Digital Pre-Distortion

Derek Kozel
What is Digital Pre-Distortion (DPD)

- A technique for improving the linearity of power amplifiers
- Ideally the output signal of a PA is the input scaled up perfectly
- Instead the semiconductor physics causes distortions
  - Amplitude, frequency, and phase errors
- If we can predict the errors, we can try to reverse them
High Level Flow

DPD Compensates for PA Distortion (Nonlinear Pre-Equalizer)

PA Bias Reduced, Cooler, and More Efficient

PA Soft Compresses

Intermod Distortion

Why use DPD?

- Want to get as much power out of an amplifier as possible
  - Start getting close to limits of the device
  - Output power starts compressing
    - 1 dB increase in input -> < 1 dB increase in output
  - Output signal now a distorted version of the input!
- PA efficiency best when driven near saturation

www.electronicdesign.com/
Background Transistor Theory
Ideal Field Effect Transistor

- Voltage controlled current source
- Three terminals (connections)
  - Gate: “control port”
  - Drain and Source: variable resistor
- Changing the voltage across these terminals changes the resistance between Drain and Source and thus the current flowing

bradysalz.com/technical/the-mosfet/
FET as an amplifier

- Usually the Gate to Source voltage is the input
- Voltage at the Drain is the output
IV Curve and Load-Line

- Shows how much does current change for a given change in Gate to Source voltage
- Load line shows the path the amplifier ideally operates on
- Looks mostly linear, but rounds off at the extremes of the load line
Distortion
Ideal Transfer Function

- Ideally an amplifier’s output voltage (across some load impedance) is:

\[ v_o(t) = a v_i(t) \]

- Where \( a \) is the voltage gain of the amplifier
Two Tone Test Setup
Non-Linear Transfer Function

- What the output actually looks like can be modelled using a Volterra series polynomial

\[ v_o(t) = a_1 v_i(t) + a_2 v_i(t)^2 + a_3 v_i(t)^3 + \ldots \]

- We see the linear gain, \( a_1 \), and additional terms for higher order distortion
- This is only a *behavioral* model, it does not try to simulate the circuit
- Output only depends on current input value
Second Order Distortion

- The polynomial has terms for both odd and even degree terms
- Let's look at what happens when a tone is squared

\[
\sin(\omega t)^2 = \frac{1}{2} \left( \cos(2\omega t) + 1 \right)
\]

- The result is a tone at twice the original frequency!
Third Order Distortion

- Now what about cubed?

\[
\sin(\omega t)^3 = \frac{1}{4} (3 \cos(\omega t) + \cos(3\omega t))
\]

- The output has energy at both the original frequency and third harmonic!
- Interesting takeaway:
  - Even order distortion does not cause tones near the fundamental
  - Odd order distortion does
Simplified Volterra Series

- Let us assume that we only care about distortion resulting in signals near our fundamental
  - Only include odd power terms

\[ v_o(t) = a_1 v_i(t) + a_3 v_i(t)^3 + a_5 v_i(t)^5 + \ldots \]

- For completeness, here’s the 5th order expansion
  - Note that there is energy at the first, third, and fifth harmonics!

\[ \sin(\omega t)^5 = \frac{1}{16} (10 \cos(\omega t) + 5 \cos(3\omega t) + \cos(5x)) \]
Two Tone Distortion

- Input signal:
  \[ v_i(t) = v \cos(\omega_1 t) + v \cos(\omega_2 t) \]

- Results in In-Band distortion
  - Third order distortion will cause:
    \[ v_{oIM3}(t) = \left( \frac{3}{4} a_3 v^3 + \frac{25}{8} a_5 v^5 \right) \cos(2\omega_{1,2} - \omega_{2,1}) \]

- Takeaways
  - Fundamental tone will be distorted by all odd power non-linearity
  - Sum and difference tones have energy from all higher order non-linearities
Two Tone Distortion
Non-Linear Two Tone Test
Determining Coefficients

- Now we have an equation that I assert models the behavior of a PA reasonably well
- Need to determine the $a_1$, $a_3$, $a_5$ coefficients for a particular PA
- Common approach:
  - Use a single tone test signal and sweep input power range
  - Measure output power (AM-AM plot)
  - Use Least Mean Squares algorithm to estimate the coefficients
… And Phase too

- Power amplifiers also distort phase
- The Volterra series can be expanded by making the coefficients complex
Pre-Distortion
Pre-Distortion

- Need to increase the input power to account for the distortion
- Can only increase to the limit of the input driver
  - Total dynamic range decreased, but is now more linear

Inverting the Transfer Function

- Possible to do algebraically, but the equations become lengthy quickly
  - Direct Learning method
- Most frequently an optimization loop is used
  - Algorithmically vary the coefficients while measuring PA output distortion
  - Least Mean Squares, Recursive Mean Squares, others
  - Indirect Learning

“A SiGe PA With Dual Dynamic Bias Control and Memoryless Digital Predistortion for WCDMA Handset Applications”
GNU Radio Blocks
Full band DPD

- Uses Recursive Least Squares to find coefficients
- Written by Srikanth Pagadarai
  - Published in 2016 IEEE 83rd Vehicular Technology Conference
    - Srikanth Pagadarai ; Rohan Grover ; Samuel J. Macmullan ; Alexander M. Wyglinski
    - “Digital Predistortion of Power Amplifiers for Spectrally Agile Wireless Transmitters”
    - GNU Radio assistance by Travis Collins
- https://github.com/SrikanthPagadarai/gr-dpd
- Includes OFDM test code
Sub Band DPD

- Can isolate and compensate for a single intermodulation product
- Developed by Chance Tarver and Mahmoud Abdelaziz
  - Published in 2017 IEEE International Symposium on Circuits and Systems
    - Chance Tarver; Mahmoud Abdelaziz; Lauri Anttila; Joseph R. Cavallaro
    - “Multi component carrier, sub-band DPD and GNURadio implementation”
- Uses a memoryless polynomial
- Includes the volterra series PA model used in the examples today
- Also indirect learning model

Suppression of all left hand IM3 spurs
Future Plans

● Merge existing code into single OOT module
  ○ Authors of both existing modules supportive and able to help
● Adapt testbenches to use standard GNU Radio OFDM blocks
  ○ Increase flexibility, demonstrate full TX->RX impact
● Add documentation
● Add implementations of memory polynomials
  ○ Thermal and capacitive effects mean the output is not only dependant on the current input
● Possible Google Summer of Code project
  ○ Already some interested students
Thanks and Questions?

The latest version of these slides can be found at
www.derekkozel.com/talks

@derekkozel

@dkozel@social.coop