Practical Digital Pre-Distortion Techniques for PA Linearization in 3GPP LTE

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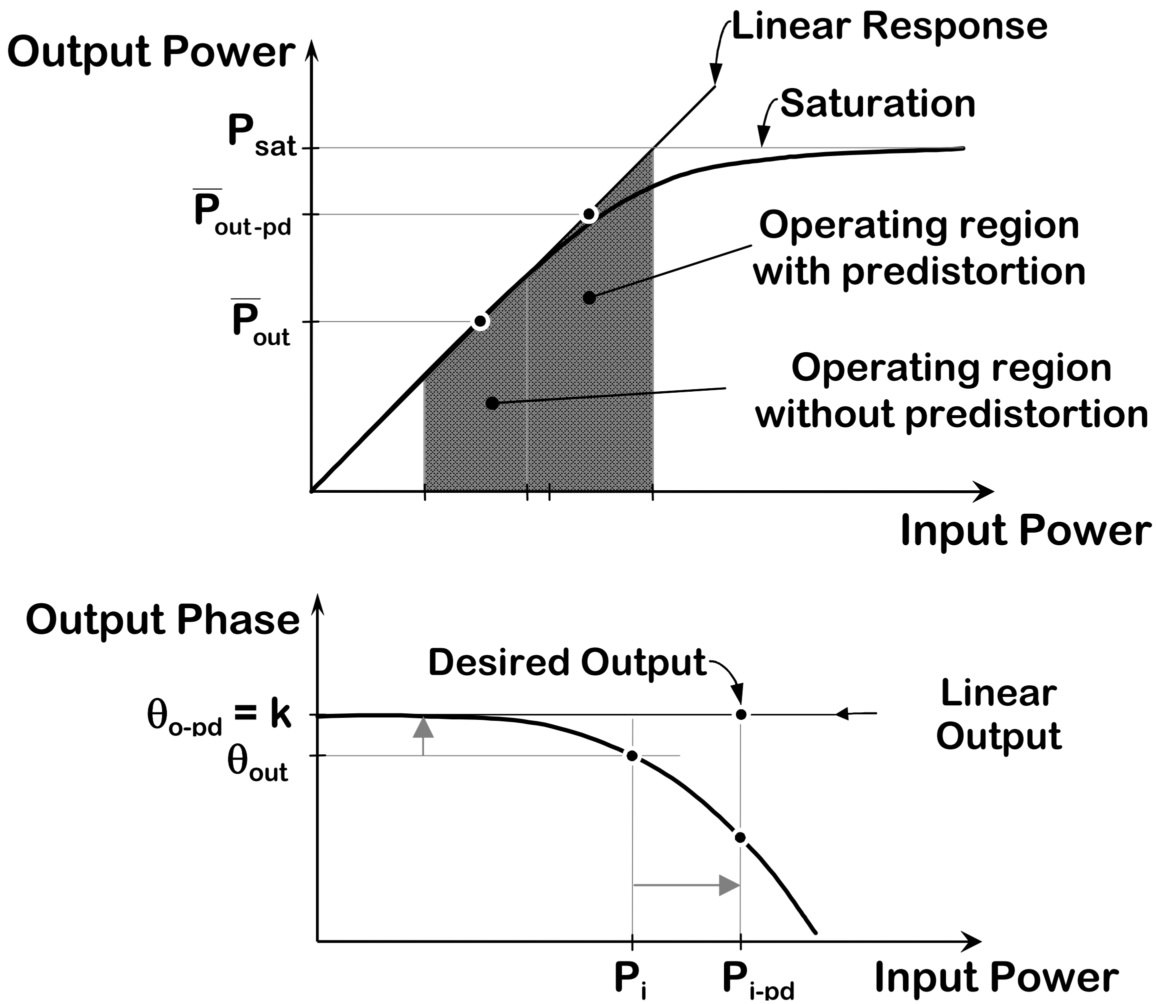
Agenda

- Digital PreDistortion----Principle
- Crest Factor Reduction
- Digital PreDistortion Simulation
- Digital PreDistortion Hardware Verification

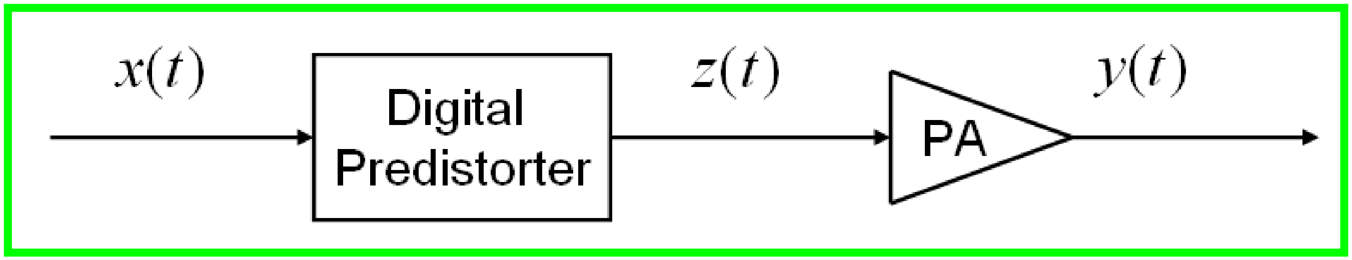
Digital Pre-Distortion----- Principle



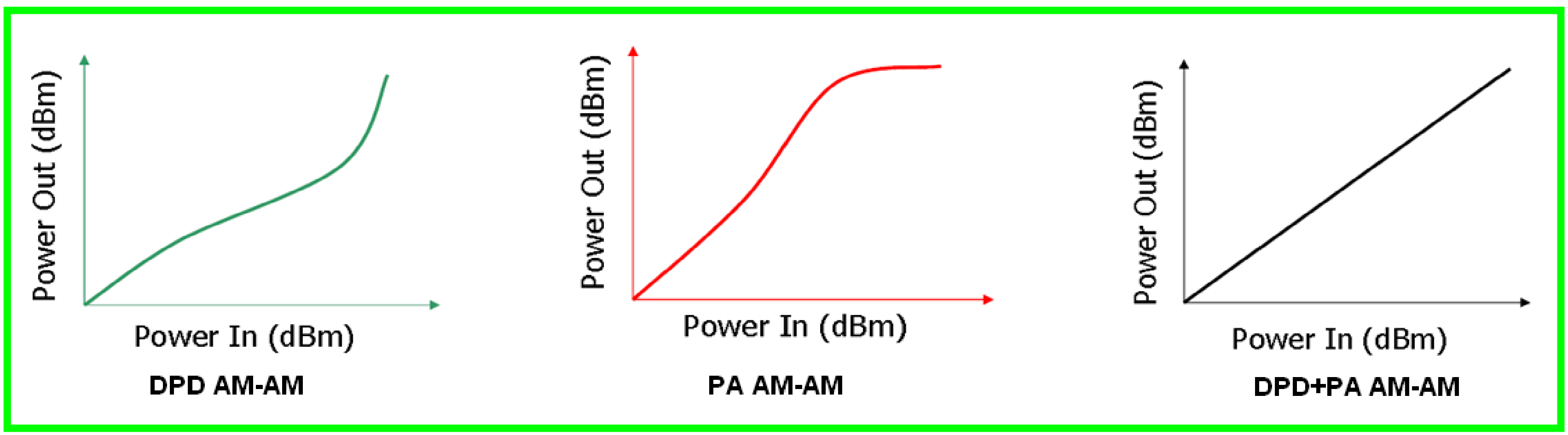
Digital Pre-Distortion----- Principle

The DPD-PA cascade attempts to combine two nonlinear systems into one linear result which allows the PA to operate closer to saturation.

The objective of digital predistorter is to have $y(t) \approx Cx(t)$, where C is a constant.



The most important step is to extract PA nonlinear behavior accurately and efficiently.



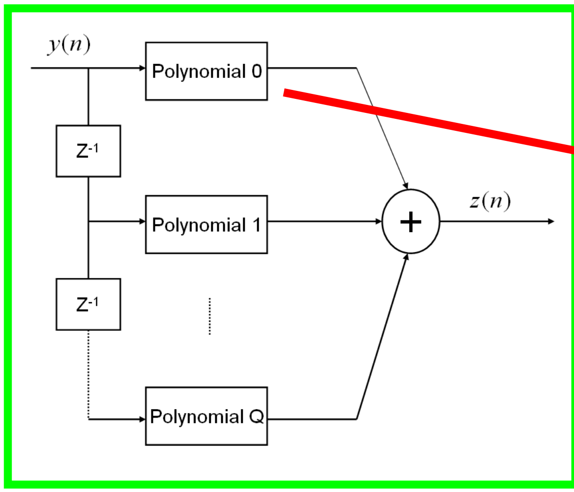
Memory Polynomial Algorithm

- As the signal (such as 3GPP LTE) bandwidth gets wider, power amplifiers begin to exhibit memory effects. Memoryless (LUT) pre-distortion can achieve only very limited linearization performance.
- Volterra series is a general nonlinear model with memory. It is unattractive for practical applications because of its large number of coefficients.
- Memory polynomial reduces Volterra's model complexity. It is interpreted as a special case of a generalized Hammerstein model. Its equation is as follows:

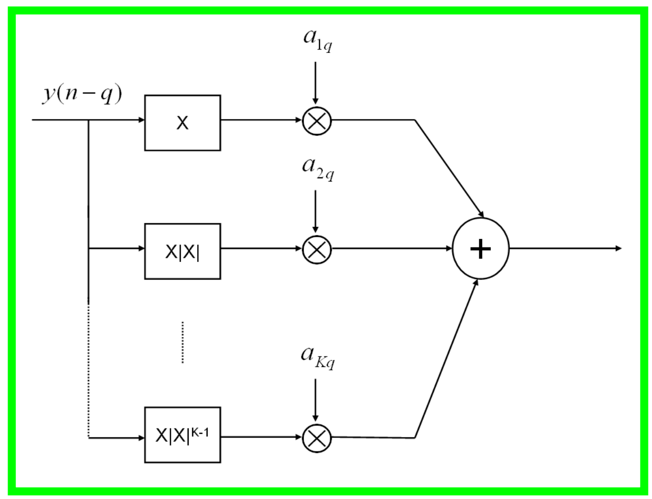
$$z(n) = \sum_{k=1}^{K} \sum_{q=0}^{Q} a_{kq}\, y(n-q) \left| y(n-q) \right|^{k-1}$$

K is Nonlinearity order and *Q* is Memory order

Memory Polynomial Structure

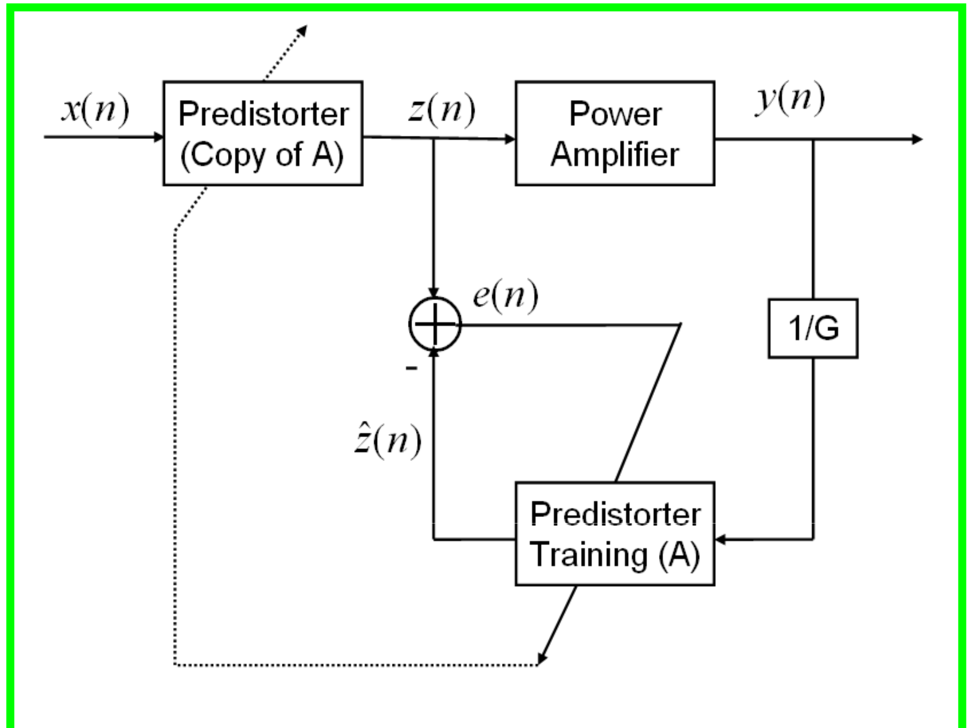


Polynomial Structure



Signal Training to derive the Memory Polynomial

1. Pre-distorter training: Nonlinear coefficients are extracted from the PA input and PA output waveforms (ie – on real physical behavior)
2. Copy of PA : The DPD model accurately captures the nonlinearity with memory effects



Memory Polynomial Coefficients

$$\hat{a} = (U^H U)^{-1} U^H z$$

$$\hat{a} = \left[\hat{a}_{10}, \cdots, \hat{a}_{K0}, \cdots, \hat{a}_{1Q}, \cdots, \hat{a}_{KQ}\right]^T$$

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

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

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

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

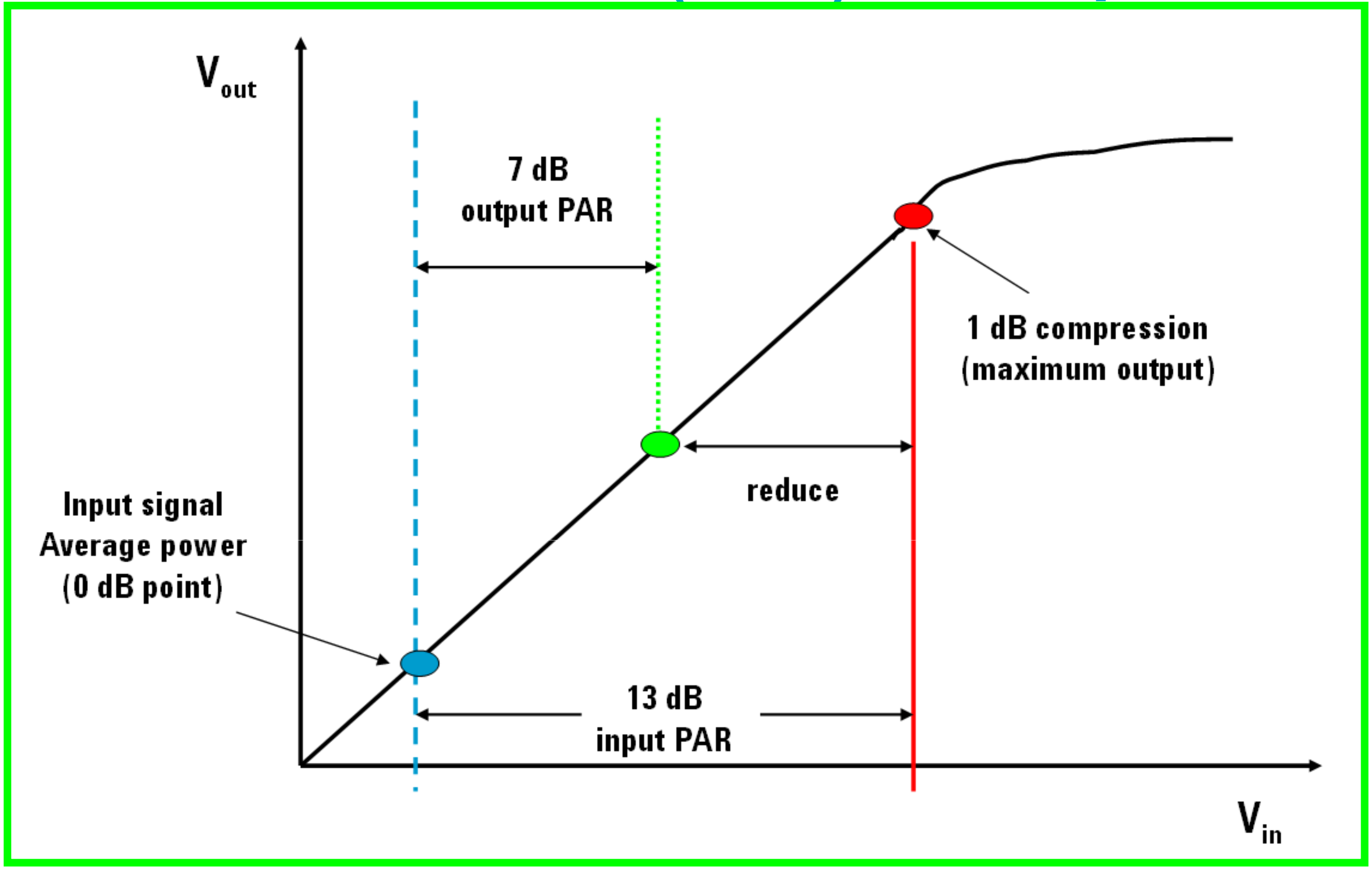
Crest Factor Reduction (CFR) Concepts

- 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 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

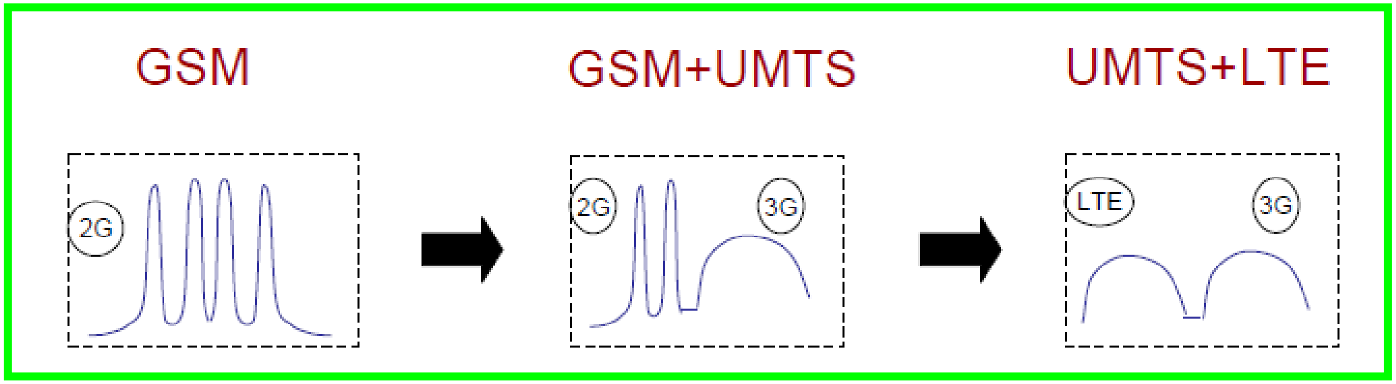


If you can reduce the Peak-to-Average Ratio of the signal, then for a given amplitude Peak, you can raise the Average power (up & to the right, above) with no loss in signal quality.

Thus, CFR enables higher PA efficiency by reducing the back-off, often by 6dB

Crest Factor Reduction for Multiple-Carrier Signals

- Multiple-Carrier Signals (such as GSM, WCDMA, WiMAX) already have high PAPR.
- In the future, they will also include multiple waveforms (ie - LTE with 3G WCDMA).
- Therefore CFR will increase in importance for Multi-Carrier PA (MCPA) linearization.

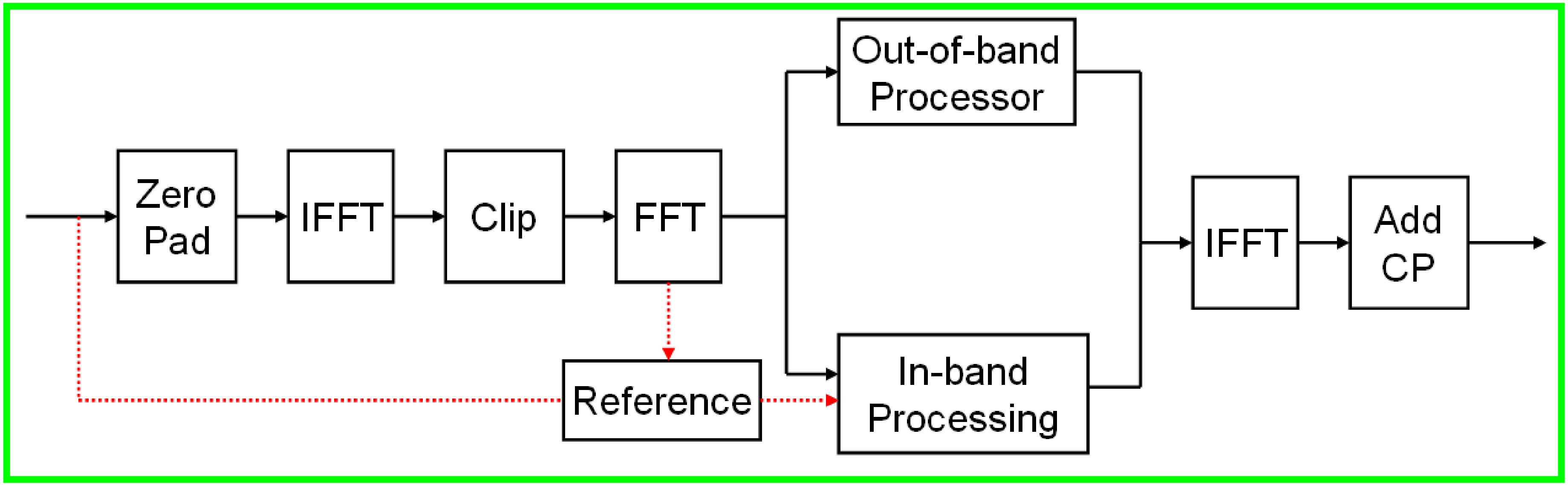


CFR algorithm for multiple carrier signals

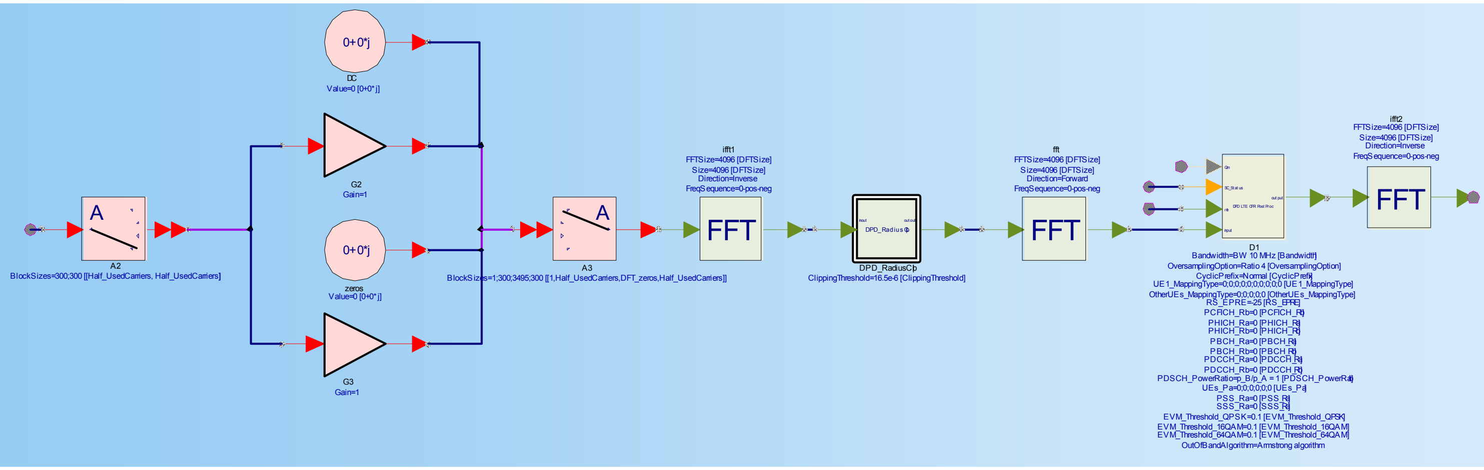
- PW (Peak Windowing)-CFR
- NS (Noise-Shaping) -CFR
- PI (Pulse Injection)-CFR
- PC (Peak Cancellation)-CFR

CFR for 3GPP LTE DL OFDM Signal

- 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.
- All control channels (PDCCH, PBCH, PCFICH and PHICH) adopts QPSK threshold.



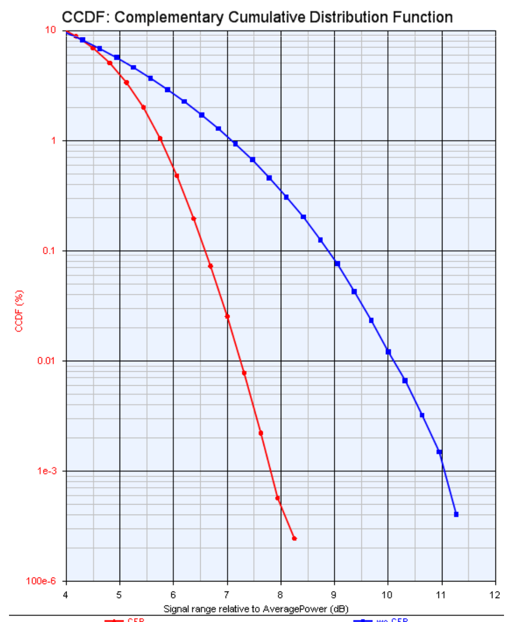
LTE CFR (Crest Factor Reduction)

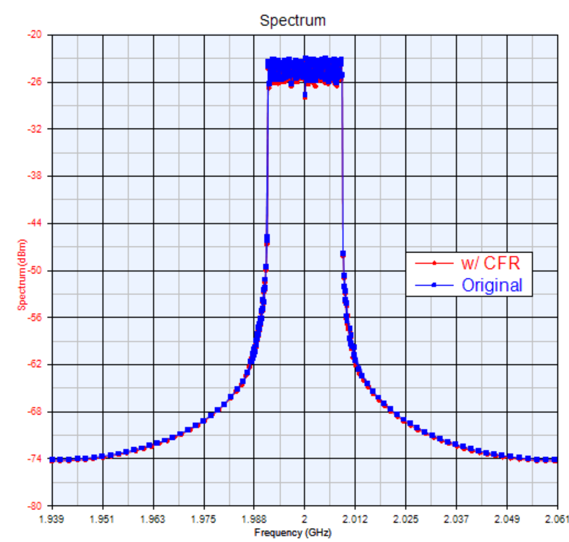


Simulation Results

LTE Downlink 10MHz,
Sampling Rate 61.44MHz,
QPSK,
EVM threshold 10%

Origin_PAPR	CFR_PAPR
9.05	6.685





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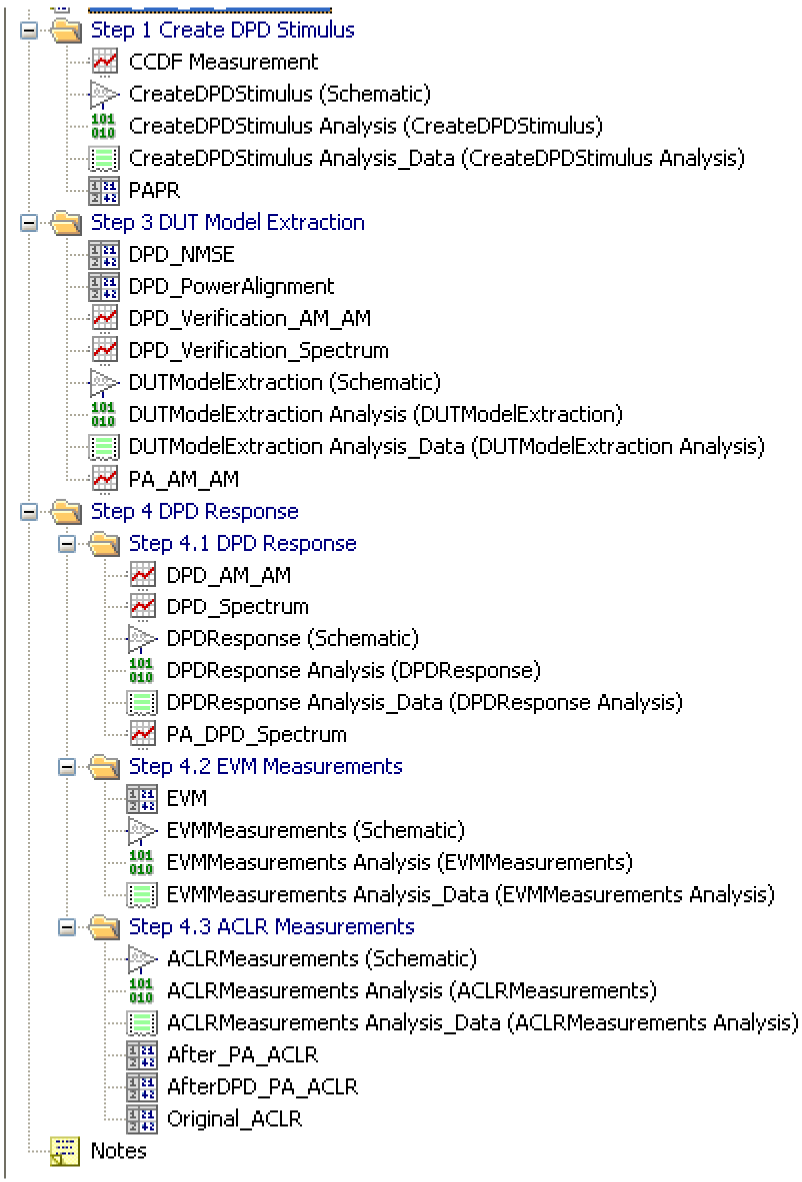
DPD Simulation Workspace



Step 1 is to Generate Waveform for DPD

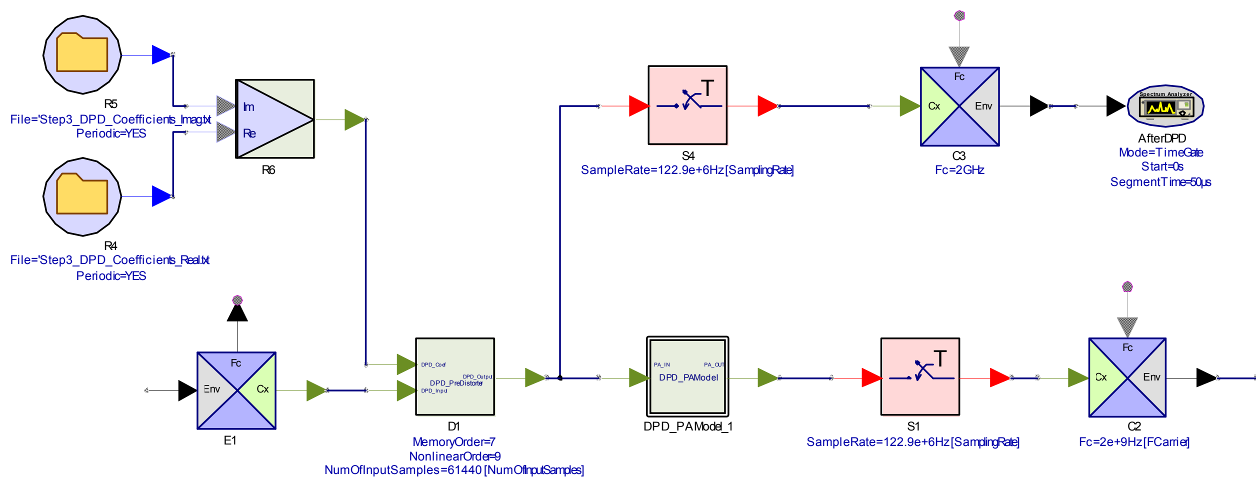
Step 3 is for DUT Model Extraction

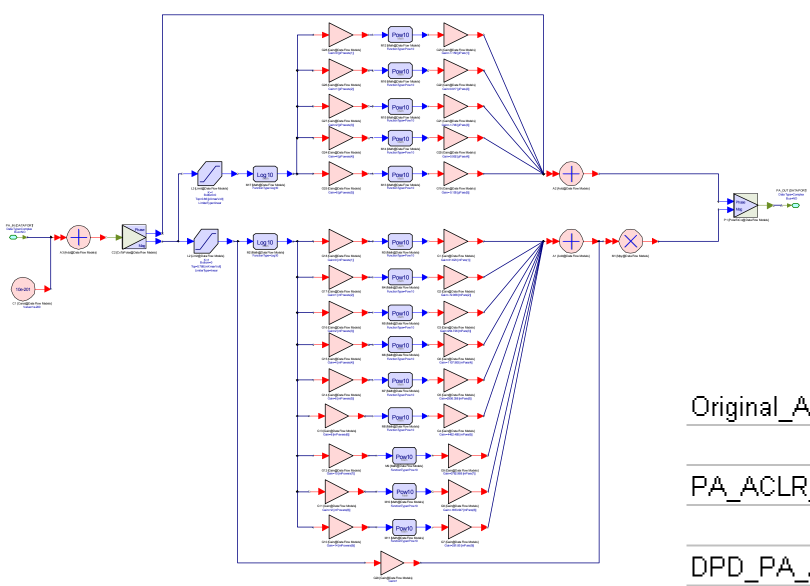
Step 4 is for DPD Response

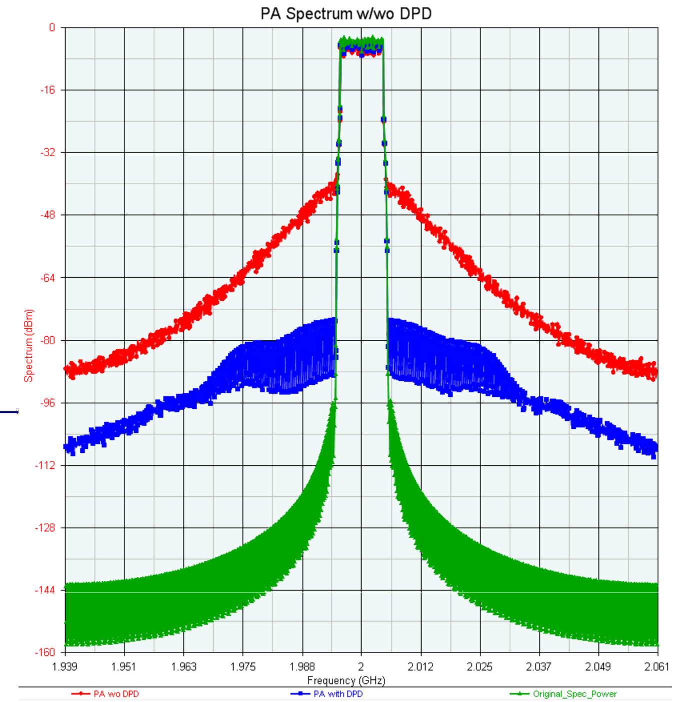
Compared with hardware verification tool, simulation tool does not include Step 2 and Step 5.

Hardware verification toll will be introduced later.

LTE DPD simulation for a memoryless nonlinear PA







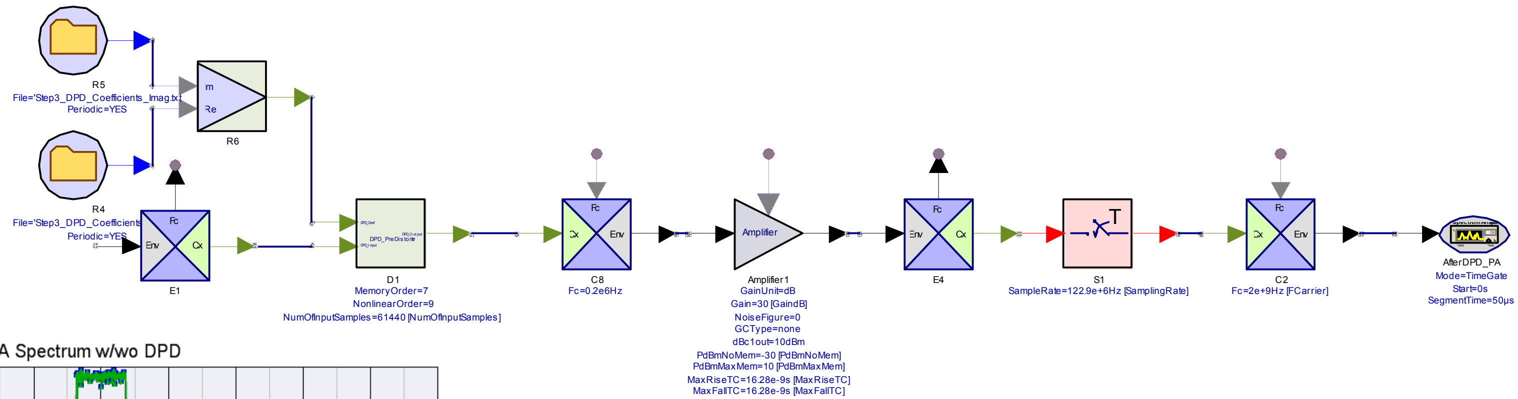
EVM (dB)

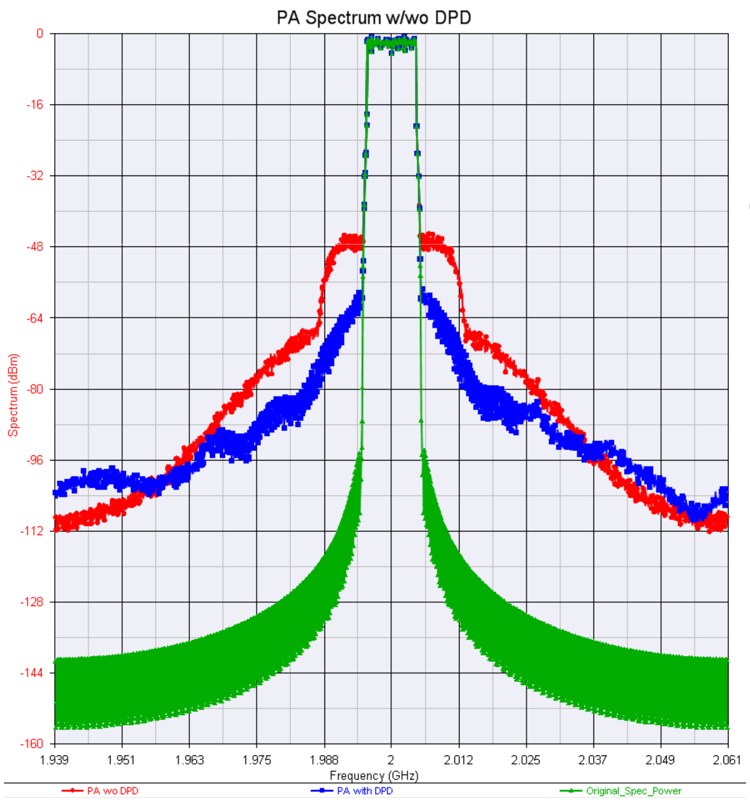
Index	AfterDPD_PA	Original	After_PA
1	-26.802	-26.804	-24.986
2	-26.787	-26.789	-24.974

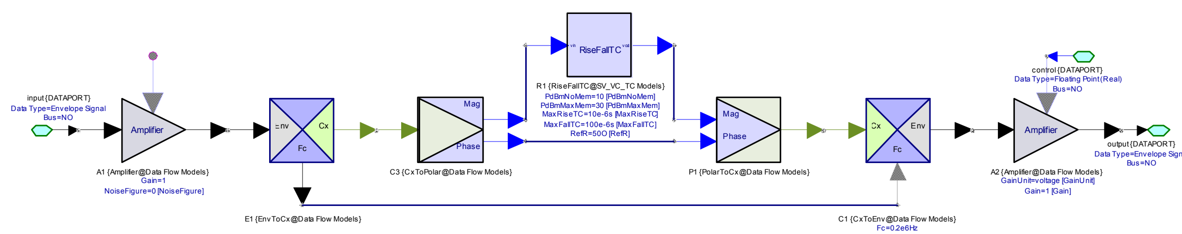
ACLR (dB)

Original_ACLR_L_2BW	Original_ACLR_L_BW	Original_ACLR_U_BW	Original_ACLR_U_2BW
72.036	64.23	63.542	71.869
PA_ACLR_L_2BW	PA_ACLR_L_BW	PA_ACLR_U_BW	PA_ACLR_U_2BW
51.075	38.899	38.963	51.151
DPD_PA_ACLR_L_2BW	DPD_PA_ACLR_L_BW	DPD_PA_ACLR_U_BW	DPD_PA_ACLR_U_2BW
71.651	64.067	63.404	71.497

LTE DPD simulation for a nonlinear PA with memory







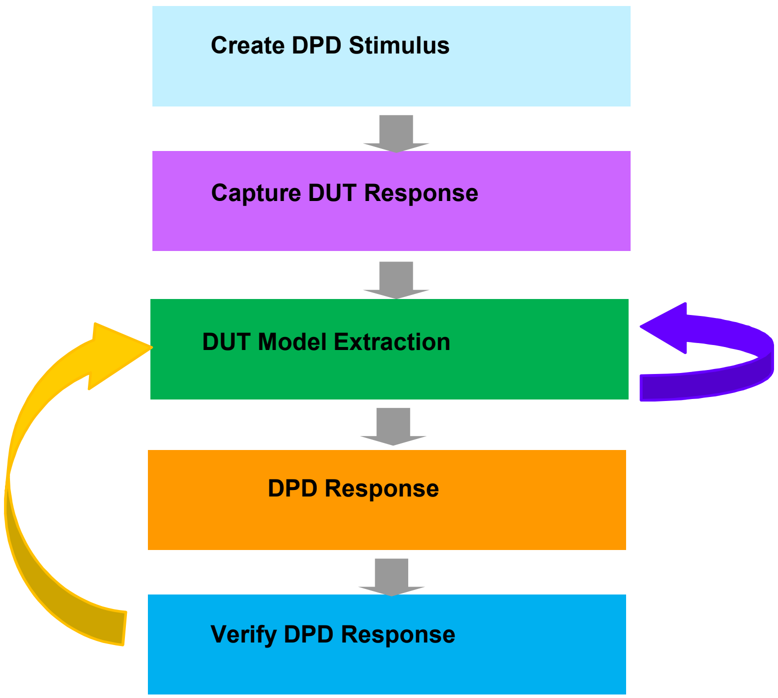
EVM (dB)

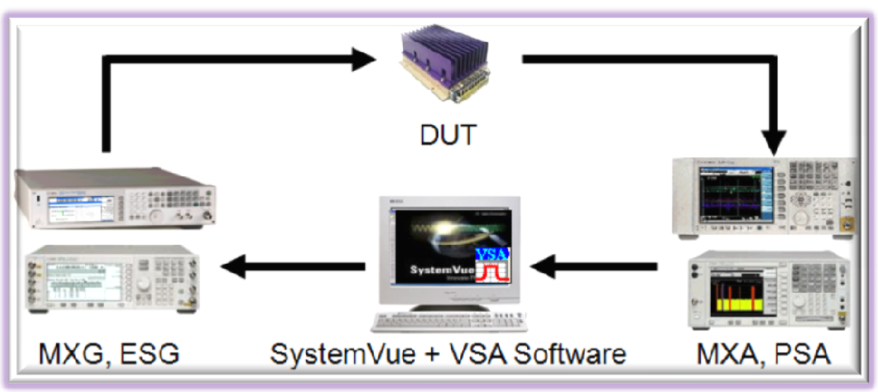
Index	AfterDPD_PA	Original	After_PA
1	-26.792	-26.804	-26.673
2	-26.777	-26.789	-26.659

ACLR (dB)

Original_ACLR_L_2BW	Original_ACLR_L_BW	Original_ACLR_U_BW	Original_ACLR_U_2BW
72.036	64.23	63.542	71.869
PA_ACLR_L_2BW	PA_ACLR_L_BW	PA_ACLR_U_BW	PA_ACLR_U_2BW
67.729	47.099	47.133	67.713
DPD_PA_ACLR_L_2BW	DPD_PA_ACLR_L_BW	DPD_PA_ACLR_U_BW	DPD_PA_ACLR_U_2BW
71.841	61.013	60.504	71.871

DPD Hardware Verification Flowchart





DPD HW Flowchart consists of 5 steps:

- Step 1 (Create DPD Stimulus) is to download waveform (LTE or User defined) into ESG/MXG.
- Step 2 (Capture DUT Response) is to capture both waveforms before power amplifier and after power amplifier from PSA/MXA/PXA by using VSA89600 software.
- Step 3 (DUT Model Extraction) is to extract PA nonlinear coefficients based on both captured PA input and PA output waveforms and then to verify DPD by using PA nonlinear coefficients.
- Step 4 (DPD Response) is to download the waveform (LTE or User Defined) after pre-distorter (by using PA nonlinear coefficient from Step 3) into ESG/MXG, this real signal passes through the PA DUT, capture PA output waveform from PSA/MXA/PXA by using VSA89600 software.
- Step 5 (Verify DPD Response) is to show the performance improvement after DPD.

DPD Hardware Verification Workspace Structure

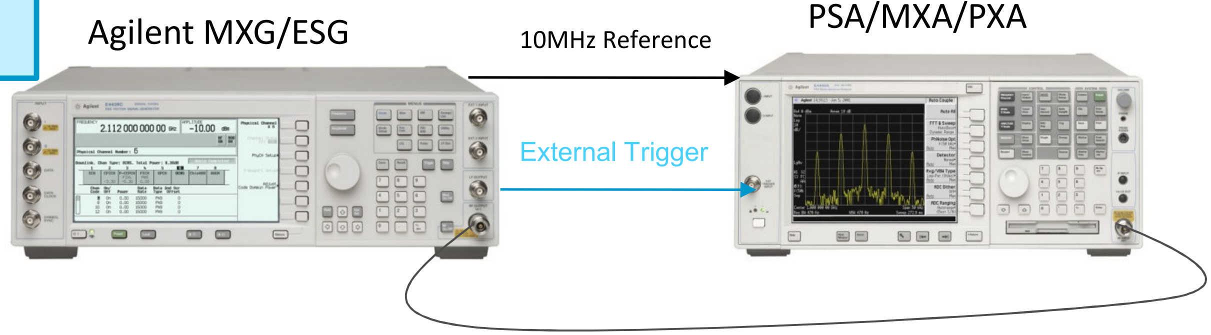
- DPD_LTE_DL
  - Step 1 Create DPD Stimulus
    - CCDF Measurement
    - CreateDPDStimulus (Schematic)
    - CreateDPDStimulus Analysis (CreateDPDStimulus)
    - CreateDPDStimulus Analysis_Data (CreateDPDStimulus Analysis)
    - PAPR
  - Step 2 Capture DUT Response
    - CaptureDUTResponse (Schematic)
    - CaptureDUTResponse Analysis (CaptureDUTResponse)
    - CaptureDUTResponse Analysis_Data (CaptureDUTResponse Analysis)
  - Step 3 DUT Model Extraction
    - DPD_NMSE
    - DPD_PowerAlignment
    - DPD_Verification_AM_AM
    - DPD_Verification_Spectrum
    - DUTModelExtraction (Schematic)
    - DUTModelExtraction Analysis (DUTModelExtraction)
    - DUTModelExtraction Analysis_Data (DUTModelExtraction Analysis)
    - PA_AM_AM
  - Step 4 DPD Response
    - Step 4.1 Power Alignment
    - Step 4.2 Apply DPD
    - Step 4.3 Capture DPD-PA Output Waveform
  - Step 5 Verify DPD Response
    - Step 5.1 Download Waveform (No DPD) to ESG
    - Step 5.2 Capture PA Output Waveform (No DPD)
    - Step 5.3 Spectrum Comparison
    - Step 5.4 EVM Measurements
    - Step 5.5 ACLR Measurements

- Step 4 DPD Response
  - Step 4.1 Power Alignment
    - PowerAlignment (Schematic)
    - PowerAlignment_AM_AM
    - PowerAlignment_Analysis (PowerAlignment)
    - PowerAlignment_Analysis_Data (PowerAlignment_Analysis)
  - Step 4.2 Apply DPD
    - DPD_Spectrum
    - LTE_DL_DPD (Schematic)
    - LTE_DL_DPD_Analysis (LTE_DL_DPD)
    - LTE_DL_DPD_Analysis_Data (LTE_DL_DPD_Analysis)
  - Step 4.3 Capture DPD-PA Output Waveform
    - CaptureDPD-PAOutputData (Schematic)
    - CaptureDPD-PAOutputData Analysis (CaptureDPD-PAOutputData)
    - CaptureDPD-PAOutputData Analysis_Data (CaptureDPD-PAOutputData Analysis)
- Step 5 Verify DPD Response
  - Step 5.1 Download Waveform (No DPD) to ESG
    - LTE_DL_NoDPD_To_ESG (Schematic)
    - LTE_DL_NoDPD_To_ESG_Analysis (LTE_DL_NoDPD_To_ESG)
    - LTE_DL_NoDPD_To_ESG_Analysis_Data (LTE_DL_NoDPD_To_ESG_Analysis)
  - Step 5.2 Capture PA Output Waveform (No DPD)
    - CaptureNoDPD-PAOutputData (Schematic)
    - CaptureNoDPD-PAOutputData Analysis (CaptureNoDPD-PAOutputData)
    - CaptureNoDPD-PAOutputData Analysis_Data (CaptureNoDPD-PAOutputData Analysis)
  - Step 5.3 Spectrum Comparison
    - SpectrumComparison
    - SpectrumPlot (Schematic)
    - SpectrumPlot Analysis (SpectrumPlot)
    - SpectrumPlotComparison (SpectrumPlot Analysis)
  - Step 5.4 EVM Measurements
    - EVM
    - EVMMeasurements (Schematic)
    - EVMMeasurements Analysis (EVMMeasurements)
    - EVMMeasurements Analysis_Data (EVMMeasurements Analysis)
  - Step 5.5 ACLR Measurements
    - ACLRMeasurements (Schematic)
    - ACLRMeasurements Analysis (ACLRMeasurements)
    - ACLRMeasurements Analysis_Data (ACLRMeasurements Analysis)
    - After_PA_ACLR
    - AfterDPD_PA_ACLR
    - Original_ACLR

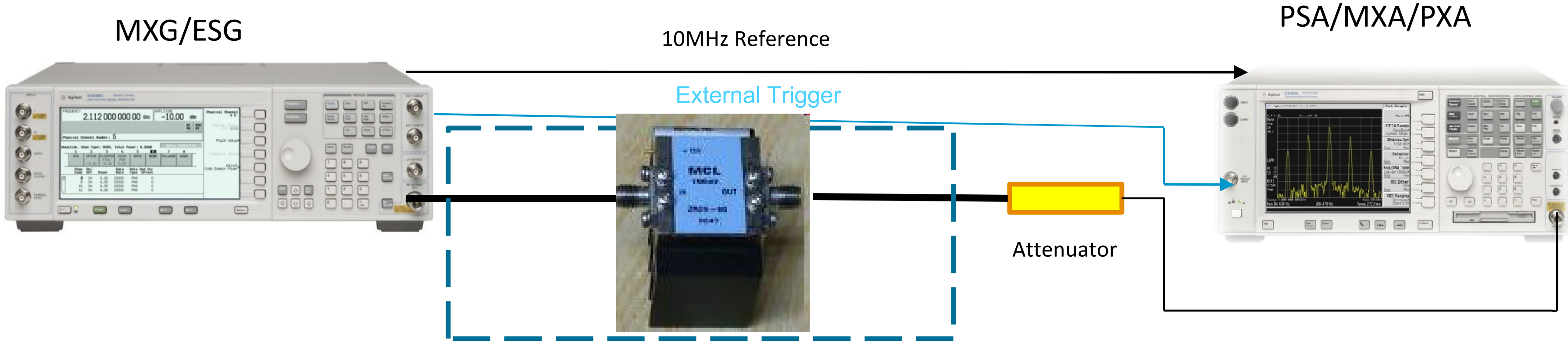
DPD Hardware Verification Platform

1. PA input signal capture

Signal source:
LTE 10MHz

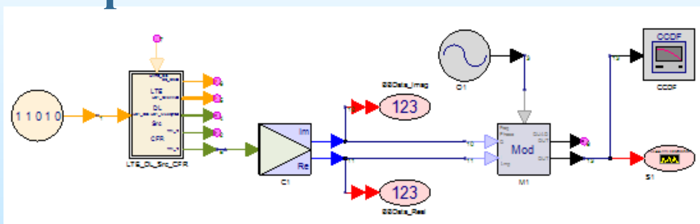


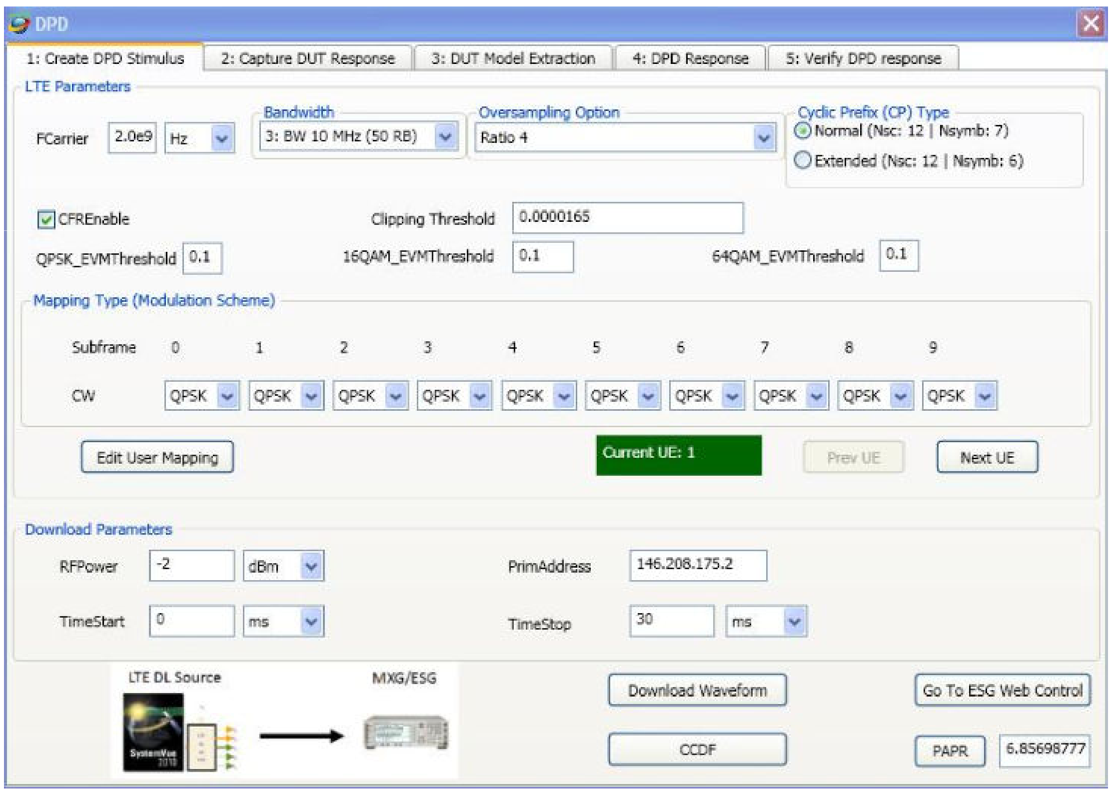
2. PA output signal capture



DPD Hardware Verification – LTE (Step 1)

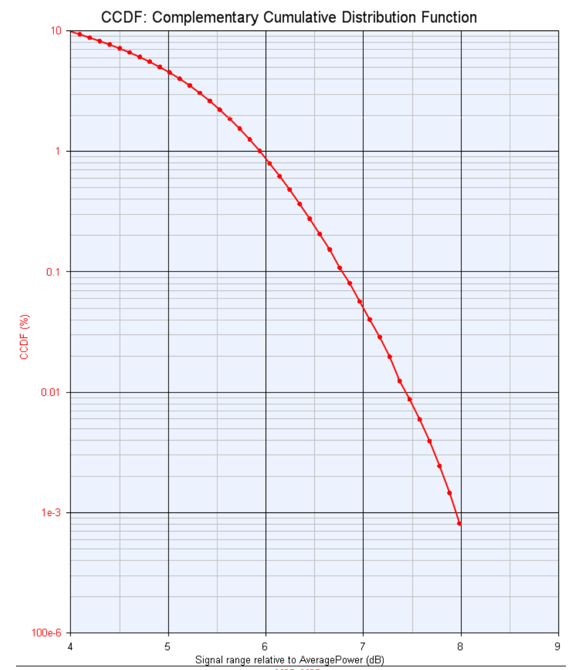
Step 1: Create Stimulus





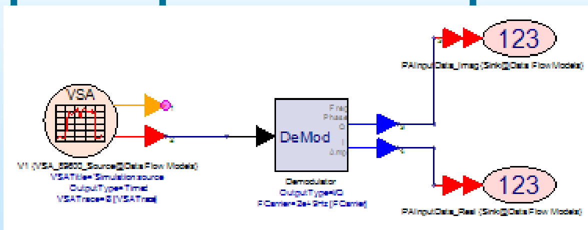
The CFR must be enable in LTE source.
LTE paramters (such as bandwidth, Resource Block allocation and etc) can be set.

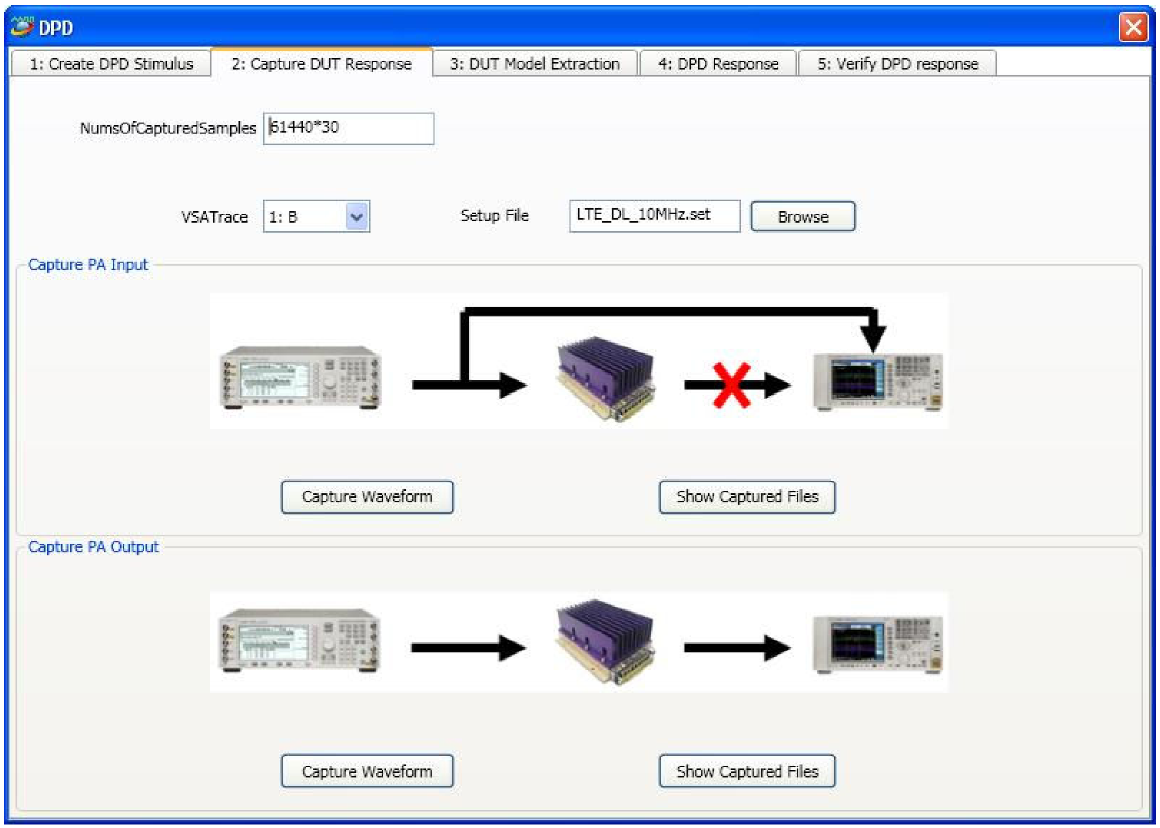
The download waveform transmit power, length also can be set.



DPD Hardware Verification – LTE (Step 2)

Step 2: Capture DUT Response



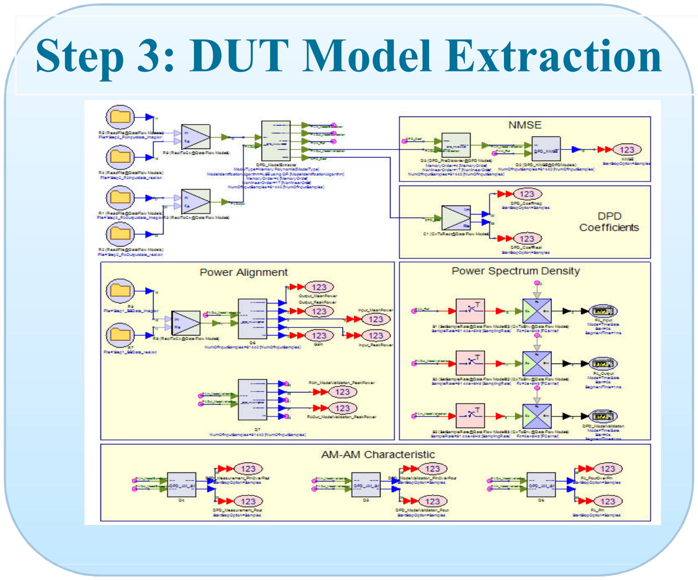


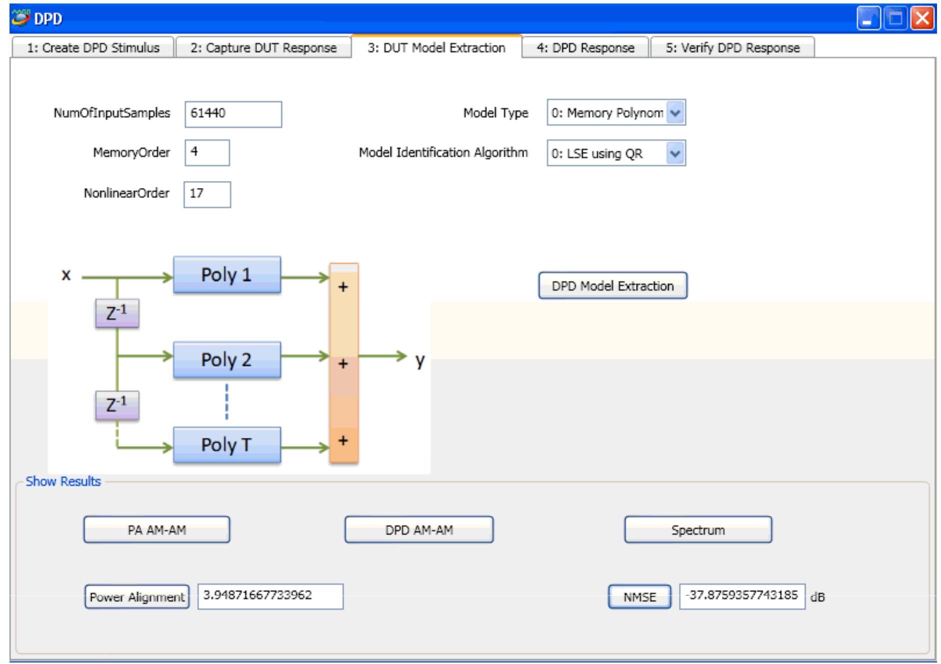
Firstly, connect the ESG directly with the PSA/PXA and click the "Capture Waveform" button in the "Capture PA Input" panel in the GUI. The captured signal is the input of the PA DUT.

Then, connect the ESG with the DUT, and then connect the DUT with the PSA/PXA and click the "Capture Waveform" button in the "Capture PA Output" panel in the GUI. The captured signal is the output of the PA DUT.

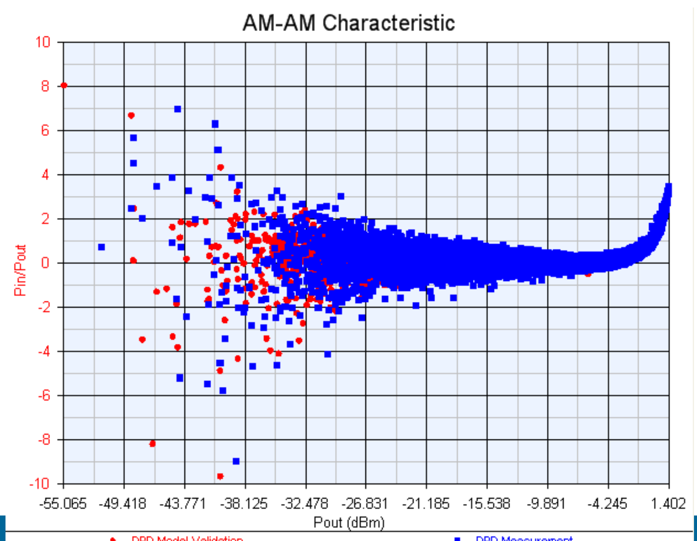
These I/Q files are stored for further usage.

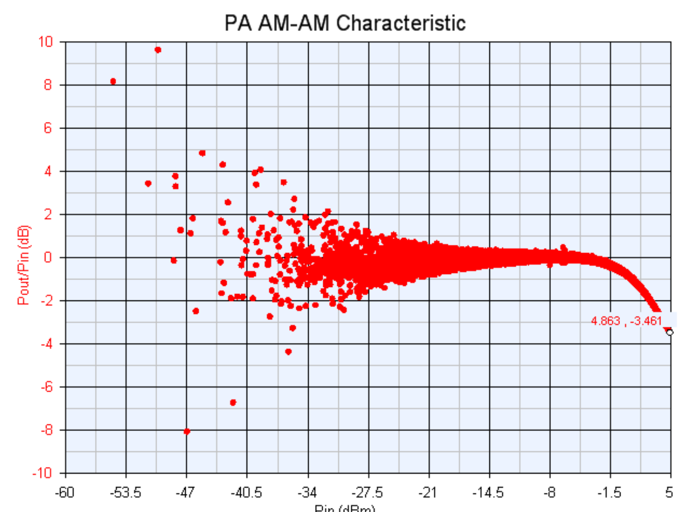
DPD Hardware Verification – LTE (Step 3)





DPD Verification AM-AM





This step is to extract PA nonlinear coefficient from the PA input and PA output waveform and get the coefficients of the DPD model.

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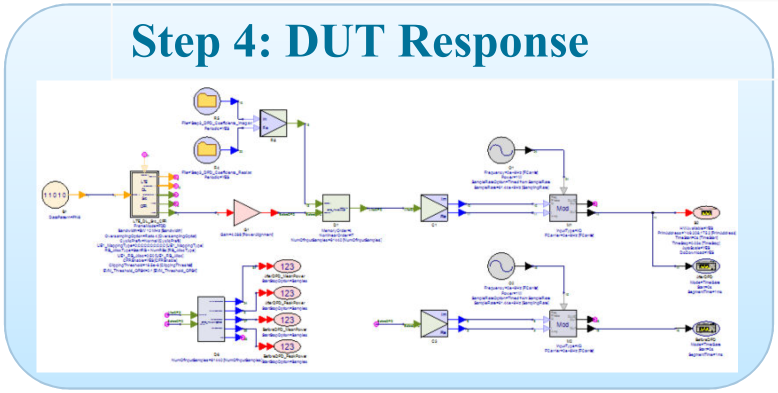
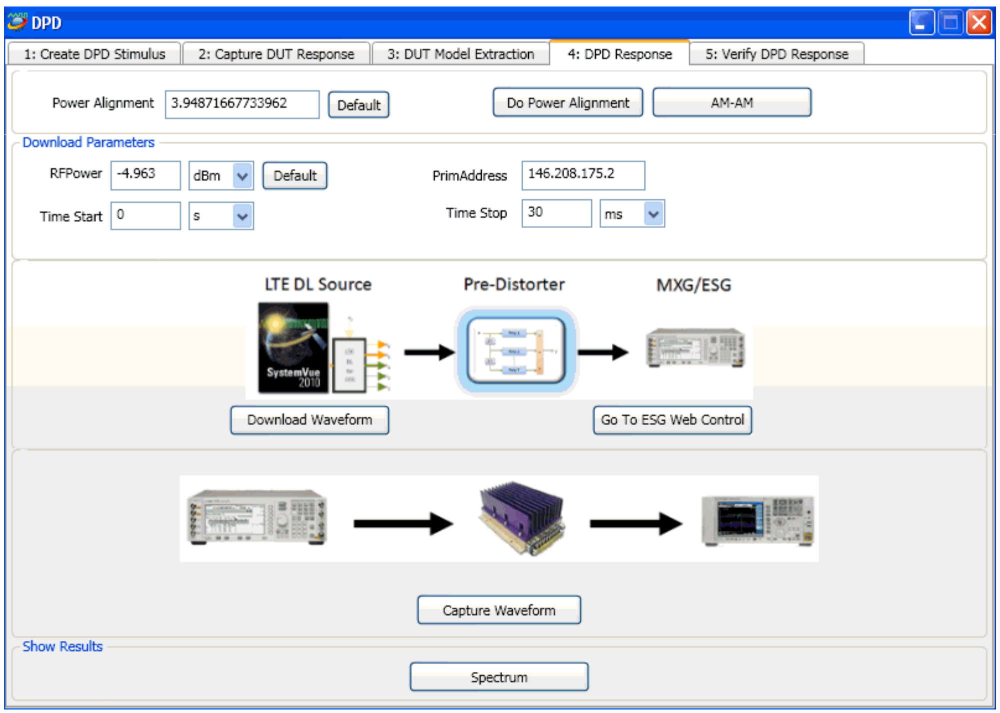
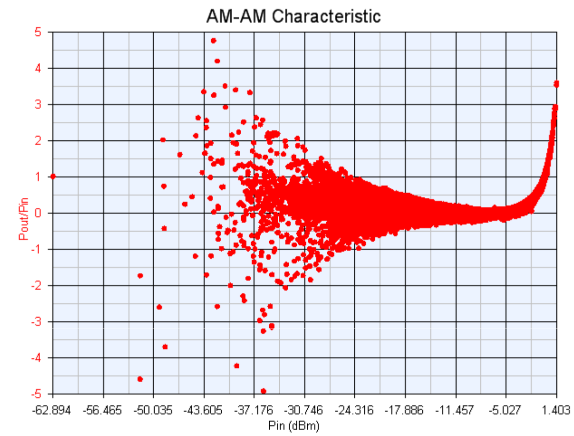
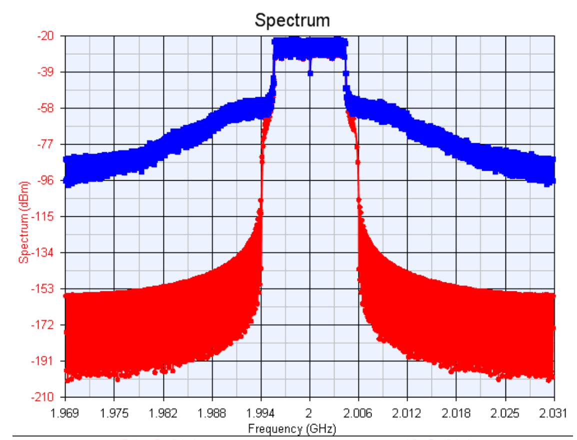
DPD Hardware Verification – LTE (Step 4)



This step is to apply the DPD model extracted in Step 3. The generated LTE downlink signal is firstly pre-distorted by the extracted model, and then downloaded into the ESG.





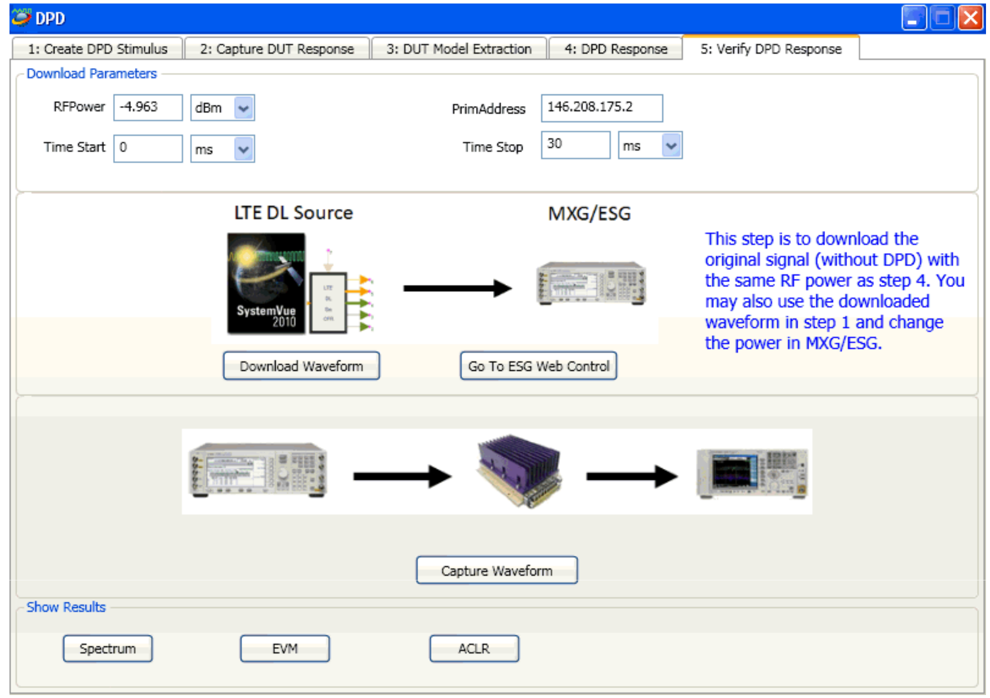


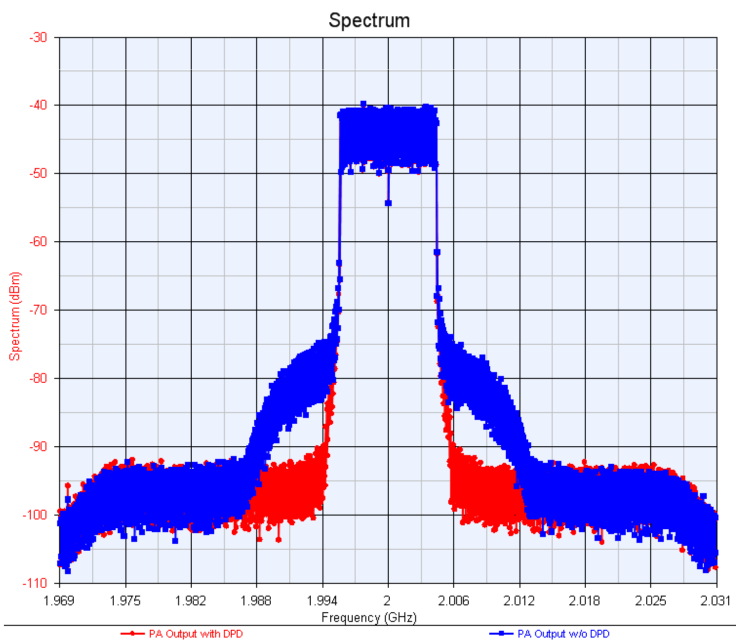
DPD Hardware Verification – LTE (Step 5)

Step 5: Verify DUT Response

Spectrum
EVM
ACLR

This step is to verify the performances of the DPD (including spectrums of the DUT output signal w/ and w/o DPD, EVM and ACLR).





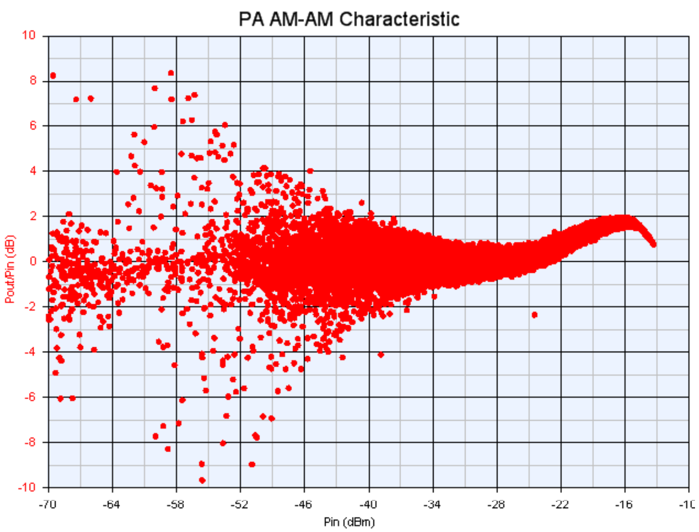
EVM (dB)

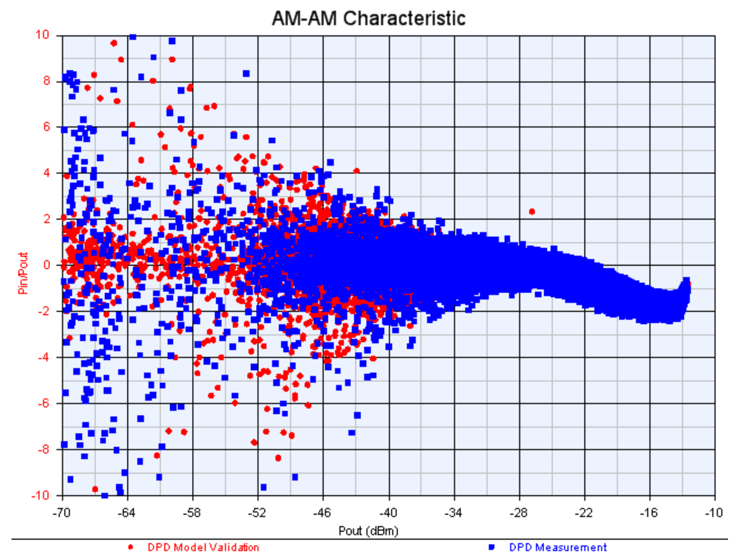
Index	AfterDPD_PA	Original	After_PA
1	-19.443	-19.382	-18.577
2	-18.84	-18.844	-18.071

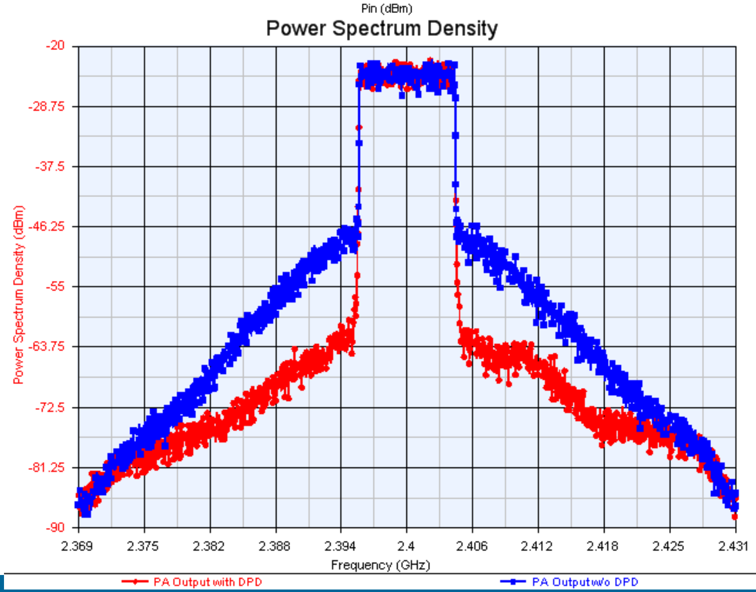
ACLR (dB)

Original_ACLR_L_2BW	Original_ACLR_L_BW	Original_ACLR_U_BW	Original_ACLR_U_2BW
53.179	50.653	51.252	53.363
PA_ACLR_L_2BW	PA_ACLR_L_BW	PA_ACLR_U_BW	PA_ACLR_U_2BW
51.307	38.244	38.361	51.23
DPD_PA_ACLR_L_2BW	DPD_PA_ACLR_L_BW	DPD_PA_ACLR_U_BW	DPD_PA_ACLR_U_2BW
52.437	50.514	50.611	52.825

Hardware Verification Results of Doherty PA







EVM (dB)

Index	AfterDPD_PA	Original	After_PA
1	-19.531	-19.384	-18.625
2	-19.438	-19.392	-18.616

ACLR (dB)

Original_ACLR_L_2BW	Original_ACLR_L_BW	Original_ACLR_U_BW	Original_ACLR_U_2BW
51.614	50.992	50.005	51.821
PA_ACLR_L_2BW	PA_ACLR_L_BW	PA_ACLR_U_BW	PA_ACLR_U_2BW
43.585	27.643	27.422	42.262
DPD_PA_ACLR_L_2BW	DPD_PA_ACLR_L_BW	DPD_PA_ACLR_U_BW	DPD_PA_ACLR_U_2BW
50.147	42.426	42.082	47.779

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.
10. Amplifier Pre-Distortion Linearization and Modeling Using X-Parameters, Agilent EEsof EDA