Digital Pre-Distortion

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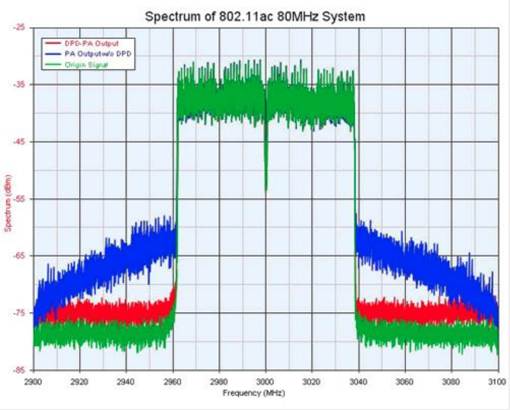
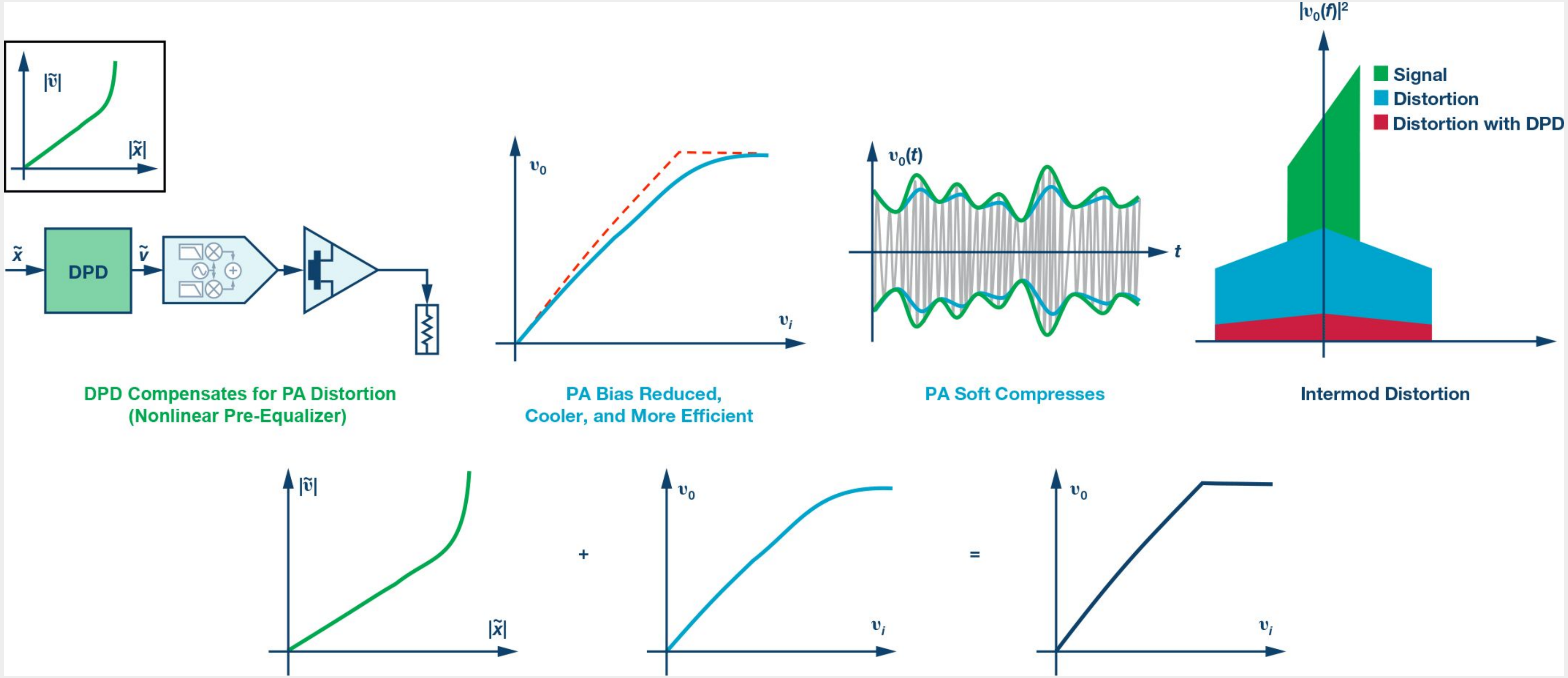
What is Digital Pre-Distortion (DPD)

- 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



keysight.com

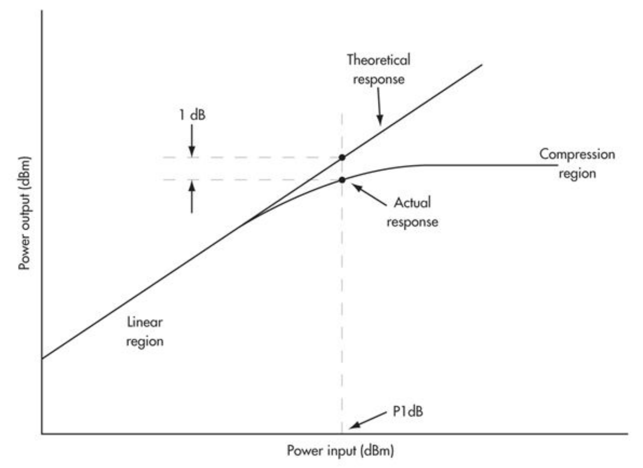
High Level Flow



https://www.analog.com/en/analog-dialogue/articles/ultrawideband-digital-predistortion-rewards-and-challenge-of-implementation-in-cable-system.html

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

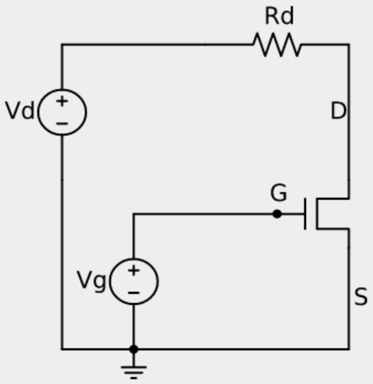


www.electronicdesign.com/

Background Transistor Theory

Ideal Field Effect Transistor

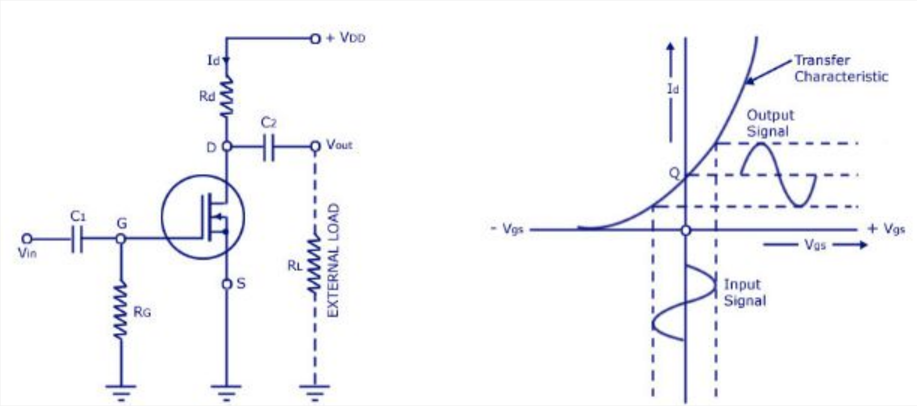
- Voltage controlled current source
- Three terminals (connections)
  - Gate: “control port”
  - Drain and Source: variable resistor
- Changing the voltage across these terminals changes the resistance between Drain and Source and thus the current flowing



bradysalz.com/technical/the-mosfet/

FET as an amplifier

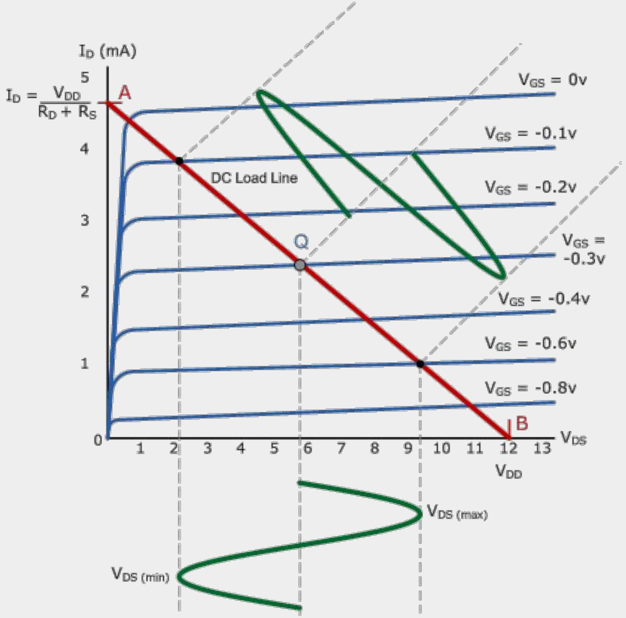
- Usually the Gate to Source voltage is the input
- Voltage at the Drain is the output



electronicspost.com/mosfet-amplifier/

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



https://electronics.stackexchange.com/questions/313357/

Distortion

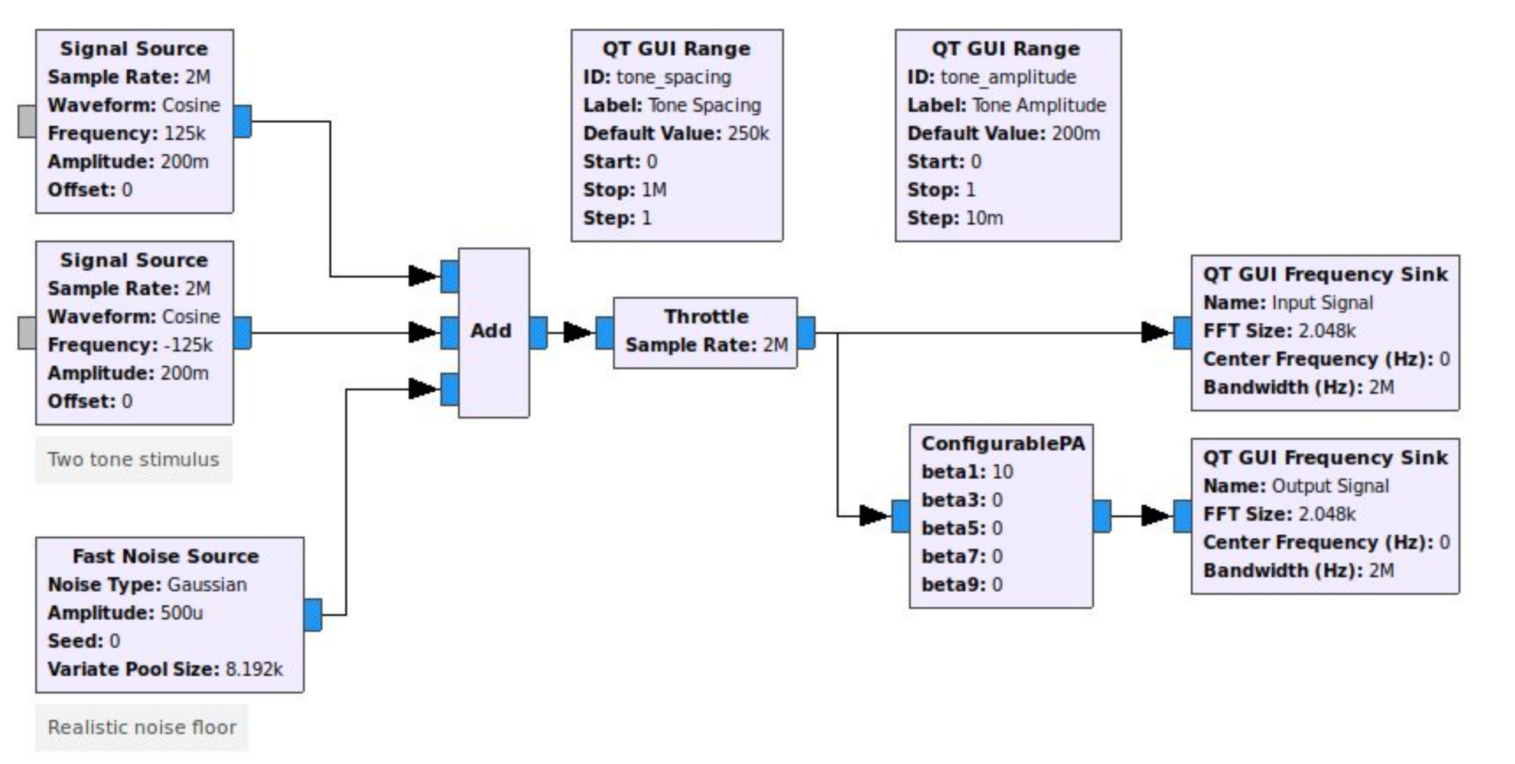
Ideal Transfer Function

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

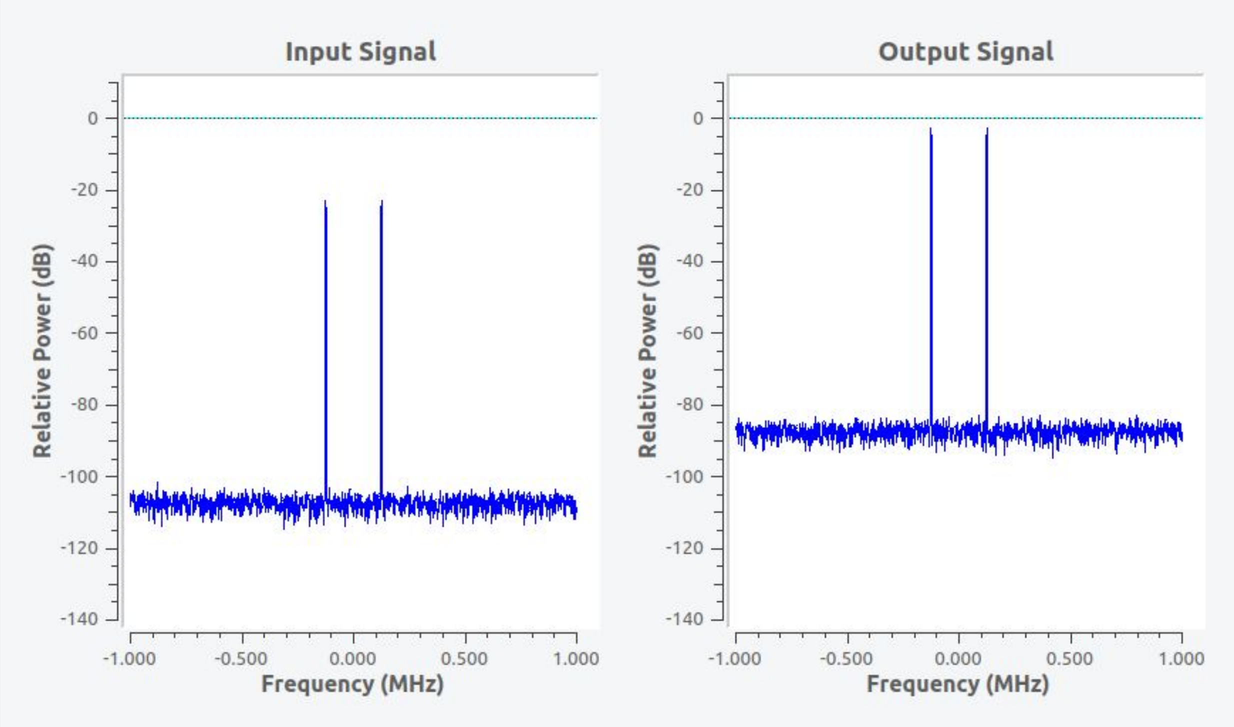
$$v_o(t) = av_i(t)$$

- Where ***a*** is the voltage gain of the amplifier

Two Tone Test Setup



Ideal Two Tone Result



Non-Linear Transfer Function

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

$$v_o(t) = a_1 v_i(t) + a_2 v_i(t)^2 + a_3 v_i(t)^3 + ...$$

- We see the linear gain, ***a1***, 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

$$\sin(\omega t)^2 = \frac{1}{2}(\cos(2\omega t) + 1)$$

- 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:

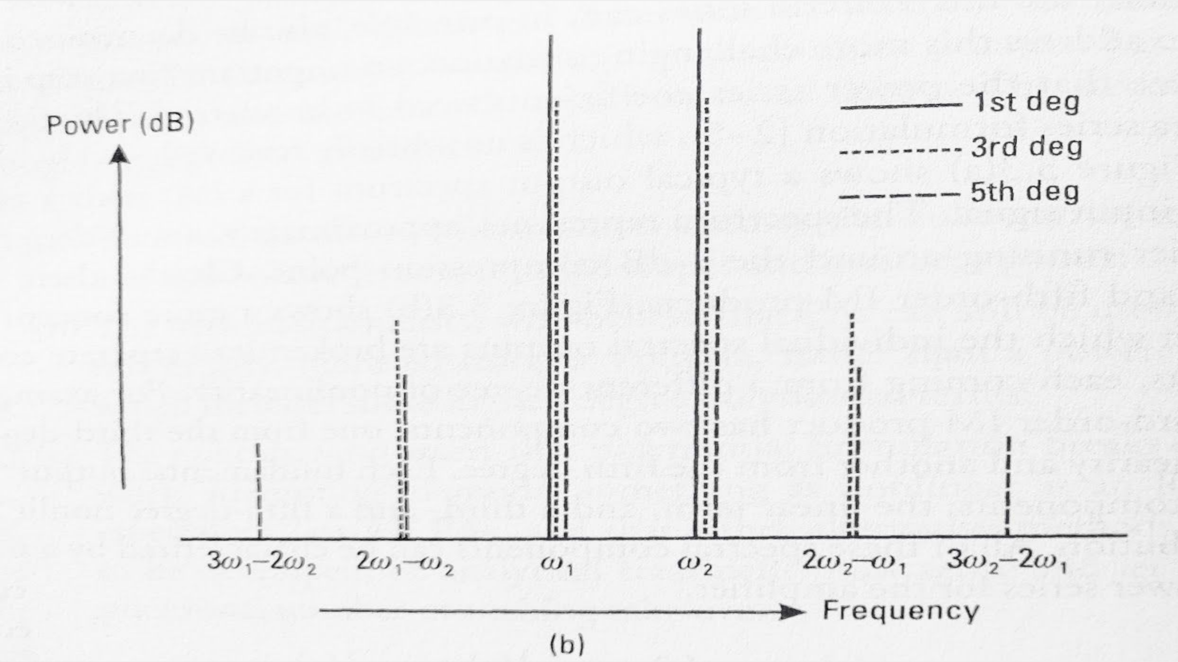
$$v_i(t) = v\cos(\omega_1 t) + v\cos(\omega_2 t)$$

- Results in In-Band distortion
  - Third order distortion will cause:

$$v_{oIM3}(t) = \left(\frac{3}{4}a_3 v^3 + \frac{25}{8}a_5 v^5\right)\cos(2\omega_{1,2} - \omega_{2,1})$$

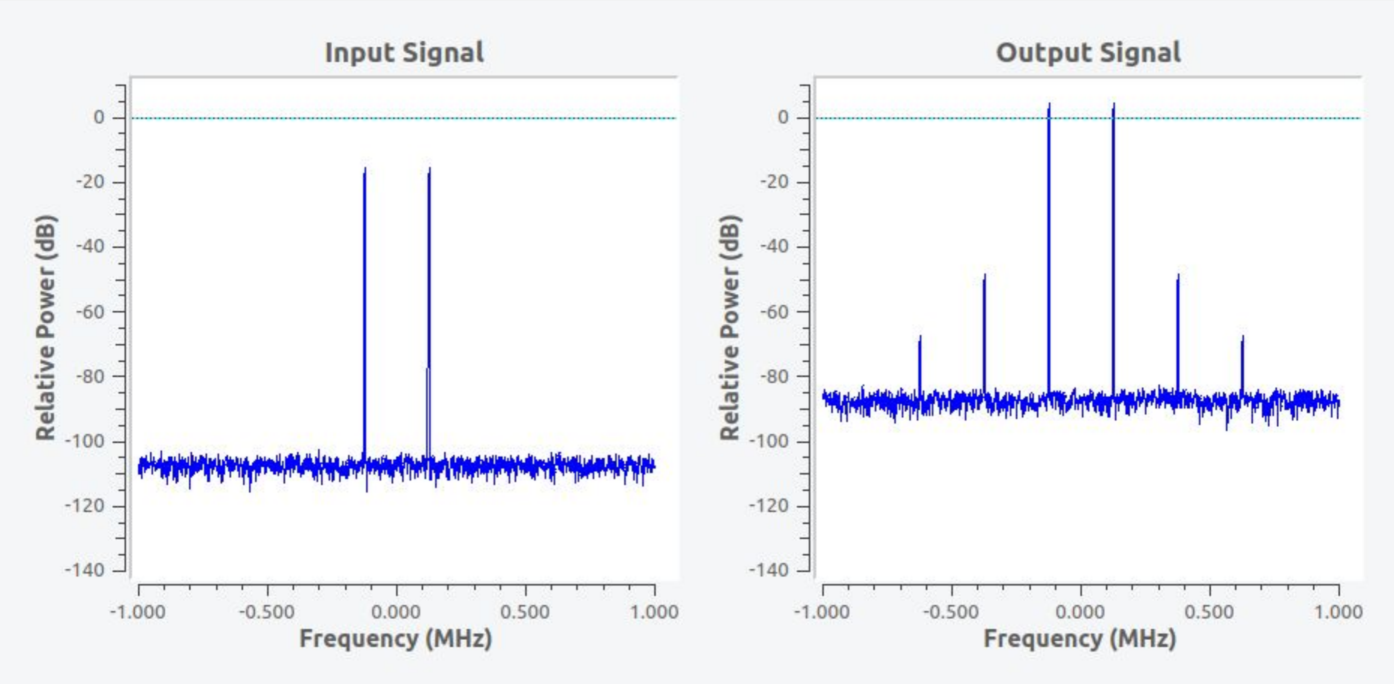
- Takeaways
  - Fundamental tone will be distorted by all odd power non-linearity
  - Sum and difference tones have energy from all higher order non-linearities

Two Tone Distortion

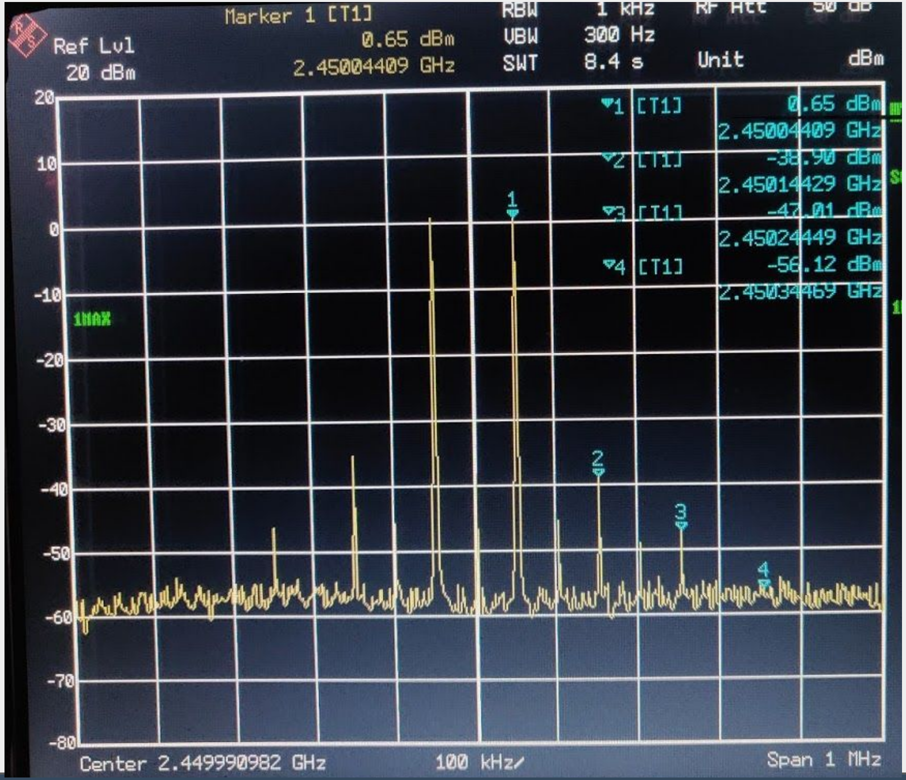


Advanced Techniques in RF Power Amplifier Design (S. C. Cripps)

Non-Linear Two Tone Test

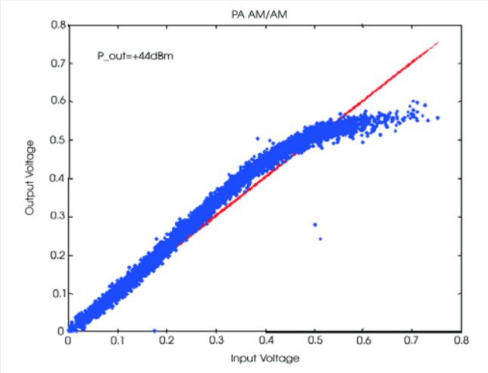


Output of an SDR driven to maximum gain



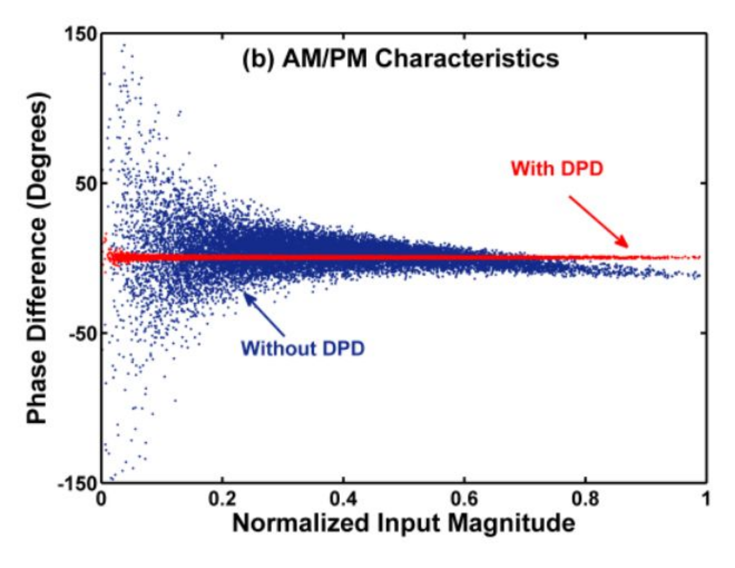
Determining Coefficients

- 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

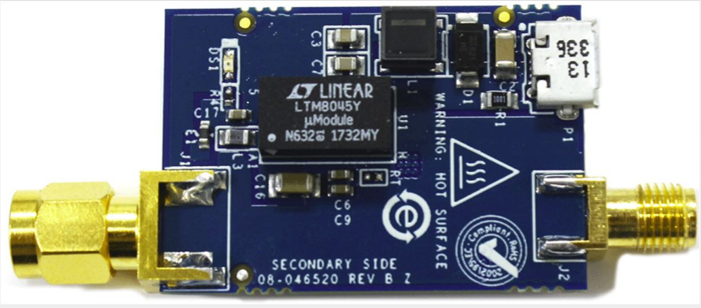
- Power amplifiers also distort phase
- The Volterra series can be expanded by making the coefficients complex



Analog Devices CN0417

CN0417 - 2.4 GHz USB powered amplifier

17295-011



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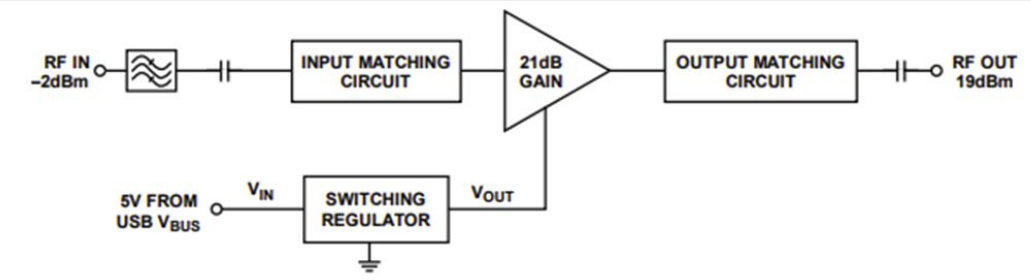
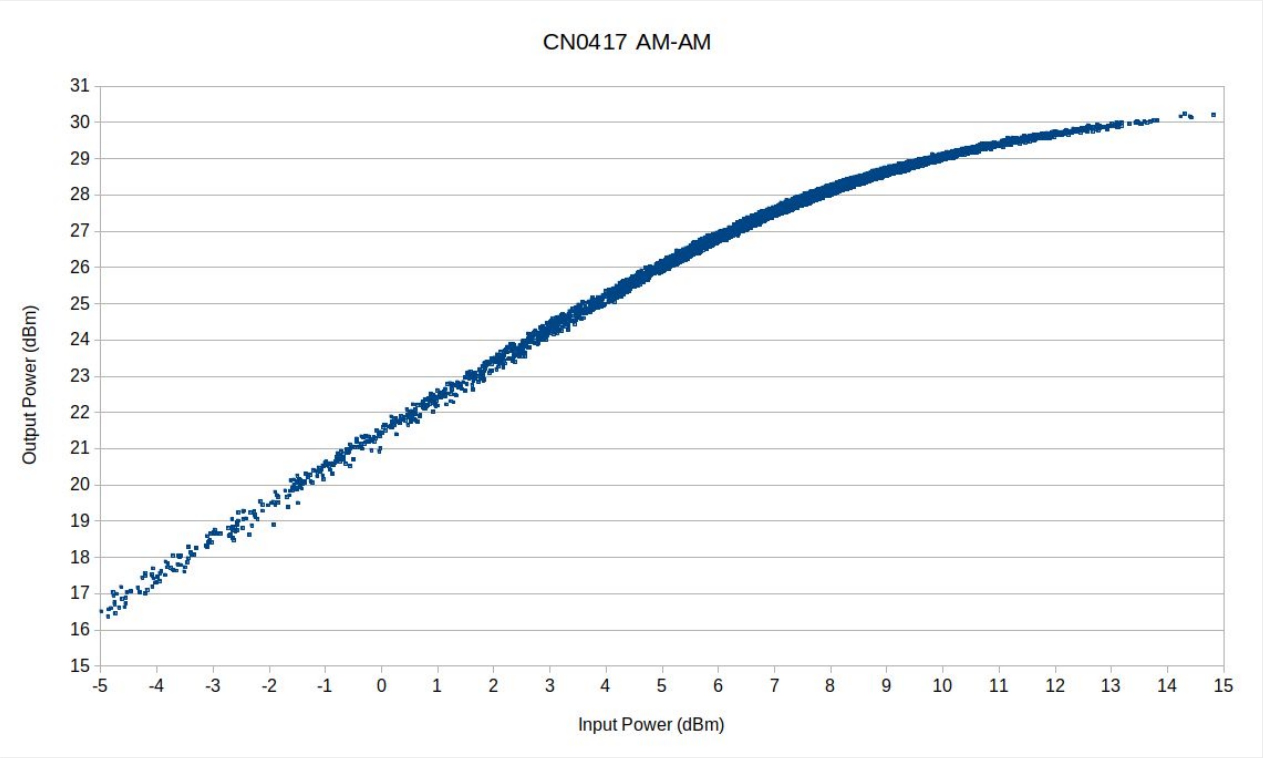
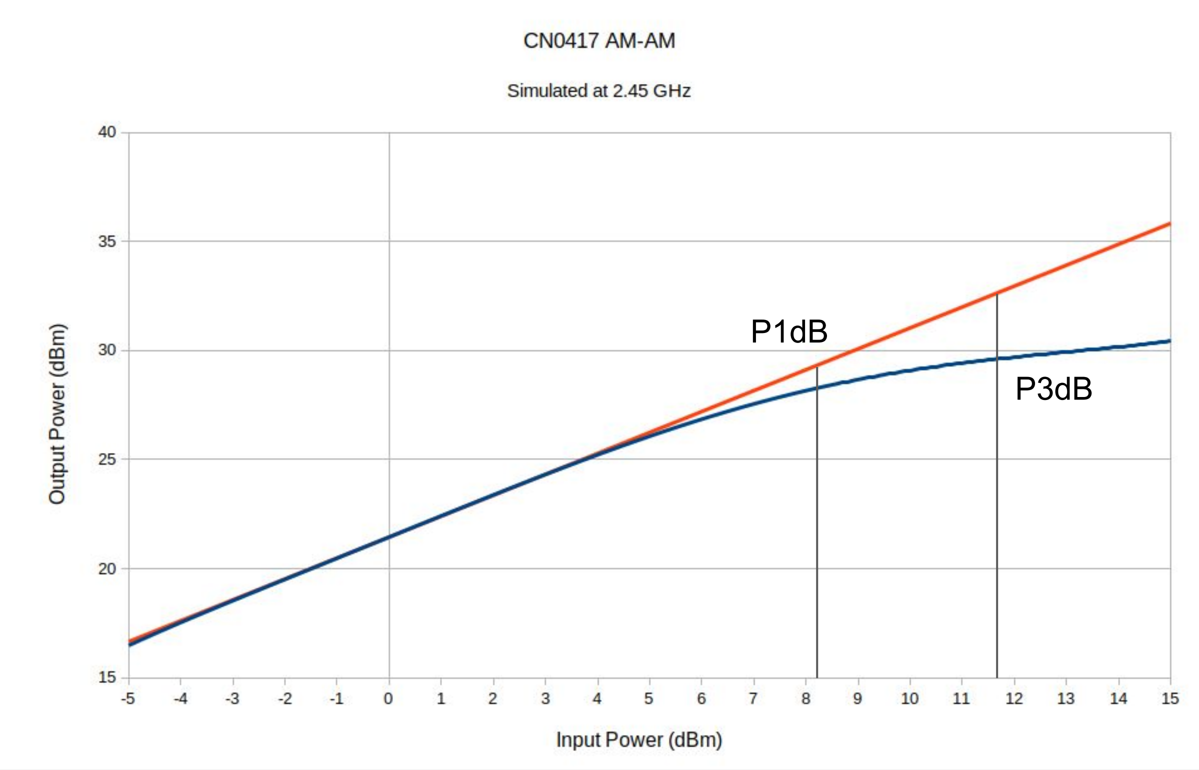


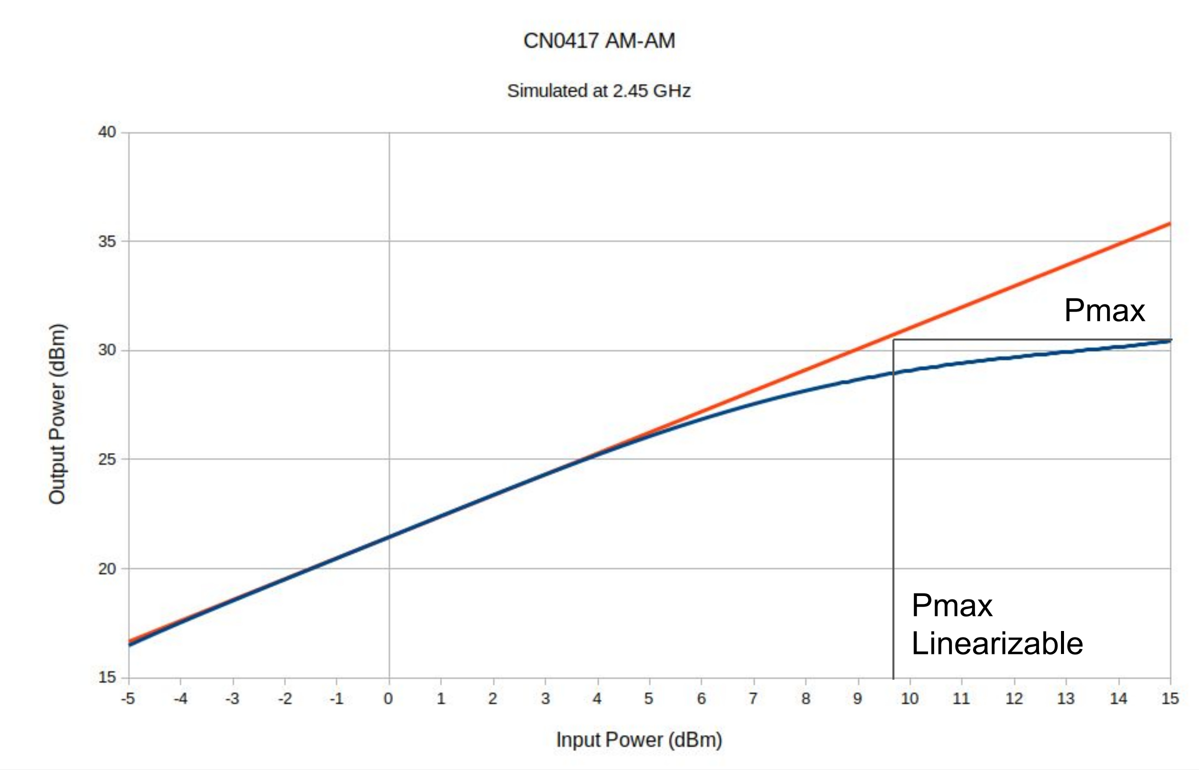
Amplitude - Amplitude Distortion



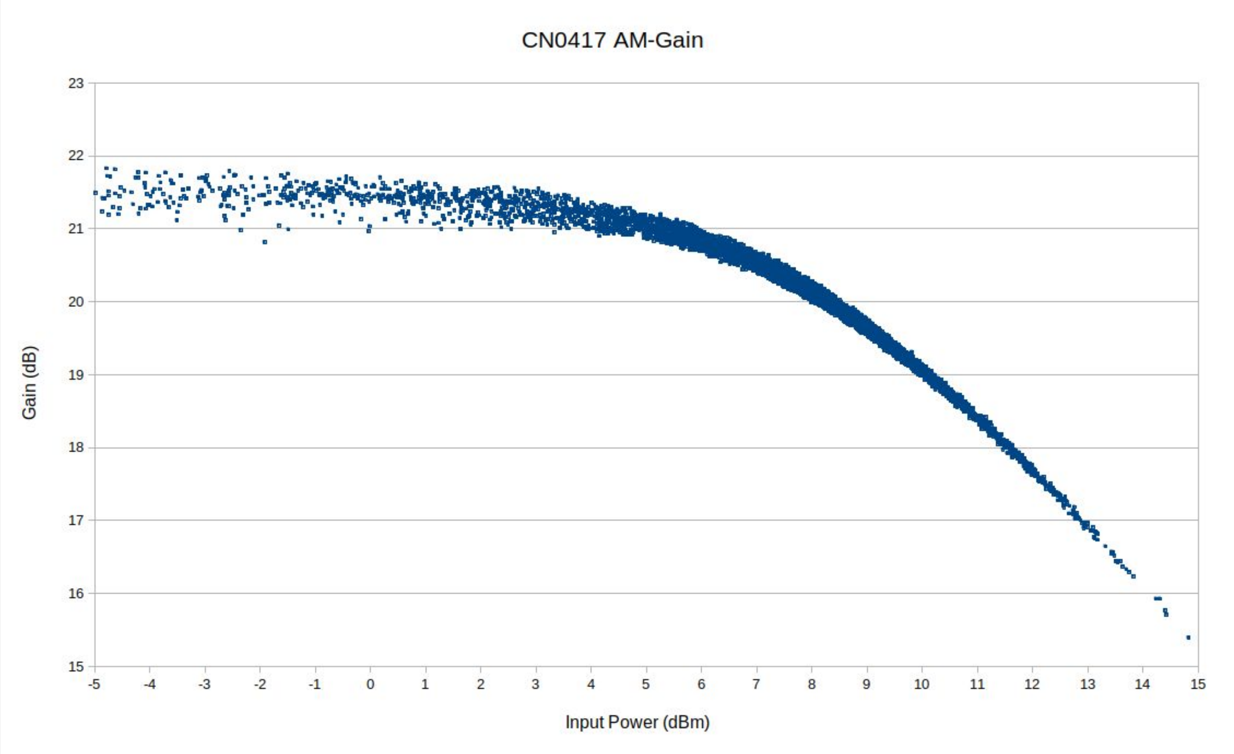
Simulated AM-AM



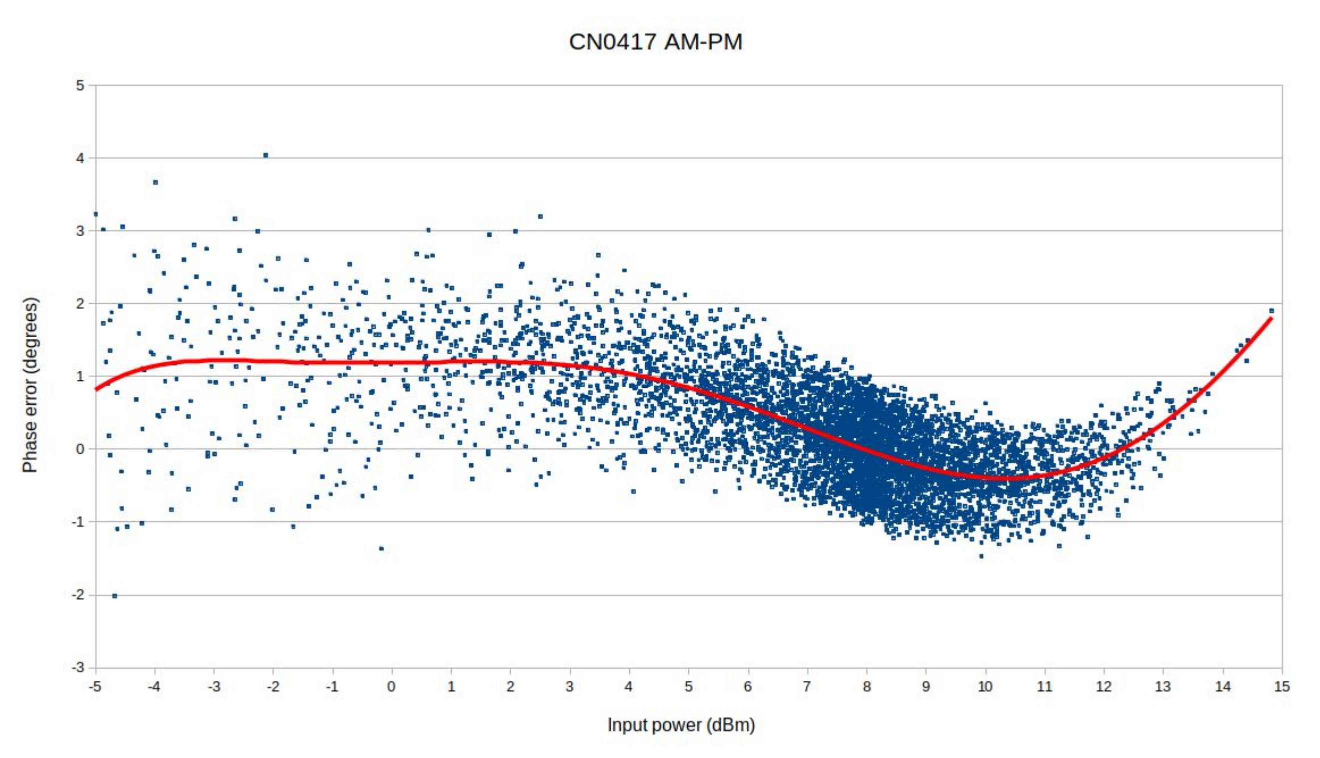
Maximum Linearizable Power



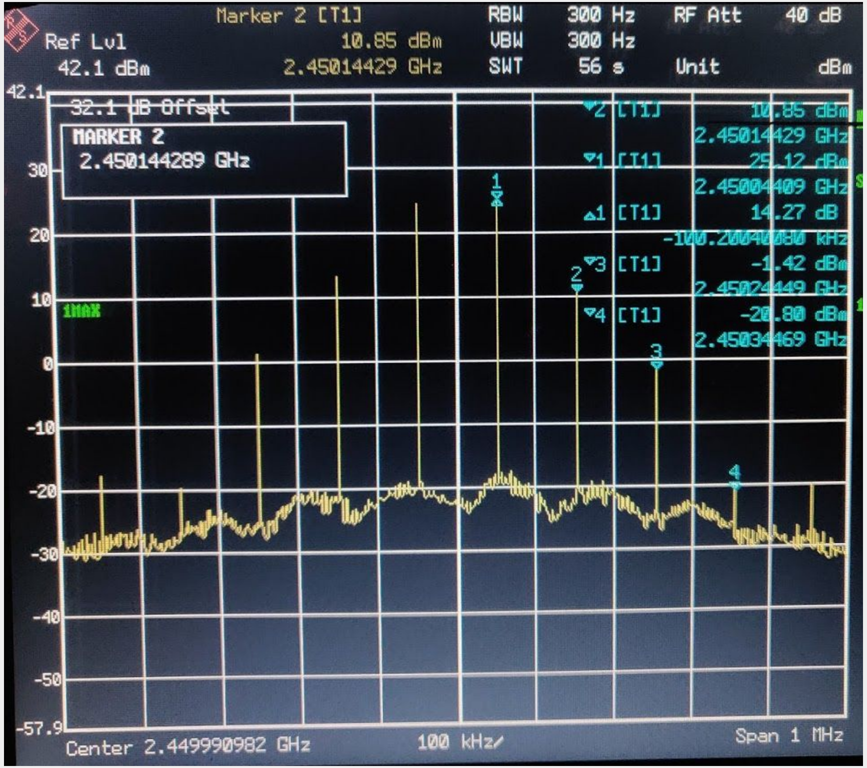
Amplitude - Gain (aka Saturation)



Amplitude - Phase Distortion



Output of the amplifier

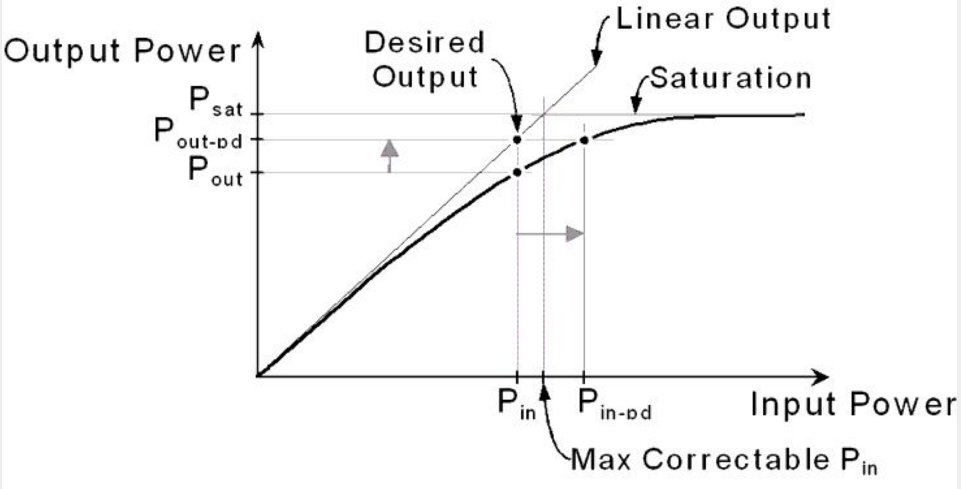


Main tones and previous amplifier IMD both amplified + extra distortion

Pre-Distortion

Pre-Distortion

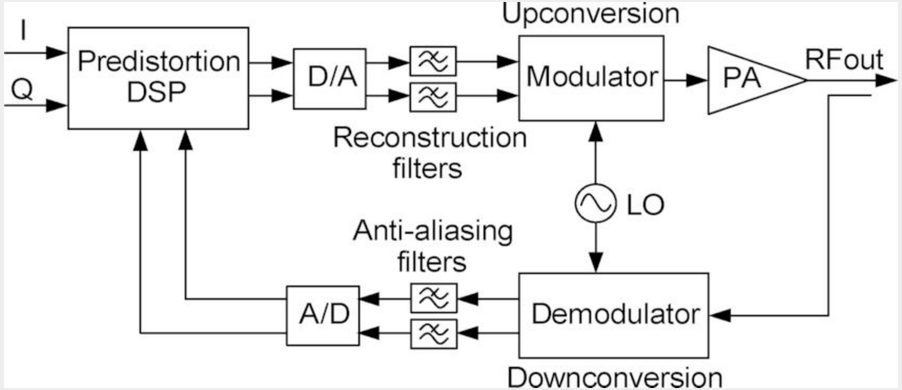
- Need to increase the input power to account for the distortion
- Can only increase to the limit of the input driver
  - Total dynamic range decreased, but is now more linear



http://edadocs.software.keysight.com/display/ads2009/Theory+of+Operation+for+Digital+Predistortion

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

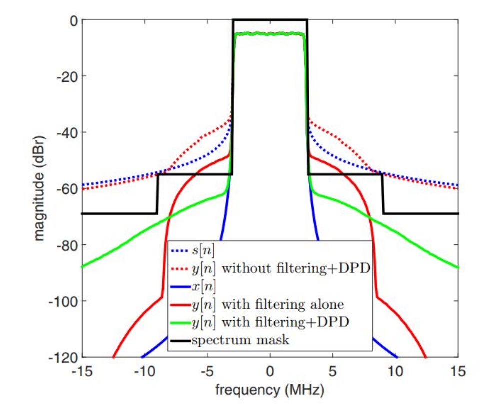


“A SiGe PA With Dual Dynamic Bias Control and Memoryless Digital Predistortion for WCDMA Handset Applications”

GNU Radio Blocks

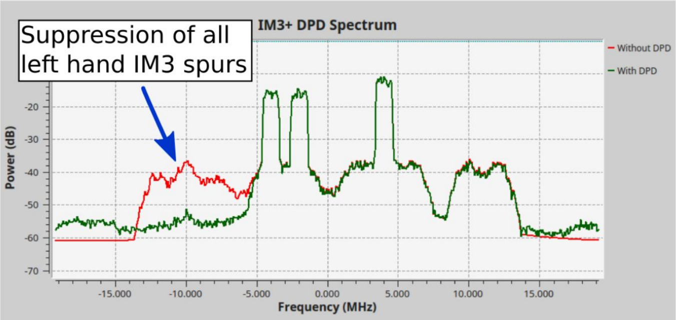
Full band DPD

- 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



Future Plans

- Merge existing code into single OOT module
    - Authors of both existing modules supportive and able to help
- Google Summer of Code project
    - Already some interested students
- Adapt testbenches to use standard GNU Radio DVB 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

Thanks and Questions?

The latest version of these slides can be found at

www.derekkozel.com/talks

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