Wideband Digital Pre-Distortion Modeling for LTE-Advanced

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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?
Solution: Preconditioning the signal (CFR) and correcting for the hardware (DPD) will both be discussed in this presentation.
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 principles – compressing PA

INPUT POWER

OUTPUT POWER

Psat
Pdesired
Pactual

Lineraar Gain

PA, WITH GAIN COMPRESSION

Pin
Pin needed to achieve Pdesired

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Digital Pre-distortion principles – pre-expansion

OUTPUT POWER

DPD GAIN EXPANSION

LINEAR GAIN

Psat

PA, WITH GAIN COMPRESSION

Maximum correctable power

LINEAR REGION

DPD REGION

INPUT POWER

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Digital Pre-distortion principles – linearized result

\[ \text{Linearized result} = \text{DPD gain expansion} + \text{PA, with gain compression} \]

**Graphical Representation:**
- **Output Power** vs. **Input Power**
- **Psat** indicates the maximum correctable power.
- **Linear Region** and **DPD Region**
- **Linearized DPD + PA**
- **Digital Predistorter** and **Power Amplifier (PA)**

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Linear Operation with time-varying envelope

- Linear Gain
- Input Power
- Output Power
- Psat
- Peak-to-Avg Power Ratio (PAPR)

Wideband DPD for LTE-A

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Nonlinear Operation – peaks are compressed

Output Power vs. Input Power graph showing the linear gain and peak-to-average power ratio (PAPR). The figure illustrates how the peaks are compressed at the output power level when the input power exceeds the saturation point ($P_{sat}$). The complementary cumulative distribution function (CCDF) for LTE is also shown, indicating the signal range relative to average power (dB).
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

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

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

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
Generalized Wireless Transmitter Path

1. Which blocks are included with your final product?
2. What IP do you have access to? Or, are able to imitate? Able to modify?
3. What final system specifications do you need to test against?
Agilent Measurement-based DPD Modeling Platform

W1461 SystemVue

W1918 LTE-A IP Library
Also: 3G, WLAN, 60GHz, DVB, OFDM
BB TX PHY
CFR
DPD model
Throughput
BER/FER
ACPR
EVM
BB RX PHY

W1716 DPD Step-by-Step GUI
Generate Coefficients
DAC
Up convert

89600 VSA
Optional Reference RX

Vector Signal Generator
AWG
ESG, MXG, PSG

PA

Up convert
Down convert

W1716 Step-by-Step GUI

Vector Signal Analyzer
MXA, PXA, Modular

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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

MXG
DC Power Analyzer
Adjust current to control switch
MXA / PXA
Power Splitter
THRU
DUT
Switch

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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

- 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**

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

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

Wideband DPD for LTE-A
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Measurement-Based DPD Modeling Simplification: Calculated *PA Input, Measured PA Output*

- **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)

<table>
<thead>
<tr>
<th>ACLR</th>
<th>-2BW Lower</th>
<th>-1BW Lower</th>
<th>+1BW Upper</th>
<th>+2BW Upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw PA output</td>
<td>54.06</td>
<td>35.33</td>
<td>35.68</td>
<td>53.58</td>
</tr>
<tr>
<td>DPD+PA w/ BB input</td>
<td>55.05</td>
<td>50.15</td>
<td>52.28</td>
<td>54.59</td>
</tr>
<tr>
<td>DPD+PA w/ PA input</td>
<td>55.80</td>
<td>51.23</td>
<td>54.32</td>
<td>55.41</td>
</tr>
</tbody>
</table>

6-Carrier GSM

Measured RF input

RESULTS

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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

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

**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.

PA AM-to-AM Characteristic

DPD AM-to-AM Characteristic

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Step 4. Capture DPD+PA Response

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

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

Custom DPD Model Extraction (.m math language)

Custom Digital Pre-distorter (.m math language)
DPD of LTE-Advanced DL with Doherty PA (50W)
Spectrum, ACLR and EVM results (5 MHz DL System)

**ACLR (dB)**

<table>
<thead>
<tr>
<th>ACLR</th>
<th>-2BW Lower</th>
<th>-1BW Lower</th>
<th>+1BW Upper</th>
<th>+2BW Upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF input (HW)</td>
<td>61.75</td>
<td>53.01</td>
<td>53.52</td>
<td>62.33</td>
</tr>
<tr>
<td>Raw PA output</td>
<td>50.25</td>
<td>31.98</td>
<td>31.56</td>
<td>48.19</td>
</tr>
<tr>
<td>DPD+PA output</td>
<td>57.96</td>
<td>49.00</td>
<td>48.63</td>
<td>58.57</td>
</tr>
</tbody>
</table>

**EVM**

<table>
<thead>
<tr>
<th></th>
<th>EVM (dB)</th>
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</thead>
<tbody>
<tr>
<td>Input signal</td>
<td>-23.44</td>
</tr>
<tr>
<td>Raw PA output</td>
<td>-21.33</td>
</tr>
<tr>
<td>DPD+PA output</td>
<td>-23.36</td>
</tr>
</tbody>
</table>

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

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)

<table>
<thead>
<tr>
<th>ACLR</th>
<th>-2BW Lower</th>
<th>-1BW Lower</th>
<th>+1BW Upper</th>
<th>+2BW Upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>BB input (sim)</td>
<td>58.67</td>
<td>49.63</td>
<td>49.17</td>
<td>58.01</td>
</tr>
<tr>
<td>Raw PA output</td>
<td>49.90</td>
<td>28.69</td>
<td>28.35</td>
<td>47.31</td>
</tr>
<tr>
<td>DPD+PA output</td>
<td>48.88</td>
<td>45.10</td>
<td>45.16</td>
<td>48.83</td>
</tr>
</tbody>
</table>

EVM

<table>
<thead>
<tr>
<th></th>
<th>EVM (%)</th>
<th>EVM (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation BB input</td>
<td>5.33</td>
<td>-24.46</td>
</tr>
<tr>
<td>Raw PA output</td>
<td>10.13</td>
<td>-19.89</td>
</tr>
<tr>
<td>DPD+PA output</td>
<td>5.52</td>
<td>-25.16</td>
</tr>
</tbody>
</table>

CFR was applied to this LTE-Advanced DL signal, with a maximum EVM target of 10% for 16-QAM.
DPD of LTE-Advanced DL with LDMOS Doherty PA (200W)
Spectrum, ACLR and EVM results (20MHz DL System)

ACLR (dB)

<table>
<thead>
<tr>
<th>ACLR</th>
<th>-2BW Lower</th>
<th>-1BW Lower</th>
<th>+1BW Upper</th>
<th>+2BW Upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>BB input (sim)</td>
<td>64.73</td>
<td>55.09</td>
<td>57.10</td>
<td>64.92</td>
</tr>
<tr>
<td>Raw PA output</td>
<td>51.01</td>
<td>30.69</td>
<td>30.04</td>
<td>49.50</td>
</tr>
<tr>
<td>DPD+PA output</td>
<td>50.31</td>
<td>45.16</td>
<td>45.56</td>
<td>51.40</td>
</tr>
</tbody>
</table>

EVM

<table>
<thead>
<tr>
<th></th>
<th>EVM (%)</th>
<th>EVM (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BB input signal (sim)</td>
<td>6.10</td>
<td>-24.28</td>
</tr>
<tr>
<td>Raw PA output</td>
<td>8.87</td>
<td>-21.04</td>
</tr>
<tr>
<td>DPD+PA output</td>
<td>6.88</td>
<td>-23.24</td>
</tr>
</tbody>
</table>

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.

Vector Source: MXG
Vector Analyzer: PXA

Anticipate Accelerate Achieve

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"Wideband DPD for LTE-A"
LTE-A Results with 200W LDMOS Doherty PA

Raw PA Output (DL 20MHz System)

EVM = 8.8740 %rms
EVM Pk = 33.241 %
Data EVM = 9.0243 %rms
LTE-A Results with 200W LDMOS Doherty PA

**DPD+PA Output (DL 20MHz System)**

![Graph showing LTE-A results with DPD+PA output.](image)

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVM</td>
<td>6.8805%</td>
</tr>
<tr>
<td>EVM Pk</td>
<td>26.044%</td>
</tr>
<tr>
<td>Data EVM</td>
<td>7.0741%</td>
</tr>
</tbody>
</table>

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

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

### ACLR (dB)

<table>
<thead>
<tr>
<th></th>
<th>-2BW Lower</th>
<th>-1BW Lower</th>
<th>+1BW Upper</th>
<th>+2BW Upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>BB input (sim)</td>
<td>63.11</td>
<td>56.75</td>
<td>56.70</td>
<td>62.72</td>
</tr>
<tr>
<td>Raw PA output</td>
<td>50.58</td>
<td>30.80</td>
<td>30.22</td>
<td>49.06</td>
</tr>
<tr>
<td>DPD+PA output</td>
<td>51.74</td>
<td>45.75</td>
<td>45.73</td>
<td>51.18</td>
</tr>
</tbody>
</table>

### CC0 EVM (QPSK)

<table>
<thead>
<tr>
<th></th>
<th>EVM (%)</th>
<th>EVM (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseband signal (sim)</td>
<td>0.21</td>
<td>-53.43</td>
</tr>
<tr>
<td>Raw PA output</td>
<td>3.03</td>
<td>-30.37</td>
</tr>
<tr>
<td>DPD+PA output</td>
<td>1.93</td>
<td>-34.28</td>
</tr>
</tbody>
</table>

### CC1 EVM (16-QAM)

<table>
<thead>
<tr>
<th></th>
<th>EVM (%)</th>
<th>EVM (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseband signal (sim)</td>
<td>0.20</td>
<td>-54.11</td>
</tr>
<tr>
<td>Raw PA output</td>
<td>3.12</td>
<td>-30.11</td>
</tr>
<tr>
<td>DPD+PA output</td>
<td>1.93</td>
<td>-34.31</td>
</tr>
</tbody>
</table>
Multi-Standard Radio (MSR) into LDMOS Doherty PA (200W)

- 2 Carriers
  - GSM
  - WCDMA
  - LTE
  - EDGE

Raw PA output PA+DPD

Wideband DPD for LTE-A

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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 EEsot 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

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

- M9392A PXI VSA (>140MHz)
- or N9030A PXA (<140 MHz)
- M9330A AWG if > 100 MHz
- N5182 MXG, or E8257D PSG as external modulator
- RF DUT
- Attenuator
- External Trigger
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

W1461 SystemVue

- W1918 LTE-A IP Library
- Also: 3G, WLAN, 60GHz, DVB, OFDM
- BB TX PHY
- CFR
- DPD Step-by-Step GUI
- DPD model
- Generate Coefficients
- DAC
- Up convert
- PA
- ADC
- Down convert
- Optional Reference RX

89600 VSA

Agilent ADS
Agilent GoldenGate
RF circuit-level EDA software

Throughput
BER/FER
ACPR
EVM

<table>
<thead>
<tr>
<th>BB RX PHY</th>
</tr>
</thead>
</table>

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Simulation-based, predictive DPD
SystemVue co-simulation with circuit-level PA in ADS

ADS reads data from SystemVue
ADS sends data to SystemVue

ADS circuit-level PA, needs Circuit Envelope 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
Simulation-based, predictive DPD
SystemVue co-simulation with circuit-level PA in ADS

6-Carrier GSM
Carrier Spacing: 4MHz
Sampling Rate: 256 * 270.8333kHz = 69.3333 MHz

40dB improvement after 2 iterations

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

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

Verify
See linearized result, including DPD

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

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**

- EVM w/o DPD
- EVM with DPD

**ACP vs. Output Power**

- Lower/Upper ACLR w/o DPD
- ACLR with DPD

**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

MDP offers little benefit

Output < 0 dBm

0 < Output < +16.5 dBm

DPD offers significant benefit
Verification of simulation-based DPD
Sweep power, constant DPD coefficients, watch EVM, ACP

**Question:** “Do I need Adaptive DPD?”

**EVM versus Output Power with a fixed set of DPD coefficients**
- **EVM w/o DPD**
- **EVM with DPD**

**ACP versus Output Power with a fixed set of DPD coefficients**
- **Lower/Upper ACLR w/o DPD**
- **Lower/Upper ACLR with DPD**

Different (or fewer) DPD coefficients needed
Useful Range for this set of DPD coefficients
PA may be less correctable
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. $P_{in}$

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)

<table>
<thead>
<tr>
<th>ACPR</th>
<th>Lower</th>
<th>Upper</th>
<th>EVM (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original input</td>
<td>-56.19</td>
<td>-57.20</td>
<td>-47.16</td>
</tr>
<tr>
<td>PA Output (No DPD)</td>
<td>-36.66</td>
<td>-38.43</td>
<td>-29.88</td>
</tr>
<tr>
<td>DPD+PA Iter1</td>
<td>-50.28</td>
<td>-49.95</td>
<td>-42.20</td>
</tr>
<tr>
<td>DPD+PA Iter2</td>
<td>-53.39</td>
<td>-52.18</td>
<td>-44.41</td>
</tr>
</tbody>
</table>

### Volterra Series (24 coefficients)

<table>
<thead>
<tr>
<th>ACPR</th>
<th>Lower</th>
<th>Upper</th>
<th>EVM (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original input</td>
<td>-56.19</td>
<td>-57.20</td>
<td>-47.16</td>
</tr>
<tr>
<td>PA Output (No DPD)</td>
<td>-36.68</td>
<td>-38.45</td>
<td>-29.90</td>
</tr>
<tr>
<td>DPD+PA Iter1</td>
<td>-51.60</td>
<td>-49.79</td>
<td>-42.90</td>
</tr>
<tr>
<td>DPD+PA Iter2</td>
<td>-54.05</td>
<td>-54.29</td>
<td>-46.06</td>
</tr>
<tr>
<td>DPD+PA Iter3</td>
<td>-54.71</td>
<td>-55.26</td>
<td>-46.40</td>
</tr>
</tbody>
</table>
Verification after DPD model extraction

Verifying Memory Order and Nonlinear Order in Memory Polynomial

EVM and ACP are stable when memory order \( \geq 3 \).

Memory effect almost removed when memory order \( \geq 3 \).

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

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

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

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

EVM and ACP are stable when nonlinear order \( \geq 7 \).
Verification after DPD model extraction

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

-39dB

-56dB

Order=3

Order=11

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)

Order=5

ACPR vs Memory Order after DPD
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 base station 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

**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 and channel estimation of DL
CFR of LTE-Advanced 20MHz Downlink
QPSK modulation, CFR algorithm set to Max EVM = 10%

PAPR=9dB w/o CFR
PAPR=6.8dB w/ CFR

Spectrums with and w/o CFR are same!
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

Wideband DPD for LTE-A

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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)

```
Carrier #1 with CFR

Carrier #2 with CFR

... (up to N carriers)

Carrier #N with CFR
```

**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

```
Carrier #1 Filtering

Polar Clipping

Carrier #2 Filtering

... (up to N carriers)

Carrier #N Filtering
```
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.

Parameter
CFREnable=YES
CFR of LTE-Advanced with Carrier Aggregation

Approach 1: 2x20MHz contiguous CA

CC0 PAPR = 7.2 dB
CC1 PAPR = 6.7 dB

2x20MHz 2CC with CFR #1
PAPR ≤ 8.2 dB

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%
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.
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

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%
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
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
• 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
“LTE-Advanced DPD using Agilent SystemVue”

THANK YOU

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