Digital Pre-Distortion Techniques for RF Power Amplifiers

John Wood

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It doesn’t matter what the raw linearity of the PA looks like, the DPD will take care of it!
Outline

• Modern Communication’s Signals and RFPAs
  ▪ Signals, Linearity, and Efficiency

• Some Linearizer Basics
  ▪ What’s nonlinearity?
  ▪ What are memory effects?
  ▪ What does a linearizer do?

• Digital Pre-Distortion  DPD
  ▪ System Architecture
  ▪ Linearization Results
Linearity Requirements

- Wireless Communications Standards place stringent requirements on linearity performance of PAs

- ACLR1 – Adjacent Channel Power Ratio
- ACLR2 – Alternate Channel Power Ratio
- Spectral Emission Mask – an absolute power limit
Crest Factor and Peak-to-Average Power Ratio

- **Crest Factor**

\[ CF = \frac{\text{Peak Magnitude}}{\text{Sqrt( Average Power )}} \]

- **Peak-to-Average Ratio**

\[ \text{PAR} = \text{CF}^2 = \frac{\text{Peak Power}}{\text{Average Power}} \]

- **PAR** usually expressed in dB as

\[ 10\times\log_{10}( \text{PAR} ) \]
Amplifier PAR Effects

- Peaks will be clipped even with ideal amplifier if input exceeds $P_{\text{in, max}}$
- With enough clipping it appears as Gaussian noise to the receiver
- Effects of clipping:
  - In-band distortion
    - Degradation of BER
    - Higher EVM
  - Out of Band Radiation
    - ACI problems
    - ACLR degradation
Measuring PAR

- Finding absolute max of a data signal is difficult!!
- PAR easier to determine if statistically defined.

I and Q parts of signal are Gaussian

Magnitude considered Rayleigh

- Create a probability density function of signal with histogram
Cumulative Complementary Distribution Function

CCDF

- This is a statistical measure for digital signals
CCDF – Statistical Measure of PAR

From histogram of data CCDF can be derived

CCDF shows the probability that a signal will exceed the peak power

0.01% PAR value means that the 99.99% of the signal has a magnitude lower than this PAR value (9dB in this case)
What does this mean for the PA?

- We want to operate the PA at highest efficiency
- This point is at peak output power
- We need to ensure the signal peak is no higher than P-1dB
- For high PAR signals the average efficiency is extremely low

Cripps, RFPA, Ch. 8, p. 225, Figure 8.3
High-Efficiency PA Modes

• Circuit architectures to maximize efficiency
• Harmonically-loaded PAs
  ▪ Class E, F,…
• Load modulation
  ▪ Doherty, LINC
• Bias modulation
  ▪ Drain modulation, Envelope Tracking (ET), EER
• Switching PAs
  ▪ Class D, S,…
• High efficiency generally means very nonlinear
  ⇒ Need for Linearization
Linearity and Efficiency

• A Design Compromise
  • Highest efficiency is the most nonlinear regime of operation

• Figure of Merit
  • Highest efficiency at specified OBO, while still meeting ACLR, spectral mask specifications

Linearizer or Pre-Distorter is essential
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Nonlinearity in a PA

\[ y(t) = f(u(t)) = a_1 u(t) + a_2 u^2(t) + \ldots + a_N u^N(t) = \sum_{n=1}^{N} a_n u^n(t) \]

Apply a single-tone CW RF Signal

\[ u(t) = A_1 \cos(\omega_0 t + \phi) \]

yields

\[ y(t) = a_1 A_1 \cos(\omega_0 t + \phi) + a_2 A_1^2 \cos^2(\omega_0 t + \phi) + \ldots + a_n A_1^2 \cos^2(\omega_0 t + \phi) \]
Trigonometric expansion...

Writing out the response $y(t)$

\[
y(t) = a_1 A_1 \cos(\omega_0 t + \phi_1) \quad \text{Linear gain} \quad + a_3 \frac{3 A_1^3}{4} \cos(\omega_0 t + \phi_1) \quad \text{AM-AM & AM-PM}
\]

\[
+ a_2 \frac{A_1^2}{2} \quad \text{DC Offset, or self-bias}
\]

\[
- a_2 \frac{A_1^2}{2} \cos(2\omega_0 t + 2\phi_1) \quad \text{2nd Harmonic distortion}
\]

\[
+ a_3 \frac{A_1^3}{4} \cos(3\omega_0 t + 3\phi_1) \quad \text{3rd Harmonic distortion}
\]

… etc.
Measures of Distortion

• Harmonic Distortion
  - Clearly the nonlinear polynomial function will give rise to *harmonics* of a single-tone input

• AM-to-AM Conversion
  - Nonlinear changes in the output signal amplitude in response to input amplitude changes

• AM-to-PM Conversion
  - Nonlinear changes in the output signal phase in response to input amplitude changes
Envelope Distortion

- Envelope distortion can be estimated from a Two-Tone Power Series Analysis
- The input signal is
  \[ u_i(t) = u \cos(\omega_1 t) + u \cos(\omega_2 t) \]
  and
  \[ \Delta \omega = |\omega_1 - \omega_2| \ll \omega_1, \omega_2 \]
- The 2-tone signal covers the complete dynamic range of the amplifier
  - The Peak-to-Average Power Ratio is 3 dB
- The amplifier output is a power series expansion
  \[ y = a_1 u_i + a_2 u_i^2 + a_3 u_i^3 + a_4 u_i^4 + a_5 u_i^5 + \ldots \]
Two-tone output voltage

Degree and Order

- Each line is a ‘degree’
  - power of \( v(t) \) in the polynomial expansion

- The ‘order’ of the mixing frequency is the number of components
  - 3\(^{rd}\)-order products are
    - \( 3\omega_1, 3\omega_2 \)
    - \( 2\omega_1\pm\omega_2, 2\omega_2\pm\omega_1 \)

\[
y(t) = a_1 u \left[ \cos(\omega_1 t) + \cos(\omega_2 t) \right] \\
+ a_2 u^2 \left[ \cos(\omega_1 t) + \cos(\omega_2 t) \right]^2 \\
+ a_3 u^3 \left[ \cos(\omega_1 t) + \cos(\omega_2 t) \right]^3 \\
+ a_4 u^4 \left[ \cos(\omega_1 t) + \cos(\omega_2 t) \right]^4 \\
+ a_5 u^5 \left[ \cos(\omega_1 t) + \cos(\omega_2 t) \right]^5 \\
\ldots
\]
Two-tone Intermodulation Products

- Odd-order mixing products are in the signal bandwidth
  - Close to carrier Intermodulation (IM) products

\[ \begin{align*}
3\omega_1 - 2\omega_2 \\
2\omega_1 - \omega_2 \\
\omega_1 \\
2\omega_2 - \omega_1 \\
3\omega_2 - 2\omega_1
\end{align*} \]
Additional Distortion Measures

- In addition to
  - Harmonic Distortion
  - AM/AM and AM/PM conversion

- Intermodulation Distortion
  - Nonlinear mixing between the various frequency components of the signal, $\omega_1$ and $\omega_2$, leading to new frequency components in the signal

- Cross Modulation Distortion
  - Nonlinear mixing between the various frequency components of the signal, $\omega_1$ and $\omega_2$, resulting in products at existing frequency components of the signal
Error Vector Measure

Assume a simple cubic model: \[ v_o = a_1 v_i + a_3 v_i^3 \]

Even though the AM-AM compression is the same, \( a_3 \) is different

S. C. Cripps, Advanced Techniques in RFPA Design, Figs 3.4 & 3.5
Modulated AM-AM & AM-PM

Gain and Phase Deviation dependences on input power, as a function of time captured using a modulated signal, showing the variations in instantaneous values. DUT is a 400 W Doherty amplifier; red = measured, blue = modeled
Memory Effects

- The output at time $t_n$ is dependent not only on the input at time $t_n$, but also on the input at previous times.
- The number of time samples that need to be considered is the memory depth, $M$.
- Practical systems have a finite memory depth: fading memory.
Sources of memory in RF PA

Short Term Memory

- Input Matching Network
- Output Matching Network
- $C_g, C_d, \tau$

Long Term Memory

- Thermal, Traps
- Gate Bias
- Drain Bias

RF Source

Vg

Vd

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RF Source

Vg

Vd
Short Term Memory Effects

• These are memory effects that occur on the timescale of the signal
  ▪ For RF PAs this can mean at the carrier timescale or the envelope timescale

• RF frequency response
  ▪ Band-pass or low-pass nature of the matching networks

• AM-PM
  ▪ Phase changes resulting from large-signal drive

• Transistor
  ▪ Device capacitances
  ▪ Transit times

\[ \{ \text{or more strictly, } \frac{\partial Q(V(t))}{\partial t} \text{ effects} \} \]
Long Term Memory Effects

• Take place on a timescale that is much longer than the signal timescale
• Thermal
  ▪ Thermal time constants in semiconductor devices can range from 10s to 100s of microseconds, to ~ 1 second
• Trapping Mechanisms
  ▪ Time constants from microseconds to seconds
  ▪ More prevalent in III-V semiconductors (HCl in MOS?)
• Bias Circuits
  ▪ RF filters, capacitors, and chokes on bias lines introduce storage times
  ▪ Relationship to VBW
Nonlinear Memory Mechanisms

- Long Term Memory
  - Filters out DC and IM2

- IM2 and IM3
- Input Matching Network
- Output Matching Network
- RF Source
- Gate Bias
- Drain Bias
- $f_1f_2$
A Simple Pre-distorter

- Let the amplifier Gain be described by a polynomial
  \[ v_o(t) = a_1 v_i + a_2 v_i^2 + a_3 v_i^3 + \ldots = F_{NL} (v_i(t)) \]
- Linear gain requires
  \[ v_{oL}(t) = a_1 v_i(t) \]
- If we can find another function, \( G \), and pass the signal through first so that:
  \[ v_o(t) = F(G(v_i(t))) = a_1 v_i(t) \]
- We get Linear Gain
- We do not get more power
- We get sharper saturation
The Pre-distorter Function

The secret is finding the pre-distorter function $G$

- The pre-distorter function is an inverse of the nonlinear contributions from the amplifier

Note increased input signal bandwidth
The Pre-Distorter…

• …increases the peak-to-average power ratio of the signal that is input to the PA
  ▪ Gain expansion characteristic of the PD

• …increases the bandwidth of the signal that is input to the PA
  ▪ Distortion components are added to the signal to cancel out the distortion of the PA
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• Digital Pre-Distortion DPD
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Digital Pre-distortion in BTS Transmitter

- Signal is sampled at PA output
- Down-converted to IF or zero-IF
- Digitization using fast ADC
- ‘Predistorter’ converts to I & Q, compares with input I & Q signals, and generates output signal which is converted to analog signal, and up-converted to RF
- Signal pre-conditioning in the digital domain
Typical Digital Pre-Distortion System

- Baseband I & Q signals are combined – can be several carriers
- Crest Factor Reduction to limit Peak-to-Average Power Ratio
- Pre-distortion Function
- DSP also accomplishes time alignment, update of DPD parameters
- Fast ADC/DAC, high dynamic range (16 bit, >200 MSPS typical)
- RF up/down-conversion
Digital Up-Converter

• The purpose of the DUC is to take the sampled data signals and up-convert to the sample rate of the digital signal processing system

• In the digital domain, the up-conversion is performed by re-sampling or interpolation:
  ▪ The digital signal is padded with zeros to reach the correct sample rate
  ▪ The signal is then interpolated between the zeros
  ▪ A digital filter is applied to retrieve the correct frequency and phase response

• Example:
  ▪ WCDMA native sampling rate is 3.84 Msps
  ▪ If the digital IF (DSP clock rate) is 61.44 MHz
  ▪ WCDMA signal needs to be oversampled by 16X
Crest Factor Reduction

Essential for DPD Applications

- The gain expansion characteristic of the pre-distorter means that the signal input to the PA is of high peak-to-average power ratio.
- CFR can reduce this PAPR to manageable levels, and can avoid the PA operating in saturation.
CFR Principle

- The signal peaks above a threshold level are detected
- The magnitude of the peak is reduced to below some target value
- Filtering is required to re-shape the signal spectrum
Resampling prior to DPD

- The bandwidth of the signal after DPD (b) is much wider than the original input signal (a).
- To reconstruct this DPD signal in the analog domain, it must be sampled at a higher rate than the input.
- Under-sampling will lead to aliasing (c).
- This cannot be removed by over-sampling at the output of the DPD.
- Over-sample at DPD input.

Figure from Zhu et al, IEEE Trans MTT 56(7) pp1524-34 (2008)
DPD Linearizer Action

Pre-distorter (PD)
- takes the input signal
- Compares with feedback signal sampled at output of PA
- Adjusts the PD function to minimize the difference
  - Gain, phase parameters of AM-AM and AM-PM
  - Coefficients in polynomial series function
- Memory effects require comparison over several time samples
Memory Polynomial Pre-Distorter

Regular polynomial, with added dimensions for delays

\[
V_a[n] = \sum_{q=0}^{Q} \sum_{p=1}^{P} \alpha_{qp} V_{in}[n-q]|V_{in}[n-q]|^{p-1}
\]
Linearizer Myths & Misunderstandings

Linearizers

- **do not** increase the output power available
- **do not** increase gain
- **do not** improve the noise floor
- have a harder saturation characteristic
  - In saturation this can create more distortion & noise
- work best at low signal levels
- do not necessarily accommodate memory effects
- have a finite linearizing bandwidth
- consume additional power, reducing system efficiency
Two Carrier GSM Performance

Before DPD

- Standard: NONE
- Tx Channels:
  - Ch1 (Ref) 43.49 dBm
  - Ch2 43.48 dBm
  - Total 46.50 dBm
- Adjacent Channel
  - Lower -40.71 dB
  - Upper -41.46 dB
- Alternate Channel
  - Lower -60.28 dB
  - Upper -71.00 dB
- 2nd Alternate Channel
  - Lower -63.49 dB
  - Upper -65.39 dB
- SWP 20 of 20

After DPD

- Standard: NONE
- Tx Channels:
  - Ch1 (Ref) 43.91 dBm
  - Ch2 43.96 dBm
  - Total 46.95 dBm
- Adjacent Channel
  - Lower -70.11 dB
  - Upper -70.65 dB
- Alternate Channel
  - Lower -73.40 dB
  - Upper -74.78 dB
- 2nd Alternate Channel
  - Lower -74.55 dB
  - Upper -77.04 dB

- DPD Results are achieved using TI GC5322 Evaluation Module
- Intermodulation products are below -70dBc up to 46.9dBm of output power
- 42% final stage efficiency and 36% two-stage power added efficiency
240 W Doherty PA
2C-GSM Signal at 1800 MHz

RF PA before DPD

Center 1.84244 GHz
Span 15.2 MHz

Standard: NONE

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RF PA after DPD

240 W Doherty PA
2C-GSM Signal at 1800 MHz

Class 1 linearization at $P_{out} = 47$ dBm average
RF PA before DPD

~500 W Doherty PA
4C-GSM Signal at 940 MHz

\[ P_{out} = 100 \text{ W average} \]
RF PA after DPD

~500 W Doherty PA
4C-GSM Signal at 940 MHz

Class 2 linearization at $P_{out} = 50$ dBm average
DPD of 500 W Doherty PA under Drive-up

940 MHz, 4C-GSM

Class 2 spec.
Backup
GSM/EDGE has stringent requirements