we have to go back to step1.

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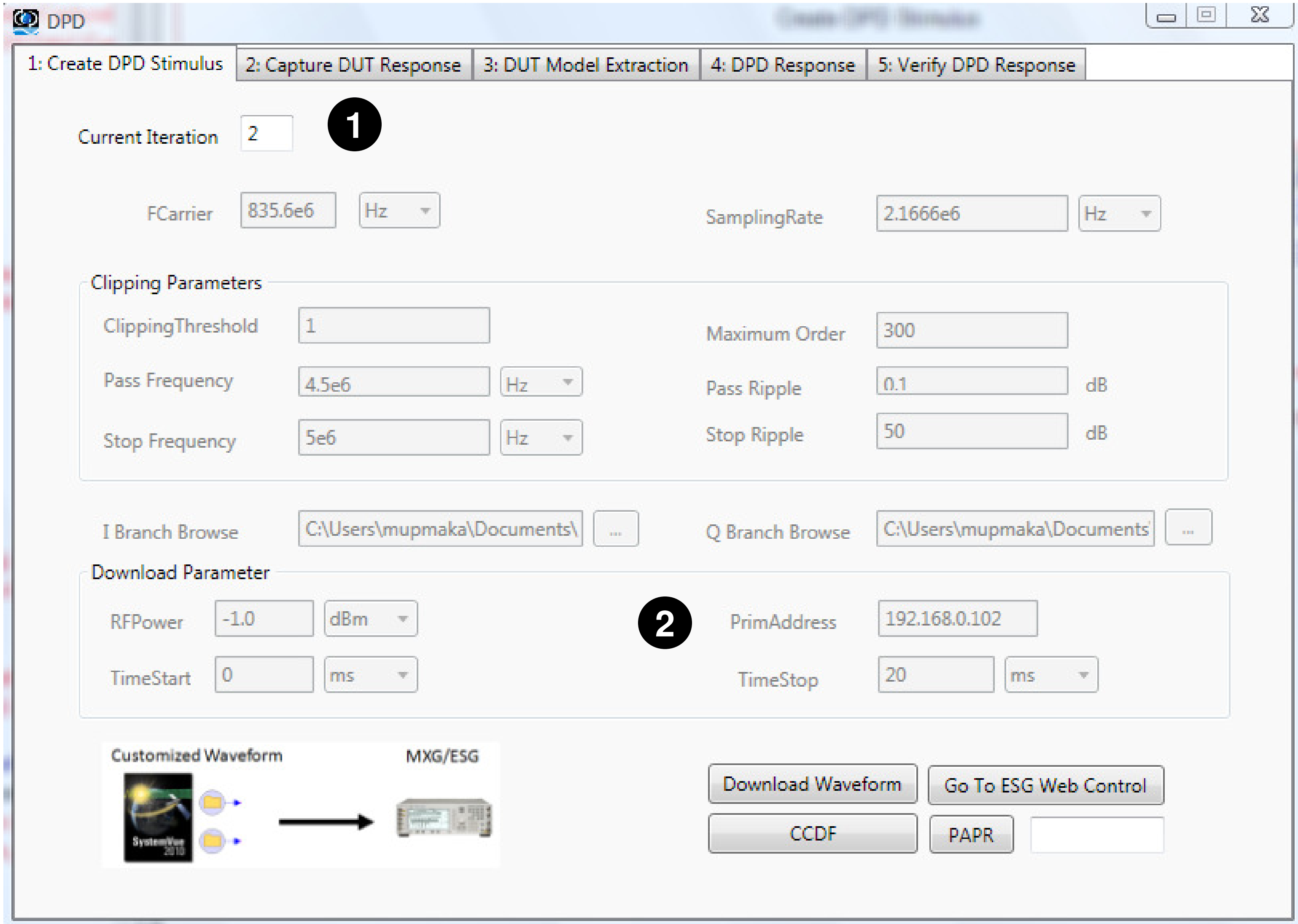
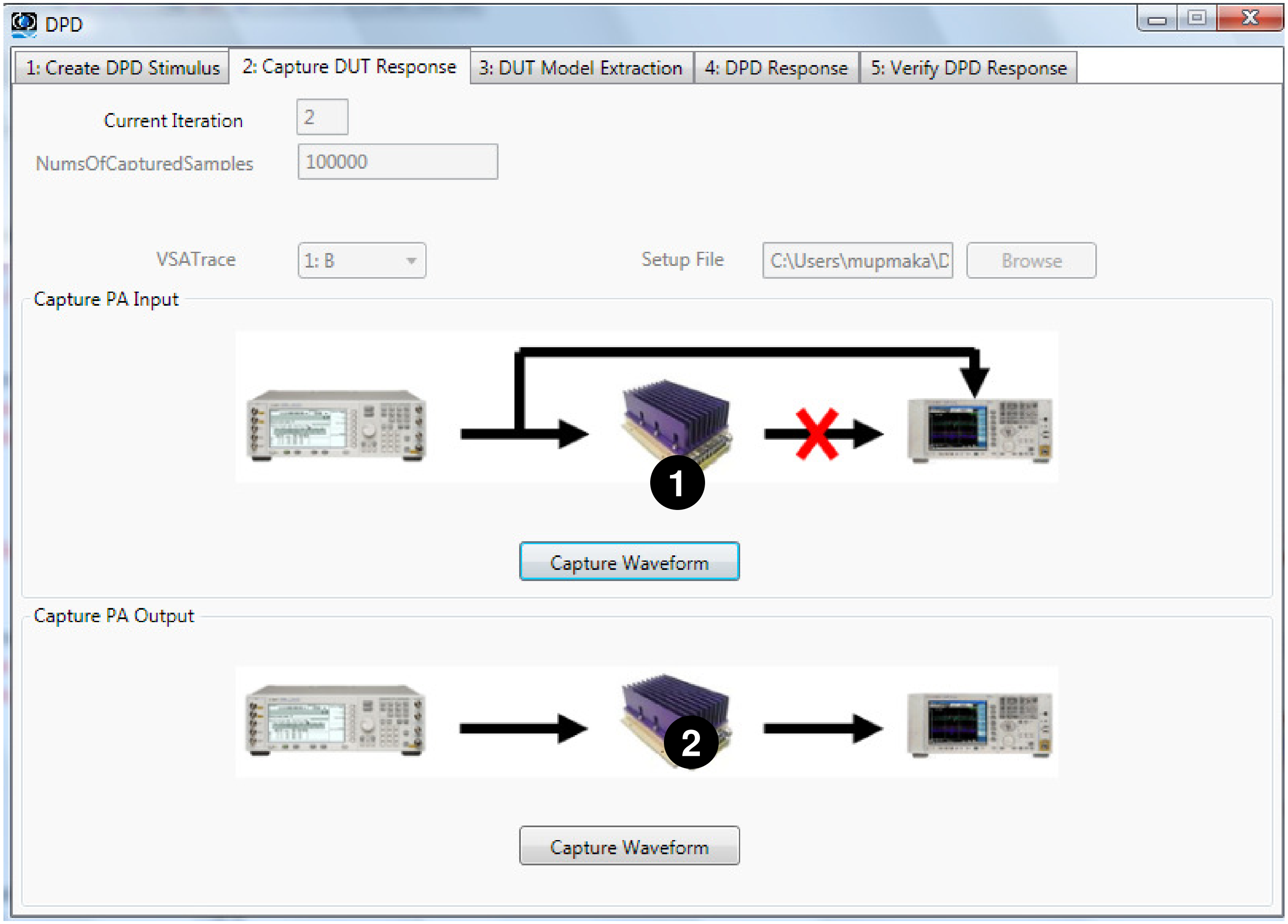
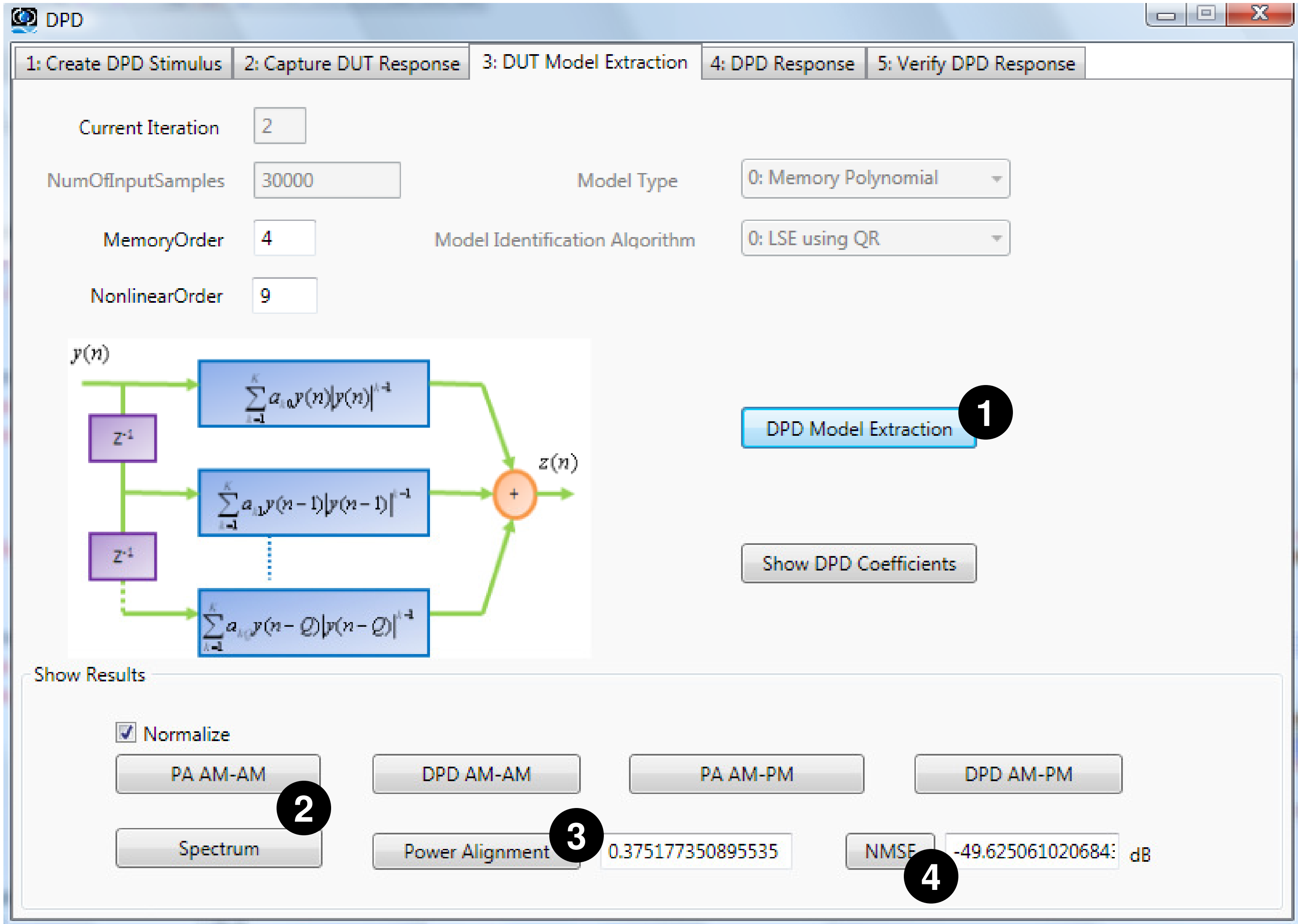
Begin--Iteration 2



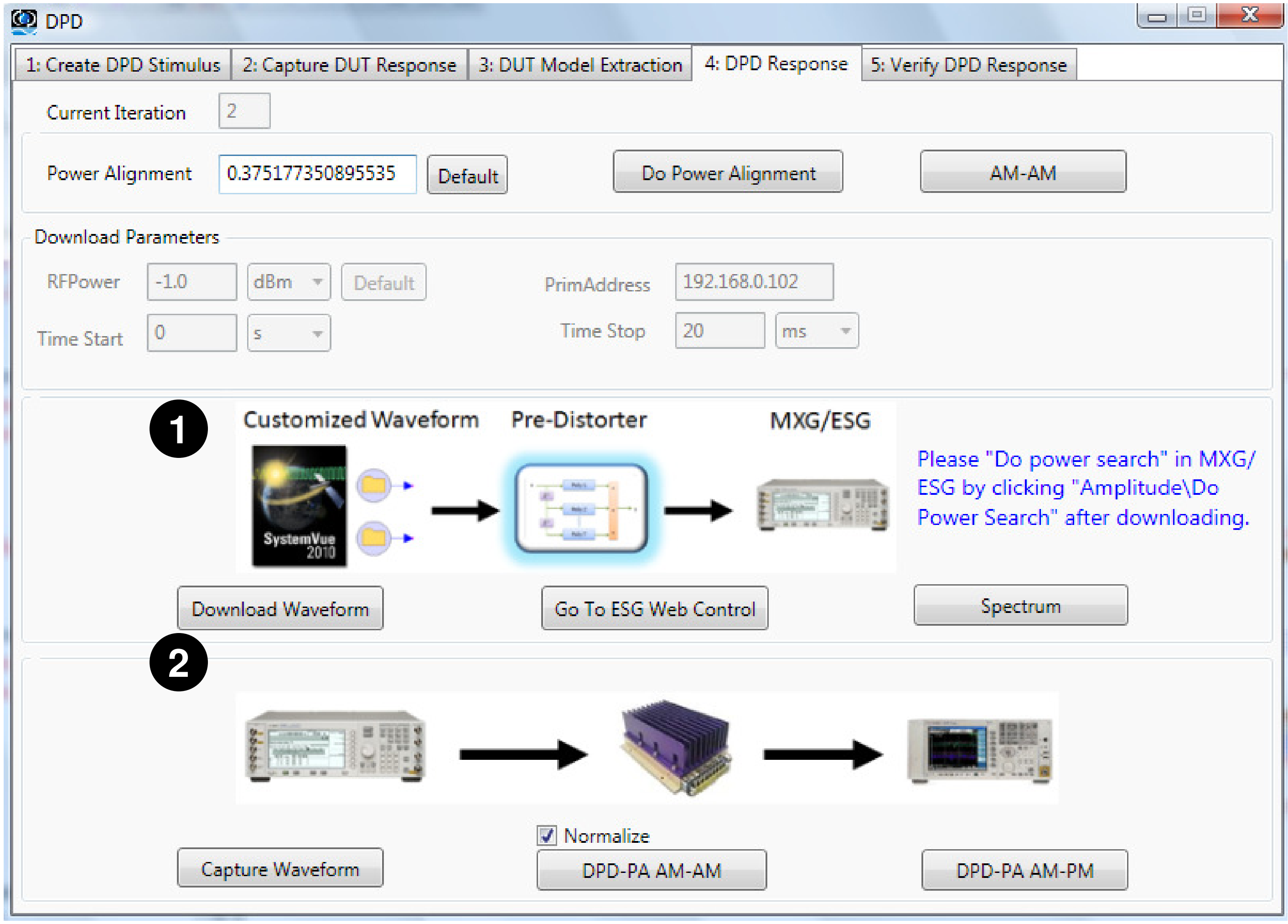
Iteration 2


DPD
1: Create DPD Stimulus
2: Capture DUT Response
3: DUT Model Extraction
4: DPD Response
5: Verify DPD Response
Current Iteration
2
NumsOfCapturedSamples
100000
VSATrace
1: B
Setup File
C:\Users\mupmaka\D
Browse
Capture PA Input
1
Capture Waveform
Capture PA Output
2
Capture Waveform

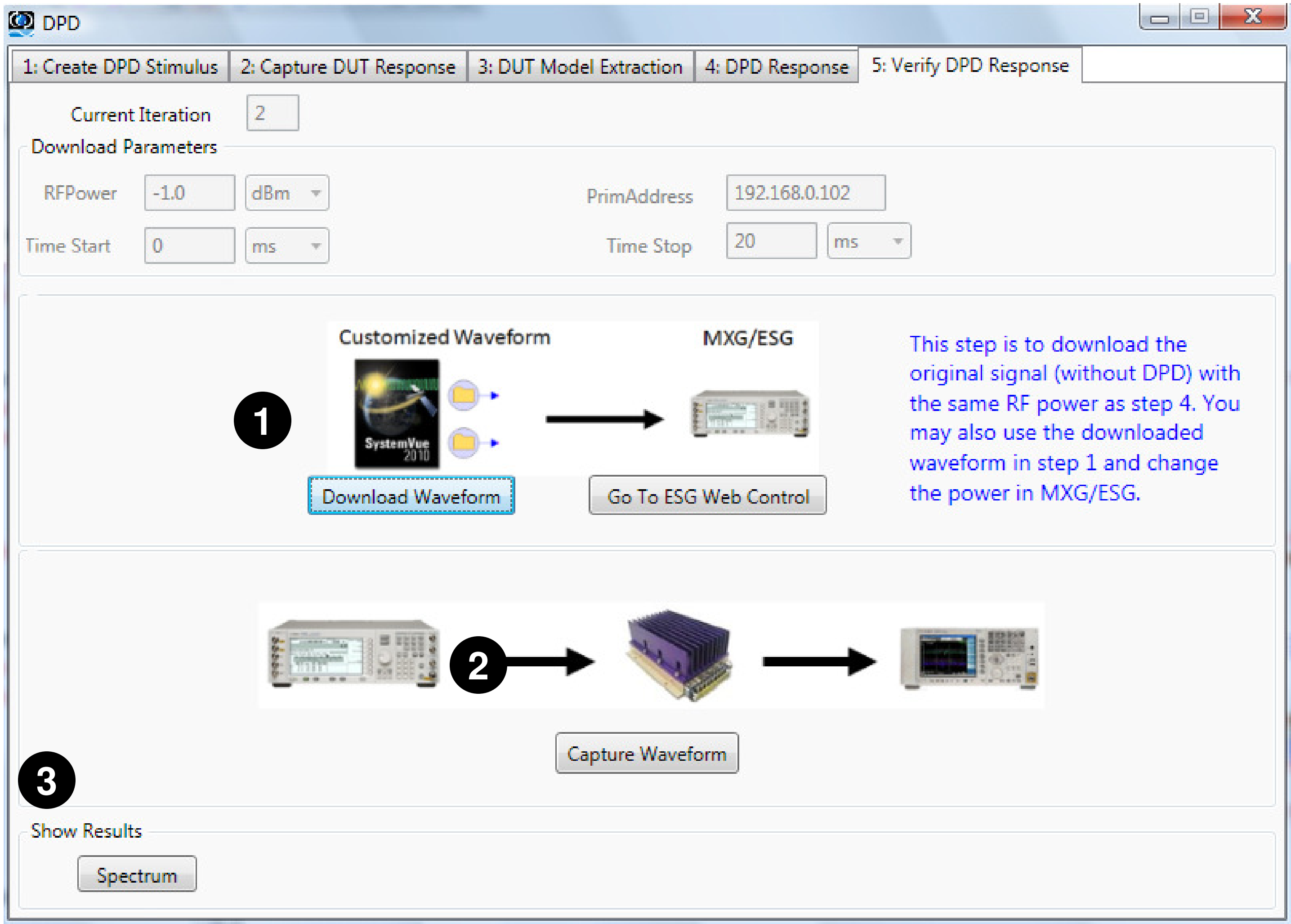
Iteration 2


DPD
1: Create DPD Stimulus
2: Capture DUT Response
3: DUT Model Extraction
4: DPD Response
5: Verify DPD Response
Current Iteration
2
NumOfInputSamples
30000
Model Type
0: Memory Polynomial
MemoryOrder
4
Model Identification Algorithm
0: LSE using QR
NonlinearOrder
9
y(n)
z(n)
DPD Model Extraction
1
Show DPD Coefficients
Show Results
Normalize
PA AM-AM
DPD AM-AM
PA AM-PM
DPD AM-PM
2
Spectrum
Power Alignment
3
0.375177350895535
NMSE
4
-49.625061020684:
dB

Iteration 2

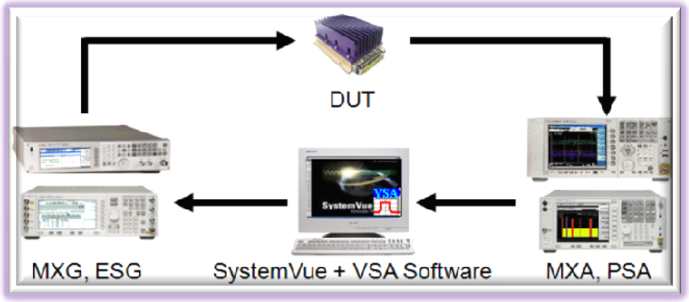

DPD
1: Create DPD Stimulus
2: Capture DUT Response
3: DUT Model Extraction
4: DPD Response
5: Verify DPD Response
Current Iteration
2
Power Alignment
0.375177350895535
Default
Do Power Alignment
AM-AM
Download Parameters
RFPower
-1.0
dBm
Default
PrimAddress
192.168.0.102
Time Start
0
s
Time Stop
20
ms
1
Customized Waveform
Pre-Distorter
MXG/ESG
SystemVue 2010
Please "Do power search" in MXG/ESG by clicking "Amplitude\Do Power Search" after downloading.
Download Waveform
Go To ESG Web Control
Spectrum
2
Normalize
Capture Waveform
DPD-PA AM-AM
DPD-PA AM-PM

End--Iteration 2

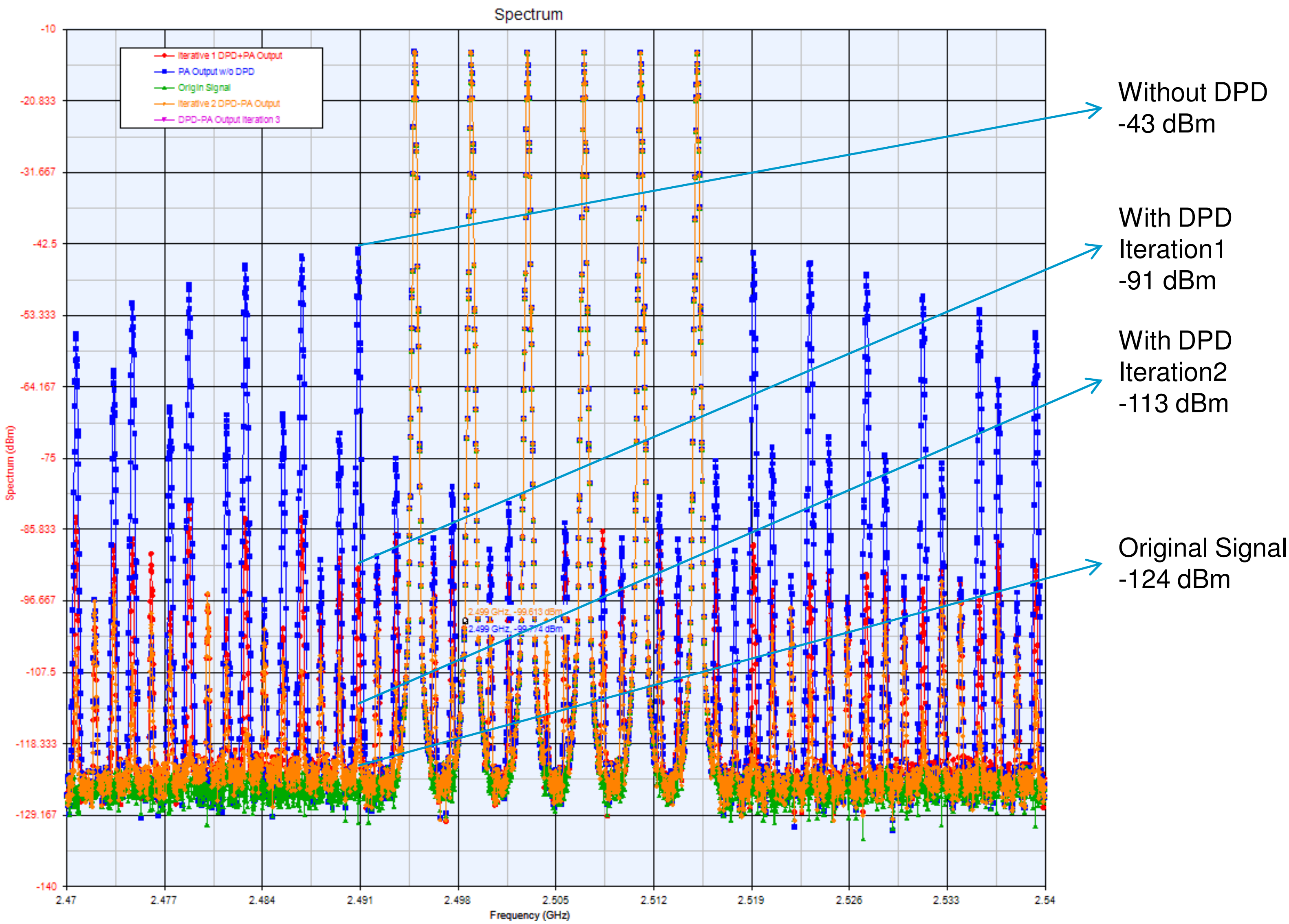


Let us review the steps

1. Create DPD Stimulus
2. Capture PA Response
3. Extract DPD Model
4. Capture DPD+PA Response
5. Verify No DPD+PA Response

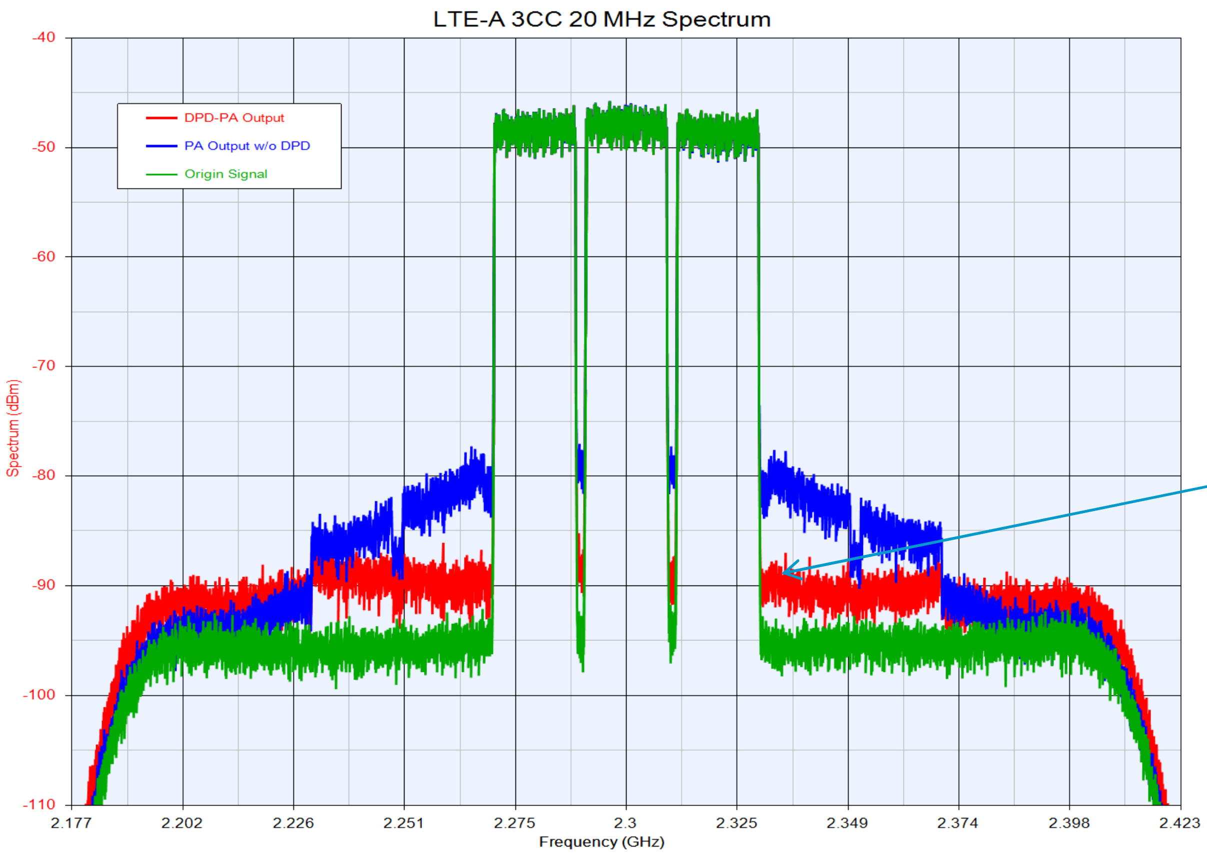


PA Circuit - DPD Algorithm in Simulation



Wideband platform

SystemVue with Modular PXI Instruments (Bandwidth ~250 MHz)



~10 dB improvement in spectral leakage

(1st iteration)

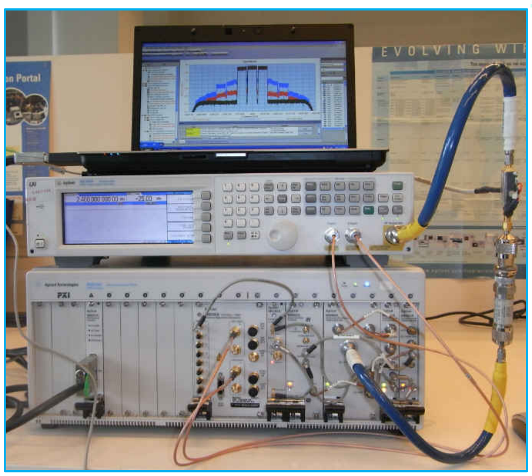
DPD of LTE-Advanced, Using M9330A/M9392A

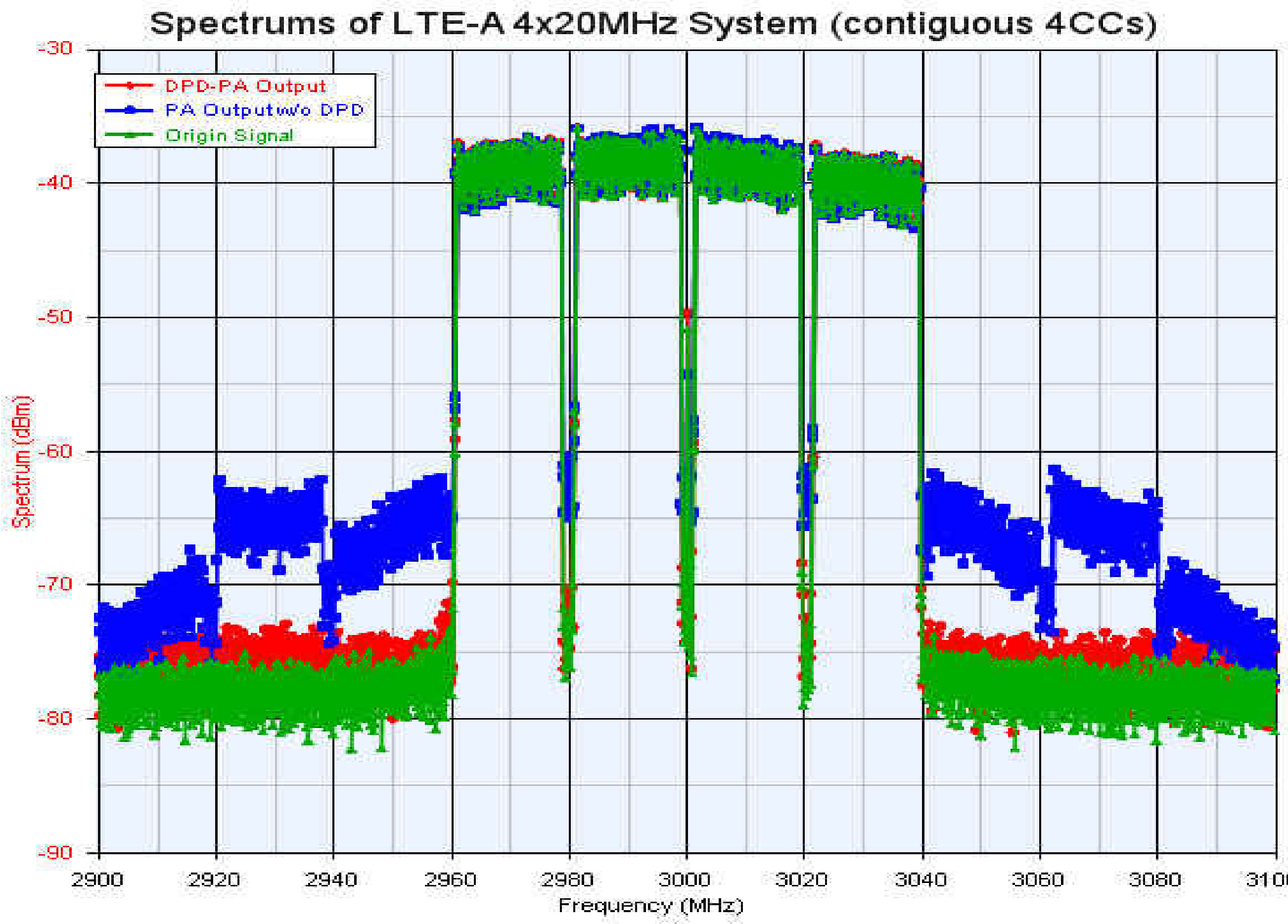
4 x 20 MHz Contiguous CCs (80 MHz Signal BW)

Source = M9330A AWG

Vector Analyzer= M9392A
- 12bits ADC
- up to 250 MHz bandwidth

PA Output Spectrum (**Blue**)
PA+DPD Spectrum (**Red**)
PA Input Spectrum (**Green**)





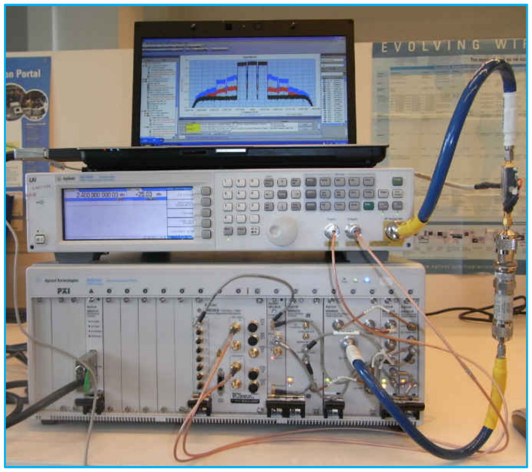
DPD of LTE-Advanced, Using M9330A/M9392A

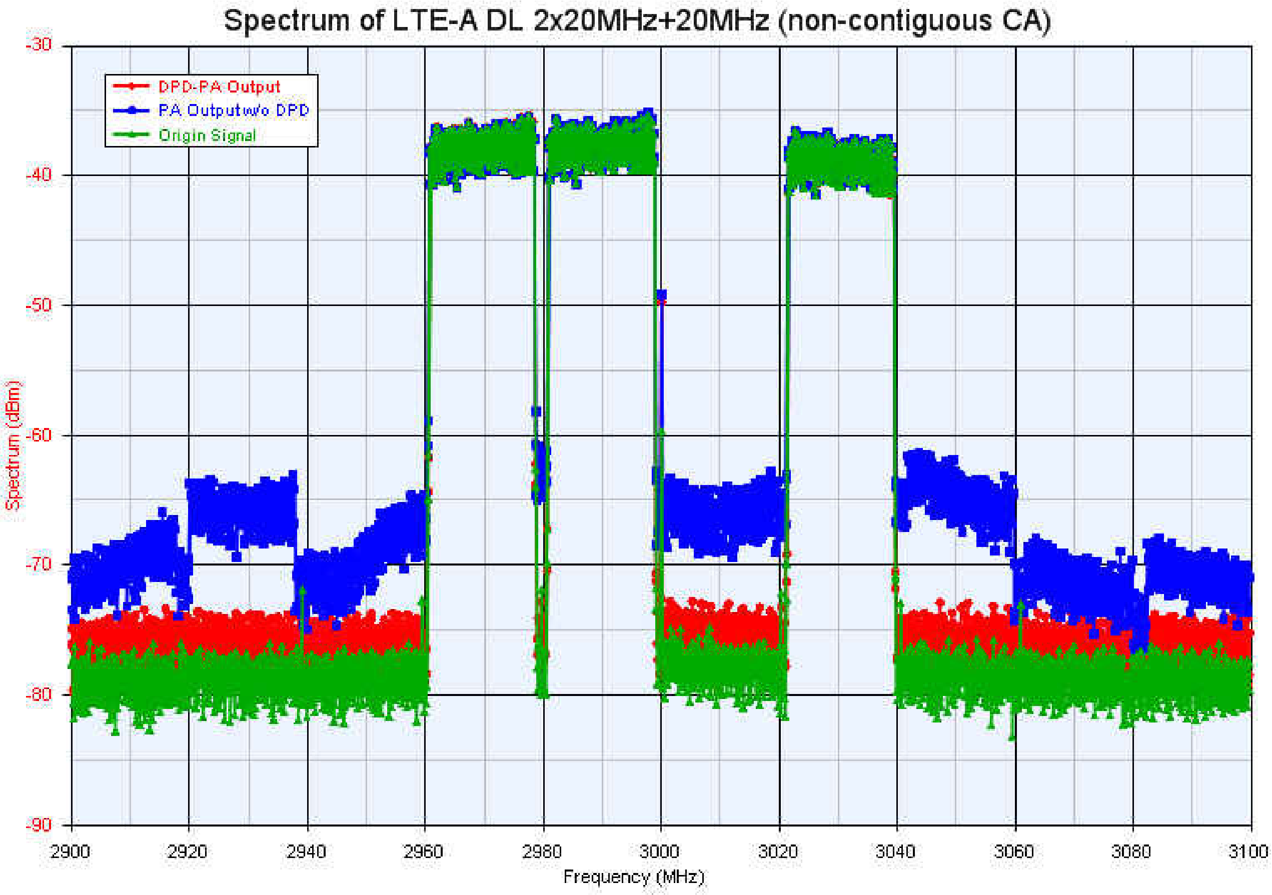
2 x 20 MHz + 20 MHz Non-contiguous CA (80 MHz Signal BW)

Source = M9330A AWG

Vector Analyzer= M9392A
- 12bits ADC
- up to 250 MHz bandwidth

PA Output Spectrum (**Blue**)
PA+DPD Spectrum (**Red**)
PA Input Spectrum (**Green**)



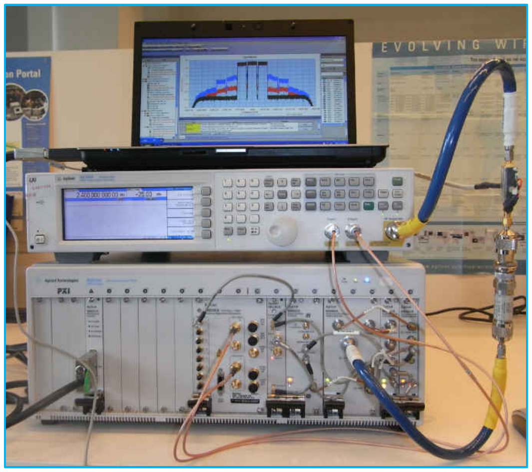


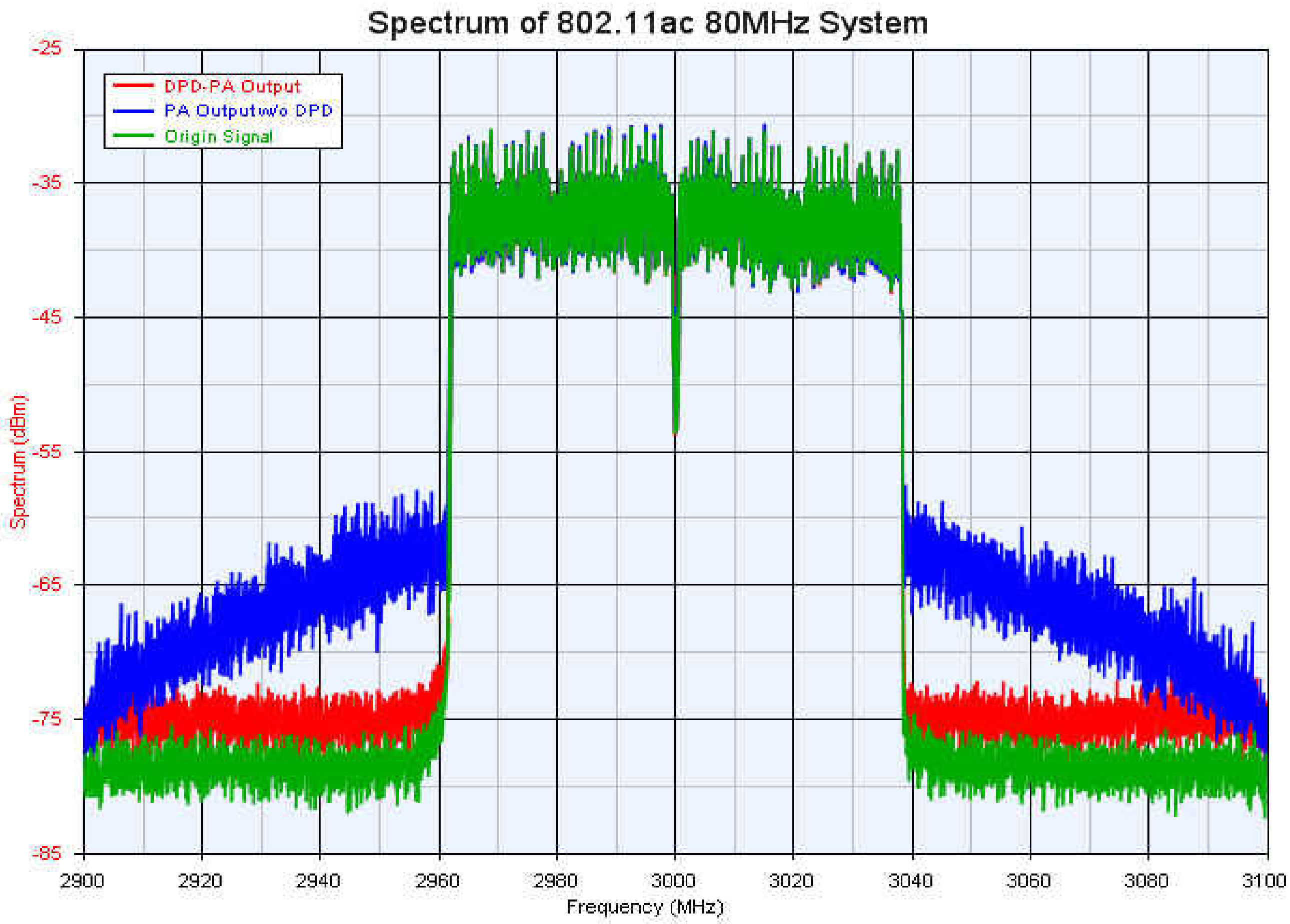
DPD of 802.11ac, Using M9330A/M9392A
(80 MHz Option)

Source = M9330A AWG

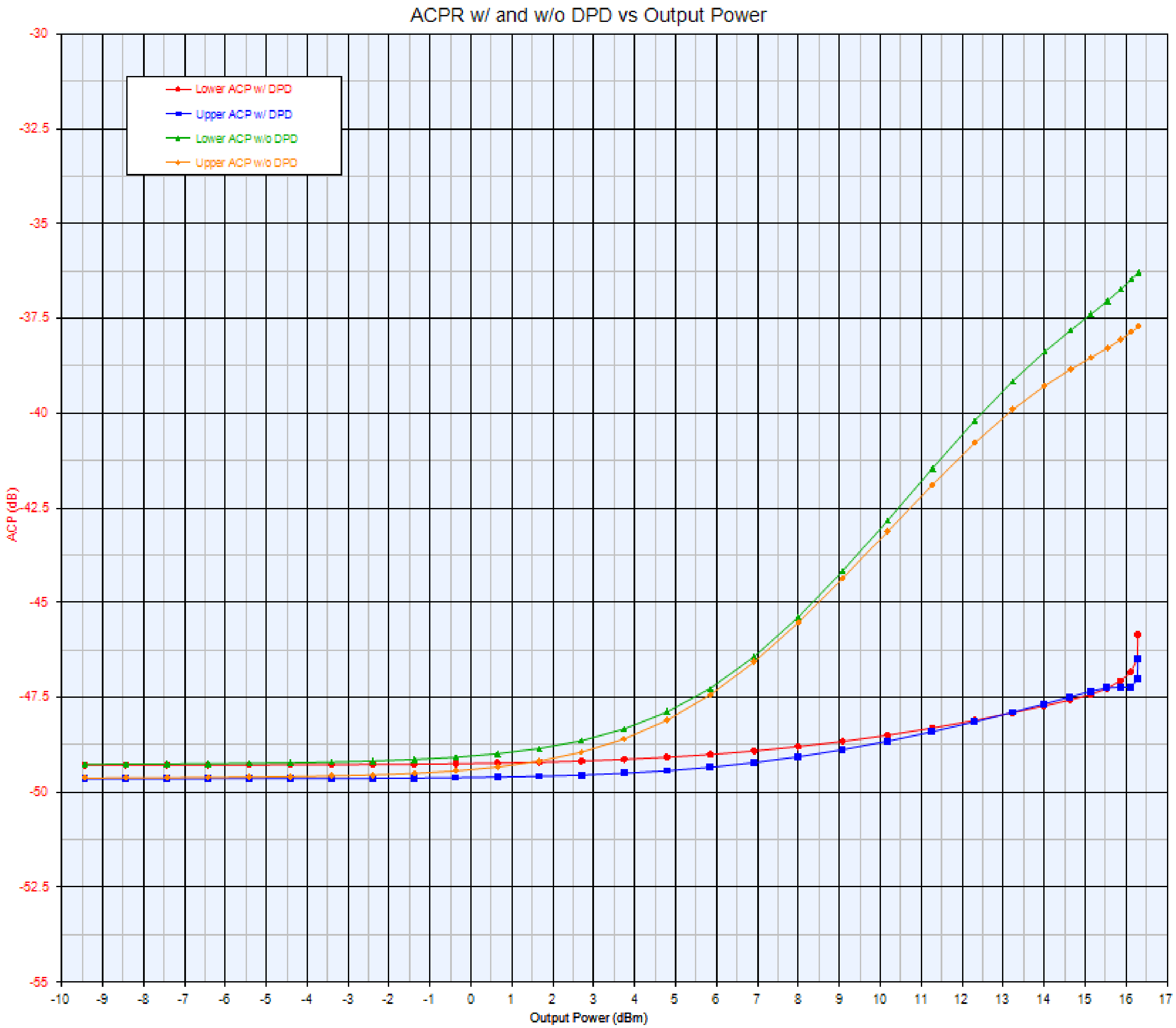
Vector Analyzer= M9392A
- 12bits ADC
- up to 250 MHz bandwidth

PA Output Spectrum (**Blue**)
PA+DPD Spectrum (**Red**)
PA Input Spectrum (**Green**)

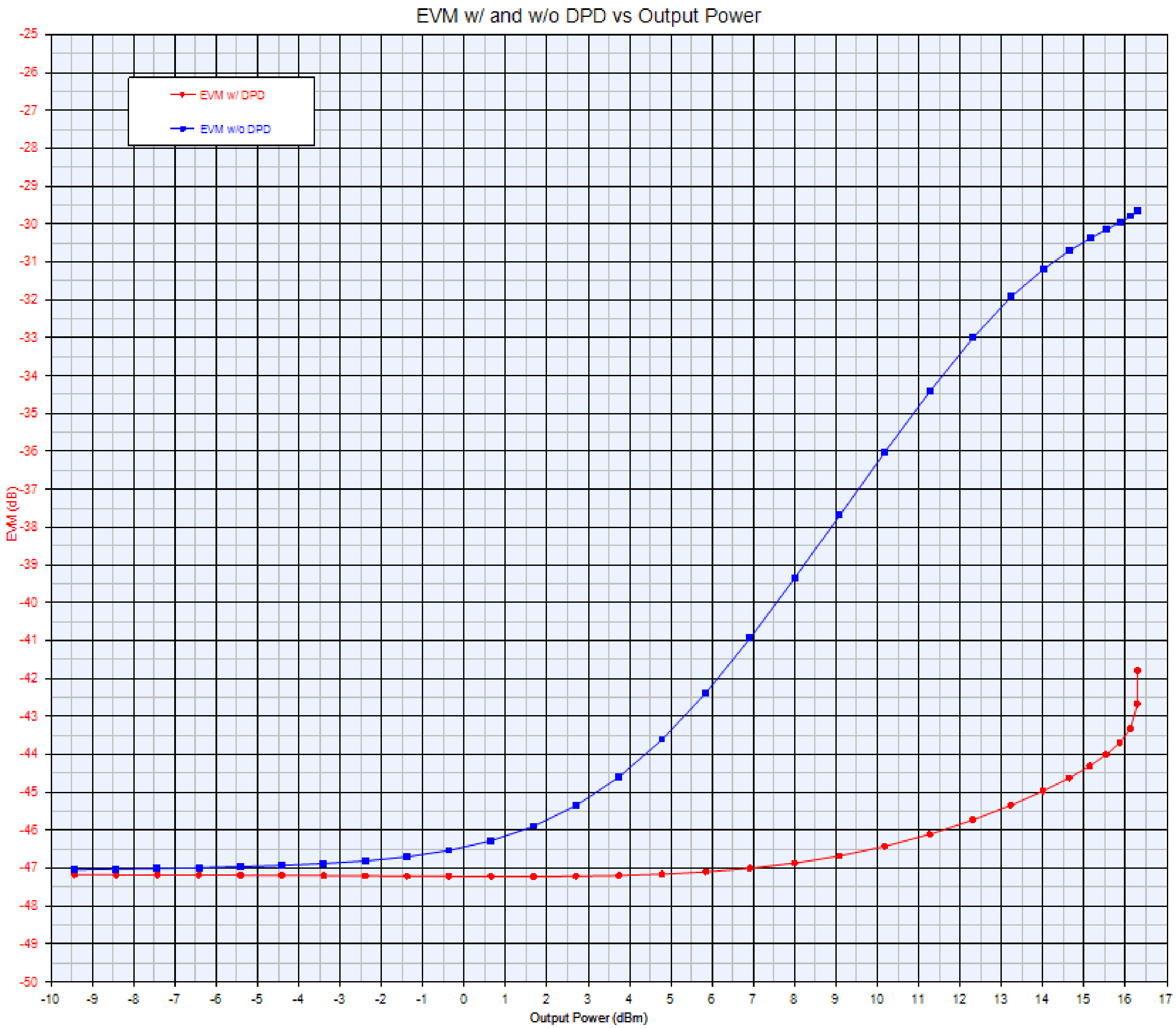




DPD of 802.11ac - Simulation



DPD of 802.11ac - Simulation



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Agenda

About Digital Pre-Distortion (DPD)

DPD challenges for 4G/wideband systems

Design a PA that is more linearizable

Understand the limits of the DPD algorithm

Some Results

Conclusion

Q&A

Conclusion

- New bandwidth and linearity requirements are driving 4G designers to spec DPD earlier in their system designs
- The velocity of the industry is pushing DPD activity in-house, where designers are taking a more active role
- Cosimulation with actual circuit gives the ability to capture Memory effects
- Establishes the boundaries of DPD algorithm
- Enables good business decision on the selection of instrumentation

Further Information

About Wideband DPD

– *Watch a demo:* http://www.youtube.com/watch?v=bocF6P74T9E

– *Read an app note:* http://cp.literature.agilent.com/litweb/pdf/5990-8883EN.pdf

About Agilent Products

– http://www.agilent.com/find/eesof-systemvue-dpd-builder

– http://www.agilent.com/find/modular

Selected DPD References

1. Lei Ding, Zhou G.T., Morgan D.R., Zhengxiang Ma, Kenney J.S., Jaehyeong Kim, Giardina C.R., "*A robust digital baseband predistorter constructed using memory polynomials*", Communications, IEEE Transactions on, Jan. 2004, Volume: 52, Issue:1, page 159-165.

2. Lei Ding, "*Digital Predistortion of Power Amplifiers for Wireless Applications*", PhD Thesis, March 2004.

3. Roland Sperlich, "*Adaptive Power Amplifier Linearization by Digital Pre-Distortion with Narrowband Feedback using Genetic Algorithms*", PhD Thesis, 2005.

4. Helaoui, M. Boumaiza, S. Ghazel, A. Ghannouchi, F.M., "*Power and efficiency enhancement of 3G multicarrier amplifiers using digital signal processing with experimental validation*", Microwave Theory and Techniques, IEEE Transactions on, June 2006, Volume: 54, Issue: 4, Part 1, page 1396-1404.

5. H. A.Suraweera, K. R. Panta, M. Feramez and J. Armstrong, "*OFDM peak-to-average power reduction scheme with spectral masking*," Proc. Symp. on Communication Systems, Networks and Digital Signal Processing, pp.164-167, July 2004.

6. Zhao, Chunming; Baxley, Robert J.; Zhou, G. Tong; Boppana, Deepak; Kenney, J. Stevenson, "*Constrained Clipping for Crest Factor Reduction in Multiple-user OFDM*", Radio and Wireless Symposium, 2007 IEEE Volume , Issue , 9-11 Jan. 2007 Page(s):341- 344.

7. Olli Vaananen, "*Digital Modulators with Crest Factor Reduction Techniques*", PhD Thesis, 2006

8. Boumaiza, et a, "On the RF/DSP Design for Efficiency of OFDM Transmitters" , *IEEE Transactions on Microwave Theory and Techniques*, Vol. 53, No. 7, July 2005, pp 2355-2361.

9. Boumaiza, Slim, "*Advanced Memory Polynomial Linearization Techniques*," IMS2009 Workshop WMC (Boston, MA), June 2009.

Recent DPD Resources from Agilent

App Notes

- http://cp.literature.agilent.com/litweb/pdf/5990-8883EN.pdf (Wideband DPD)
- http://cp.literature.agilent.com/litweb/pdf/5990-7818EN.pdf (3G/4G)
- http://cp.literature.agilent.com/litweb/pdf/5990-6742EN.pdf
- http://cp.literature.agilent.com/litweb/pdf/5990-6534EN.pdf (algorithms used)

Demonstration Videos

- http://www.youtube.com/watch?v=bocF6P74T9E (Wideband DPD)

Webcasts

"High Performance Digital Pre-Distortion (DPD) for Wideband Systems" (Sept 2011)

http://www.home.agilent.com/agilent/eventDetail.jspx?ckey=2021229&pid=1475688&nid=-34360.0&lc=eng

"4G For Everyone: Extended RF Performance with DPD" (June 2010)

http://www.home.agilent.com/agilent/eventDetail.jspx?cc=US&lc=eng&ckey=1842093&nid=-11143.0.00&id=1842093

Q&A