Wideband Digital Pre-Distortion Modeling for LTE-Advanced

Daren McClearnon, speaker
System-Level EDA, Product Mktng Mgr.,
Agilent Technologies

Jinbiao Xu, author
Sr. Applications Engineer
Agilent Technologies

Agenda

1. Introduction and Problem Statement
2. Digital Pre-Distortion (DPD) Concepts
3. DPD verification with Agilent Hardware
4. DPD simulation with Agilent EDA Tools
5. Crest Factor Reduction (CFR)
6. Summary

Digital Pre-Distortion (DPD): Problem Statement

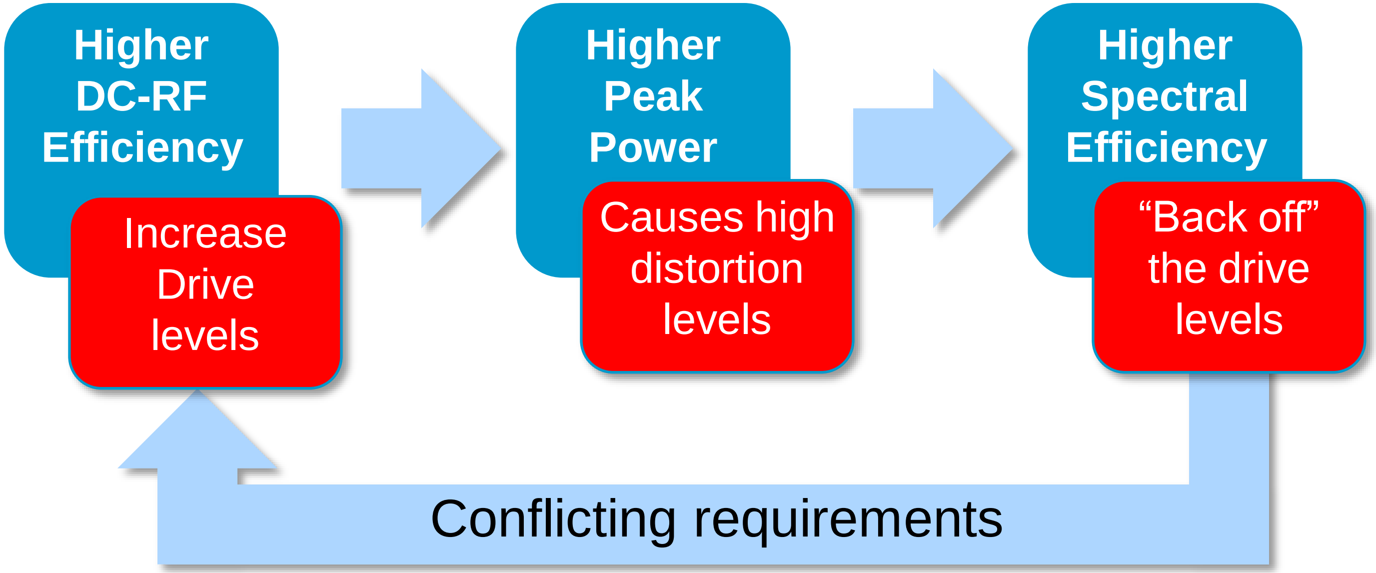
- Modern communication systems:
  - Signals have high peak-to-average power ratios (PAPR).
  - Must operate with high power-added efficiency (PAE).

- High PAPR is a consequence of high spectral efficiency
  - Multiple-Carrier Signals (MC GSM, MC WCDMA)
  - CDMA (WCDMA, CDMA2000)
  - OFDM (LTE, WiMAX)

- High PAE is achieved when the RF power amplifier (PA) is driven towards saturation

- Operation near saturation inherently results in higher signal distortion

DPD Problem Statement



Higher DC-RF Efficiency

Increase Drive levels

Higher Peak Power

Causes high distortion levels

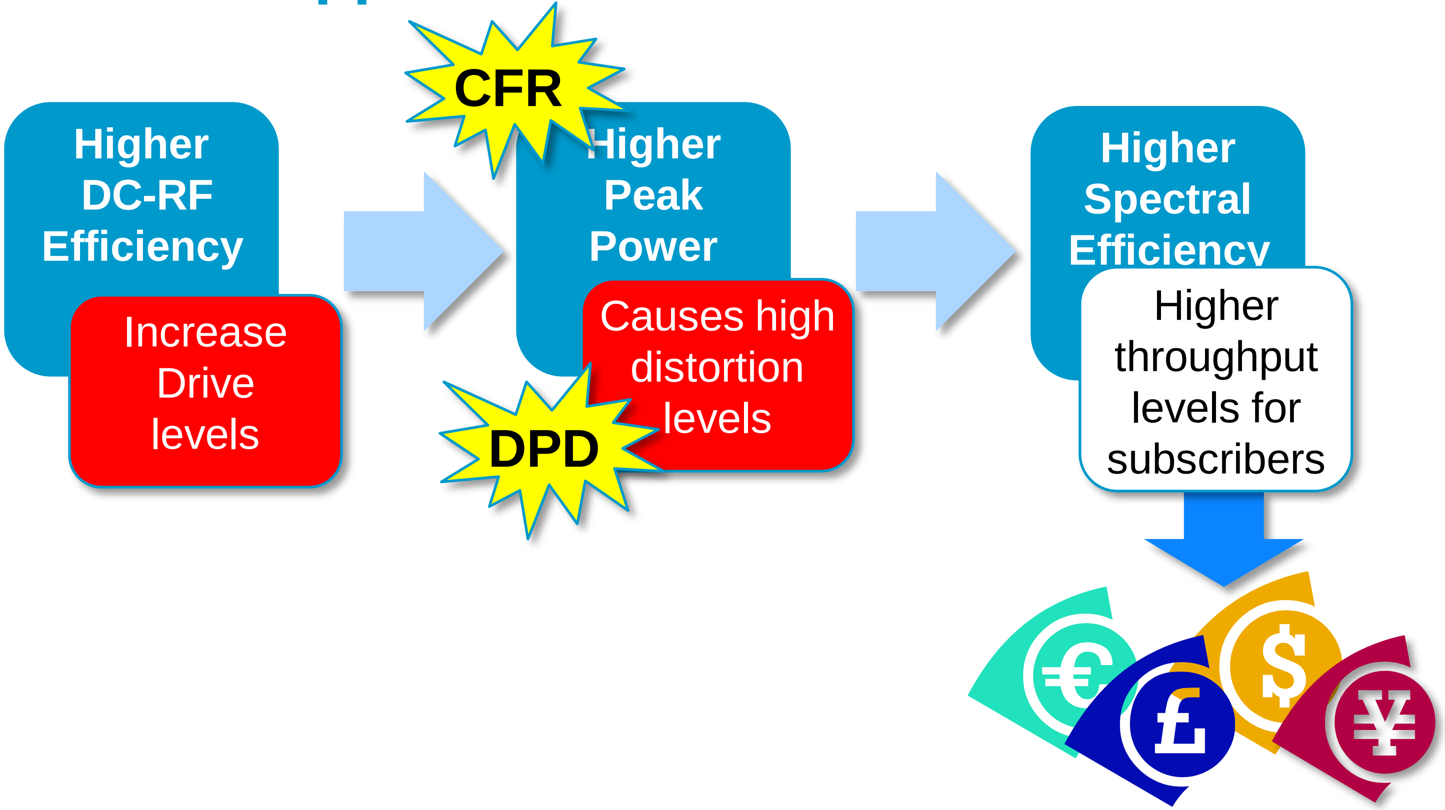
Higher Spectral Efficiency

"Back off" the drive levels

Conflicting requirements

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

DPD Solution Approach



CFR

Higher DC-RF Efficiency

Increase Drive levels

Higher Peak Power

Causes high distortion levels

DPD

Higher Spectral Efficiency

Higher throughput levels for subscribers

Solution: Preconditioning the signal (CFR) *and* correcting for the hardware (DPD) will both be discussed in this presentation

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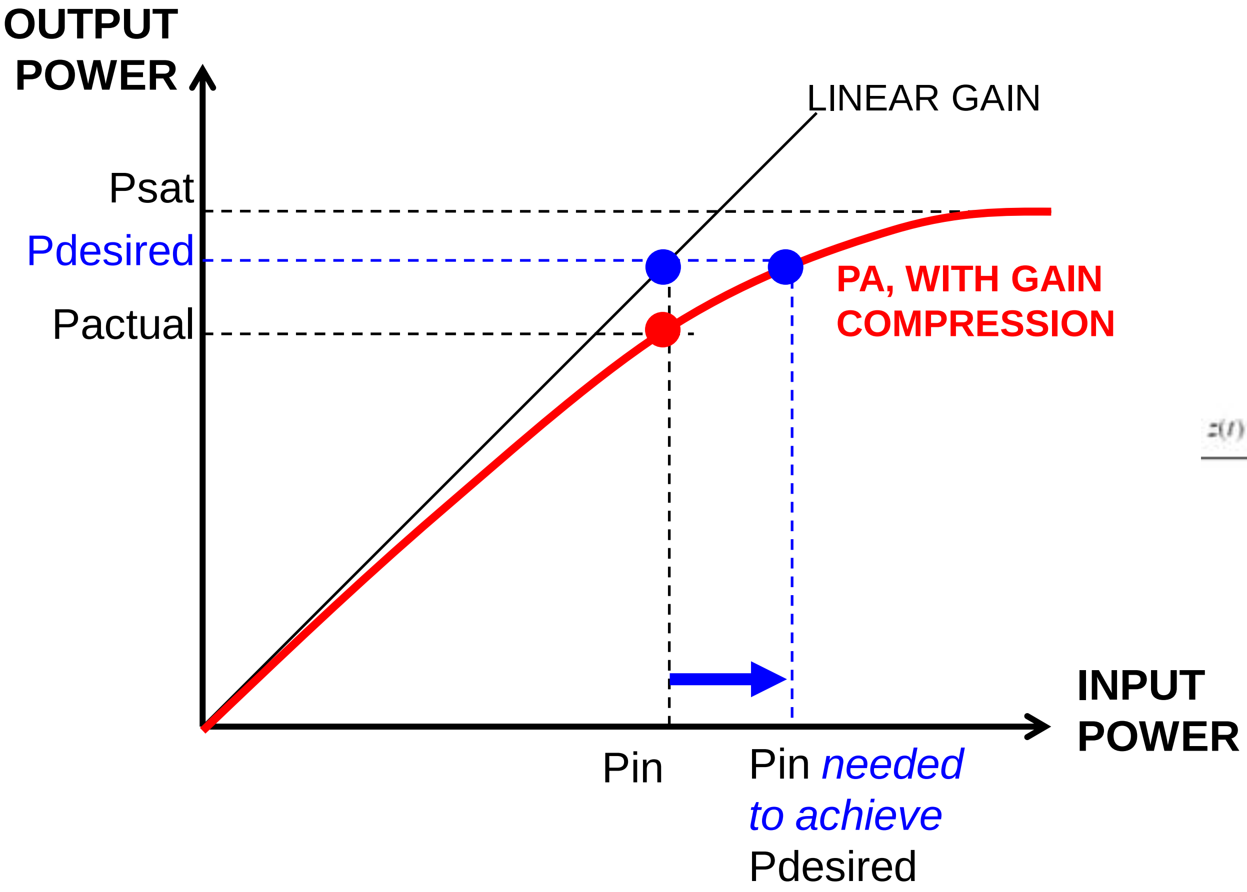
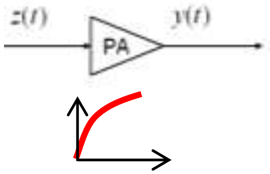
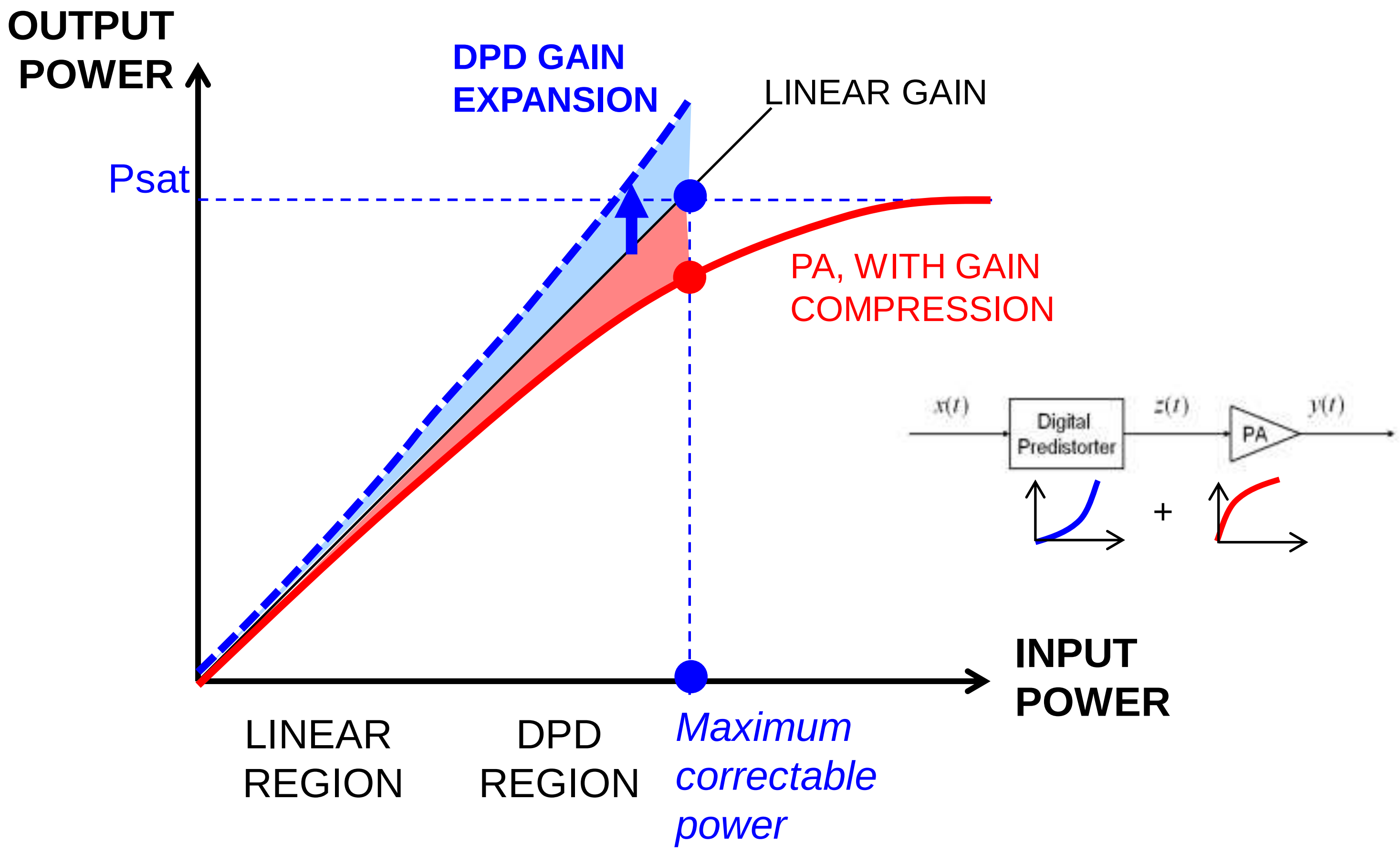
Digital Pre-distortion principles – compressing PA

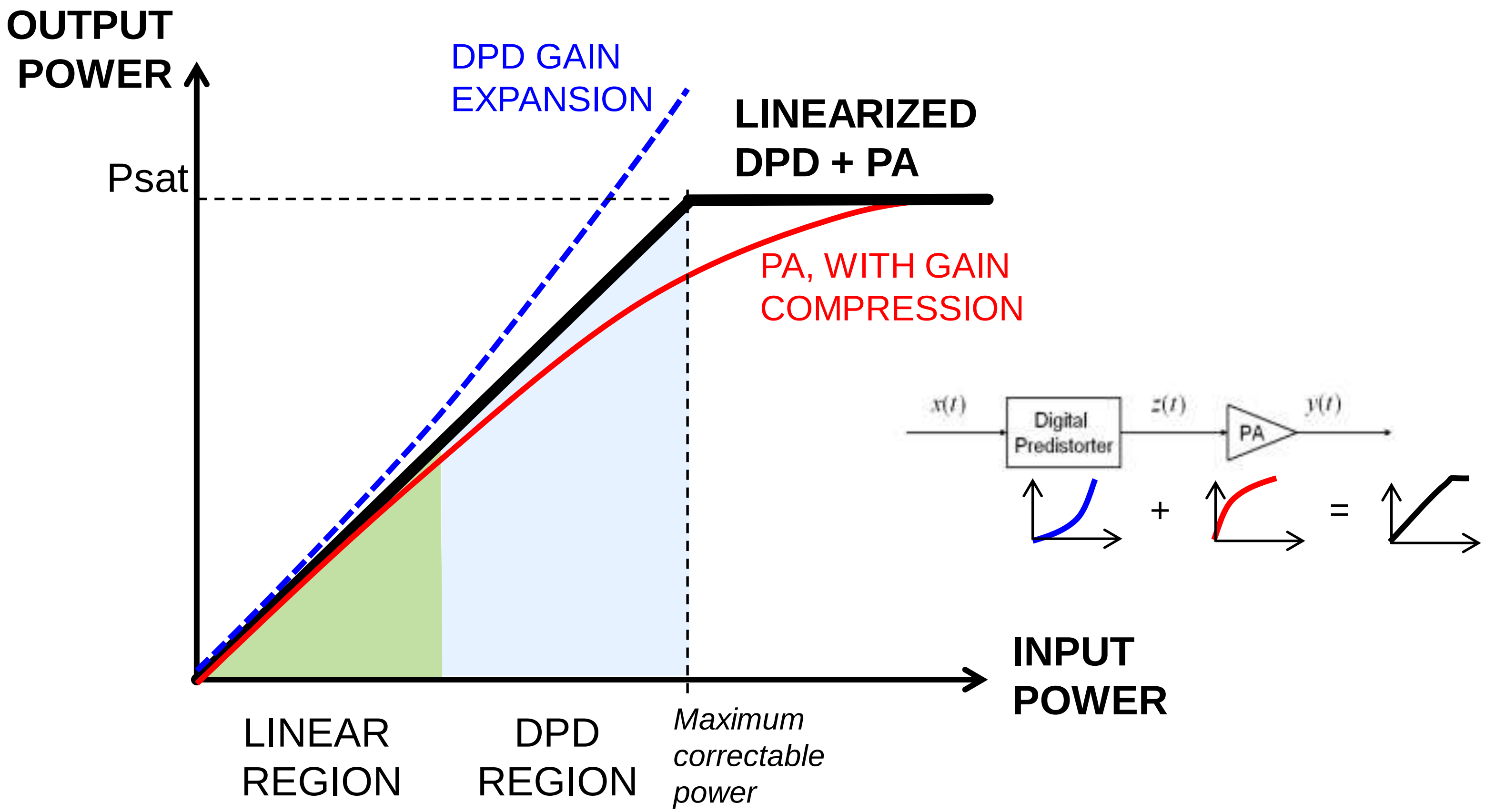




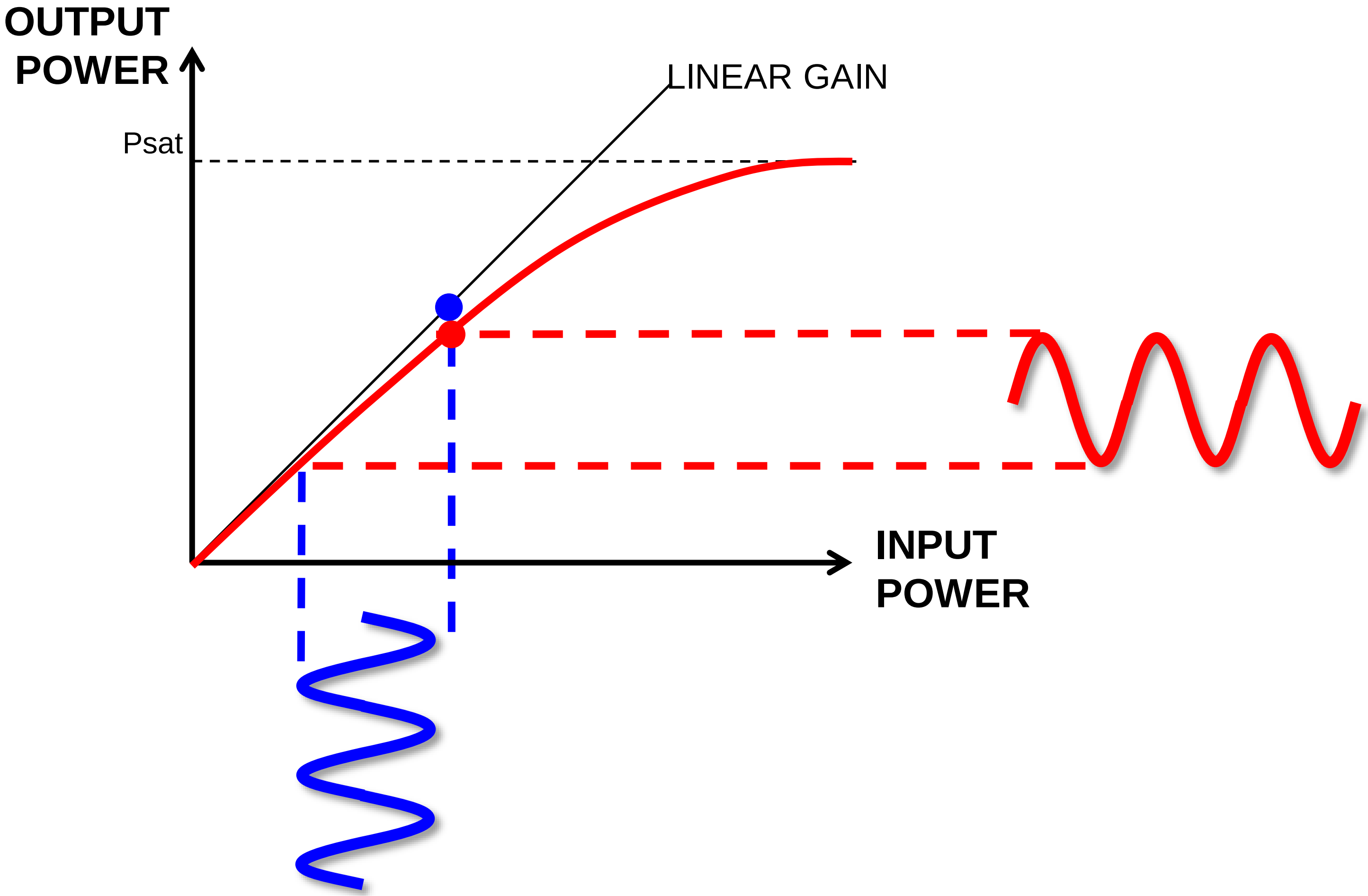
Digital Pre-distortion principles – pre-expansion



Digital Pre-distortion principles – linearized result

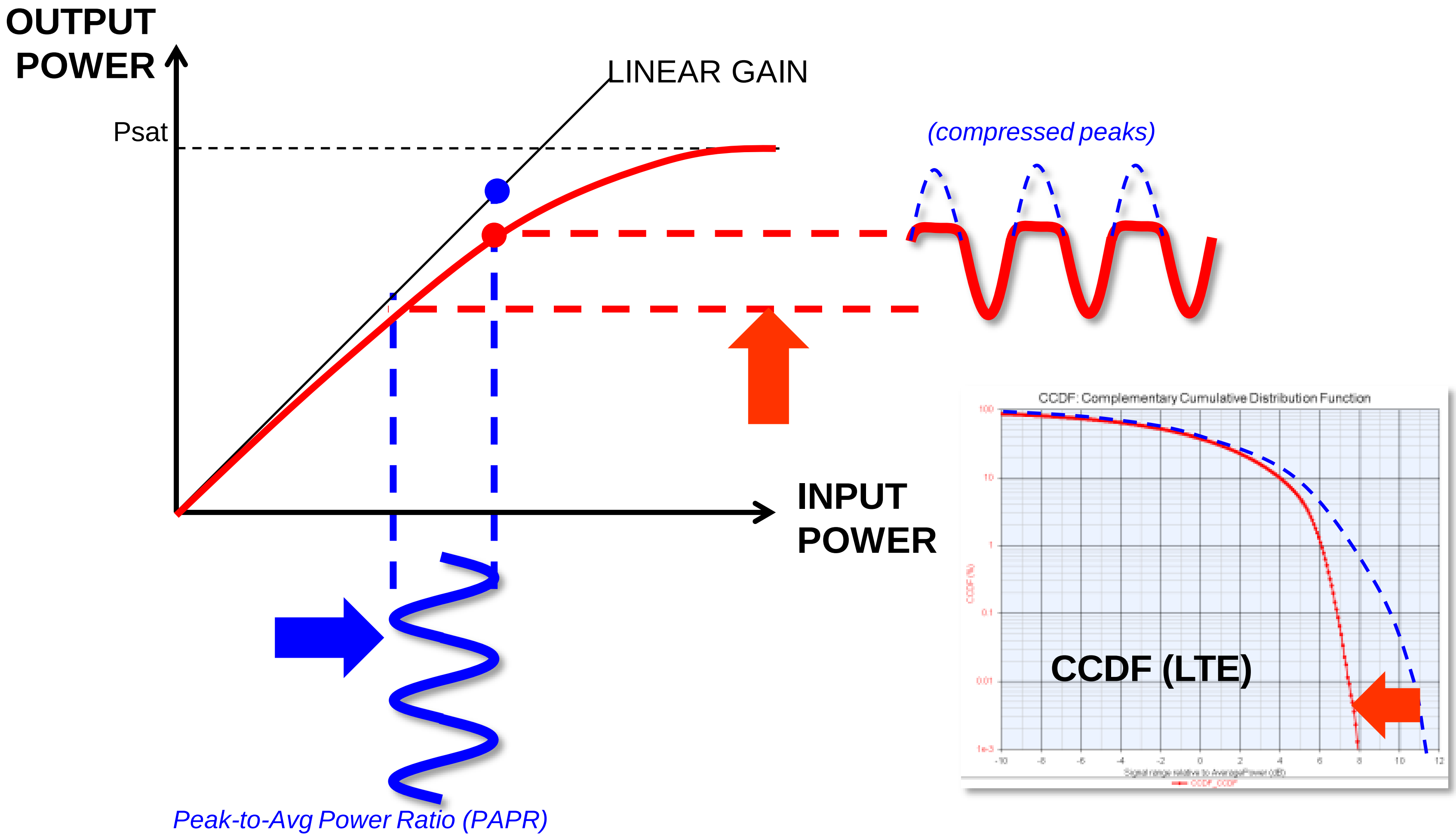


Linear Operation with time-varying envelope

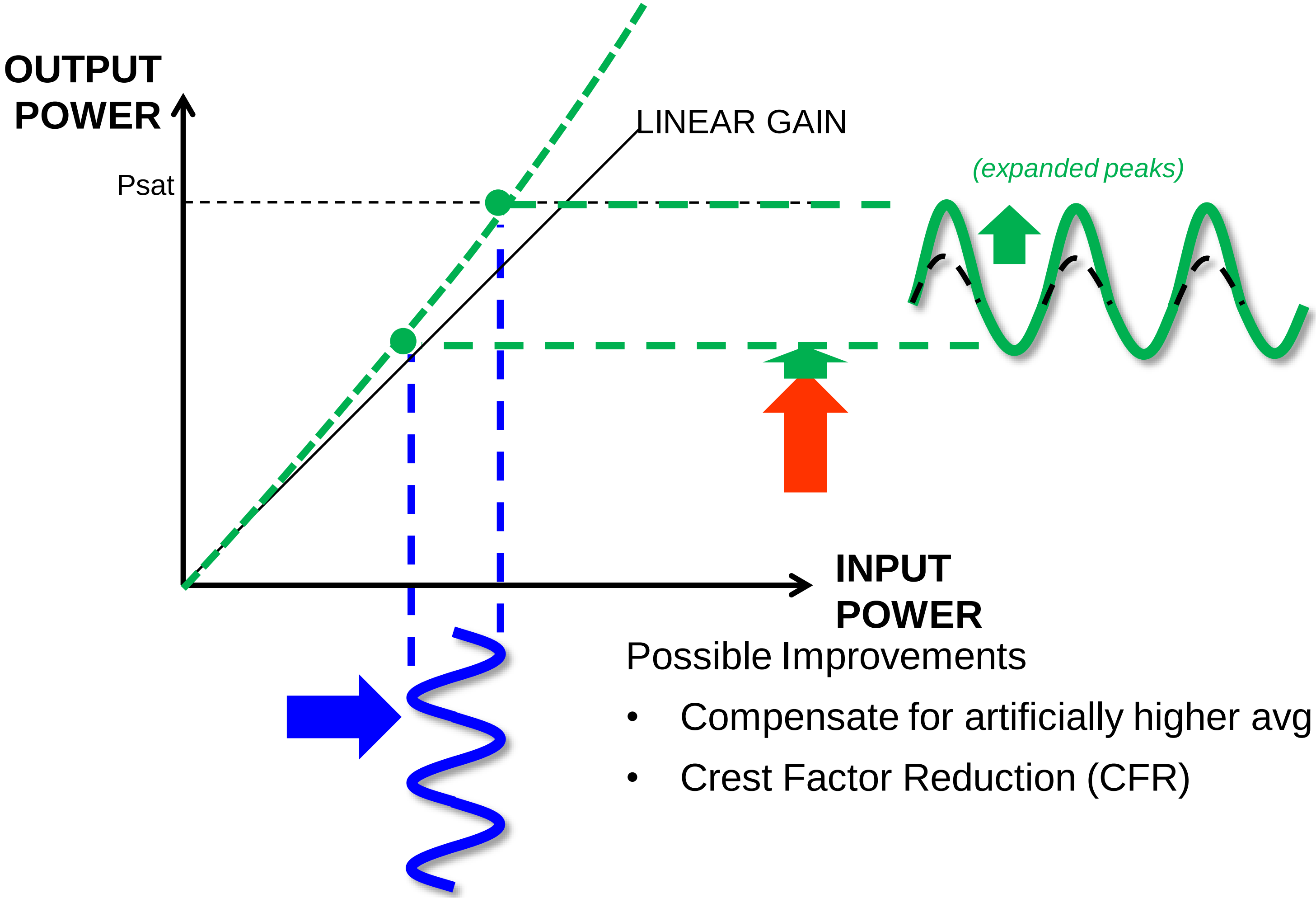


Peak-to-Avg Power Ratio (PAPR)

Nonlinear Operation – peaks are compressed



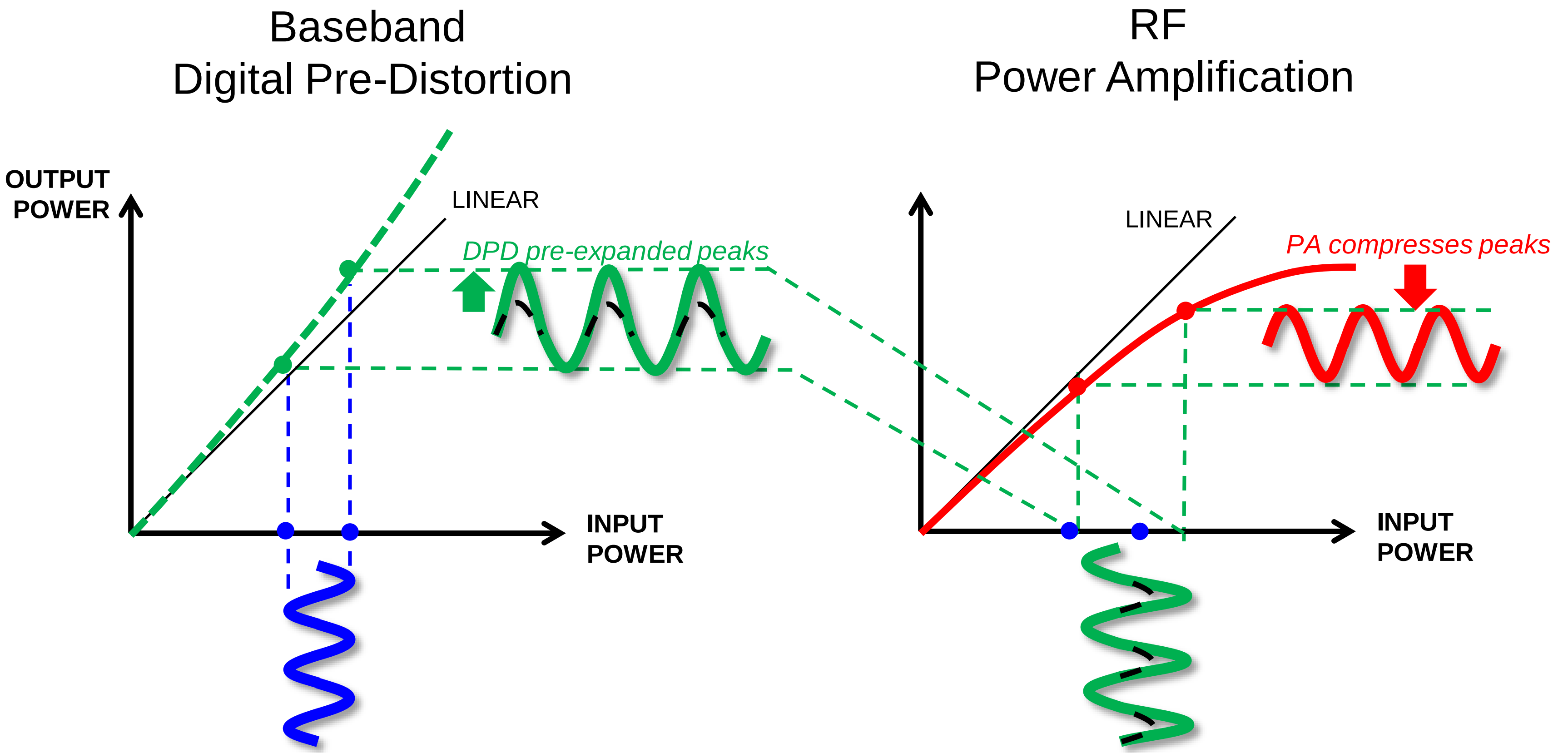
DPD Pre-Expansion – peaks are exaggerated



Possible Improvements

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

DPD Net Result: *Linear gain of complex-valued RF carrier envelope over a specific range of power levels*



What does a DPD look like? (Volterra Model)

Volterra series pre-distorter can be described by

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

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

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

DPD principles – Memory Polynomial Model

If only diagonal terms are kept, Volterra reduces to “**Memory polynomial**” model.

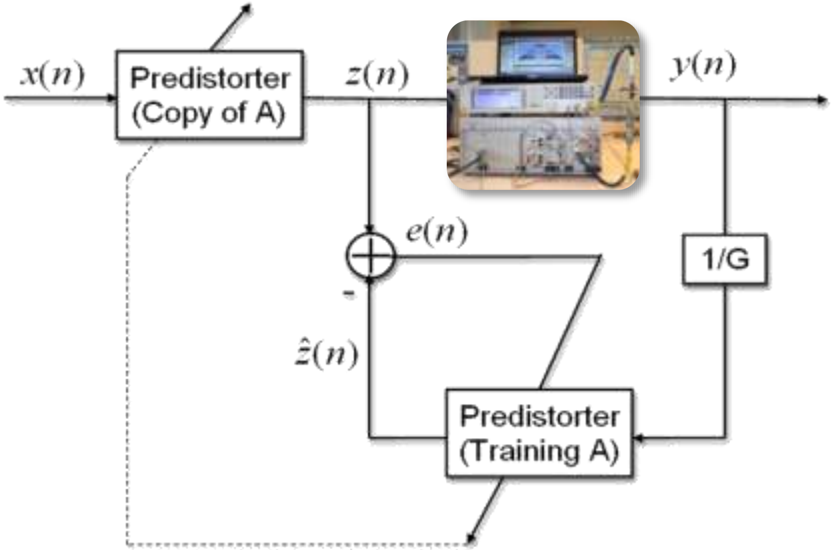
Agilent uses the “**Indirect Learning**” algorithm to extract MP coefficients.

You can now add your own model, extraction algorithm, and even your own GUI.

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

Where

- *K* is Nonlinearity order
- *Q* is Memory length



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.

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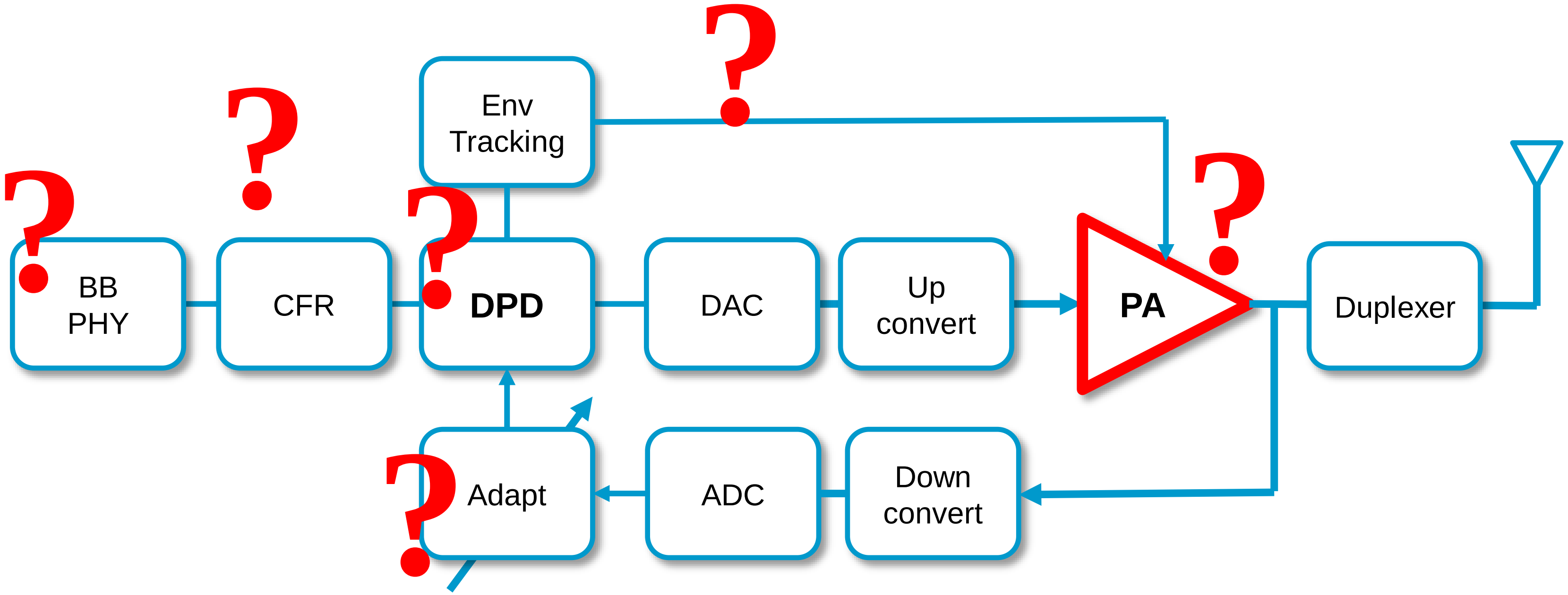
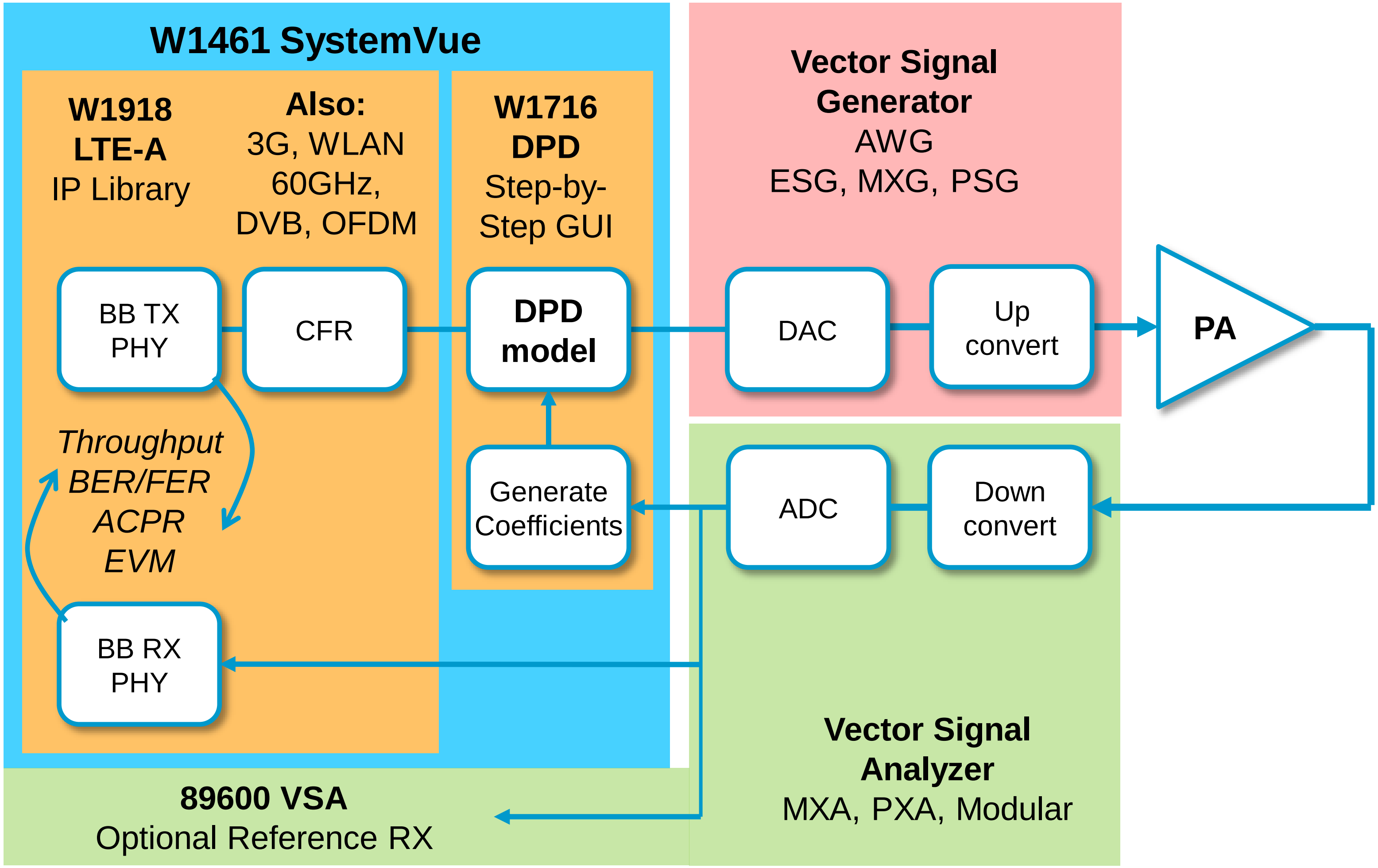
Generalized Wireless Transmitter Path



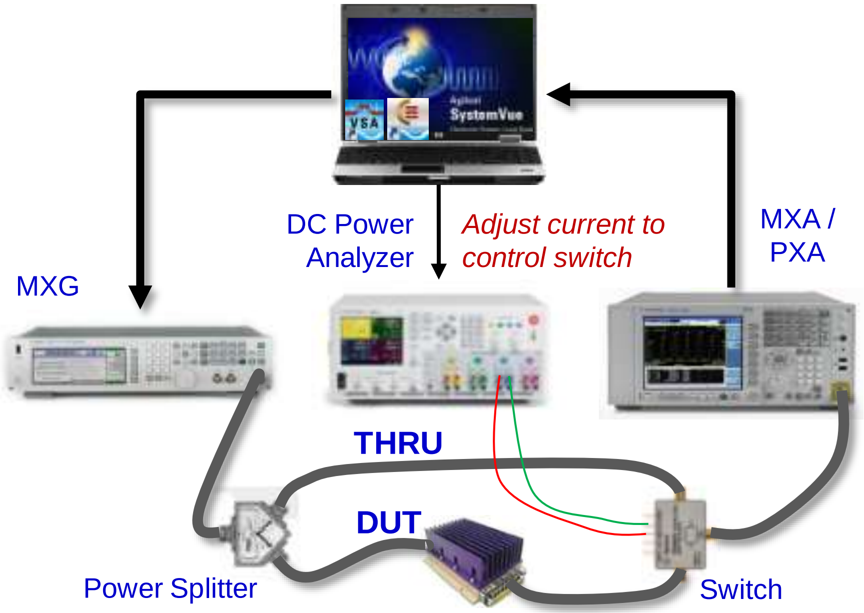
- Which blocks are included with your final product?
- What IP do you have access to? Or, are able to imitate? Able to modify?
- What final system specifications do you need to test against?

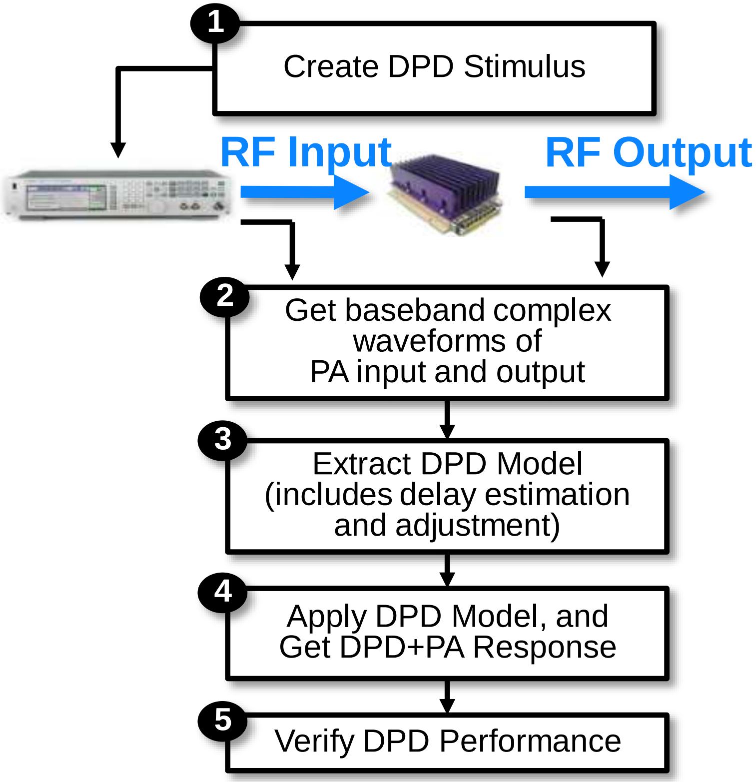
Agilent Measurement-based DPD Modeling Platform



Measurement-Based DPD Modeling Flow

Method 1 – Measure both PA Input and Output signals

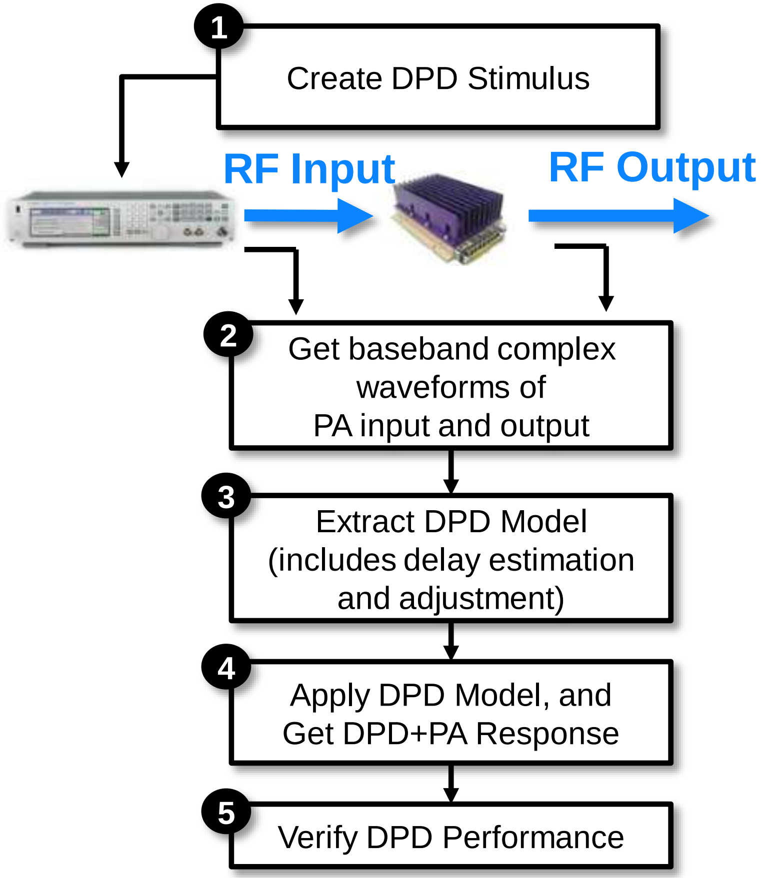




1. Create DPD Stimulus
2. Get baseband complex waveforms of PA input and output
3. Extract DPD Model (includes delay estimation and adjustment)
4. Apply DPD Model, and Get DPD+PA Response
5. Verify DPD Performance

Measurement-Based DPD Modeling Flow

Method 1 – Measure both PA Input and Output signals

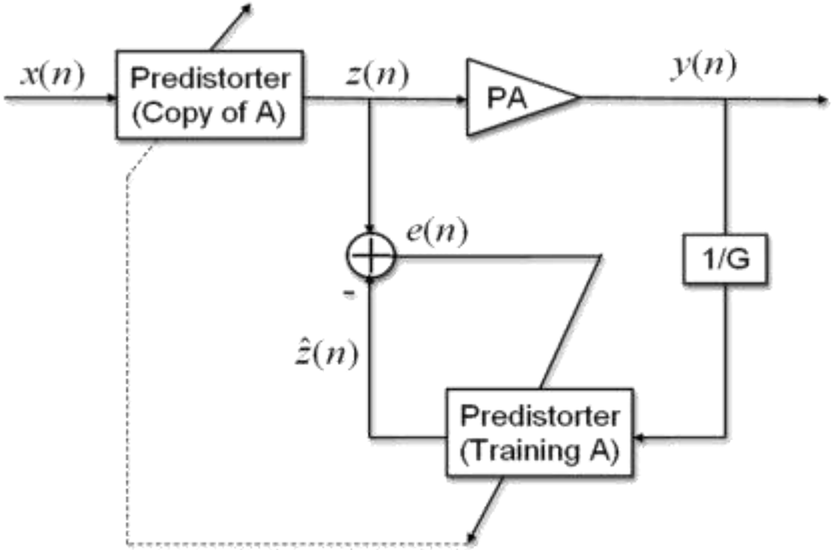


RF Input

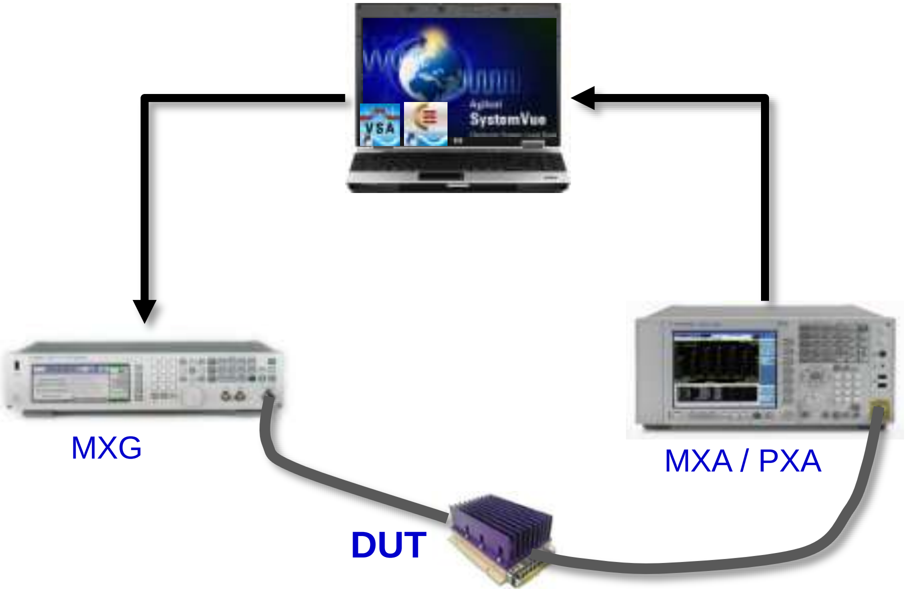
RF Output

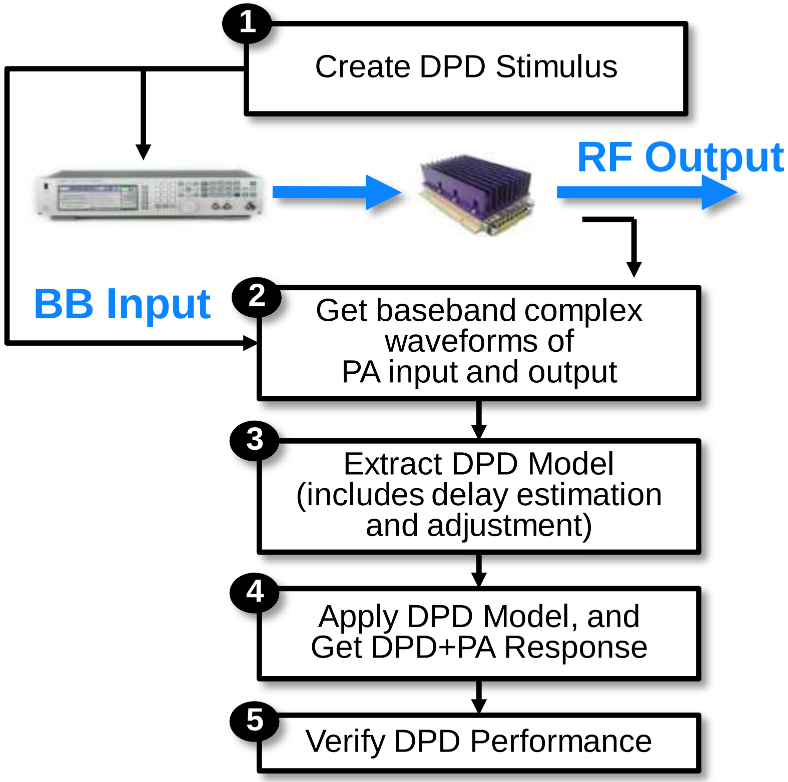
1. Create DPD Stimulus
2. Get baseband complex waveforms of PA input and output
3. Extract DPD Model (includes delay estimation and adjustment)
4. Apply DPD Model, and Get DPD+PA Response
5. Verify DPD Performance

- DPD flow consists of 5 steps in SystemVue
- Convergence improves with more iterations
- 2-3 iterations are typical for real PAs



Measurement-Based DPD Modeling Simplification: Calculated *PA Input, Measured PA Output*





1. Create DPD Stimulus

BB Input

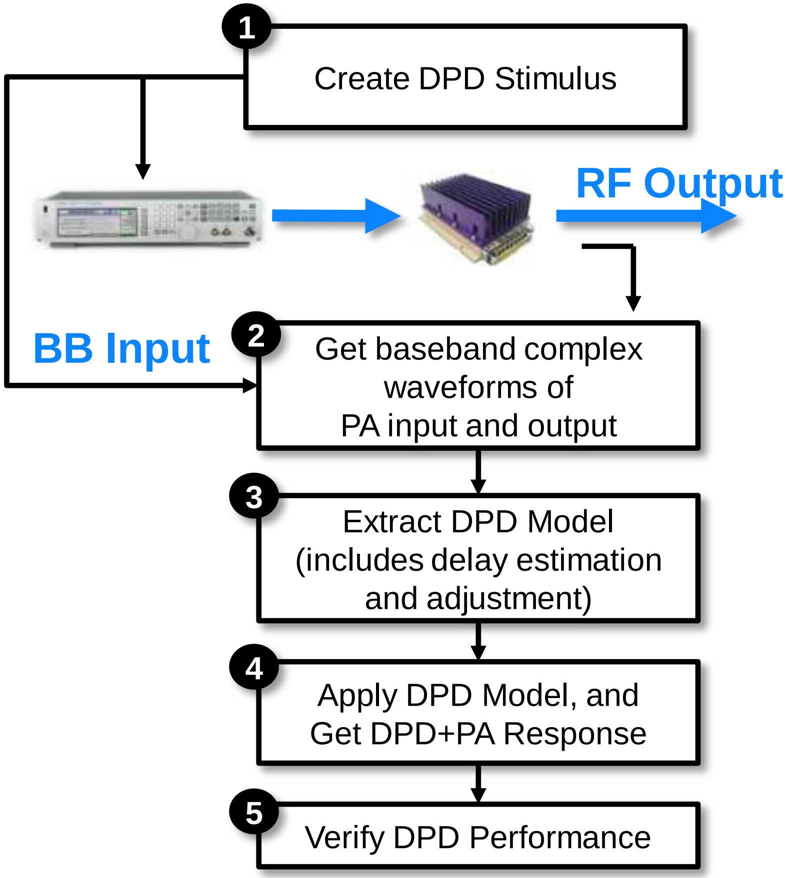
RF Output

2. Get baseband complex waveforms of PA input and output
3. Extract DPD Model (includes delay estimation and adjustment)
4. Apply DPD Model, and Get DPD+PA Response
5. Verify DPD Performance

Single connection allows automation, iterations
Eliminates one measurement, physically faster
Identical extraction algorithms, verification process

Measurement-Based DPD Modeling Simplification:

Calculated *PA Input, Measured PA Output*



RF Output

BB Input

1. Create DPD Stimulus
2. Get baseband complex waveforms of PA input and output
3. Extract DPD Model (includes delay estimation and adjustment)
4. Apply DPD Model, and Get DPD+PA Response
5. Verify DPD Performance

- Uses the Ideal BB stimulus waveform vs. measured PA output waveform to extract the DPD model.

- **Advantages**:
  - Single connection
  - PA remains “ON”
  - Easier to automate
  - Faster speed

- **Assumptions**:
  - Source flatness
  - Source linearity
  - No additional source signal conditioning

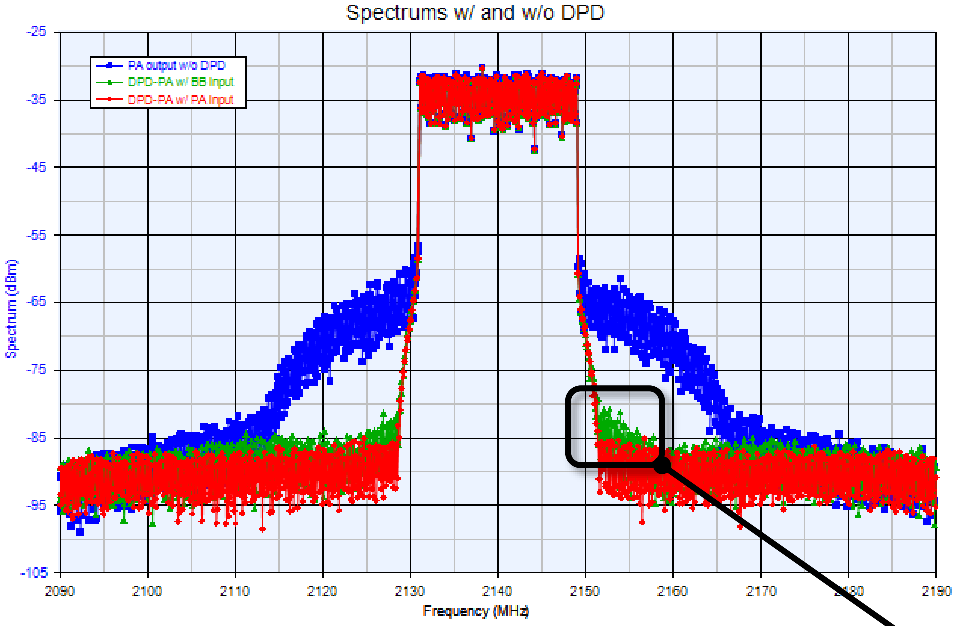
- Is typical of industry practice today

- Linearizes the entire system, not just the PA

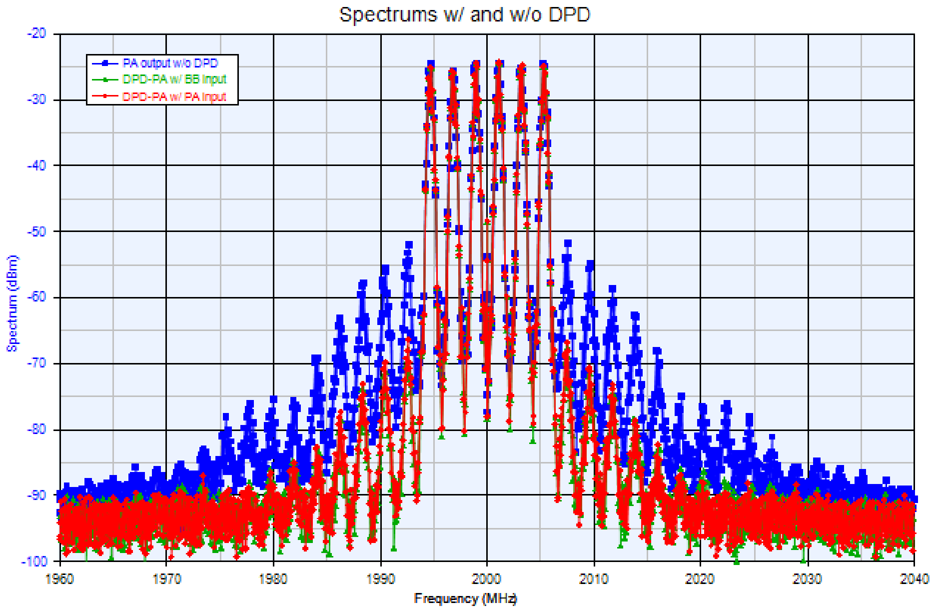
- Provides very acceptable accuracy for quick Evaluation and MFG Test applications.

Comparing Methods: BB Input vs. Measured RF

LTE-Advanced DL (20 MHz)

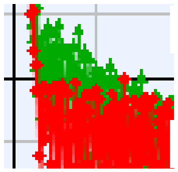


6-Carrier GSM



ACLR of DL 20 MHz System

ACLR	-2BW Lower	-1BW Lower	+1BW Upper	+2BW Upper
Raw PA output	54.06	35.33	35.68	53.58
DPD+PA w/ BB input	55.05	50.15	52.28	54.59
DPD+PA w/ PA input	55.80	51.23	54.32	55.41



BB input

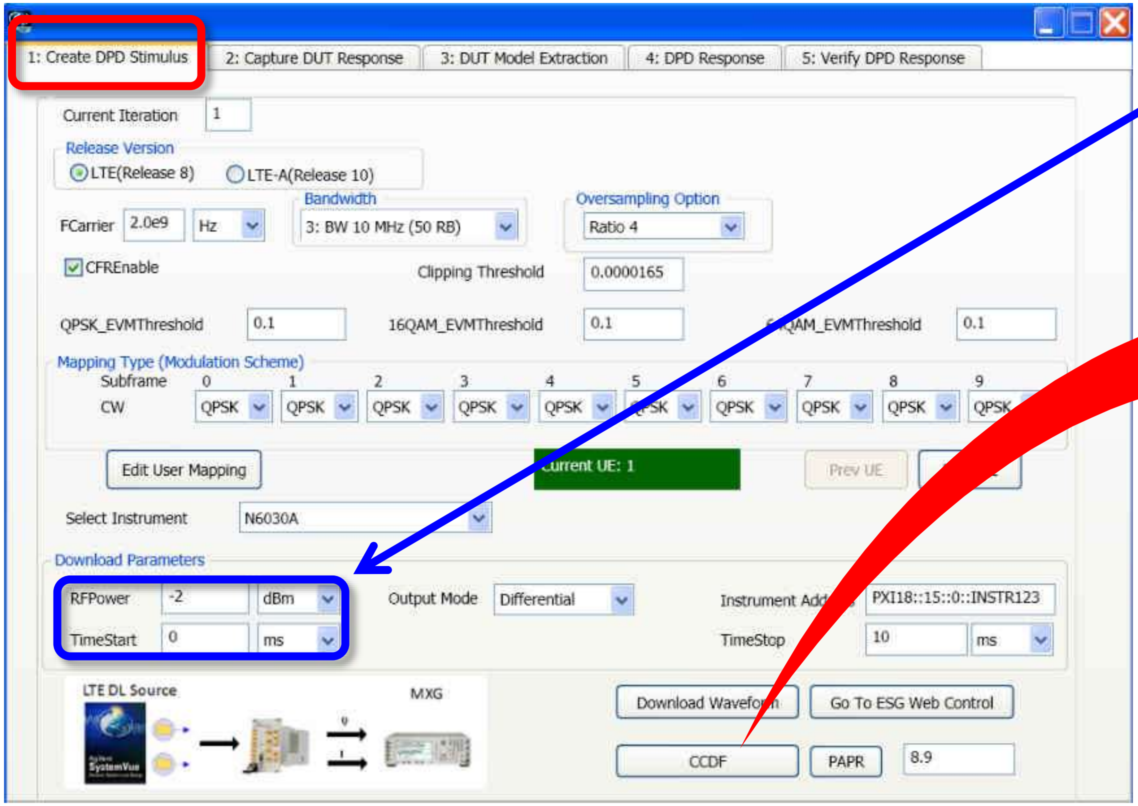
DPD+PA RESULTS

Measured RF input

SystemVue DPD Modeling Flow for LTE/LTE-A

Step 1. Create DPD stimulus waveform

- Set LTE parameters such as BW, Resource Block allocation and others
- Choose between built-in LTE or LTE-Advanced waveform generation



Current Iteration 1

Release Version
● LTE(Release 8) ○ LTE-A(Release 10)

FCarrier 2.0e9 Hz

Bandwidth 3: BW 10 MHz (50 RB)

Oversampling Option Ratio 4

☑ CFREnable

Clipping Threshold 0.0000165

QPSK_EVMThreshold 0.1

16QAM_EVMThreshold 0.1

64QAM_EVMThreshold 0.1

Mapping Type (Modulation Scheme)

Subframe	0	1	2	3	4	5	6	7	8	9
CW	QPSK	QPSK	QPSK	QPSK	QPSK	QPSK	QPSK	QPSK	QPSK	QPSK

Select Instrument N6030A

Download Parameters

RFPower -2 dBm

TimeStart 0 ms

Output Mode Differential

Instrument Address PXI18::15::0::INSTR123

TimeStop 10 ms

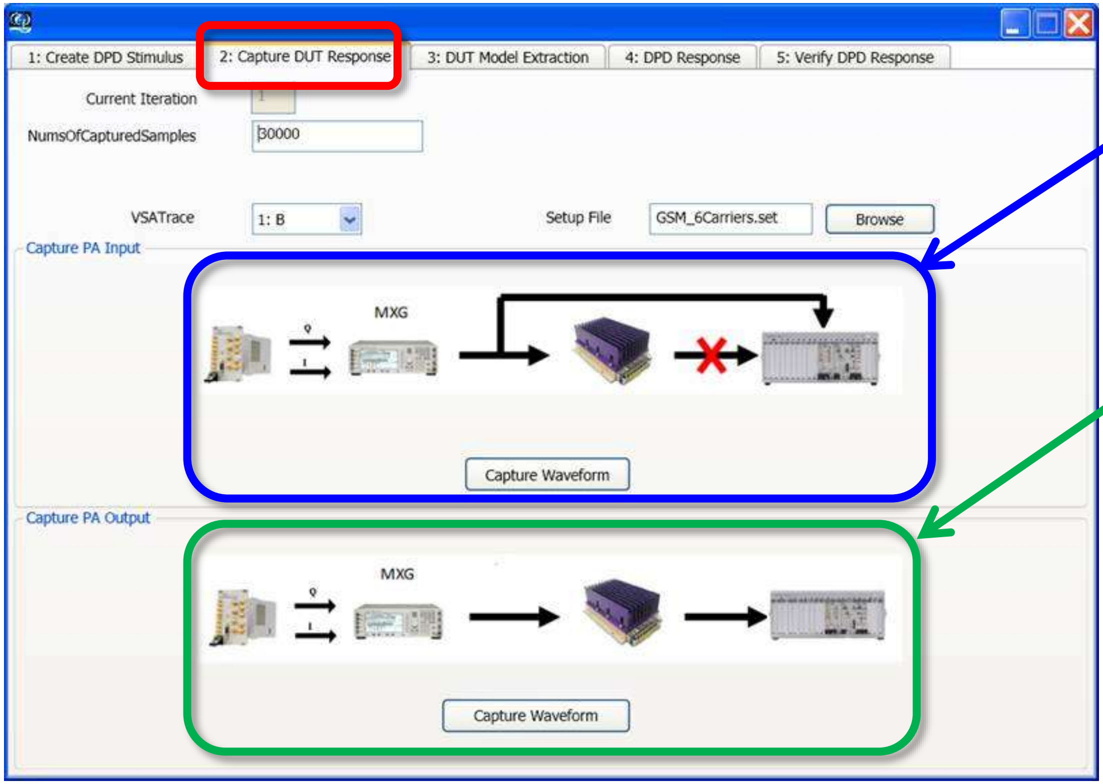
PAPR 8.9

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

SystemVue DPD Modeling Flow for LTE/LTE-A

Step 2. Capture PA response

- SystemVue downloads directly to the MXG or M9330A AWG (source), and capture data back from PXA or M9392A (analyzer).
- Equipment parameters such as number of signal, trace assignment, and file name can be set.



Current Iteration: 1
NumsOfCapturedSamples: 30000
VSATrace: 1: B
Setup File: GSM_6Carriers.set

THRU : Connect the MXG/AWG directly to the PXA/M9392A and click the “Capture Waveform” button. This is the true RF PA input.

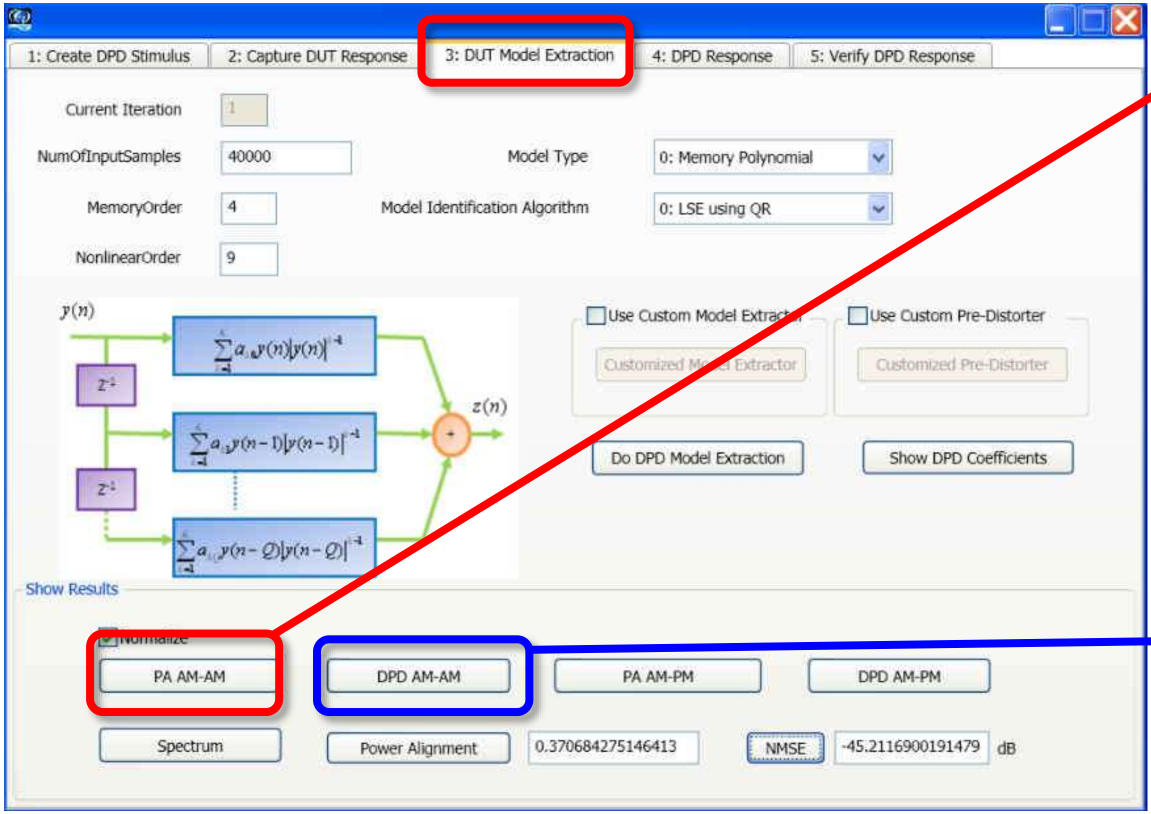
DUT: Connect the MXG to the PA, connect the PA to the PXA/M9392A, and click the “Capture Waveform” button. The captured signal is the output of the PA DUT.

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

SystemVue DPD Modeling Flow for LTE/LTE-A

Step 3. DPD Model Extraction

- DPD model parameters such as number of training samples, memory order, and nonlinear order can be set.



Current Iteration: 1

NumOfInputSamples: 40000

MemoryOrder: 4

NonlinearOrder: 9

Model Type: 0: Memory Polynomial

Model Identification Algorithm: 0: LSE using QR

☐ Use Custom Model Extractor

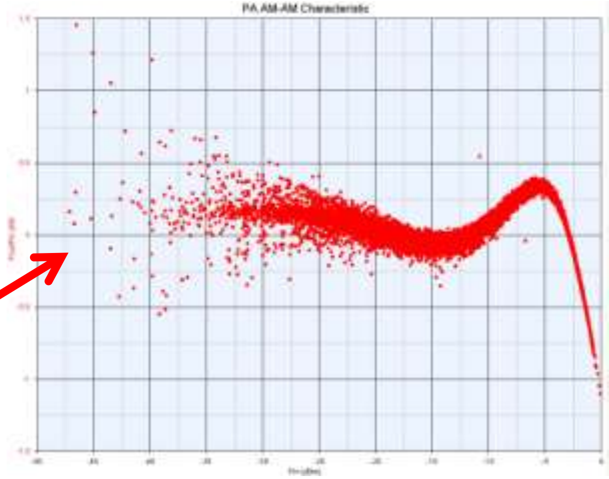
☐ Use Custom Pre-Distorter

☑ Normalize

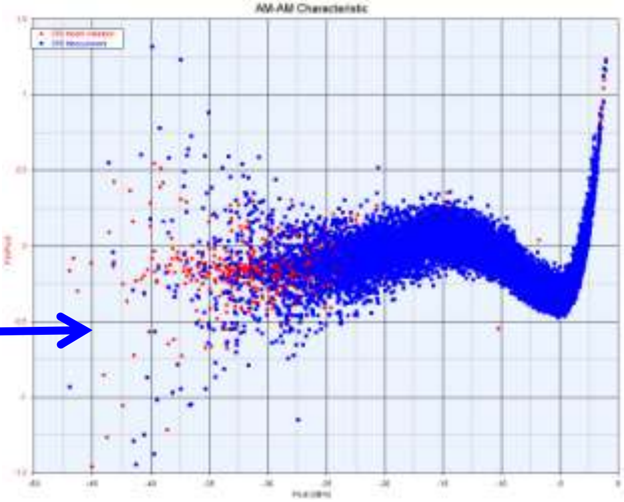
Power Alignment: 0.370684275146413

NMSE: -45.2116900191479 dB

PA AM-to-AM Characteristic



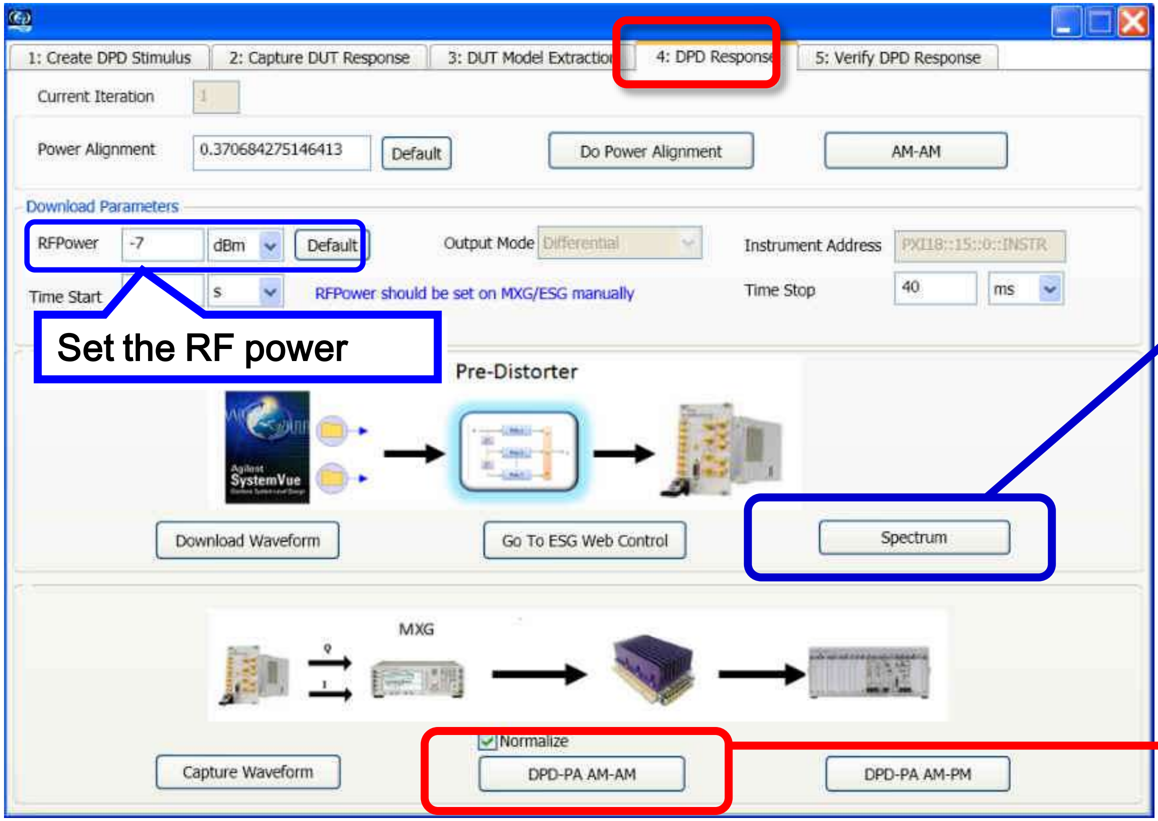
DPD AM-to-AM Characteristic



SystemVue DPD Modeling Flow for LTE/LTE-A

Step 4. Capture DPD+PA Response

- The signal is pre-distorted by the DPD model and re-downloaded into the MXG or AWG.



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

Current Iteration: 1

Power Alignment: 0.370684275146413

Download Parameters

RFPower: -7 dBm

Output Mode: Differential

Instrument Address: PXI18::15::0::INSTR

Time Start: s

RFPower should be set on MXG/ESG manually

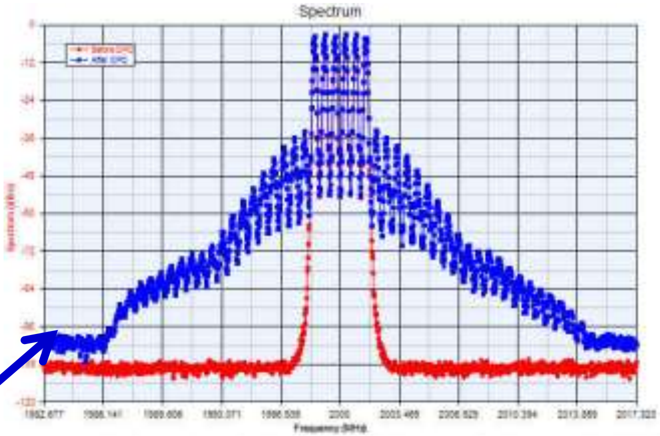
Time Stop: 40 ms

☑ Normalize

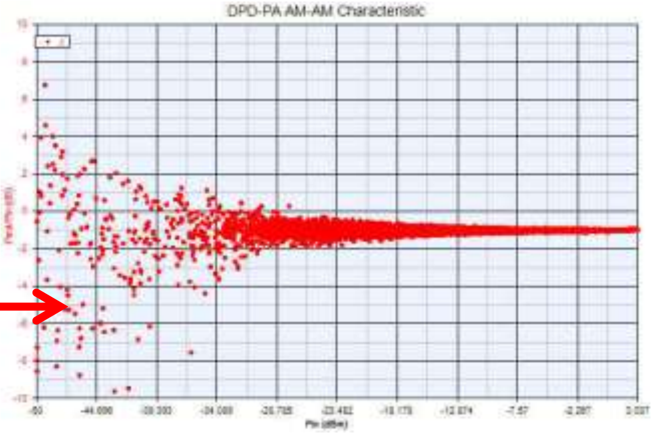
Set the RF power

DPD+PA (measured RF output)

PA input (original RF input)



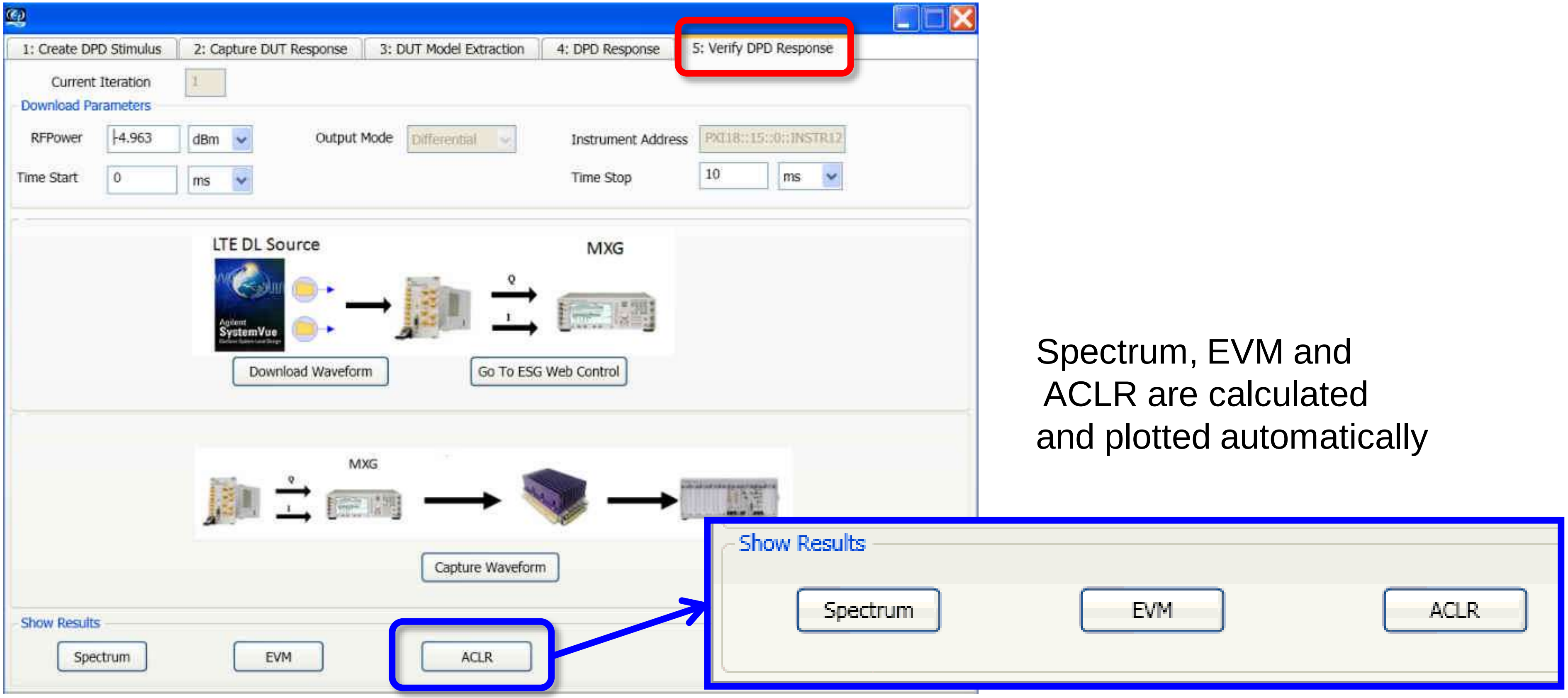
DPD+PA AM-to-AM Characteristic



SystemVue DPD Modeling Flow for LTE/LTE-A

Step 5. Verify DPD+PA response

- LTE performance for the DPD model used with the PA hardware is verified.



Current Iteration: 1

RFPower: -4.963 dBm

Output Mode: Differential

Instrument Address: PXI18::15::0::INSTR12

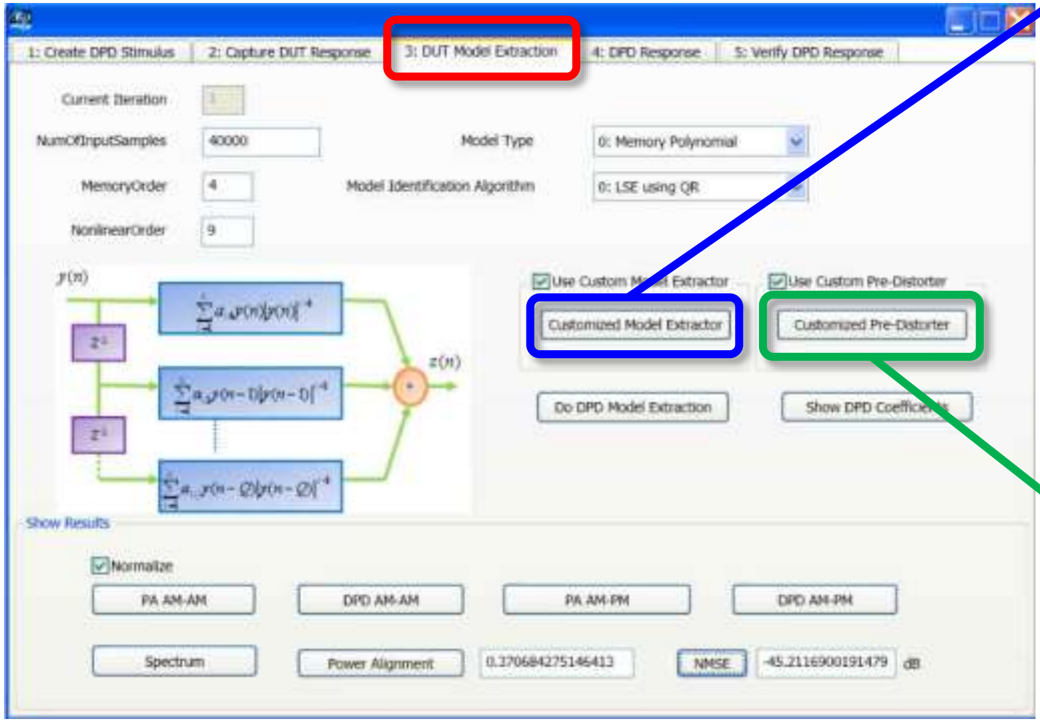
Time Start: 0 ms

Time Stop: 10 ms

Spectrum, EVM and ACLR are calculated and plotted automatically

Accommodating Proprietary IP

- Use your own extractor IP instead of Agilent's
- Continue to enjoy an integrated environment
- Allows remote & distributed DPD teamwork
- Greater user control of algorithm details, IP security, performance, delivery date, quality, etc



Current Iteration: 1

NumOfInputSamples: 40000

Model Type: 0: Memory Polynomial

MemoryOrder: 4

Model Identification Algorithm: 0: LSE using QR

NonlinearOrder: 9

☑ Use Custom Model Extractor

☑ Use Custom Pre-Distorter

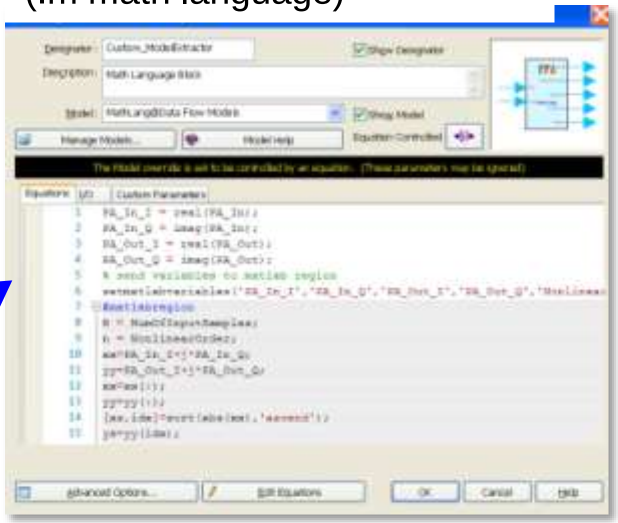
Show Results

☑ Normalize

0.370684275146413

NMSE: -45.2116900191479 dB

Custom DPD Model Extraction (.m math language)



Designator: Custom_ModelExtractor

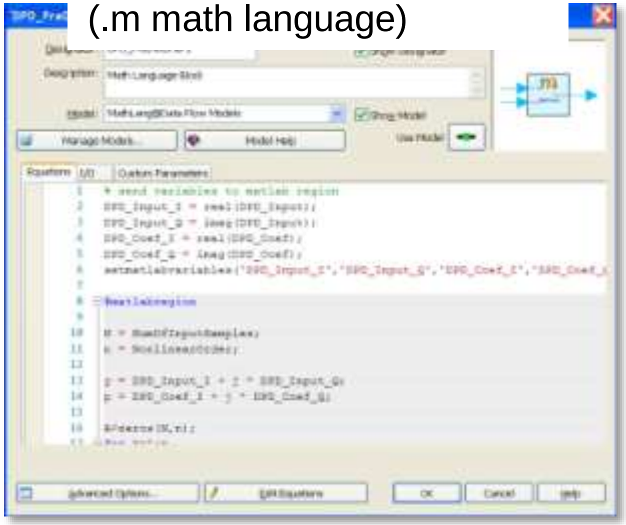
Description: Math Language Block

Model: MathLang@Data Flow Models

The Model override is set to be controlled by an equation. (These parameters may be ignored)

```
PA_In_I = real(PA_In);
PA_In_Q = imag(PA_In);
PA_Out_I = real(PA_Out);
PA_Out_Q = imag(PA_Out);
% send variables to matlab region
setmatlabvariables('PA_In_I','PA_In_Q','PA_Out_I','PA_Out_Q','Nonlinea
#matlabregion
N = NumOfInputSamples;
n = NonlinearOrder;
xx=PA_In_I+j*PA_In_Q;
yy=PA_Out_I+j*PA_Out_Q;
xx=xx(:);
yy=yy(:);
[xx,idx]=sort(abs(xx),'ascend');
yx=yy(idx);
```

Custom Digital Pre-distorter (.m math language)



Description: Math Language Block

Model: MathLang@Data Flow Models

```
% send variables to matlab region
DPD_Input_I = real(DPD_Input);
DPD_Input_Q = imag(DPD_Input);
DPD_Coef_I = real(DPD_Coef);
DPD_Coef_Q = imag(DPD_Coef);
setmatlabvariables('DPD_Input_I','DPD_Input_Q','DPD_Coef_I','DPD_Coef_

#matlabregion

N = NumOfInputSamples;
n = NonlinearOrder;

x = DPD_Input_I + j * DPD_Input_Q;
p = DPD_Coef_I + j * DPD_Coef_Q;

[illegible]
```

Anticipate __Accelerate __Achieve

Agilent Technologies

"*Wideband DPD for LTE-A*"

DPD of LTE-Advanced DL with Doherty PA (50W)

Spectrum, ACLR and EVM results (5 MHz DL System)

ACLR (dB)

ACLR	**-2BW Lower**	**-1BW Lower**	**+1BW Upper**	**+2BW Upper**
RF input (HW)	61.75	53.01	53.52	62.33
Raw PA output	50.25	31.98	31.56	48.19
DPD+PA output	**57.96**	**49.00**	**48.63**	**58.57**

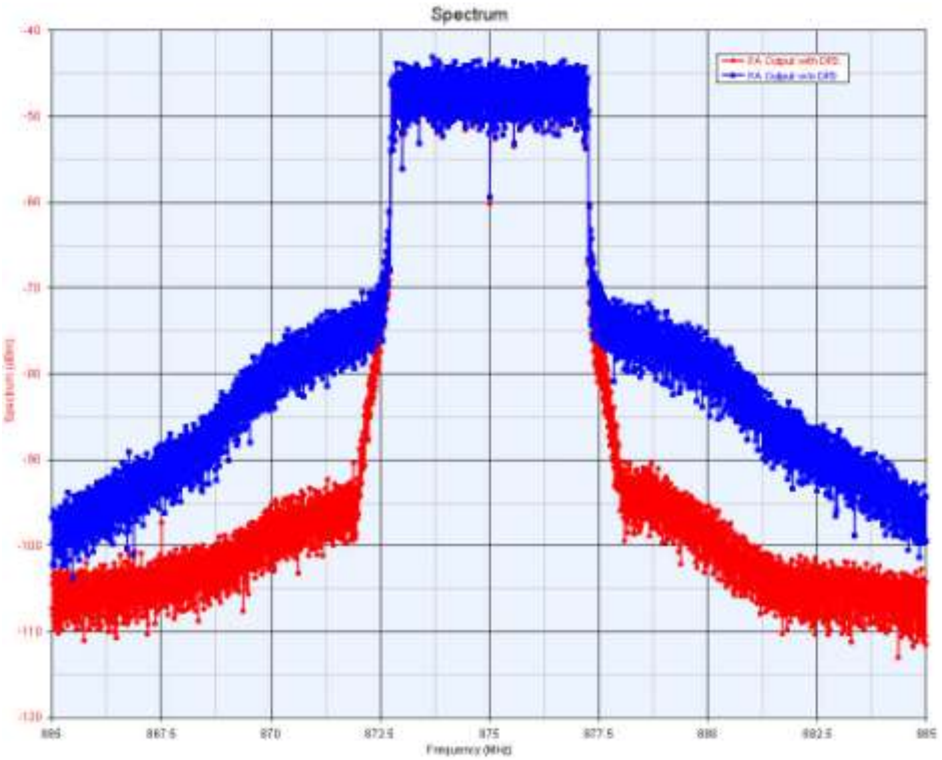
EVM

	EVM (dB)
Input signal	-23.44
Raw PA output	-21.33
DPD+PA output	-23.36

CFR was applied to this LTE-Advanced DL signal , with a maximum EVM target of 8%.

Raw PA output

PA+DPD, *after 1 iteration to extract DPD coefficients*



Vector Source : MXG
Vector Analyzer: PXA

DPD of LTE-Advanced DL with LDMOS Doherty PA (200W)

Spectrum, ACLR and EVM results (10 MHz DL System)

ACLR (dB)

ACLR	**-2BW Lower**	**-1BW Lower**	**+1BW Upper**	**+2BW Upper**
BB input (sim)	58.67	49.63	49.17	58.01
Raw PA output	49.90	28.69	28.35	47.31
DPD+PA output	**48.88**	**45.10**	**45.16**	**48.83**

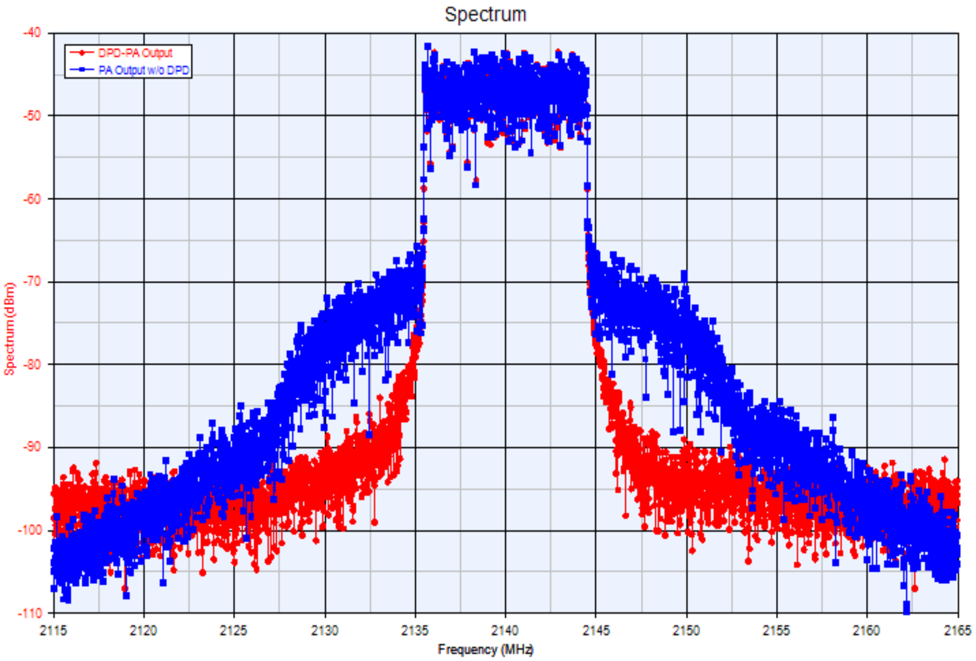
EVM

	EVM (%)	**EVM (dB)**
Simulation BB input	5.33	-24.46
Raw PA output	10.13	-19.89
DPD+PA output	5.52	-25.16

CFR was applied to this LTE-Advanced DL signal, with a maximum EVM target of 10% for 16-QAM.

Raw PA output

PA+DPD, *after 1 iteration to extract DPD coefficients*



Vector Source : MXG
Vector Analyzer: PXA

DPD of LTE-Advanced DL with LDMOS Doherty PA (200W)

Spectrum, ACLR and EVM results (20MHz DL System)

ACLR (dB)

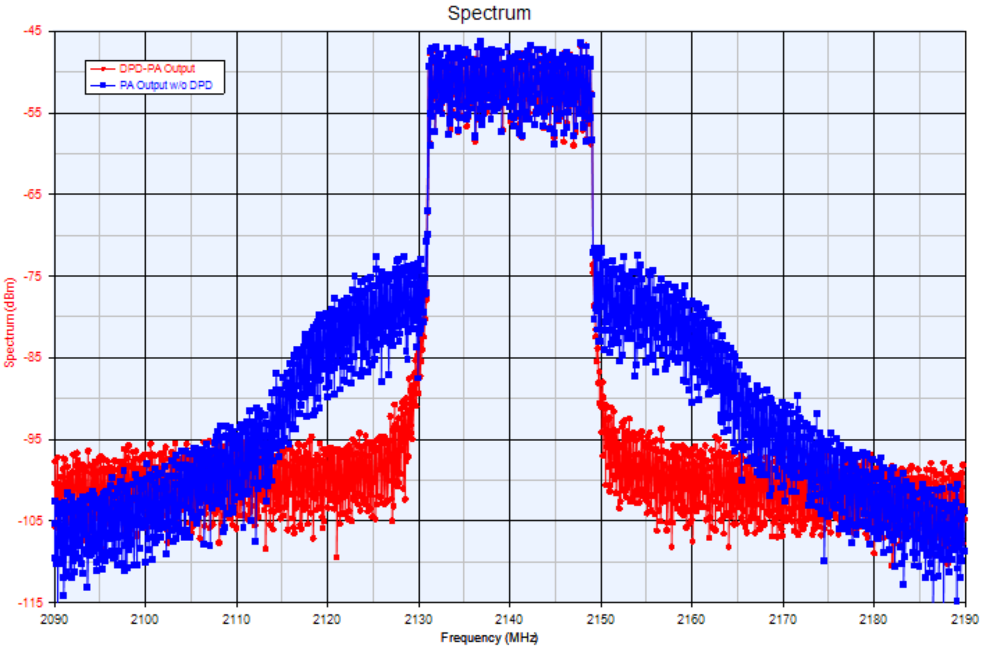
ACLR	**-2BW Lower**	**-1BW Lower**	**+1BW Upper**	**+2BW Upper**
BB input (sim)	64.73	55.09	57.10	64.92
Raw PA output	51.01	30.69	30.04	49.50
DPD+PA output	**50.31**	**45.16**	**45.56**	**51.40**

EVM

	EVM (%)	**EVM (dB)**
BB input signal (sim)	6.10	-24.28
Raw PA output	8.87	-21.04
DPD+PA output	**6.88**	**-23.24**

Raw PA output

PA+DPD, *after 1 iteration to extract DPD coefficients*

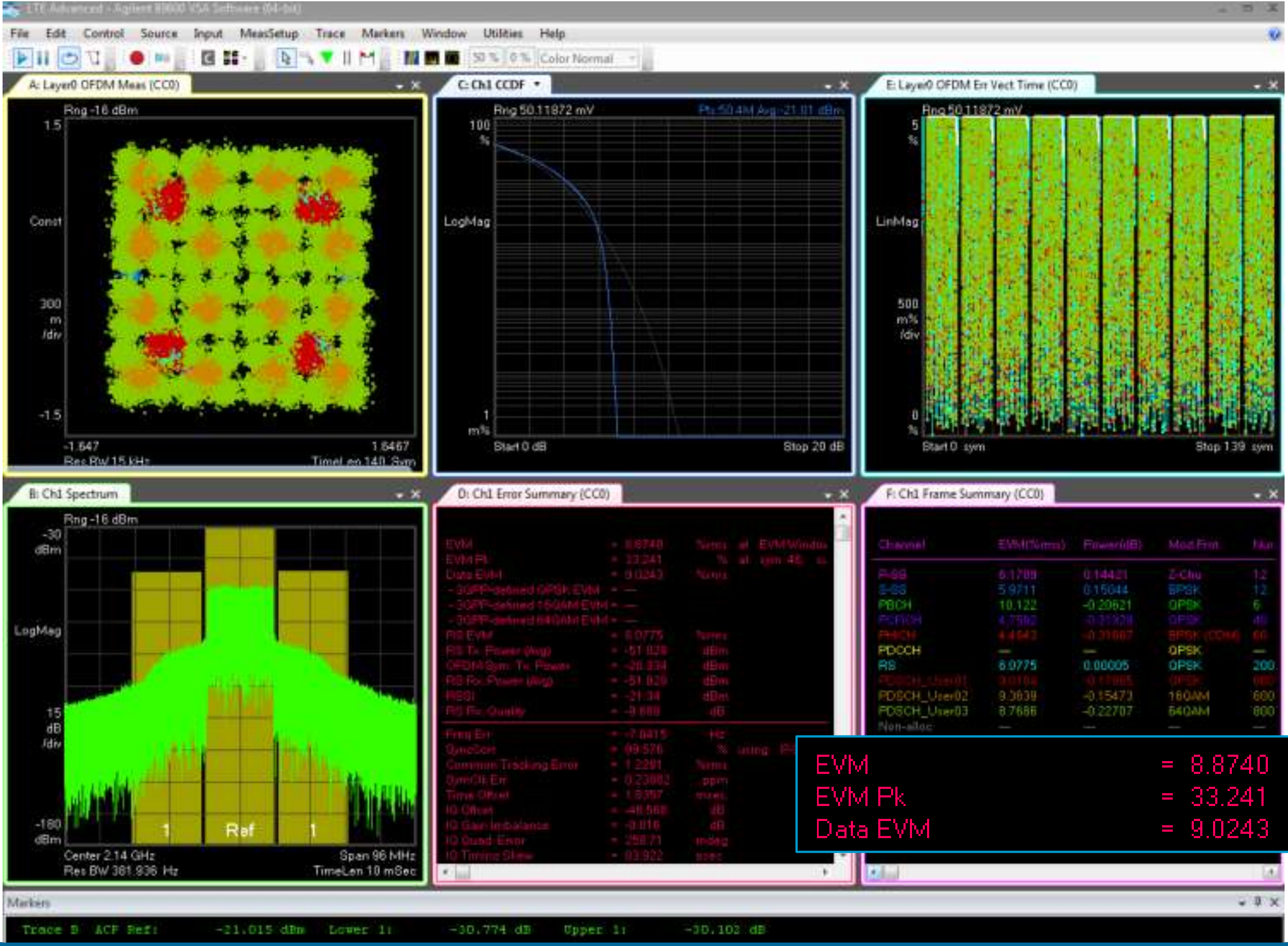


Vector Source : MXG
Vector Analyzer: PXA

CFR was applied to this LTE-Advanced DL signal with a maximum EVM target of 10%,8% and 6% for QPSK, 16-QAM and 64-QAM, respectively.

LTE-A Results with 200W LDMOS Doherty PA

Raw PA Output (DL 20MHz System)



```
EVM                          = 8.8740    %rms  at  EVM Window
EVM Pk                       = 33.241    %     at  sym 46  s
Data EVM                     = 9.0243    %rms
 - 3GPP-defined QPSK EVM     = ---
 - 3GPP-defined 16QAM EVM    = ---
 - 3GPP-defined 64QAM EVM    = ---
RS EVM                       = 6.0775    %rms
RS Tx. Power (Avg)           = -51.828   dBm
OFDM Sym. Tx. Power          = -28.334   dBm
RS Rx. Power (Avg)           = -51.828   dBm
RSSI                         = -21.34    dBm
RS Rx. Quality               = -9.888    dB
Freq Err                     = -7.0415   Hz
SyncCorr                     = 99.576    %  using  P-S
Common Tracking Error        = 1.2281    %rms
Sym Clk Err                  = 0.23882   ppm
Time Offset                  = 1.9397    usec
IQ Offset                    = -48.568   dB
IQ Gain Imbalance            = -0.016    dB
IQ Quad. Error               = 258.71    mdeg
IQ Timing Skew               = 93.922    psec
```

```
Channel        EVM(%rms)  Power(dB)  Mod.Fmt     Nu
P-SS           6.1789     0.14421    Z-Chu       12
S-SS           5.9711     0.15044    BPSK        12
PBCH           10.122     -0.20621   QPSK        6
PCFICH         4.7582     -0.21928   QPSK        48
PHICH          4.4642     -0.31667   BPSK (CDM)  60
PDCCH          ---        ---        QPSK        ---
RS             6.0775     0.00005    QPSK        200
PDSCH_User01   9.0104     -0.17865   QPSK        600
PDSCH_User02   9.3639     -0.15473   16QAM       600
PDSCH_User03   8.7686     -0.22707   64QAM       600
Non-alloc      ---        ---        ---         ---
```

```
Trace B  ACP Ref:    -21.015 dBm   Lower 1:    -30.774 dB   Upper 1:    -30.102 dB
```

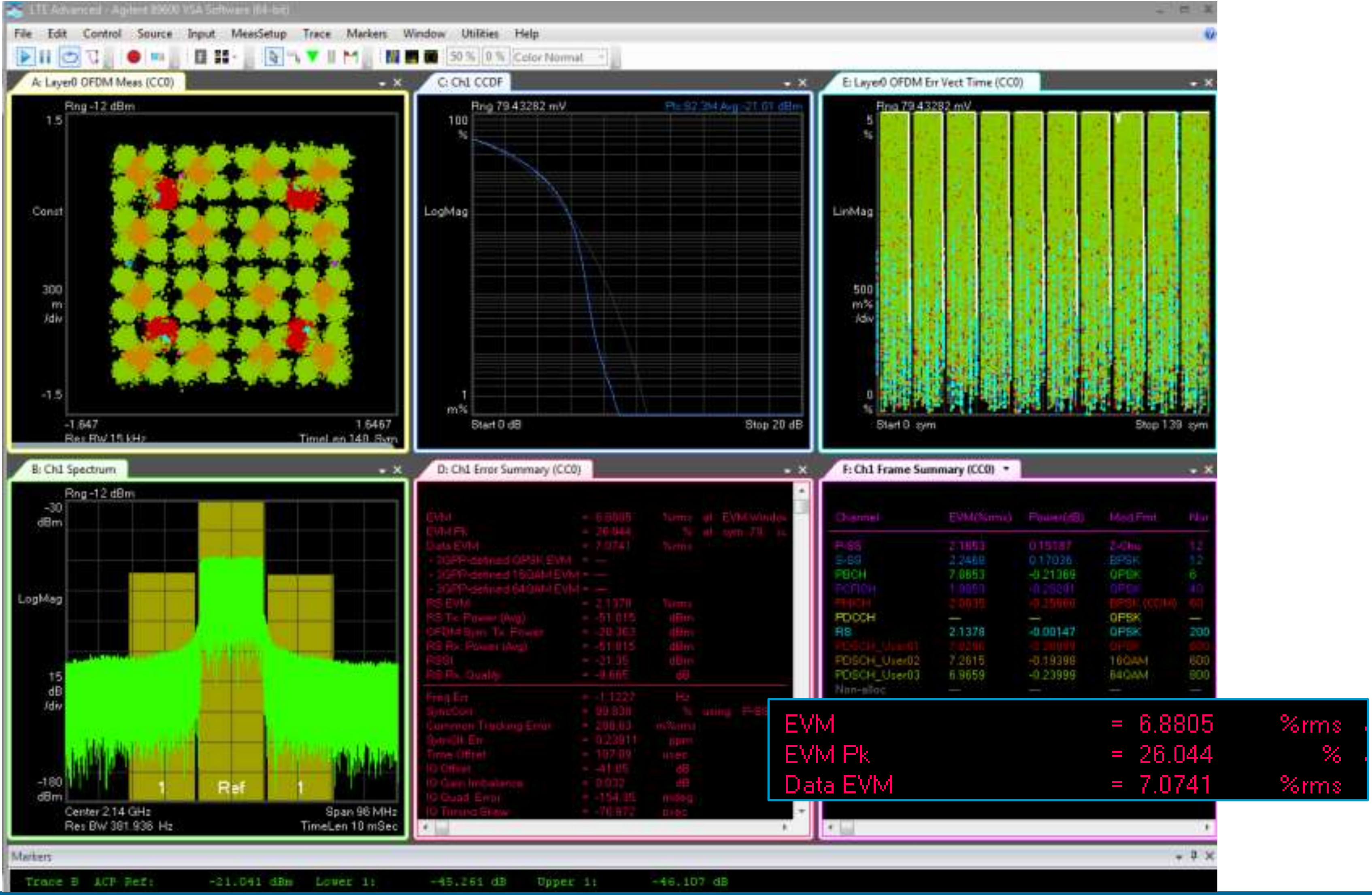
```
EVM        =  8.8740   %rms  a
EVM Pk     =  33.241   %     a
Data EVM   =  9.0243   %rms
```

Anticipate __Accelerate __Achieve

Agilent Technologies

LTE-A Results with 200W LDMOS Doherty PA

DPD+PA Output (DL 20MHz System)



```
EVM                         = 6.8805    %rms  at  EVM Window
EVM Pk                      = 26.044    %     at  sym 78
Data EVM                    = 7.0741    %rms
- 3GPP-defined QPSK EVM     = —
- 3GPP-defined 16QAM EVM    = —
- 3GPP-defined 64QAM EVM    = —
RS EVM                      = 2.1378    %rms
RS Tx Power (Avg)           = -51.015   dBm
OFDM Sym. Tx. Power         = -20.363   dBm
RS Rx. Power (Avg)          = -51.015   dBm
RSSI                        = -21.35    dBm
RS Rx. Quality              = -9.665    dB
Freq Err                    = -1.1227   Hz
SyncCorr                    = 99.938    %     using  P-SS
Common Tracking Error       = 208.63    m%rms
Symbol Clk Err              = 0.23911   ppm
Time Offset                 = 107.09    usec
IQ Offset                   = -41.05    dB
IQ Gain Imbalance           = 0.032     dB
IQ Quad. Error              = -154.35   mdeg
IQ Timing Skew              = -76.872   psec
```

Channel	EVM(%rms)	Power(dB)	Mod.Fmt	Nu
P-SS	2.1853	0.15187	Z-Chu	12
S-SS	2.2468	0.17036	BPSK	12
PBCH	7.0853	-0.21369	QPSK	6
PCFICH	[illegible]	[illegible]	QPSK	40
PHICH	[illegible]	[illegible]	BPSK (CDM)	60
PDCCH	—	—	QPSK	—
RS	2.1378	-0.00147	QPSK	200
PDSCH_User01	[illegible]	[illegible]	QPSK	600
PDSCH_User02	7.2615	-0.19398	16QAM	600
PDSCH_User03	6.9659	-0.23999	64QAM	600
Non-alloc	—	—	—	—

```
Trace B   ACP Ref:      -21.041 dBm    Lower 1:      -45.261 dB    Upper 1:      -46.107 dB
```

```
EVM        =  6.8805   %rms
EVM Pk     =  26.044   %
Data EVM   =  7.0741   %rms
```

DPD of LTE-Advanced DL with LDMOS Doherty PA (200W)

Results with (2x10MHz) Carrier Aggregation of 2 separate CC's

ACLR (dB)

ACLR	-2BW Lower	-1BW Lower	+1BW Upper	+2BW Upper
BB input (sim)	63.11	56.75	56.70	62.72
Raw PA output	50.58	30.80	30.22	49.06
DPD+PA output	**51.74**	**45.75**	**45.73**	**51.18**

CC0 EVM *(QPSK)*

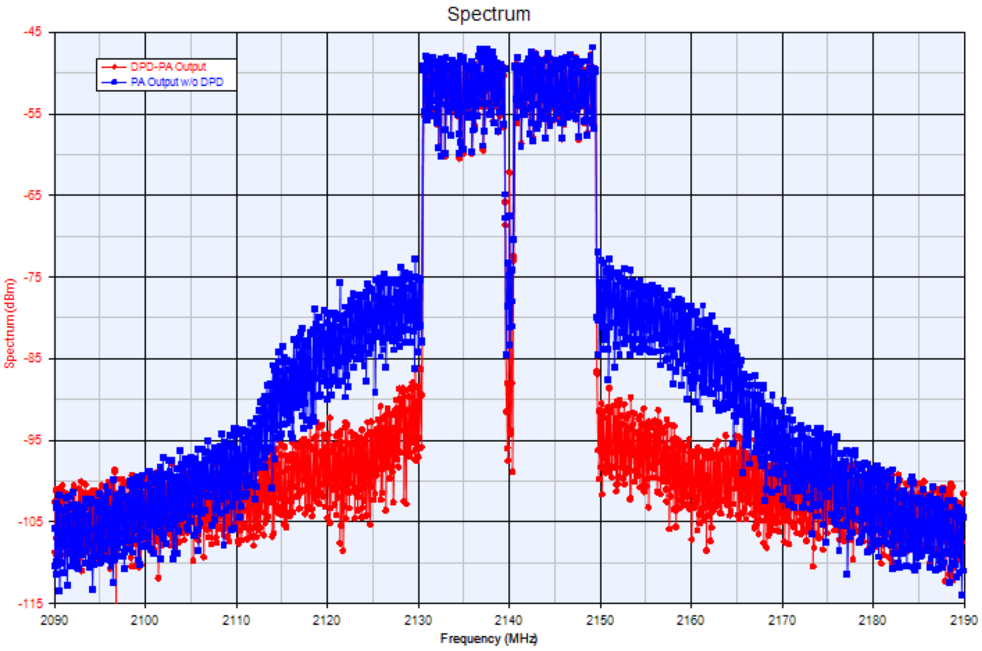
	EVM (%)	EVM (dB)
Baseband signal (sim)	0.21	-53.43
Raw PA output	3.03	-30.37
DPD+PA output	**1.93**	**-34.28**

CC1 EVM *(16-QAM)*

	EVM (%)	EVM (dB)
Baseband signal (sim)	0.20	-54.11
Raw PA output	3.12	-30.11
DPD+PA output	**1.93**	**-34.31**

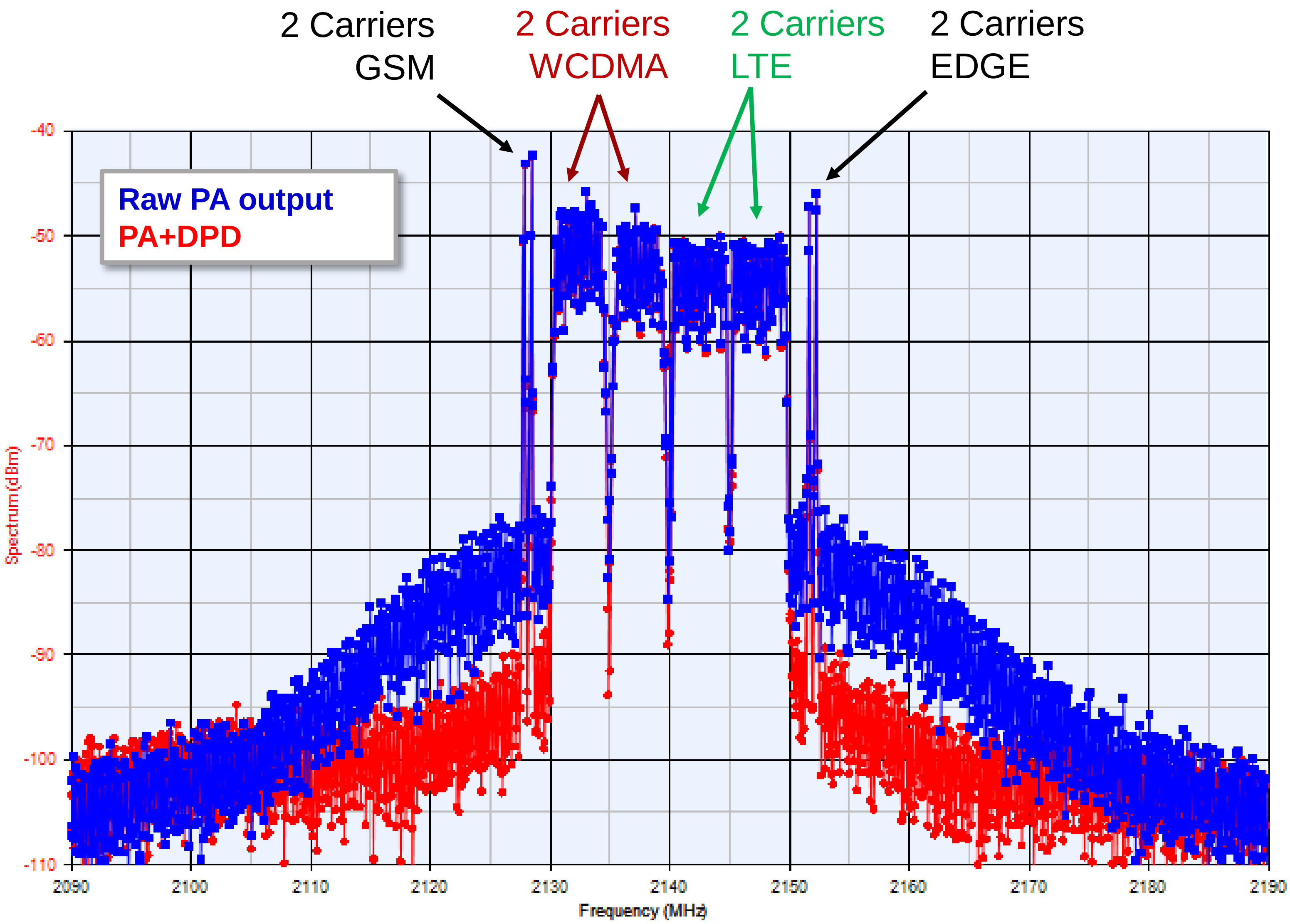
Raw PA output

PA+DPD, *after 1 iteration to extract DPD coefficients*



Vector Source : MXG
Vector Analyzer: PXA

Multi-Standard Radio (MSR) into LDMOS Doherty PA (200W)



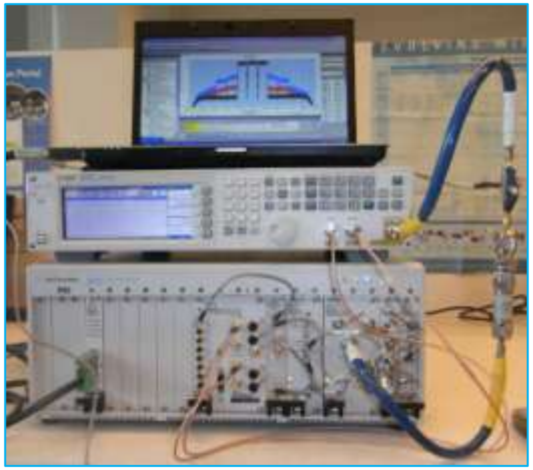
Wideband configurations: LTE-A 2x20MHz + 1x20MHz CA

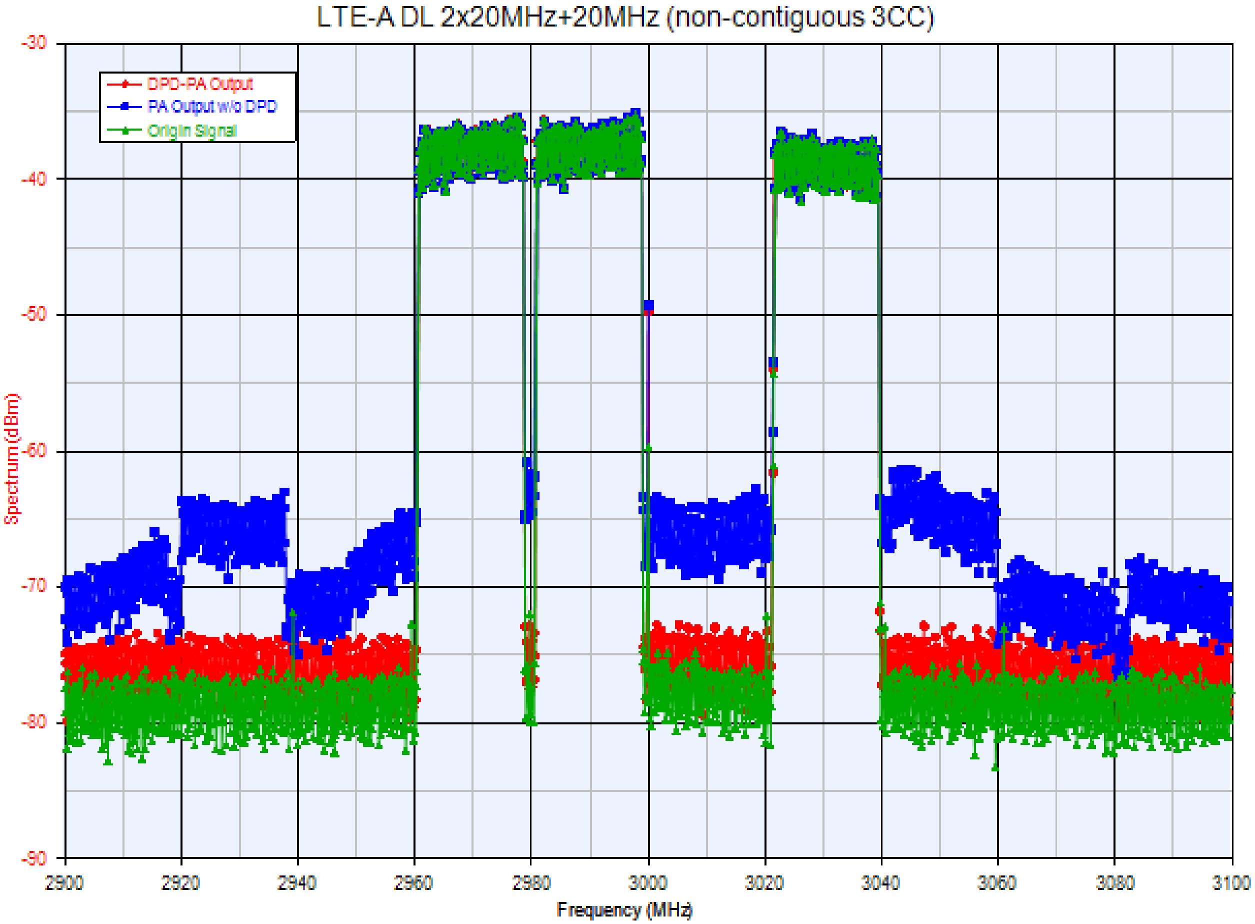
Agilent M9330A AWG, M9392A VSA

Source = M9330A AWG
N5182 MXG

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

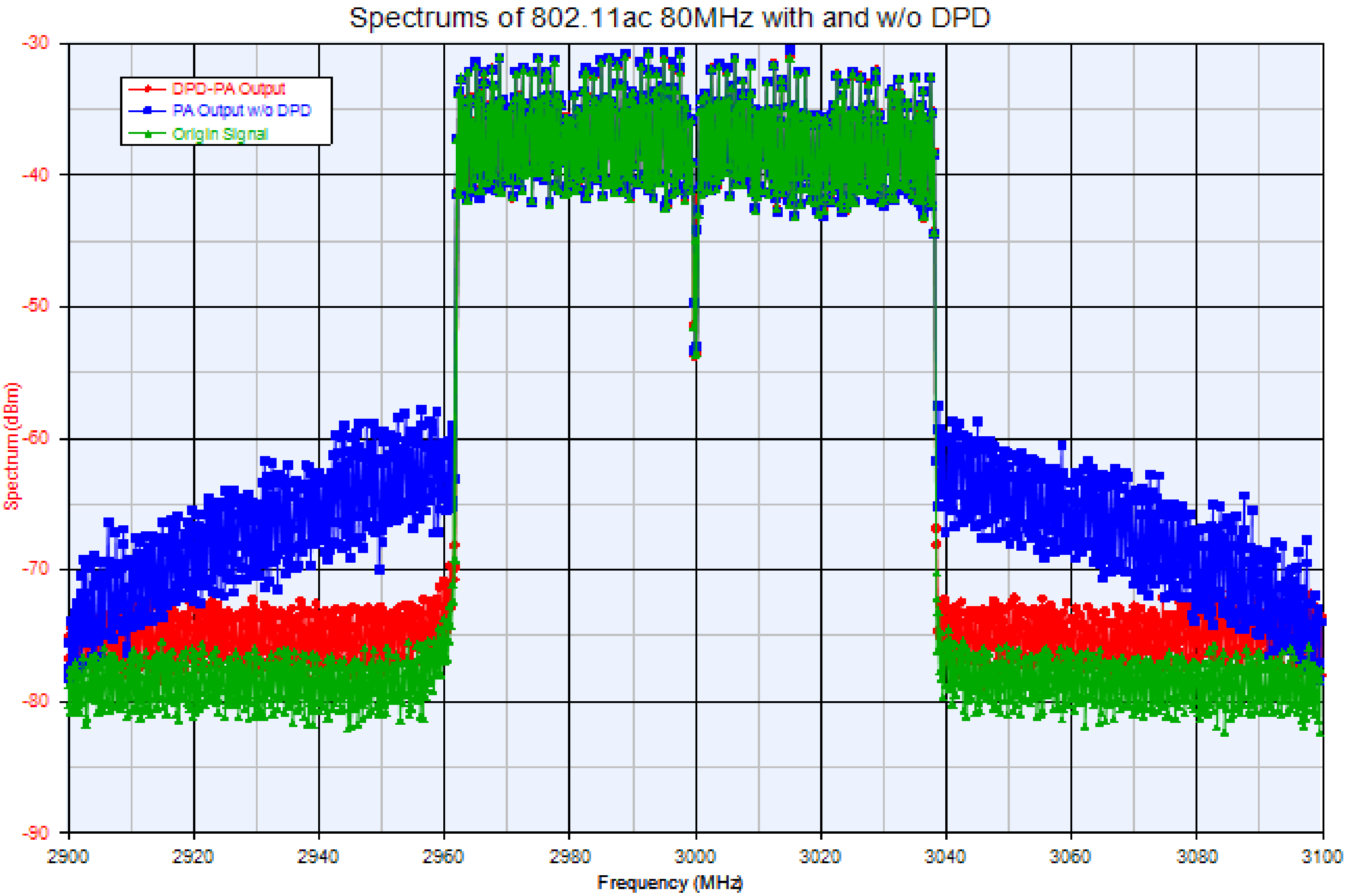
PA output Spectrum (**Blue**)
PA+DPD Spectrum (**Red**)
PA input Spectrum (**Green**)





DPD of 802.11ac, using M9330A/M9392A

(80MHz signal, with 3x oversampling = 240 MHz VSA BW)



Agenda

1. Introduction and Problem Statement
2. Digital Pre-Distortion (DPD) Concepts
3. DPD verification with Agilent Hardware
4. DPD simulation with Agilent EDA Tools
5. Crest Factor Reduction (CFR)
6. Summary

DPD with Agilent EEsof EDA tools

Predictive PA modeling and linearization

Benefits of using RF Simulation for DPD

- Predict the final DPD result, while Analog PA can still be changed
- De-risk module or wafer iteration, to save time and money
- Explore vendors, waveforms, statistical spreads, analog variables
- Validate system-level specifications with preliminary RF & BB

Trade offs:

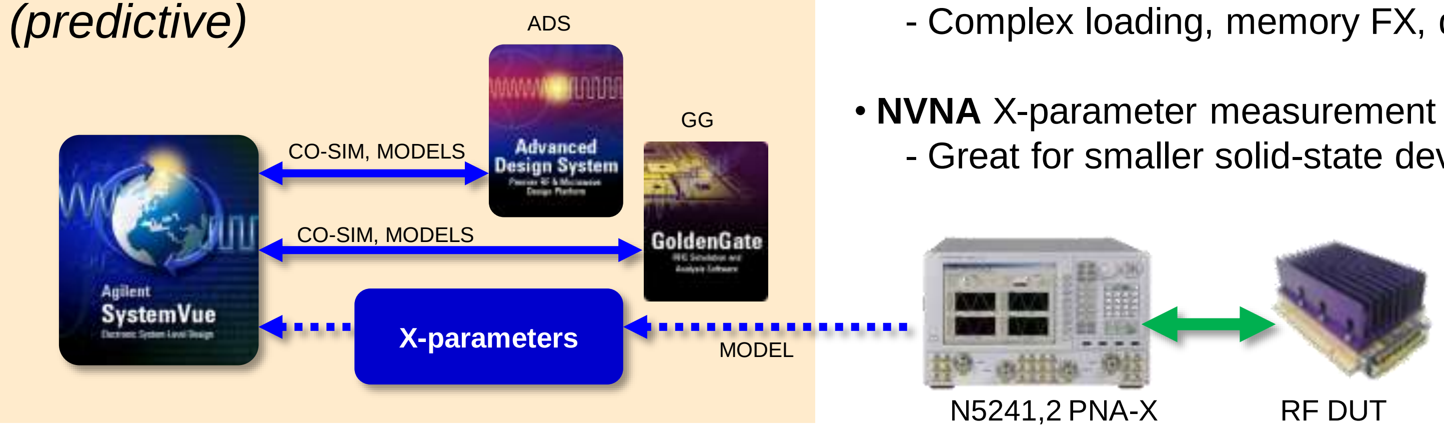
- Accuracy. Dynamic "circuit envelope" behavior depends on
  - the simulation engine (and any behavioral modeling)
  - the device-level transistor models, for traps, self-heating, mismatch
- Speed.
  - Real HW measurements >> faster than Simulations

Conclusion: it is still worth doing

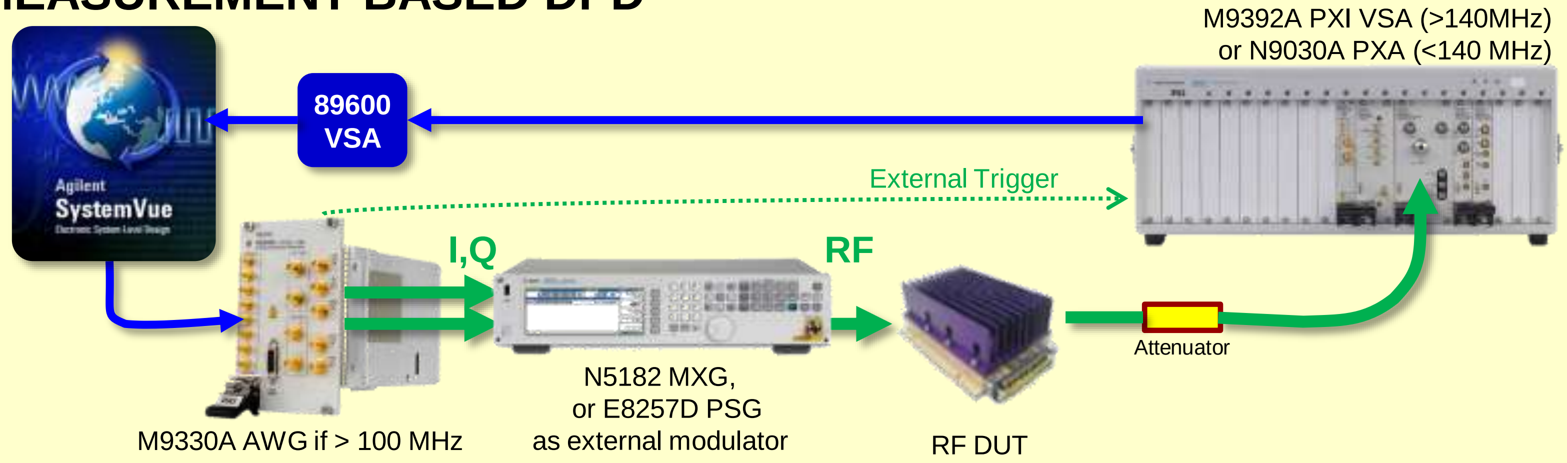
Simulation vs. Measurement DPD Extraction

SIMULATION-BASED DPD
(predictive)

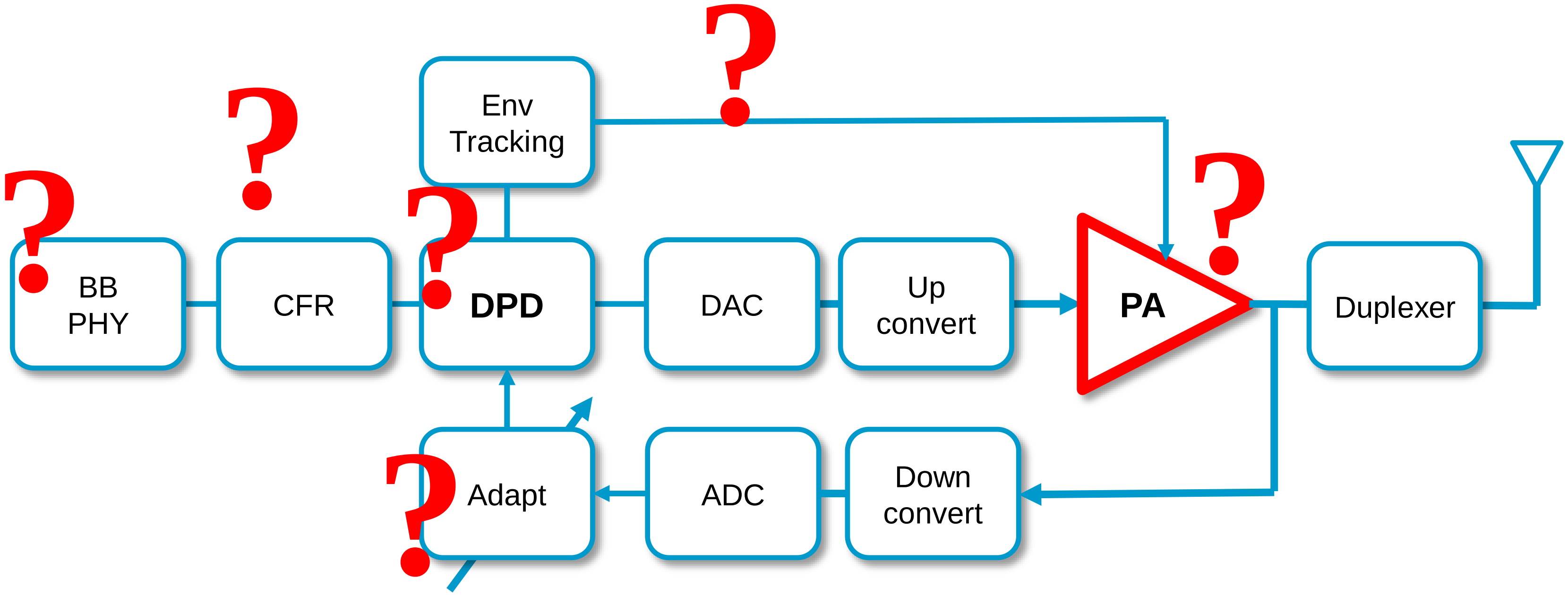
- **ADS** & **GoldenGate** Circuits as simulated RF DUTs
  - Complex loading, memory FX, dynamic behaviors
- **NVNA** X-parameter measurement model,
  - Great for smaller solid-state devices



MEASUREMENT-BASED DPD

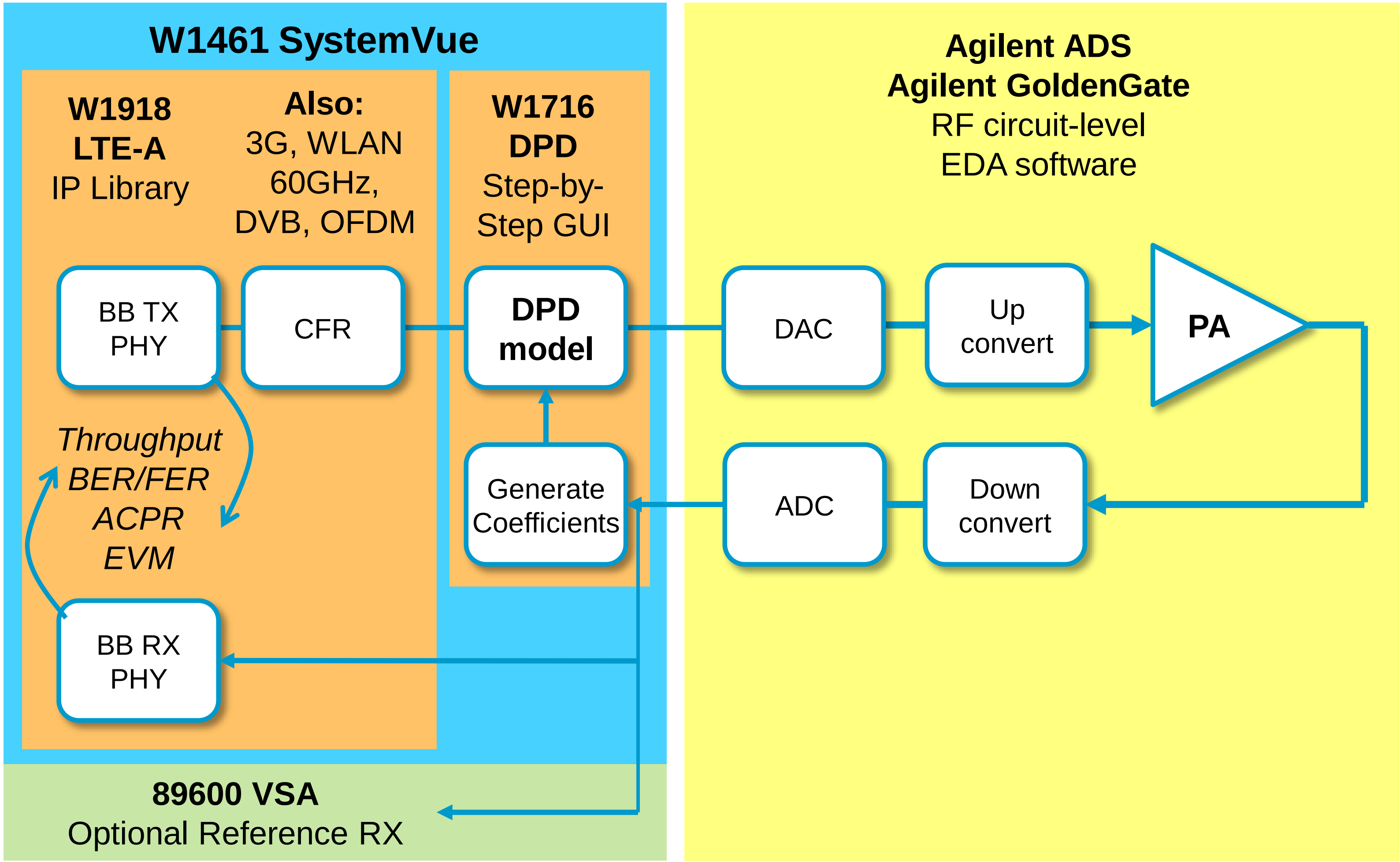


Generalized Wireless Transmitter Path



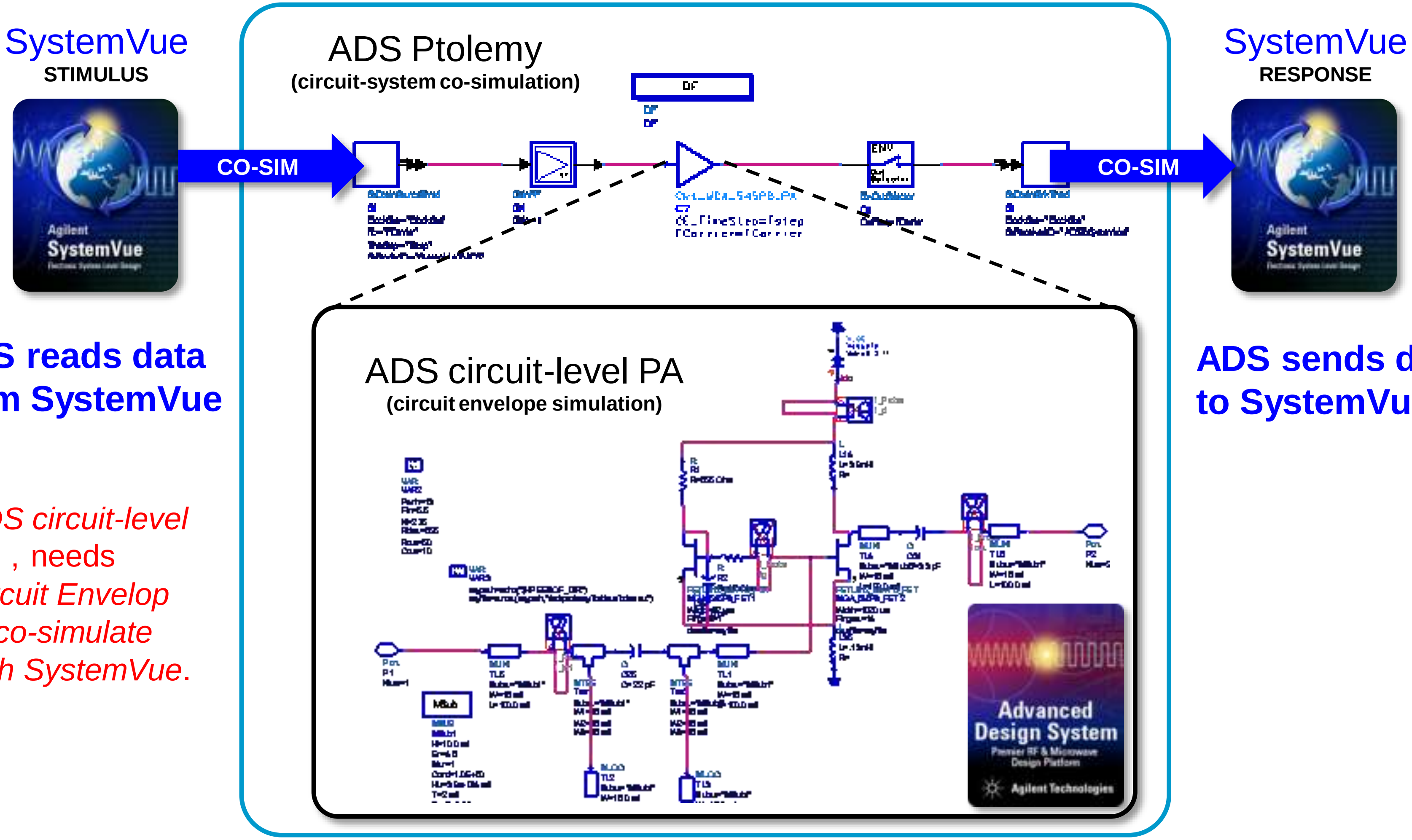
- Which blocks are included with your final product?
- What IP do you have access to? Or, are able to imitate? Able to modify?
- What final system specifications do you need to test against?

Agilent Simulation-based DPD Modeling Platform



Simulation-based, predictive DPD

SystemVue co-simulation with circuit-level PA in ADS



SystemVue
STIMULUS

ADS Ptolemy
(circuit-system co-simulation)

SystemVue
RESPONSE

CO-SIM

CO-SIM

ADS circuit-level PA
(circuit envelope simulation)

ADS reads data from SystemVue

ADS sends data to SystemVue

ADS circuit-level PA , needs Circuit Envelop to co-simulate with SystemVue.

Simulation-based, predictive DPD

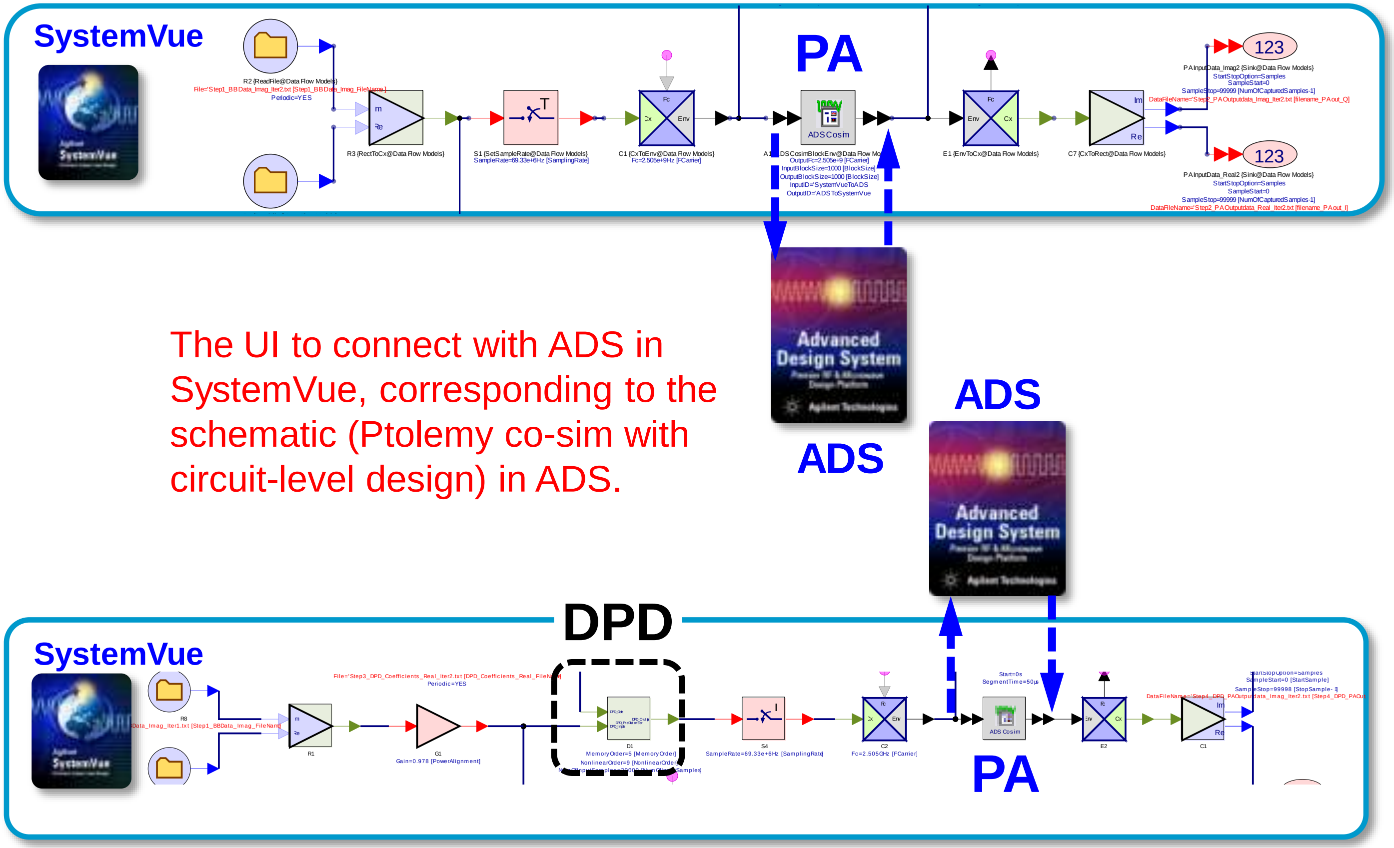
SystemVue co-simulation with circuit-level PA in ADS

Extract

Capture PA input vs. output waveforms for DPD extraction

Verify

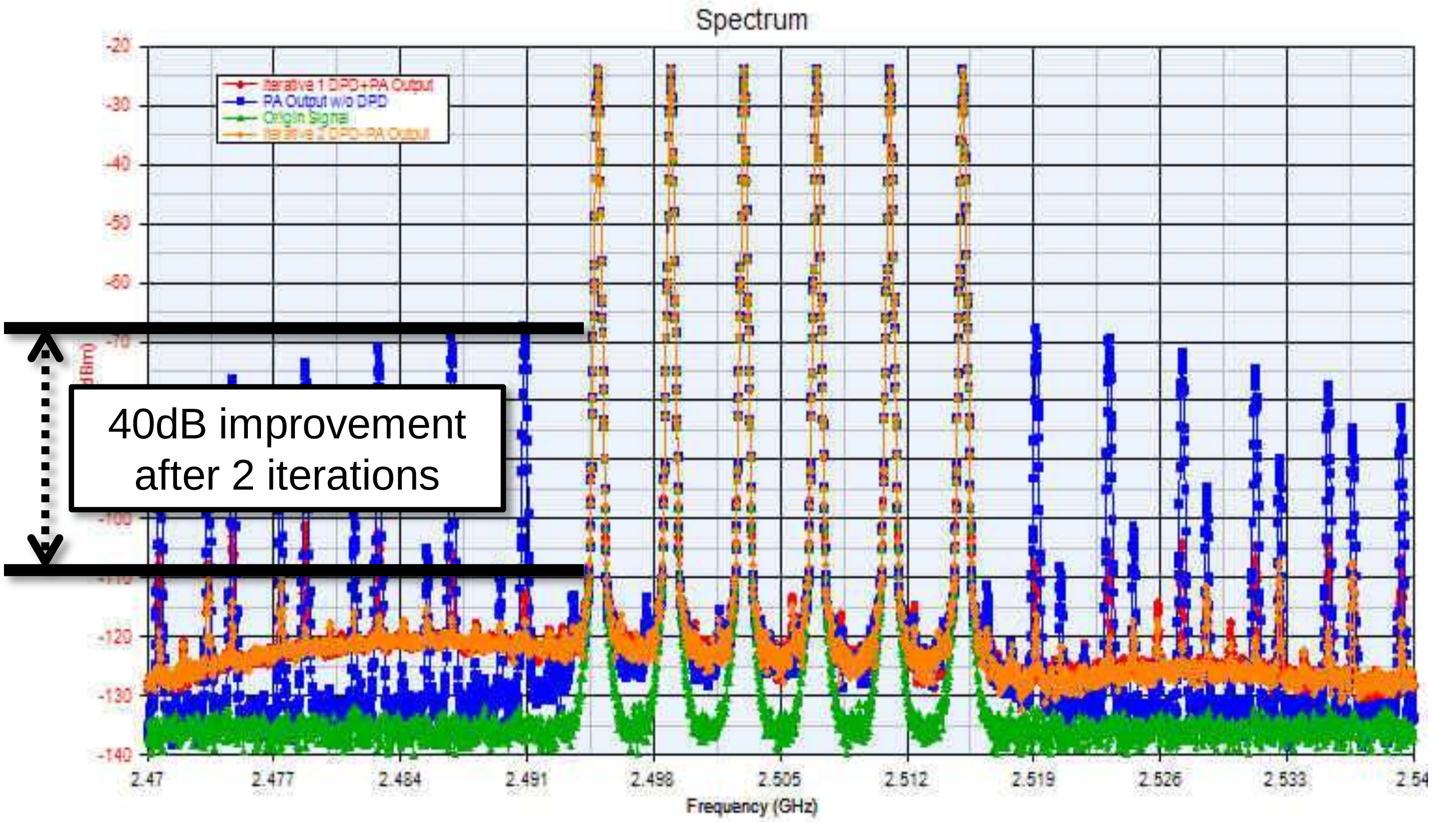
See linearized result, including DPD



The UI to connect with ADS in SystemVue, corresponding to the schematic (Ptolemy co-sim with circuit-level design) in ADS.

Simulation-based, predictive DPD

SystemVue co-simulation with circuit-level PA in ADS



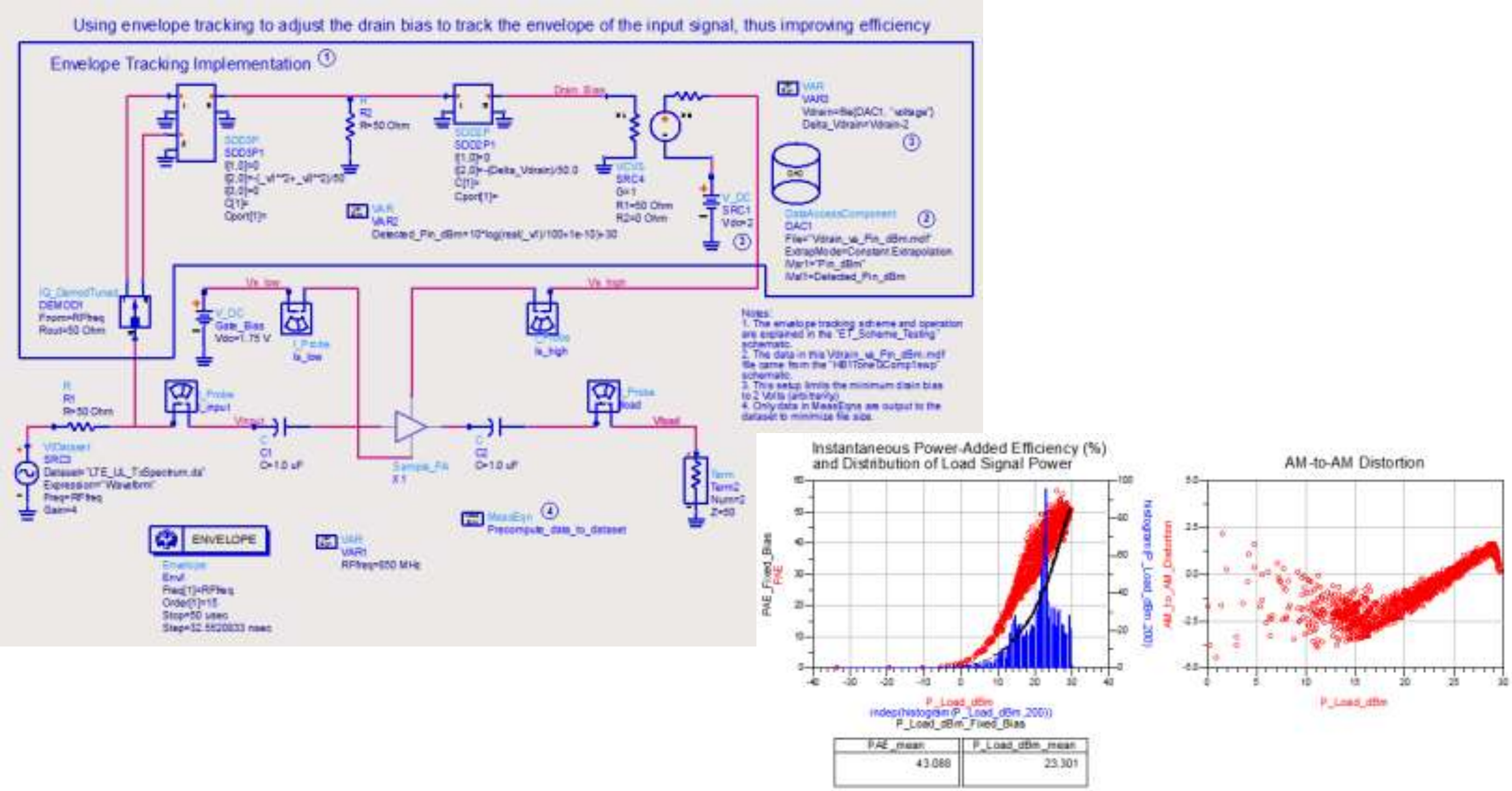
40dB improvement
after 2 iterations

6-Carrier GSM
Carrier Spacing: 4MHz

Sampling Rate :
256 * 270.8333kHz
=69.3333 MHz

PA input Spectrum (**Green)**
PA output Spectrum(**Blue**)
PA+DPD Spectrum (**Red**, first iteration)
PA+DPD Spectrum (**Orange**, Second iteration)

Envelope Tracking (ET): Using ADS "Circuit Envelope" to improve true modulated PAE



Using envelope tracking to adjust the drain bias to track the envelope of the input signal, thus improving efficiency

Notes:
1. The envelope tracking scheme and operation are explained in the "ET_Scheme_Testing" schematic.
2. The data in this Vdrain_vs_Pin_dBm.mdf file came from the "HB1ToneGCompSwp" schematic.
3. This setup limits the minimum drain bias to 2 Volts (arbitrarily).
4. Only data in MeasEqns are output to the dataset to minimize file size.

PAE_mean	P_Load_dBm_mean
43.088	23.301

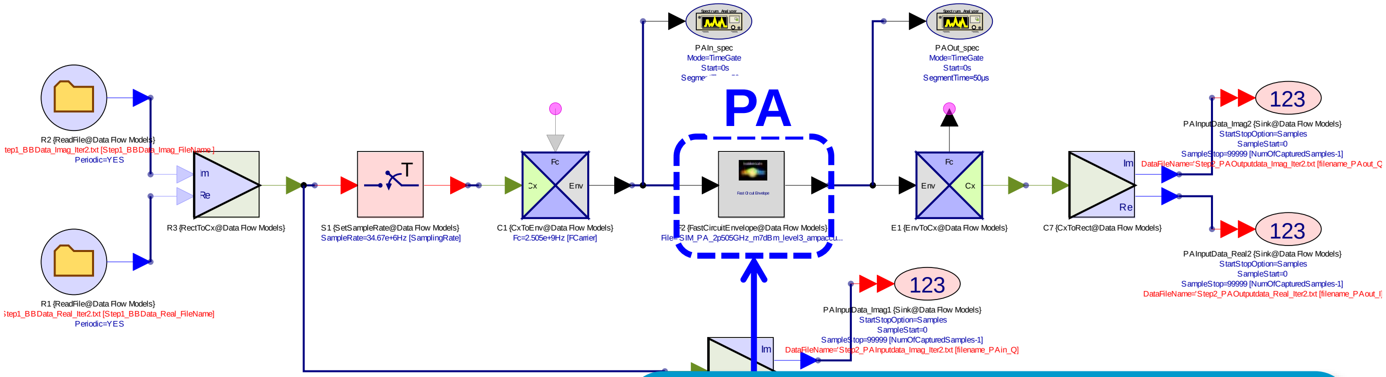
For more information about this application see blog article:

http://www.rf-design-tips.com/envelope-tracking-simulation/

Simulation-based, predictive DPD

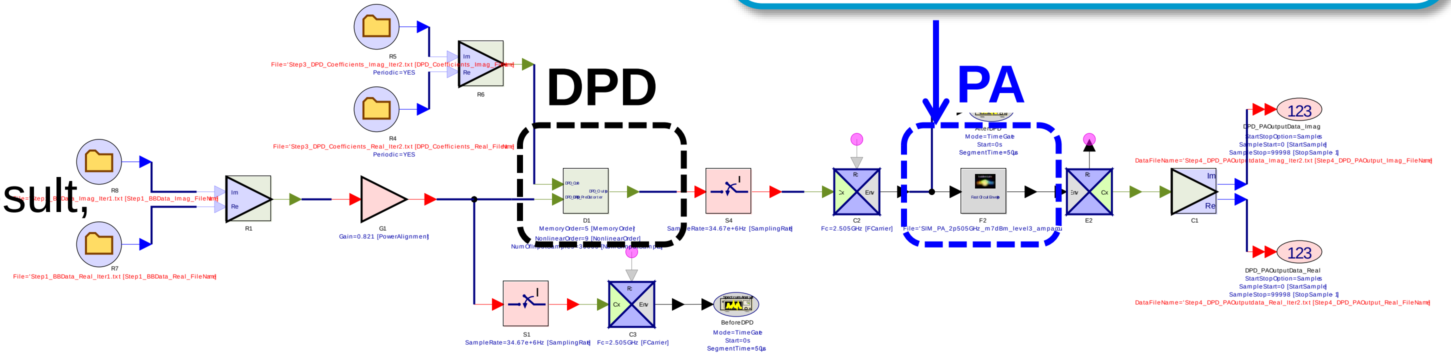
SystemVue with native FCE model, extracted from GoldenGate

Extract
Capture PA input vs. output waveforms for DPD extraction



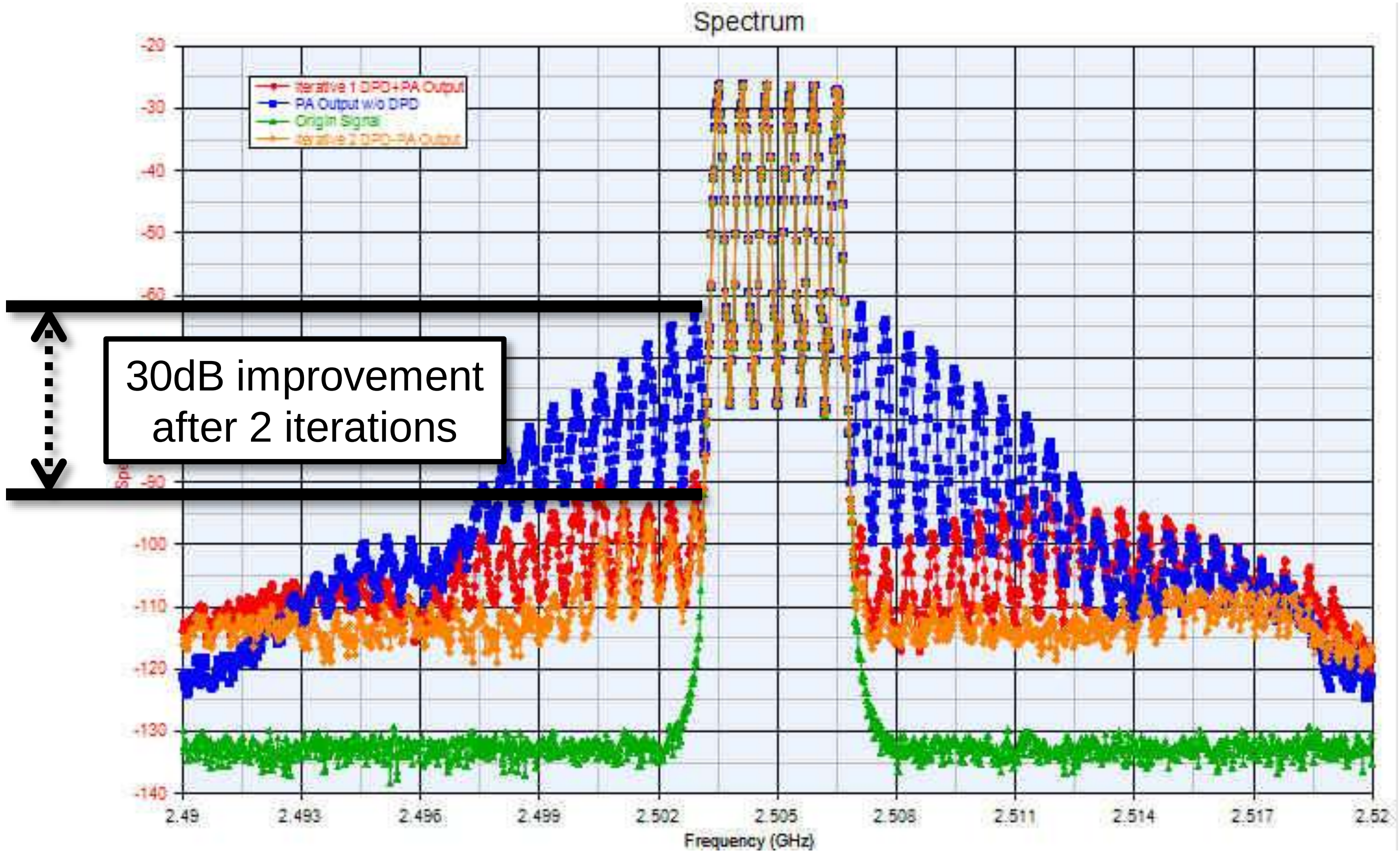
CMOS Handset PA
Fast Circuit Envelope (FCE) model extracted from GoldenGate
(direct co-sim is also possible, but slower)

Verify
See linearized result, including DPD



Simulation-based, predictive DPD

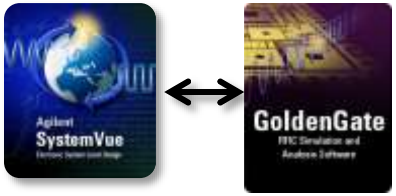
SystemVue with native FCE model, extracted from GoldenGate



30dB improvement
after 2 iterations

6-Carrier GSM
Carrier Spacing: 600kHz

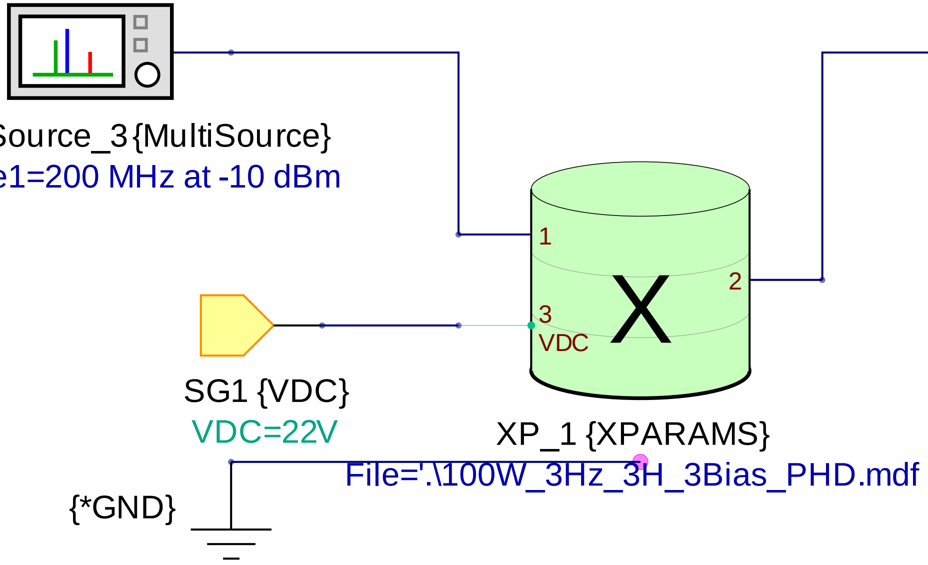
Sampling Rate :
128 * 270.8333kHz
=34.6667 MHz



PA input Spectrum (**Green**)
PA output Spectrum(**Blue**)
PA+DPD Spectrum (**Red**, first iteration)
PA+DPD Spectrum (**Orange**, Second iteration)

Simulation-based, predictive DPD

SystemVue with analog X-parameter model (100W PA)

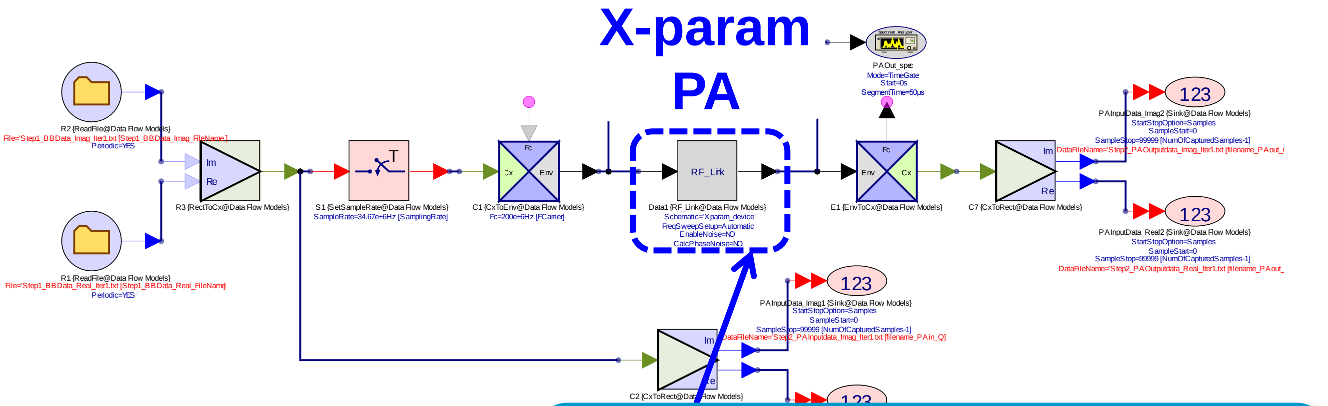


Analog X-parameter device is placed into a Spectrasys subnetwork (RF simulation domain)

Simulation-based, predictive DPD

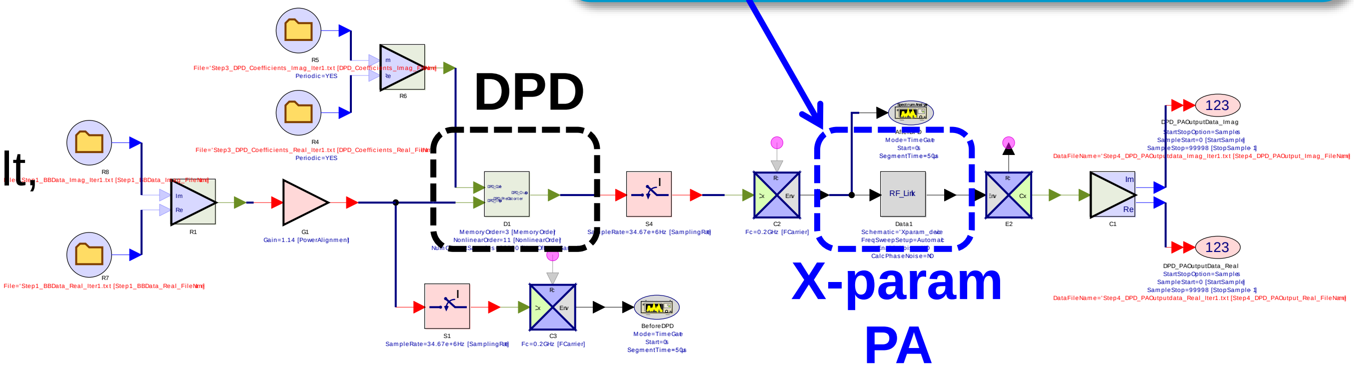
SystemVue with analog X-parameter model (100W PA)

Extract
Capture PA input vs. output waveforms for DPD extraction



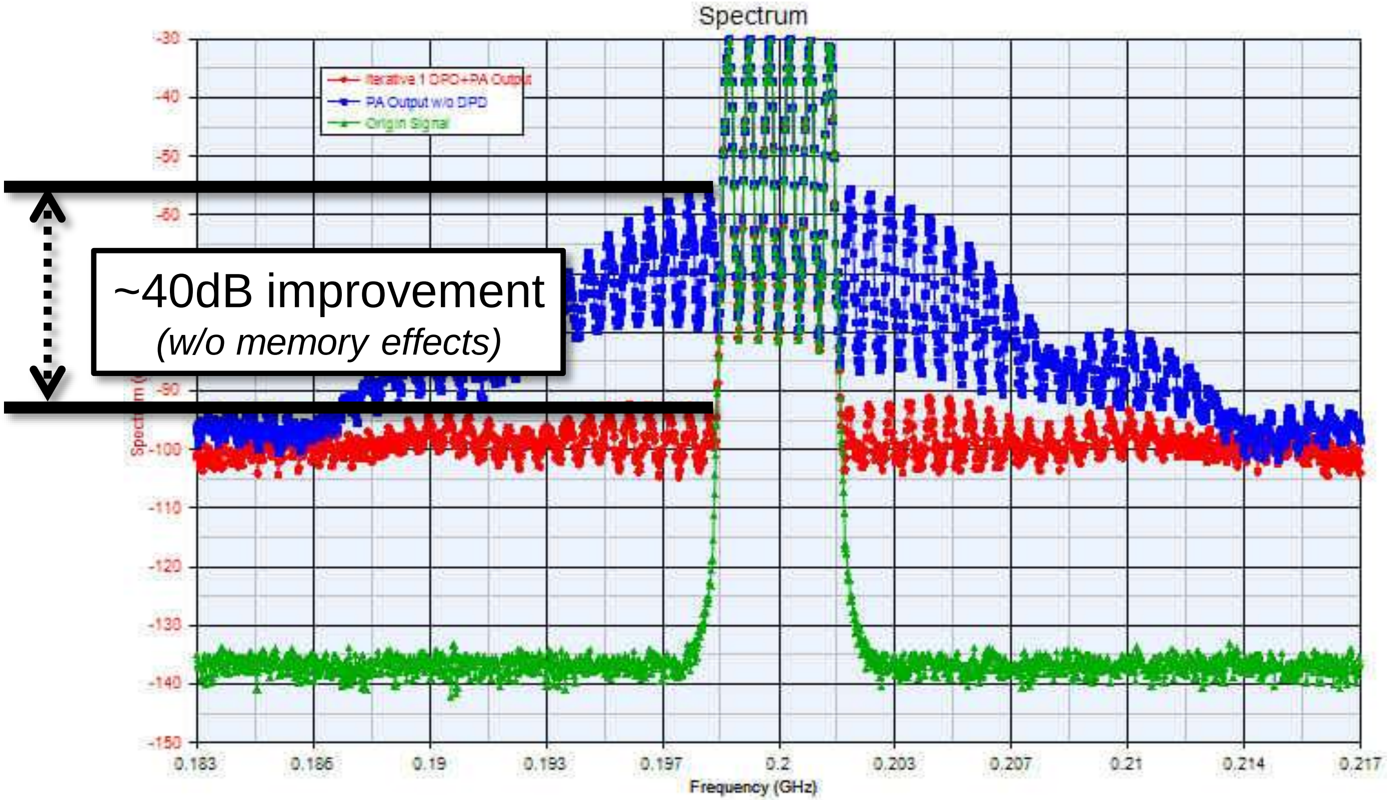
RF_Link
Brings RF networks (incl. X-parameter devices) up to the dataflow simulation

Verify
See linearized result, including DPD



Simulation-based, predictive DPD

SystemVue with analog X-parameter model (100W PA)



~40dB improvement

(w/o memory effects)

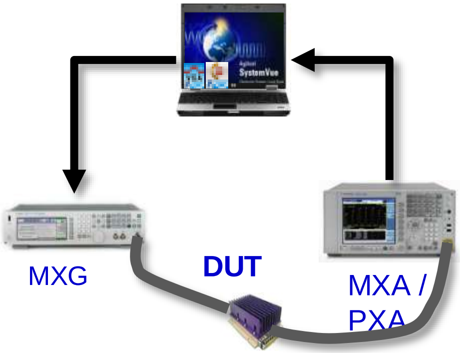
6-Carrier GSM
Carrier Spacing: 600kHz

Sampling Rate :
128 * 270.8333kHz
=34.6667 MHz

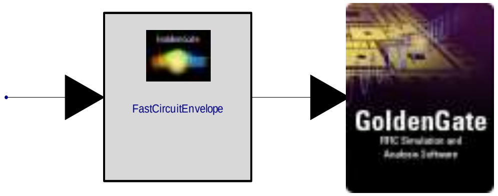
PA input Spectrum (**Green)**
PA output Spectrum(**Blue**)
PA+DPD Spectrum (**Red**

DPD Modeling Simplification: *Automation UI*

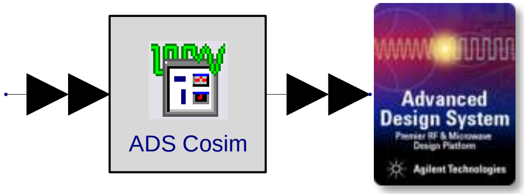
Measurement-based

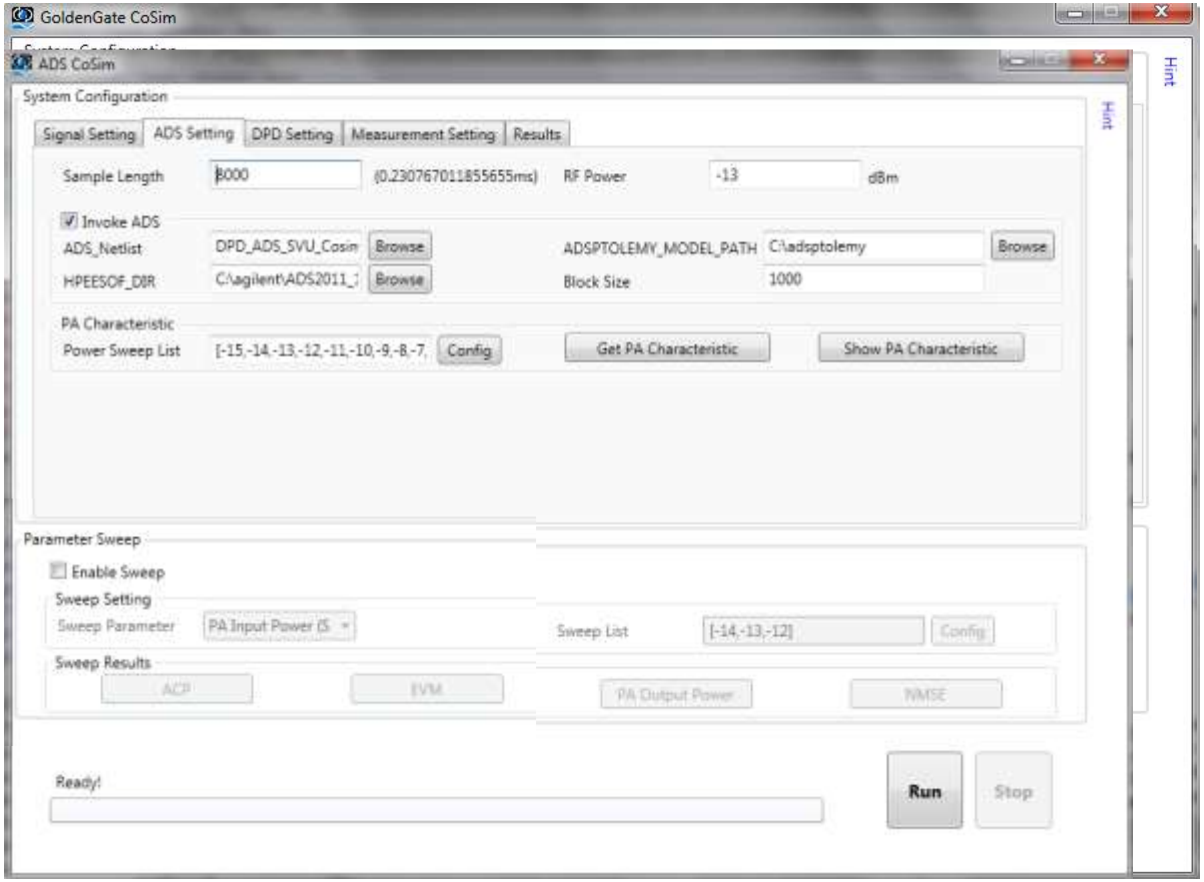


GG co-sim (or FCE model)



ADS co-sim





System Configuration

Sample Length: 8000 (0.230767011855655ms)

RF Power: -13 dBm

☑ Invoke ADS

ADS_Netlist: DPD_ADS_SVU_Cosim

HPEESOF_DIR: C:\agilent\ADS2011_1

ADSPTOLEMY_MODEL_PATH: C:\adsptolemy

Block Size: 1000

PA Characteristic

Power Sweep List: [-15,-14,-13,-12,-11,-10,-9,-8,-7,

Parameter Sweep

☐ Enable Sweep

Sweep Setting

Sweep Parameter: PA Input Power (S

Sweep List: [-14,-13,-12]

Sweep Results

Ready!

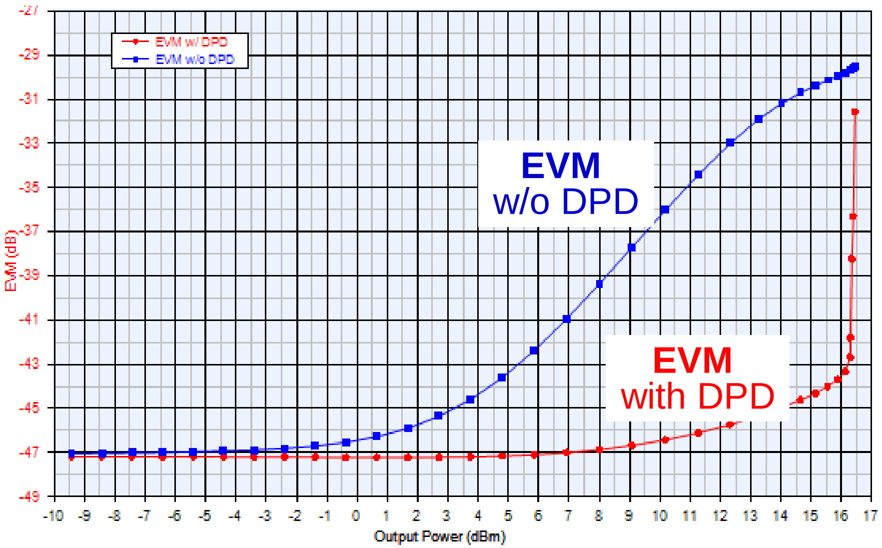
Both DPD extractions share the same UI:

- Measurement-based
- Simulation-based

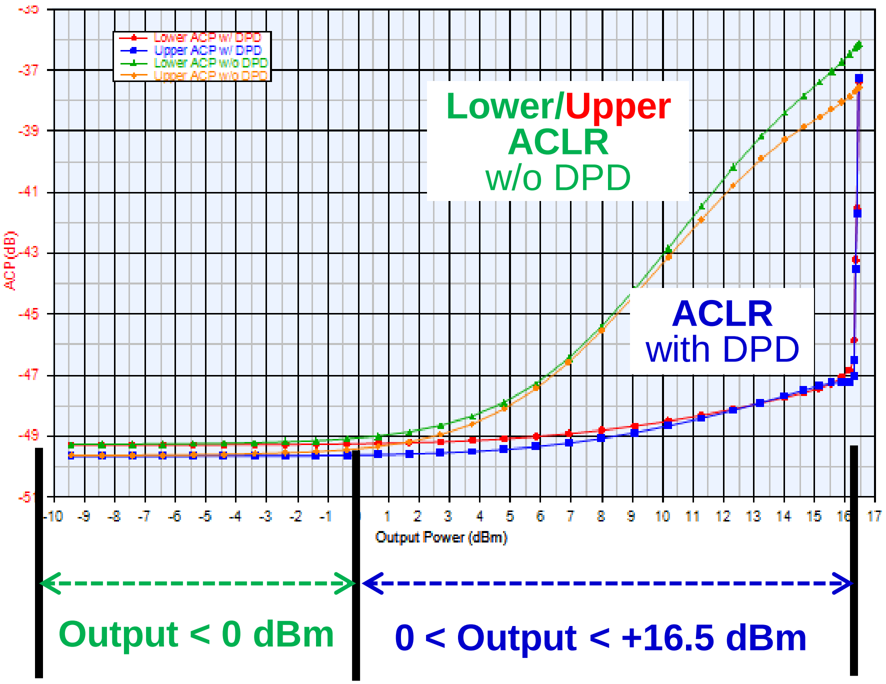
Verification of simulation-based DPD

Sweep power, re-extract DPD at each point, watch EVM, ACP

EVM vs. Output Power



ACP vs. Output Power



Output < 0 dBm

DPD offers little benefit

0 < Output < +16.5 dBm

DPD offers significant benefit

Input waveform:

- IEEE 802.11ac, 5 GHz WLAN
- No CFR (PAPR is 8.7dB)
- Bandwidth = 80MHz system
- 4x Oversampling → rate=320 MHz

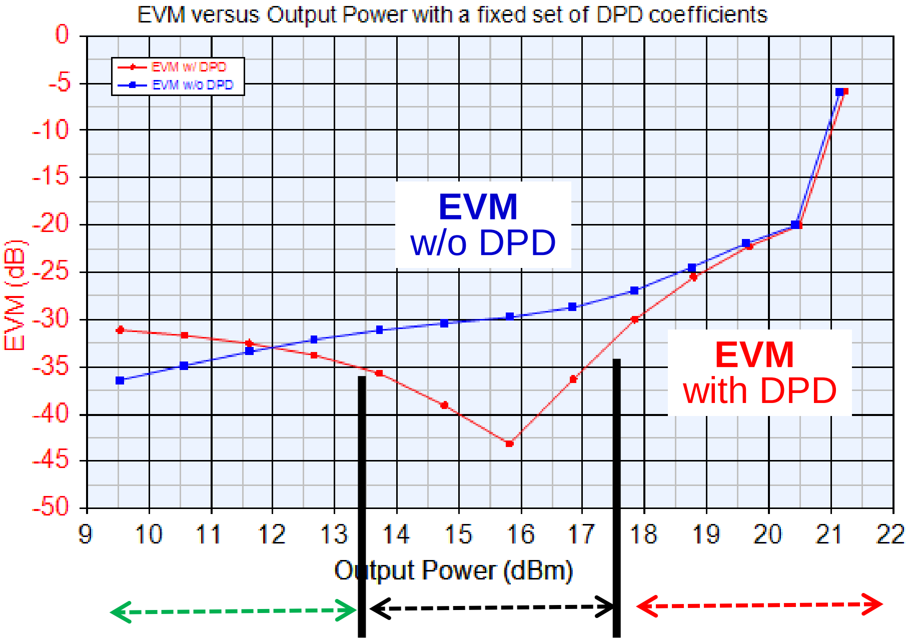
Device Under Test:

- WLAN “FCE” model extracted from Agilent GoldenGate RFIC simulator

Verification of simulation-based DPD

Sweep power, constant DPD coefficients, watch EVM, ACP

<u>Question</u>: “Do I need Adaptive DPD?”



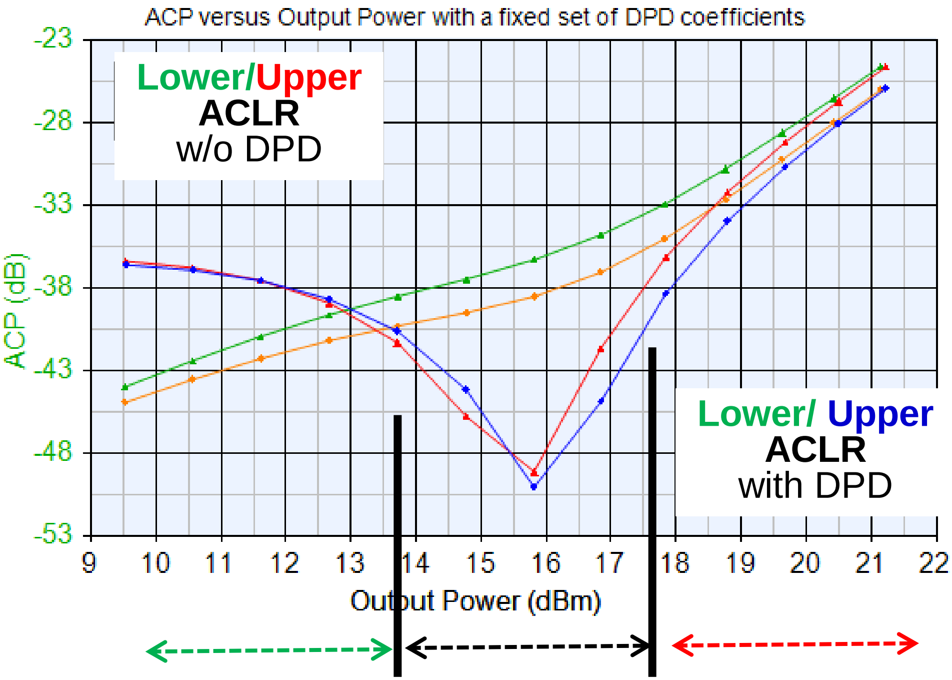
EVM
w/o DPD

EVM
with DPD

Different (or fewer) DPD coefficients needed

Useful Range for this set of DPD coefficients

PA may be less correctable



Lower/Upper
ACLR
w/o DPD

Lower/ Upper
ACLR
with DPD

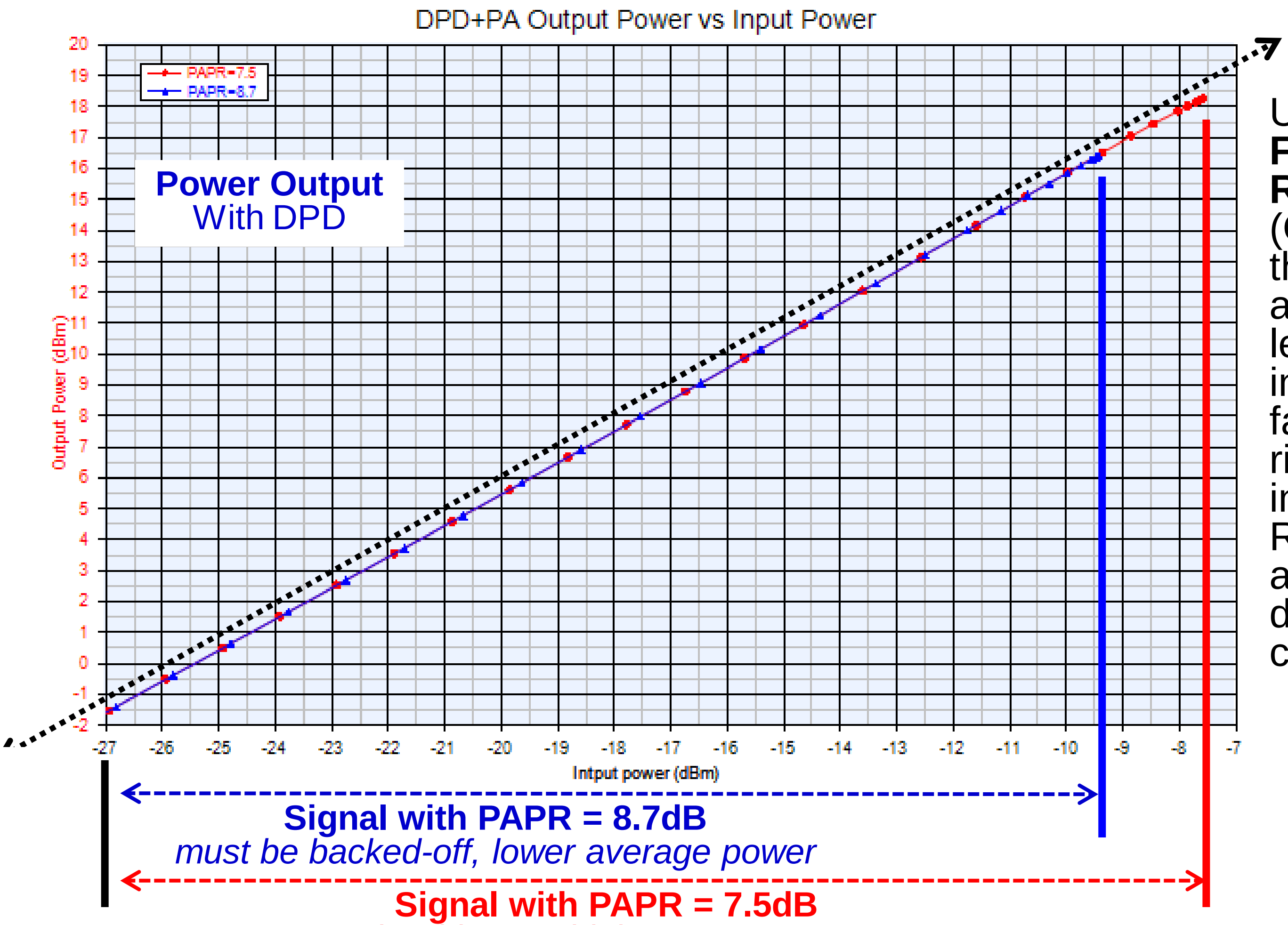
ACP may actually be *worse* out of range: turn DPD off.

ACP satisfies a spectral compliance mask

High DC-RF efficiency but poor ACP

Verification of simulation-based DPD

Sweep power, re-extract at each point, see final P_{out} vs. P_{in}



Power Output
With DPD

Linear Gain = 25.5dB

Signal with PAPR = 8.7dB
must be backed-off, lower average power

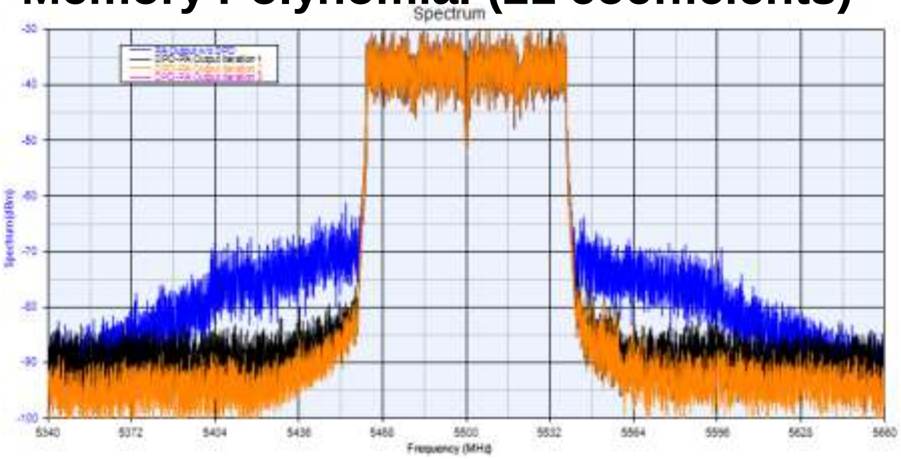
Signal with PAPR = 7.5dB
can be driven to higher average power

Using **Crest Factor Reduction** (CFR) to reduce the peaks, the average signal level can be increased farther to the right, resulting in higher DC-RF Efficiency, and longer distance coverage

Memory Polynomial vs. Volterra DPD models

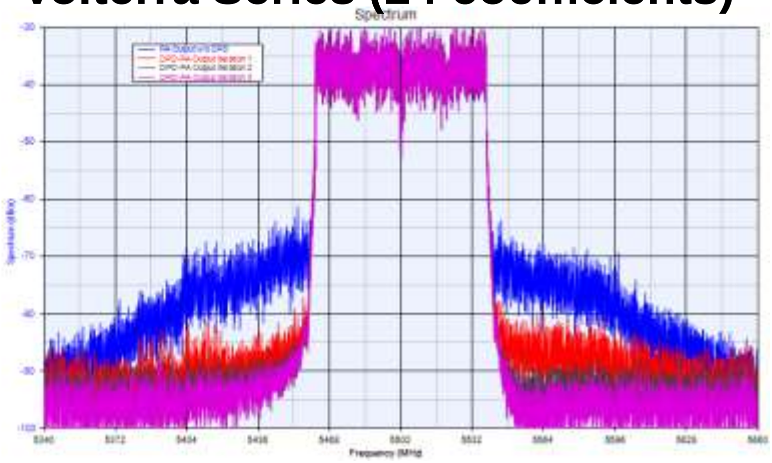
802.11ac 80MHz, FCE PA Model Co-sim

Memory Polynomial (21 coefficients)



ACPR	Lower	Upper	EVM (dB)
Original input	-56.19	-57.20	-47.16
PA Output (No DPD)	-36.66	-38.43	-29.88
DPD+PA Iter1	-50.28	-49.95	-42.20
DPD+PA Iter2	**-53.39**	**-52.18**	**-44.41**

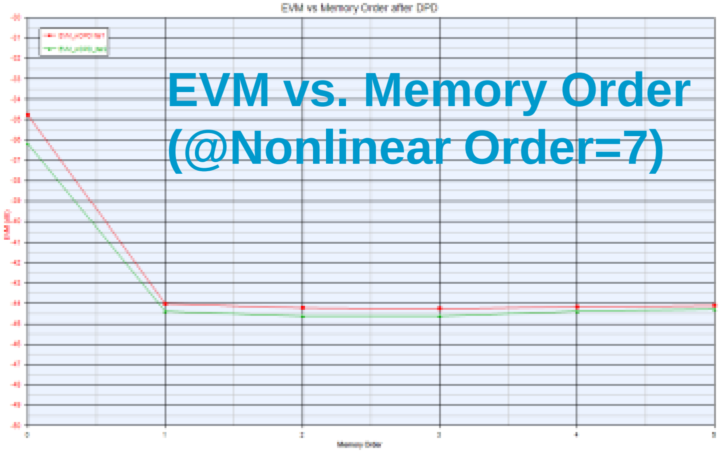
Volterra Series (24 coefficients)



ACPR	Lower	Upper	EVM (dB)
Original input	-56.19	-57.20	-47.16
PA Output (No DPD)	-36.68	-38.45	-29.90
DPD+PA Iter1	-51.60	-49.79	-42.90
DPD+PA Iter2	-54.05	-54.29	-46.06
DPD+PA Iter3	**-54.71**	**-55.26**	**-46.40**

Verification after DPD model extraction

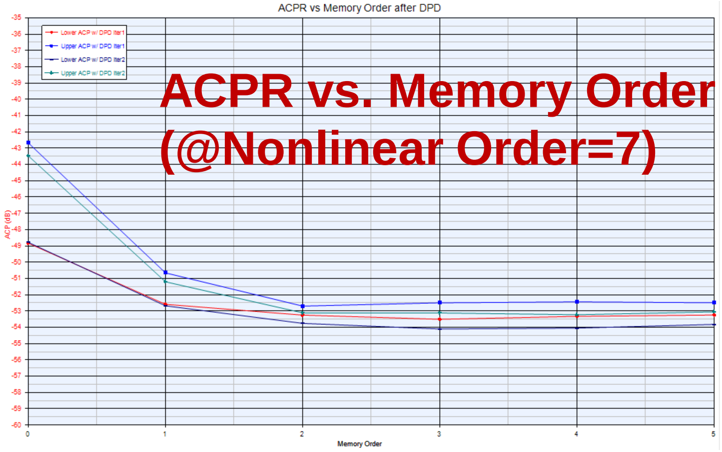
Verifying Memory Order and Nonlinear Order in Memory Polynomial



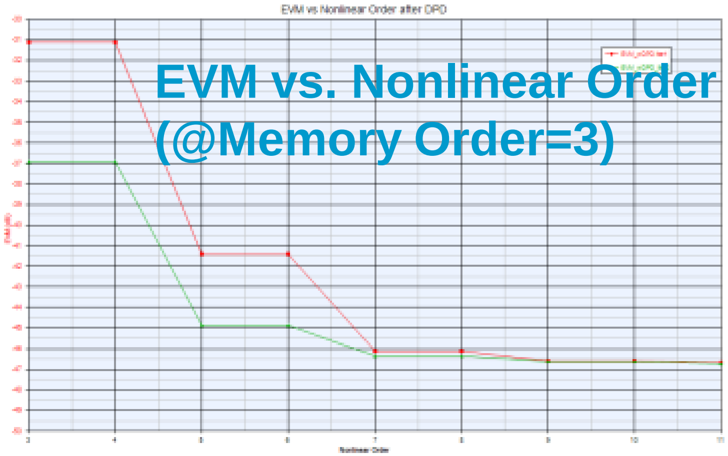
EVM vs. Memory Order (@Nonlinear Order=7)

EVM and ACP are stable when memory order>=3.

Memory effect almost removed when memory order >=3.

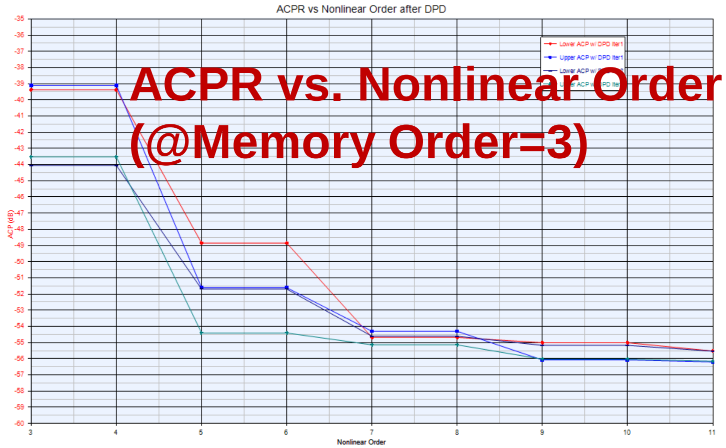


ACPR vs. Memory Order (@Nonlinear Order=7)



EVM vs. Nonlinear Order (@Memory Order=3)

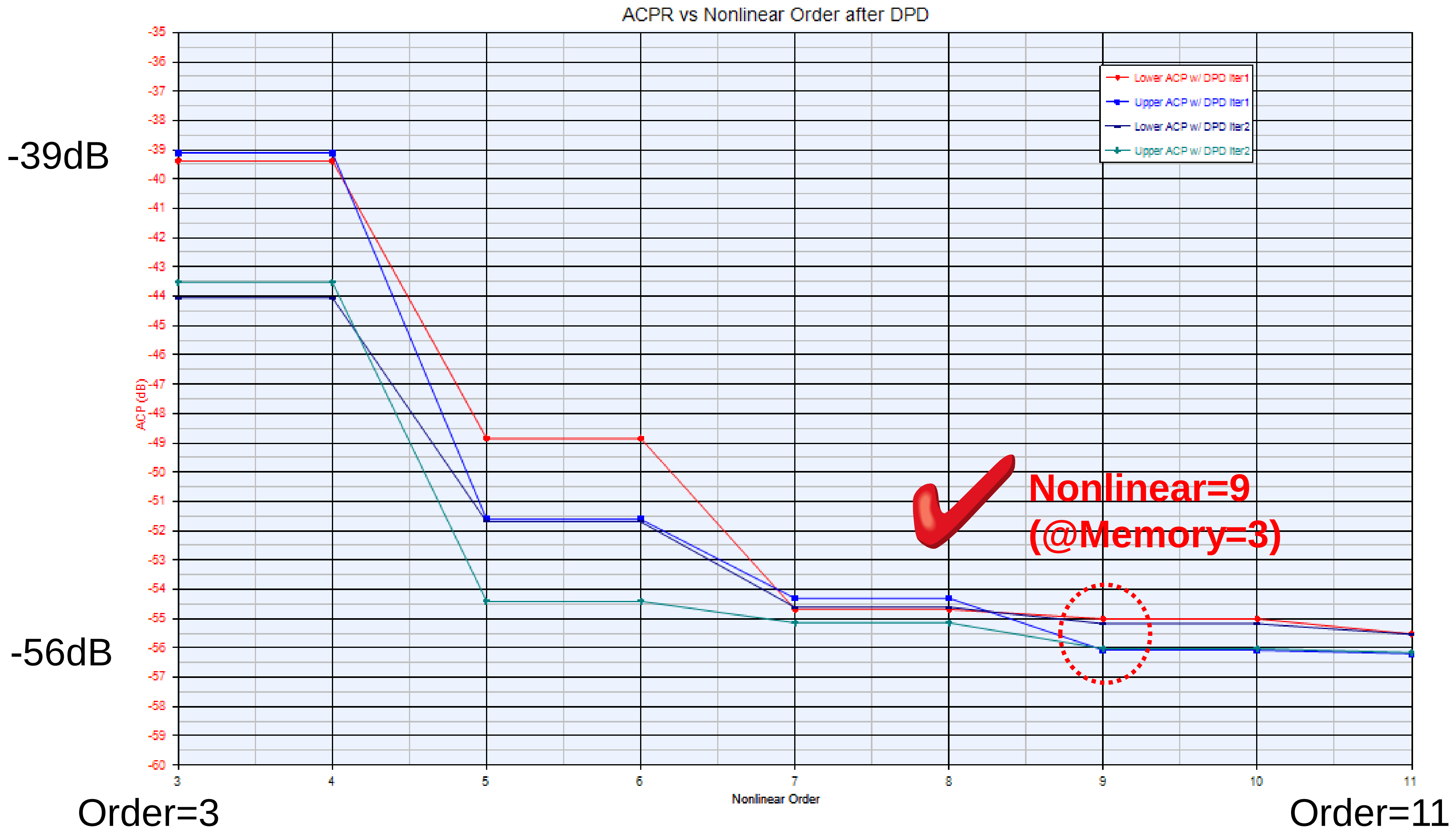
EVM and ACP are stable when nonlinear order>=7.



ACPR vs. Nonlinear Order (@Memory Order=3)

Verification after DPD model extraction

A closer look at ACPR vs. ***Nonlinear Order*** *("how many terms do I need?")*



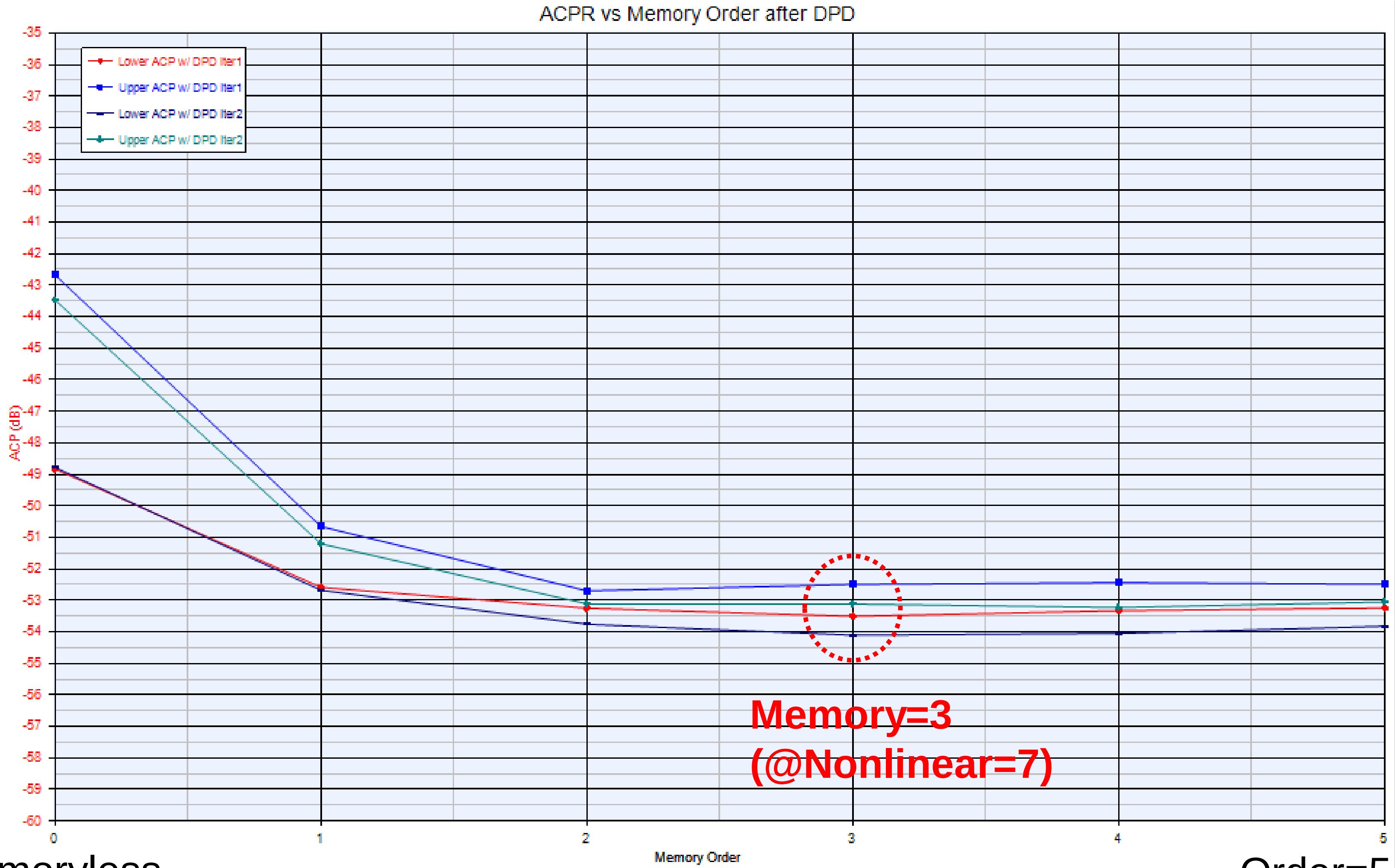
Nonlinear=9 (@Memory=3)

Verification after DPD model extraction

A closer look at ACPR vs. ***Memory Order*** *(“how many terms do I need?”)*

-43dB

-54dB



Memory=3
(@Nonlinear=7)

Memoryless

Order=5

Agenda

1. Introduction and Problem Statement
2. Digital Pre-Distortion (DPD) Concepts
3. DPD verification with Agilent Hardware
4. DPD simulation with Agilent EDA Tools
5. Crest Factor Reduction (CFR)
6. Summary

Crest Factor Reduction (CFR) Concepts

- Spectrally efficient wideband RF signals may have PAPR >13dB.
- CFR preconditions the signal to reduce signal peaks without significant signal distortion
- CFR allows the PA to operate more efficiently – it is not a linearization technique
- CFR supplements DPD and improves DPD effectiveness
- Without CFR and DPD, a basestation or handset PA must operate at significant back-off from saturated power to maintain linearity. The back-off reduces efficiency

Benefits of CFR

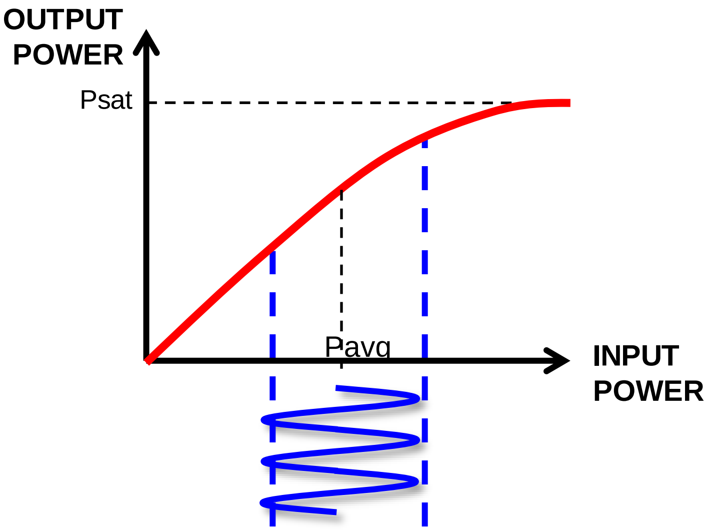
1. PAs can operate closer to saturation, for improved efficiency (PAE).
2. Output signal still complies with spectral mask and EVM specifications

Crest Factor Reduction (CFR) Concepts

WITHOUT CFR

PAPR ~13dB

Raw LTE-Advanced

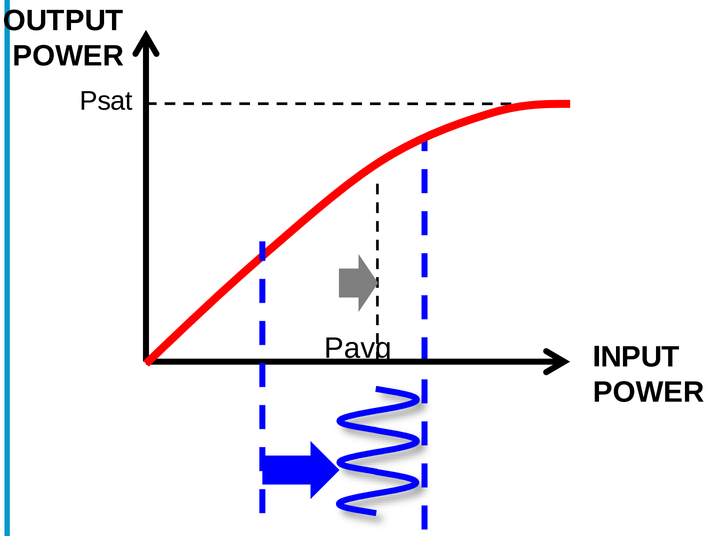


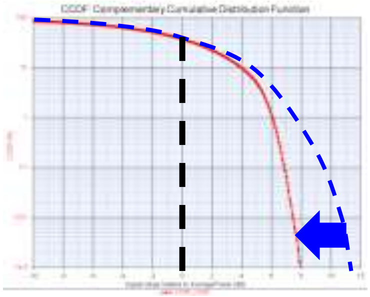
Instantaneous PAPR
(Peak-to-Avg Power Ratio)

WITH CFR

PAPR ~7dB

Run at +6dB higher avg power





Benefit:
Effectively larger RFPA with same HW BOM

CFR for LTE-Advanced Downlink OFDMA

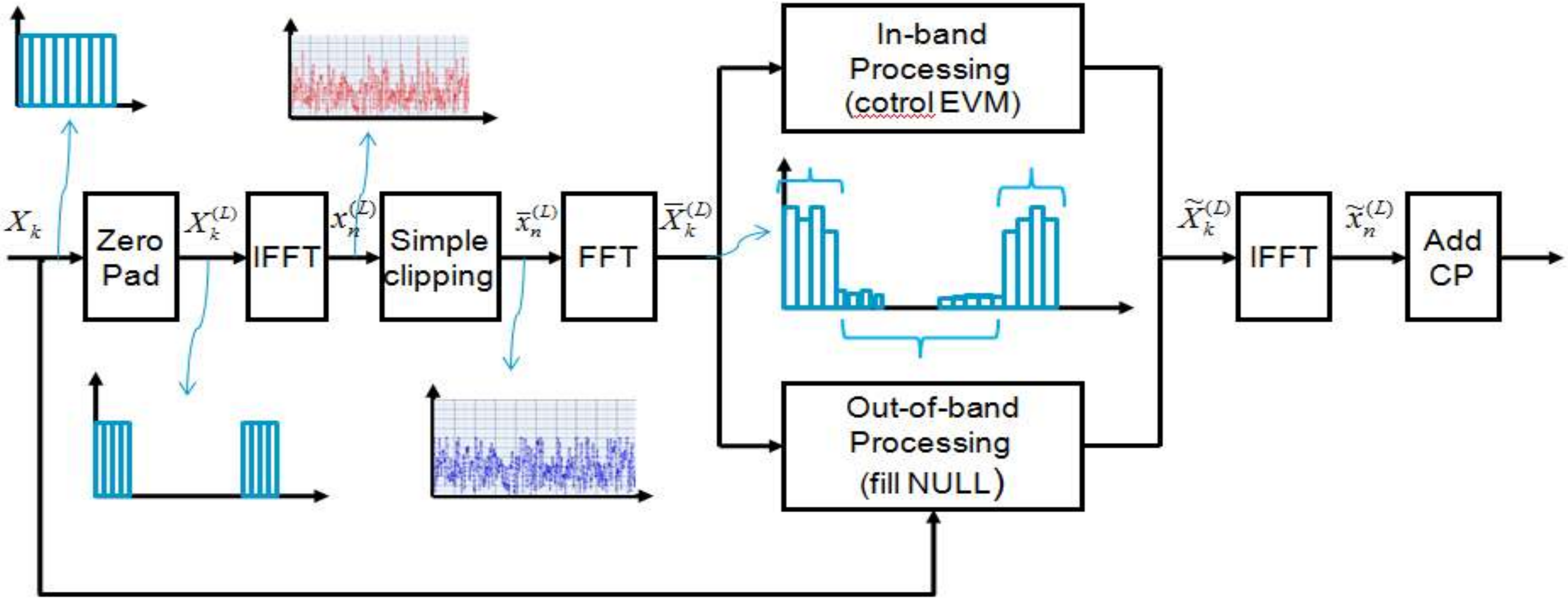
Controls EVM and band limits in the frequency domain.

- Constrains constellation errors, to avoid bit errors.
- Constrains the degradation on individual sub-carriers.

Allows QPSK sub-carriers to be degraded more than 64 QAM sub-carriers.

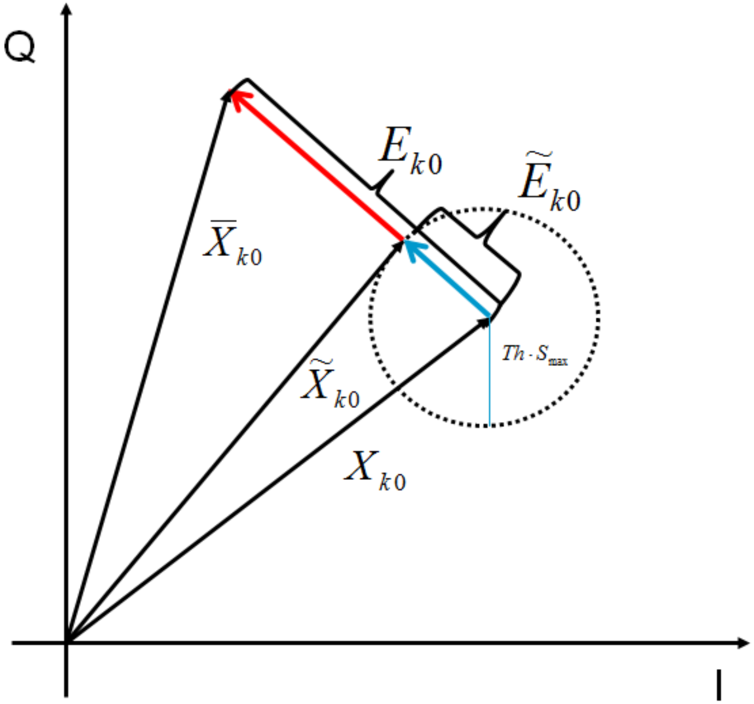
Does not degrade reference signals, P-SS and S-SS.

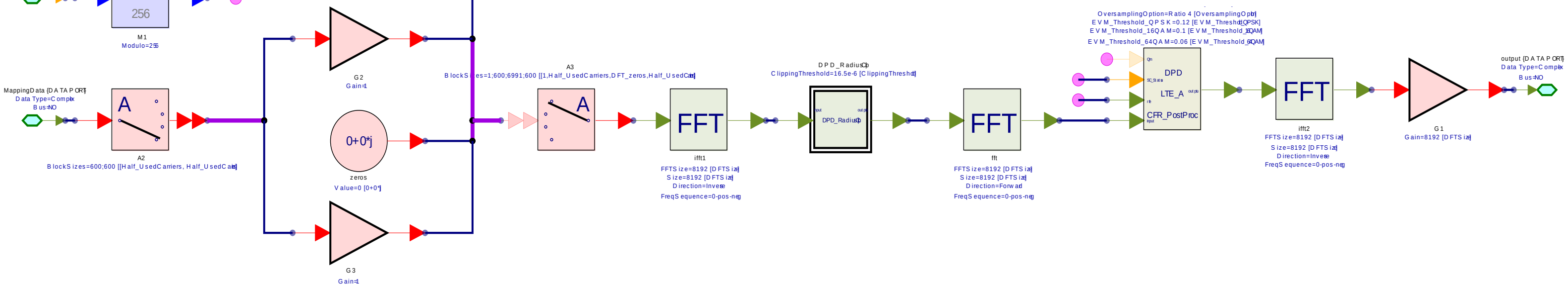
Subcarriers of out-of band are set to NULL.



CFR for LTE-Advanced Downlink OFDMA

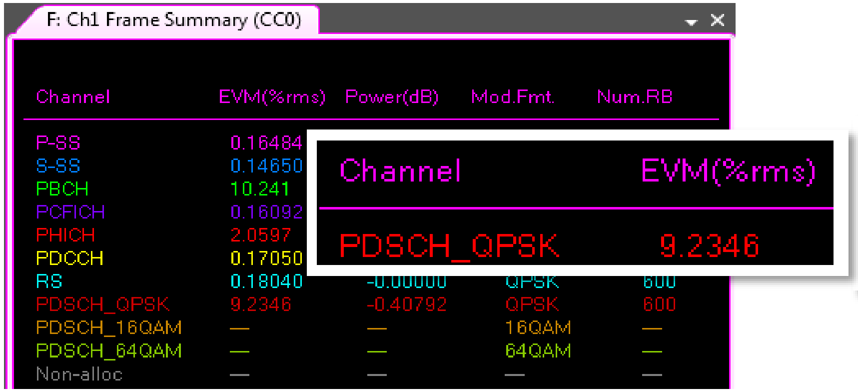
- No side modifications for receiver
- No out-of band spectral distortion (no spectral mask measurement pass/fail issue
- EVM always meets specification
- Good PAR reductions
- No impact of timing and frequency an channel estimation of DL





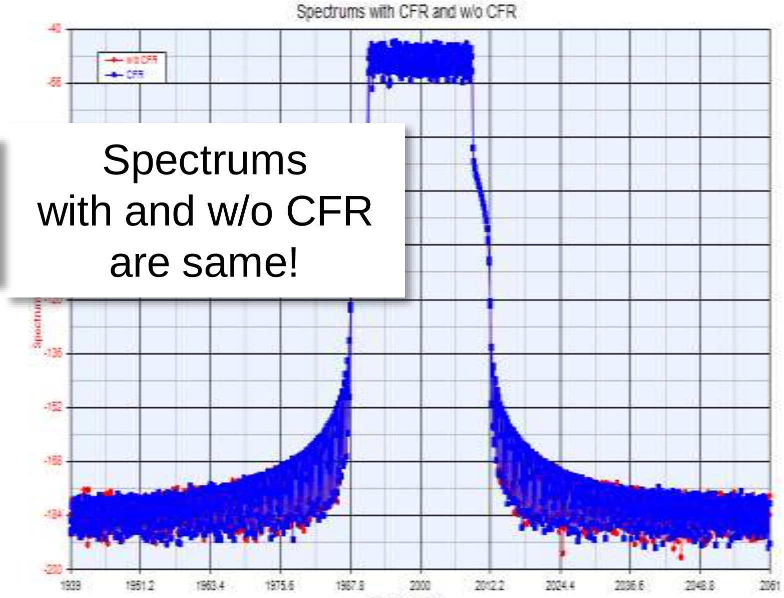
CFR of LTE-Advanced 20MHz Downlink

QPSK modulation, CFR algorithm set to Max EVM = 10%

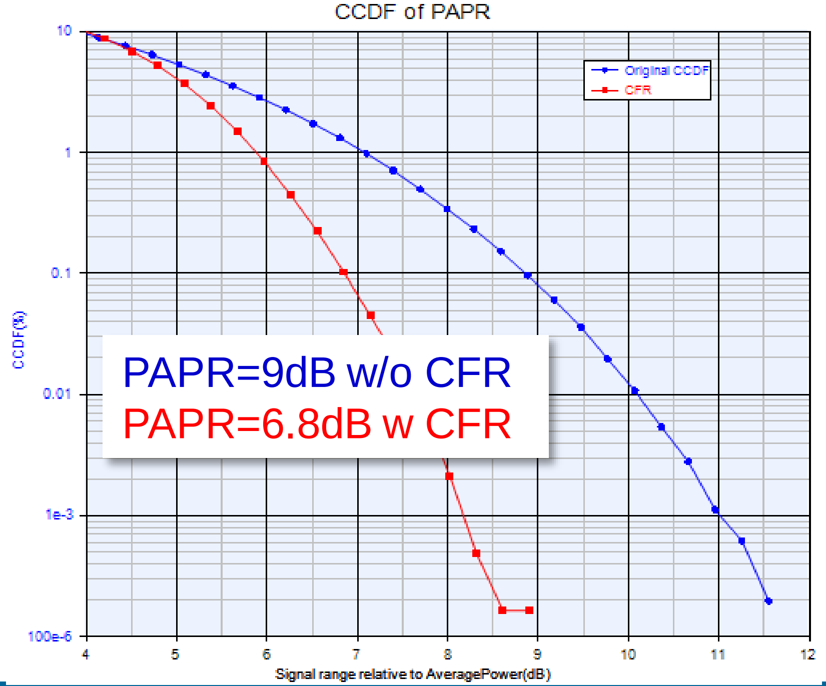


Channel	EVM(%rms)	Power(dB)	Mod.Fmt.	Num.RB
P-SS	0.16484			
S-SS	0.14650			
PBCH	10.241			
PCFICH	0.16092			
PHICH	2.0597			
PDCCH	0.17050			
RS	0.18040	-0.00000	QPSK	600
PDSCH_QPSK	9.2346	-0.40792	QPSK	600
PDSCH_16QAM	—	—	16QAM	—
PDSCH_64QAM	—	—	64QAM	—
Non-alloc	—	—	—	—

Channel	EVM(%rms)
PDSCH_QPSK	9.2346



Spectrums with and w/o CFR are same!

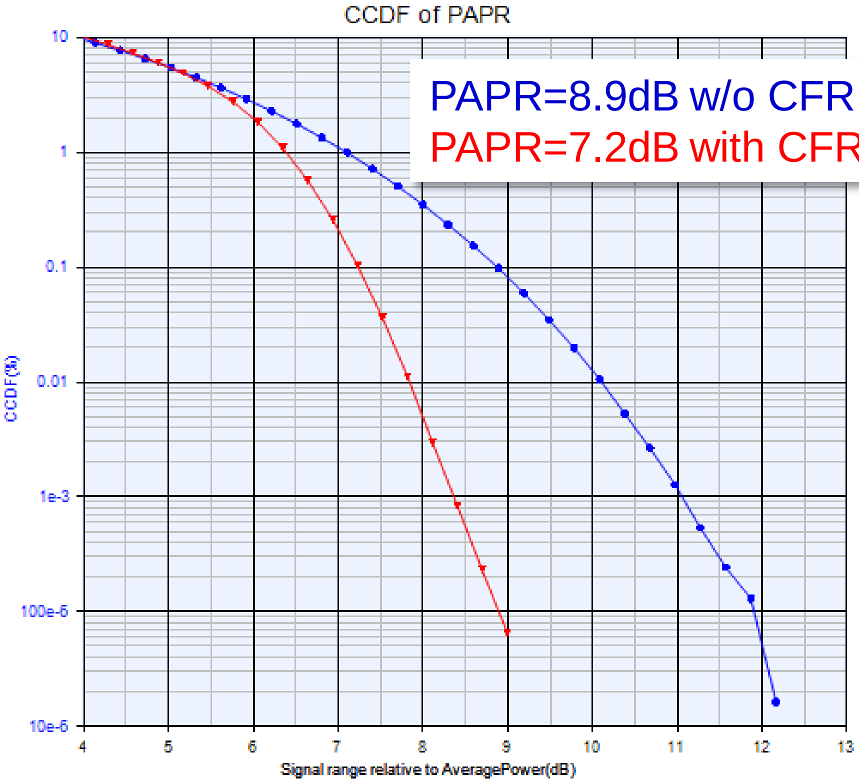


PAPR=9dB w/o CFR

PAPR=6.8dB w CFR

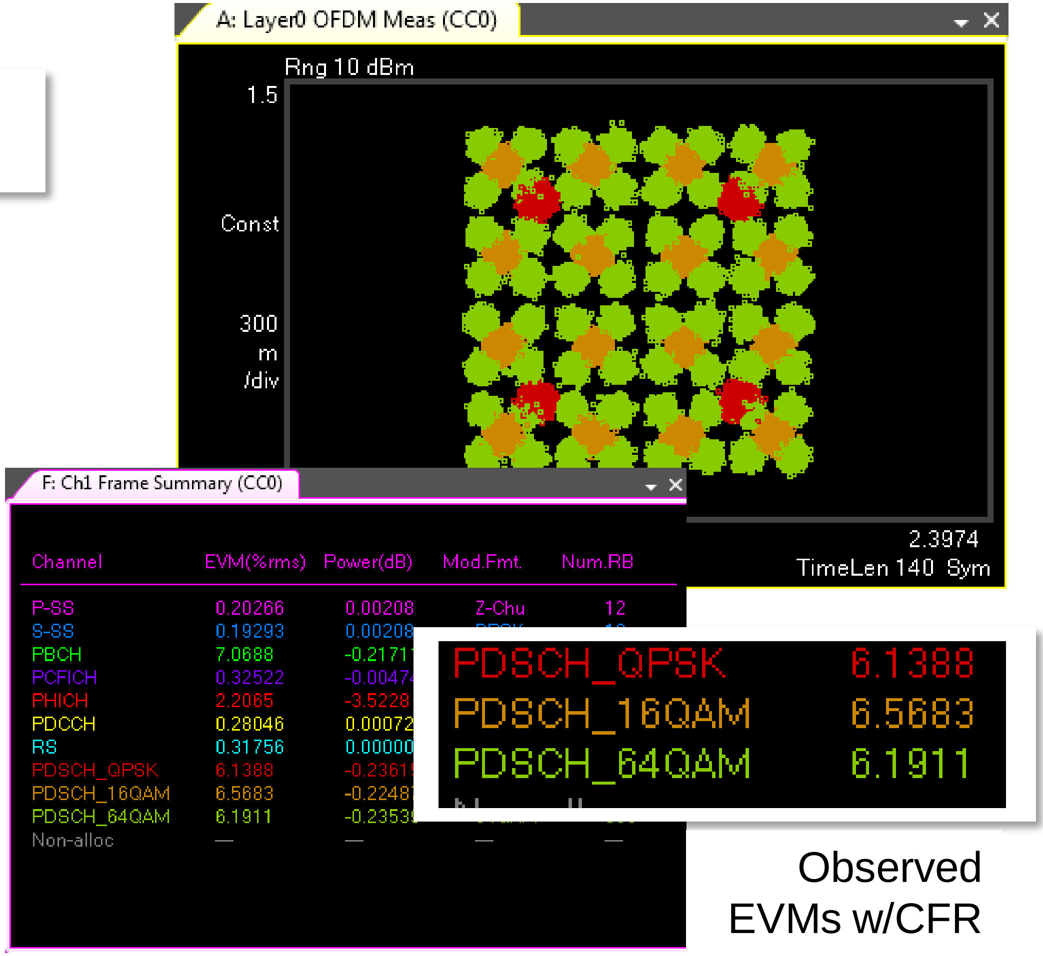
CFR of LTE-Advanced 20MHz Downlink

Algorithm EVM targets: QPSK < 10%, 16QAM < 8%, 64QAM < 6%



PAPR=8.9dB w/o CFR

PAPR=7.2dB with CFR



Channel	EVM(%rms)	Power(dB)	Mod.Fmt.	Num.RB
P-SS	0.20266	0.00208	Z-Chu	12
S-SS	0.19293	0.00208		
PBCH	7.0688	-0.2171		
PCFICH	0.32522	-0.0047		
PHICH	2.2065	-3.5228		
PDCCH	0.28046	0.00072		
RS	0.31756	0.00000		
PDSCH_QPSK	6.1388	-0.2361		
PDSCH_16QAM	6.5683	-0.2248		
PDSCH_64QAM	6.1911	-0.2353		
Non-alloc	—	—	—	—

PDSCH_QPSK	6.1388
PDSCH_16QAM	6.5683
PDSCH_64QAM	6.1911

Observed EVMs w/CFR

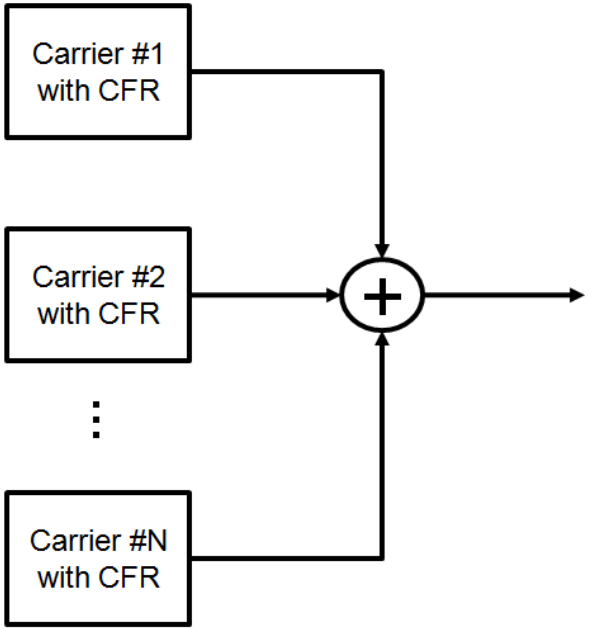
CFR of LTE-Advanced with Carrier Aggregation

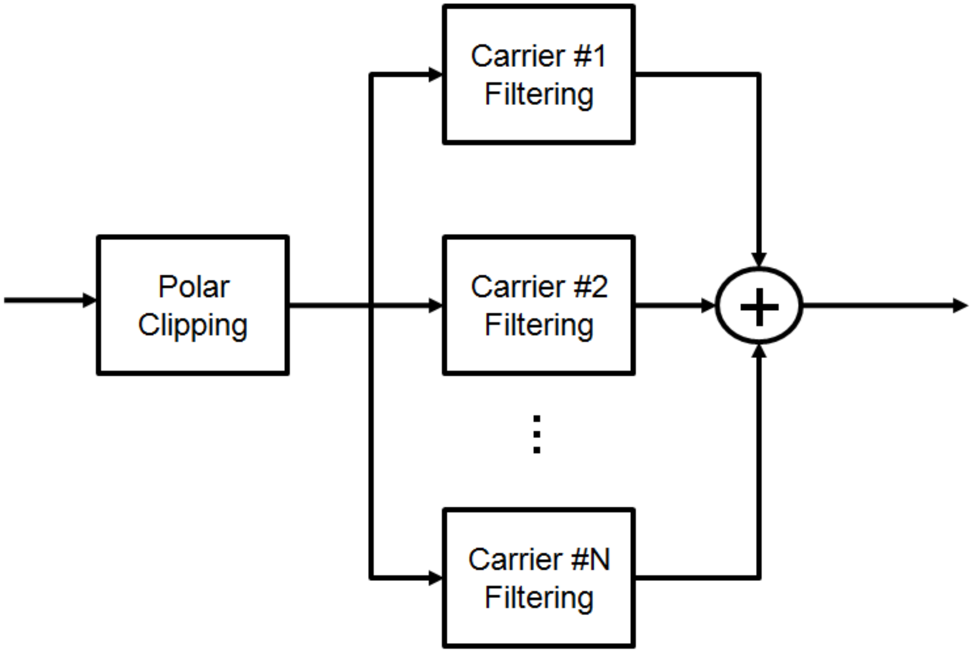
CFR Approach 1

- CFR performed separately on each Component Carrier (up to 20MHz BW)
- Component Carriers are then aggregated (summed)

CFR Approach 2

- CC's are carrier-aggregated (up to 100MHz BW), then CFR'd together
- Then each component carrier is re-filtered individually to remove out-of-band energy, and re-summed

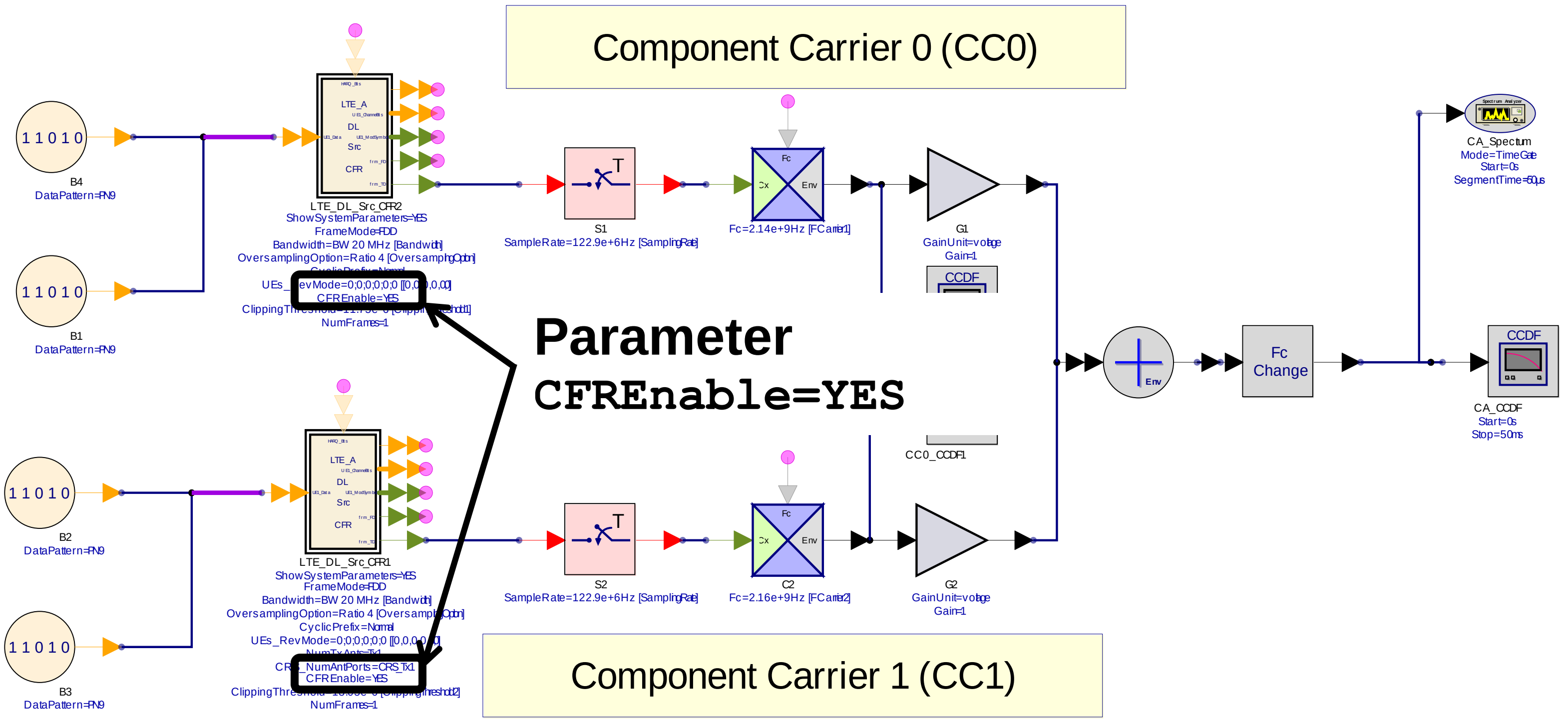




CFR of LTE-Advanced with Carrier Aggregation

Approach 1, 2x20MHz contiguous CA

1. Both CC0 and CC1 adopt 16-QAM and QPSK, respectively.
2. CC1 magnitude threshold of polar clipping is a little larger than CC0 because QPSK modulation can tolerate larger EVM limit, according to EVM specification.



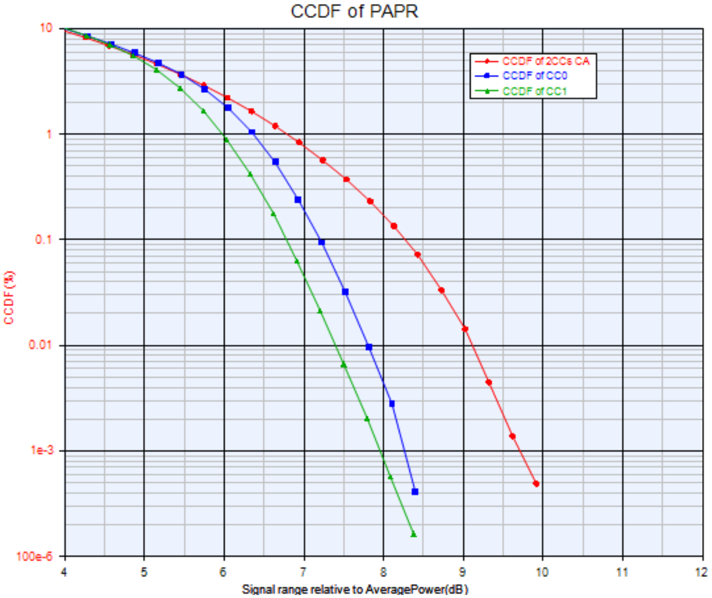
Component Carrier 0 (CC0)

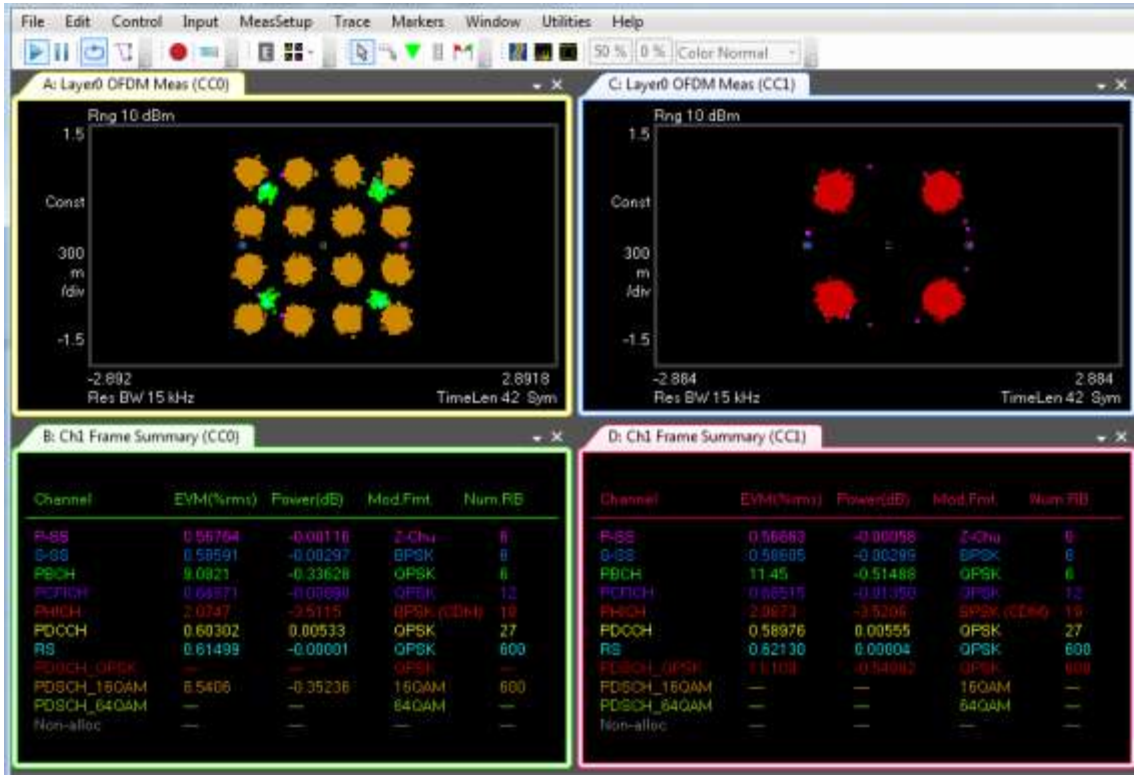
Parameter
`CFREnable=YES`

Component Carrier 1 (CC1)

CFR of LTE-Advanced with Carrier Aggregation

Approach 1: 2x20MHz contiguous CA





B: Ch1 Frame Summary (CC0)

Channel	EVM(%rms)	Power(dB)	Mod.Fmt	Num.RB
P-SS	0.56764	-0.00116	Z-Chu	6
S-SS	0.58591	-0.00297	BPSK	6
PBCH	9.0821	-0.33628	QPSK	6
PCFICH	0.66871	-0.00890	QPSK	12
PHICH	2.0747	-2.5115	BPSK (CDM)	19
PDCCH	0.60302	0.00533	QPSK	27
RS	0.61499	-0.00001	QPSK	600
PDSCH_QPSK	—	—	QPSK	—
PDSCH_16QAM	8.5406	-0.35236	16QAM	600
PDSCH_64QAM	—	—	64QAM	—
Non-alloc	—	—	—	—

D: Ch1 Frame Summary (CC1)

Channel	EVM(%rms)	Power(dB)	Mod.Fmt	Num.RB
P-SS	0.56663	-0.00058	Z-Chu	6
S-SS	0.58605	-0.00296	BPSK	6
PBCH	11.45	-0.51488	QPSK	6
PCFICH	0.66515	-0.01350	QPSK	12
PHICH	2.0873	-3.5206	BPSK (CDM)	19
PDCCH	0.58976	0.00555	QPSK	27
RS	0.62130	0.00004	QPSK	600
PDSCH_QPSK	11.108	-0.54082	QPSK	600
PDSCH_16QAM	—	—	16QAM	—
PDSCH_64QAM	—	—	64QAM	—
Non-alloc	—	—	—	—

CC0 PAPR =7.2 dB

CC1 PAPR = 6.7dB

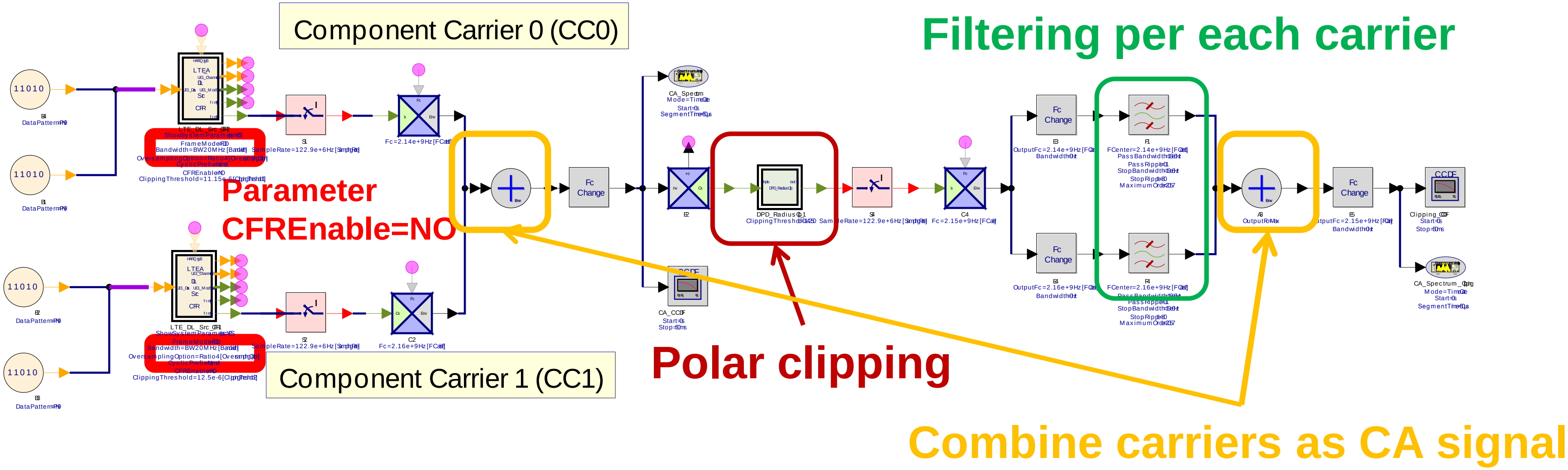
2x20MHz 2CC with CFR #1
PAPR = 8.2dB

EVM of PDSCH 16-QAM is 8.54% in CC0 and
EVM of PDSCH QPSK is 11.11% in CC1.
EVM values of P-SS, S-SS and RS <**0.65%**

CFR of LTE-Advanced with Carrier Aggregation

Approach 2: 2x20MHz contiguous CA

1. Both CC0 and CC1 adopt 16-QAM and QPSK, respectively.
2. Aggregate CC0 and CC1 first, then do polar clipping on the 40MHz bandwidth composite CA signal.
3. Each Component Carrier is filtered separately (20MHz each)
4. Combine the filtered CC0 and CC1 into one CA signal again.



Component Carrier 0 (CC0)

Component Carrier 1 (CC1)

Parameter CFREnable=NO

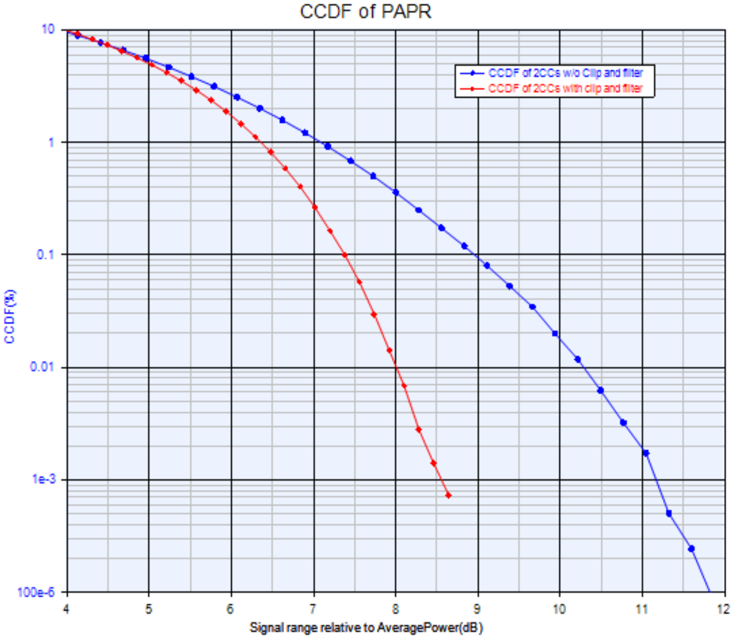
Polar clipping

Filtering per each carrier

Combine carriers as CA signal

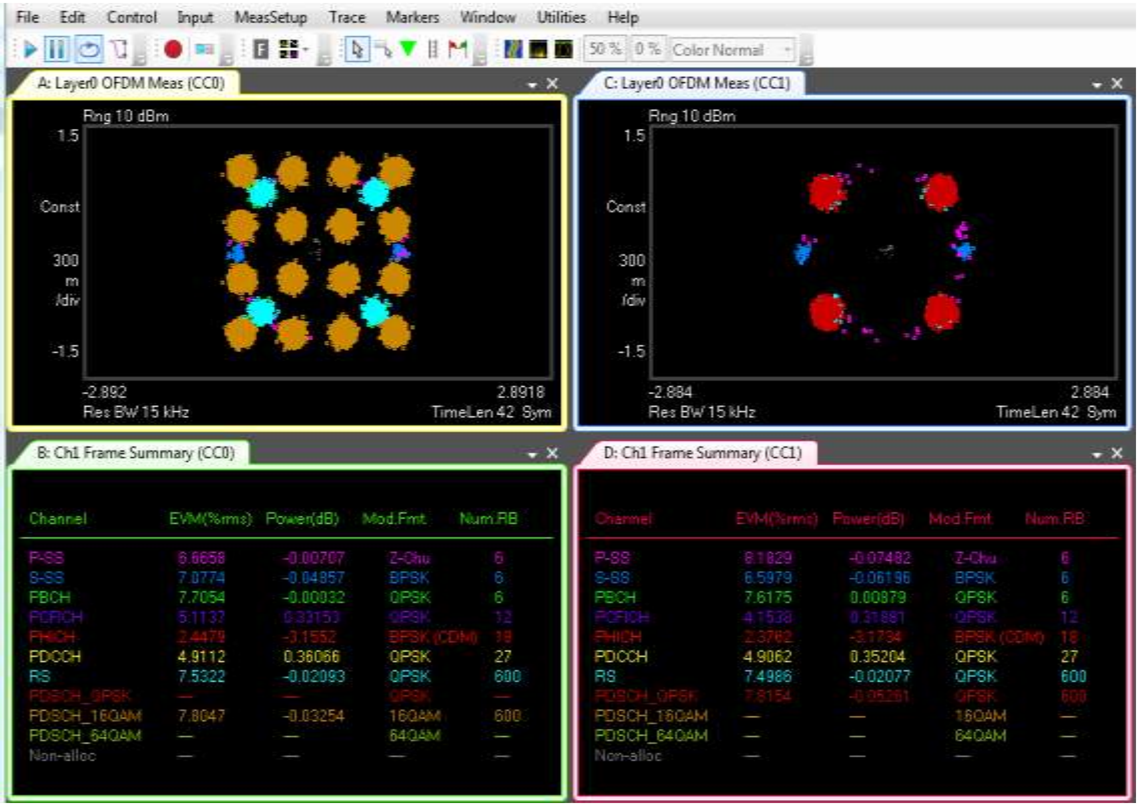
CFR of LTE-Advanced with Carrier Aggregation

Approach 2: 2x20MHz contiguous CA



2x20MHz 2CC w/o CFR
PAPR = 9 dB

2x20MHz 2CC with CFR #2
PAPR = 7.4dB



B: Ch1 Frame Summary (CC0)

Channel	EVM(%rms)	Power(dB)	Mod.Fmt	Num.RB
P-SS	6.6658	-0.00707	Z-Chu	6
S-SS	7.0774	-0.04857	BPSK	6
PBCH	7.7054	-0.00032	QPSK	6
PCFICH	5.1137	0.33153	QPSK	12
PHICH	2.4479	-3.1552	BPSK (CDM)	18
PDCCH	4.9112	0.36066	QPSK	27
RS	7.5322	-0.02093	QPSK	600
PDSCH_QPSK	—	—	QPSK	—
PDSCH_16QAM	7.8047	-0.03254	16QAM	600
PDSCH_64QAM	—	—	64QAM	—
Non-alloc	—	—	—	—

D: Ch1 Frame Summary (CC1)

Channel	EVM(%rms)	Power(dB)	Mod.Fmt	Num.RB
P-SS	8.1829	-0.07482	Z-Chu	6
S-SS	6.5979	-0.06196	BPSK	6
PBCH	7.6175	0.00879	QPSK	6
PCFICH	4.1538	0.31881	QPSK	12
PHICH	2.3762	-3.1734	BPSK (CDM)	18
PDCCH	4.9062	0.35204	QPSK	27
RS	7.4986	-0.02077	QPSK	600
PDSCH_QPSK	7.8154	-0.05261	QPSK	600
PDSCH_16QAM	—	—	16QAM	—
PDSCH_64QAM	—	—	64QAM	—
Non-alloc	—	—	—	—

EVM of PDSCH 16-QAM is 7.80% in CC0 and EVM of PDSCH QPSK is 7.82% in CC1.
All EVM values of P-SS, S-SS and RS are about **7%**

Agenda

1. Introduction and Problem Statement
2. Digital Pre-Distortion (DPD) Concepts
3. DPD verification with Agilent Hardware
4. DPD simulation with Agilent EDA Tools
5. Crest Factor Reduction (CFR)
6. Summary

Summary

Problem statement

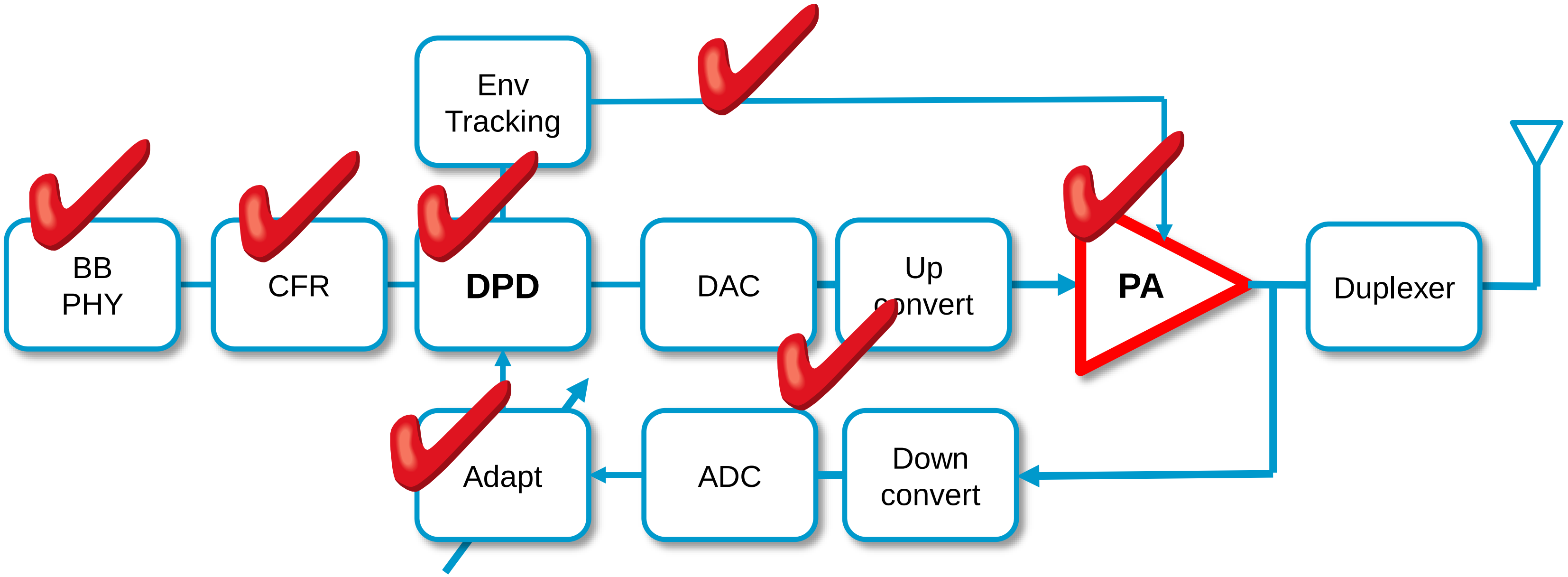
Modern communication systems try to meet conflicting requirements:

- Signals with high PAPR, that then require inefficient back-off
- RF PAs with high PAE, that then cause time & freq distortions

Solution approaches

- Digital Pre-Distortion (DPD) and Crest Factor Reduction (CFR) algorithms together help overcome conflicting requirements.
- SystemVue offers a practical DPD modeling flow
    - Connects to/from open, enterprise modeling & EDA tools
    - Control your own IP, or leverage Agilent's IP to model any HW or Algorithms you don't have access to
    - Re-use commonly available test equipment
    - Create virtual systems using simulators, test equip, scripting, UI

Generalized Wireless Transmitter Path



- Model any blocks not included with your final product, and get on with your project
- Imitate/Model key missing pieces of IP and hardware, and maintain control
- Verify against realistic system specifications, which may be controlled externally

Questions & Answers

?

“LTE-Advanced DPD using Agilent SystemVue”

THANK YOU

W1716 Digital Pre-Distortion

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