Use of Digital Signal Processing in Real Wireless Transmitter Systems

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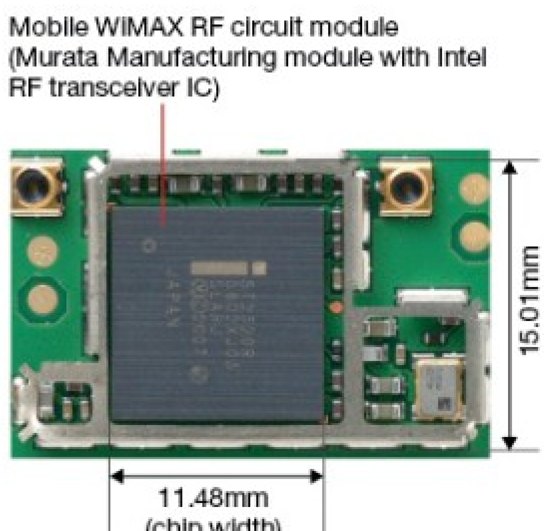
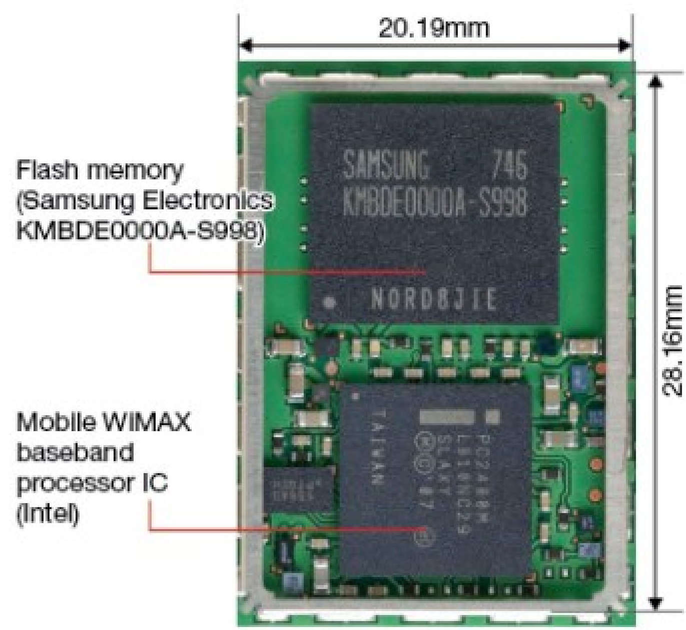
Goals

- Demonstrate an application of digital signal processing to a communications problem with significant economic impact

- Discuss tradeoffs choices when implementing a design. Tradeoffs involve: DSP, circuit design, & communications





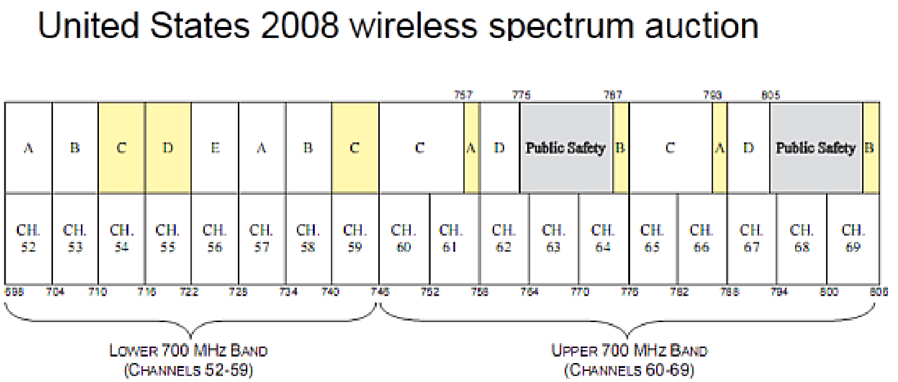
Motivation

- Learn yet another application of DSP
- Gain hands on simulation experience in working around impairments introduced by real amplifiers and efficiency concerns

Limited Bandwidth

- Cellular providers must purchase spectrum in which to offer service
- Spectrum is very expensive.
  - Providers want highest data rate in available BW
- Means using advanced modulation schemes
  - Amplitude & Phase Modulation

- United States Wireless Auction 2008



One Auction, 110MHz, One Country.
$20 billion

The licenses for Band C over the continental United States alone (22MHz) were bought by Verizon Wireless for $4.7 billion

Image: http://arstechnica.com/old/content/2007/08/700mhz-auction-whats-really-up-for-grabs-and-why-it-wont-be-monopolized.ars

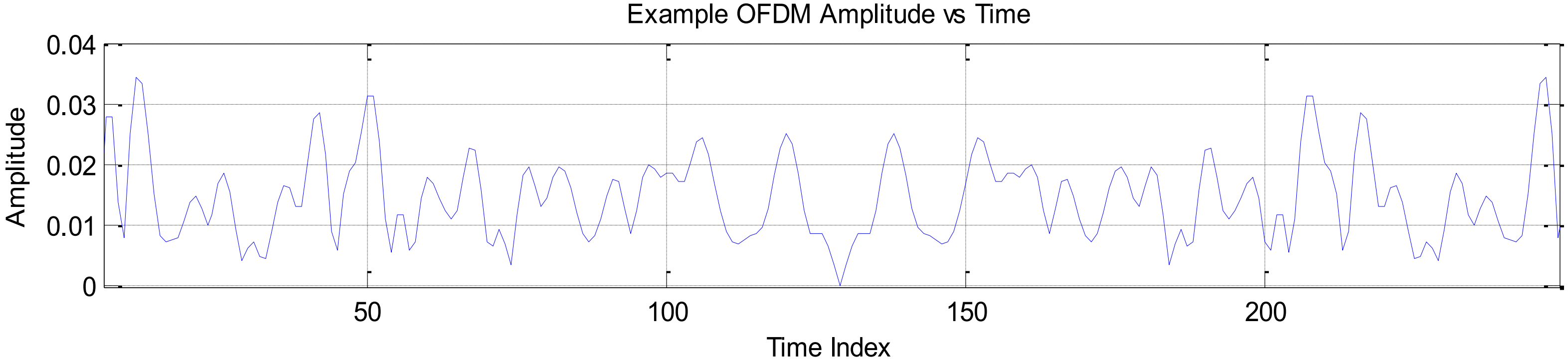
"Green Wireless"
Limited Power Consumption

- Base Stations
  - Base Stations Consume Electricity
  - High Power Consumption means designing a fancy cooling system for base station electronics plus higher operating costs
- Handsets
  - Long battery life increases device usefulness
  - High-output power amplifiers are larger, generally more expensive than low power ones

Picture of base station: http://www.flickriver.com/photos/craigjewell/2440310969

Amplitude Modulation

- Most modern modulation schemes modulate both amplitude and phase to achieve a maximum data rate in a given bandwidth
- To avoid distortion:
  - Amplifier should have constant gain across all amplitudes to be transmitted.



On to amplifiers…

- Fundamentally, the amplifier in your car is similar to the amplifier in your cell phone's transmitter.
- Where does your car do the most efficient job of converting the DC power it draws from the battery into sound power?

Sound quality?

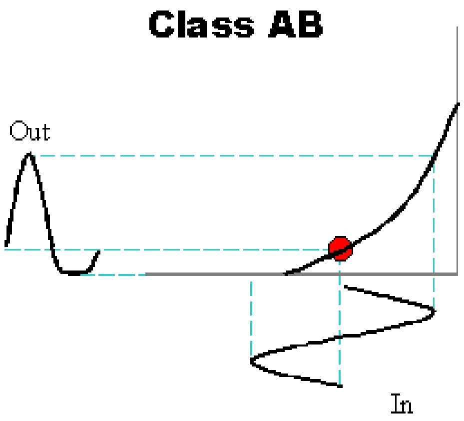
- **High efficiency operation occurs near the amplifier the peak output amplitudes.**
- What happens to the sound quality when you have the volume cranked up to be in the “highly-efficient” region?
- Can we correct for it using digital signal processing?

Power Amplifiers Classes

- Differ in the fraction of the time the waveform is “clipped”

- Power Amplifier Class A
  - Amplifies sinusoid during full cycle
  - Good linearity, low distortion without clipping
  - Inefficient due to large bias current to keep transistors “linear”

- Power Amplifier Class AB
  - Conducts between half and full of sinusoid period
  - Linearity Degradation, Produces Harmonics
  - Gains Efficiency by reducing required bias current



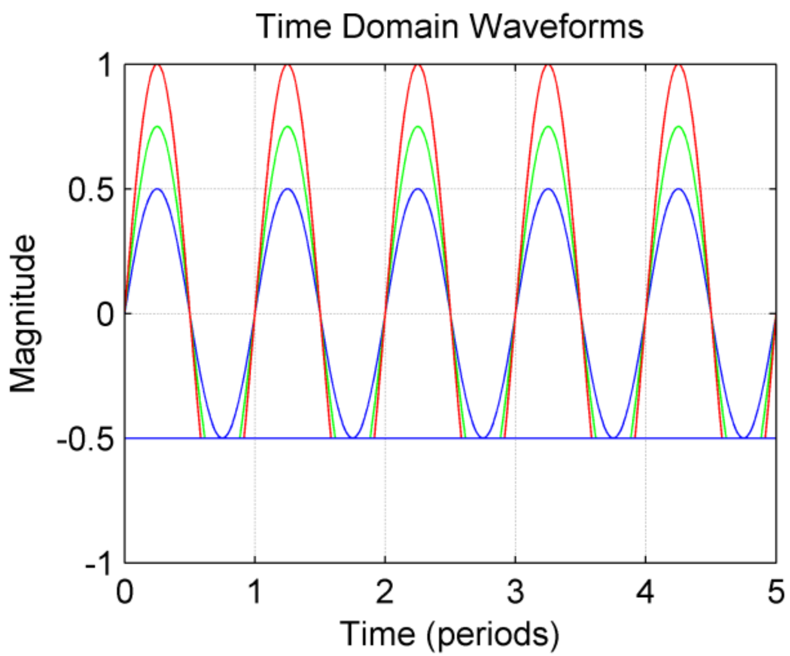
- Power Amplifier Class D
  - Square Wave Output. Switched very quickly.
  - Use an Low-Pass Filter to “Average” the value to what you want

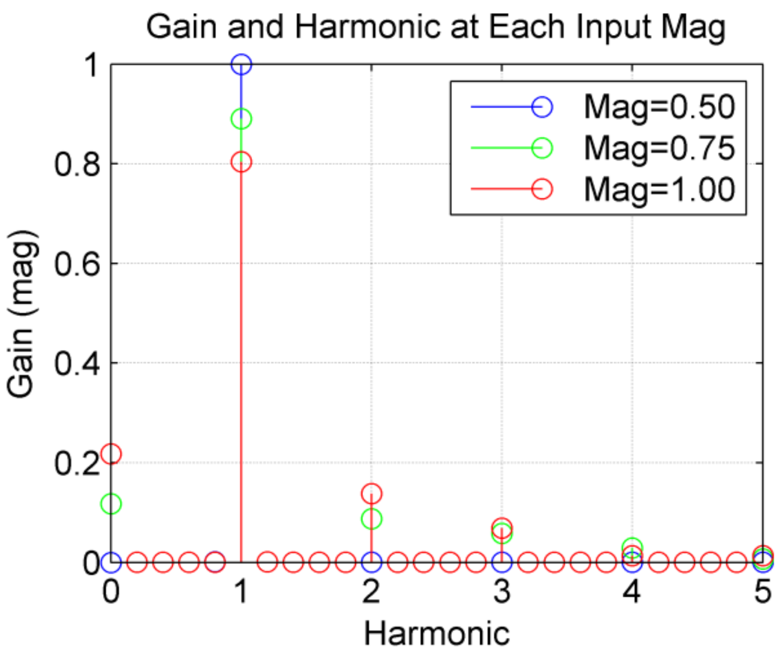
- **Design Tradeoff: Linearity vs. Efficiency**
- Other topologies exist, but the tradeoff remains

Reference: Cripps, Steve C., *RF Power Amplifiers for Wireless Communications.*

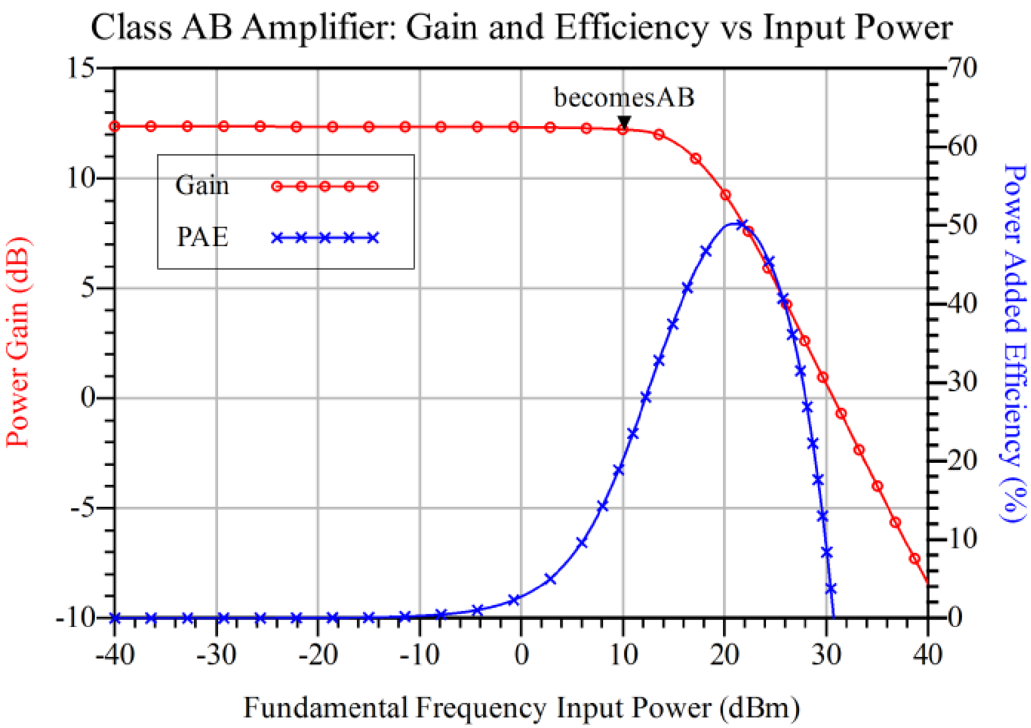
Class AB Amplifiers

- Class AB Clipping magnitude is typically fixed
  - Conduction Angle depends on Input Magnitude
  - **Gain change based on magnitude (non-linearity)**





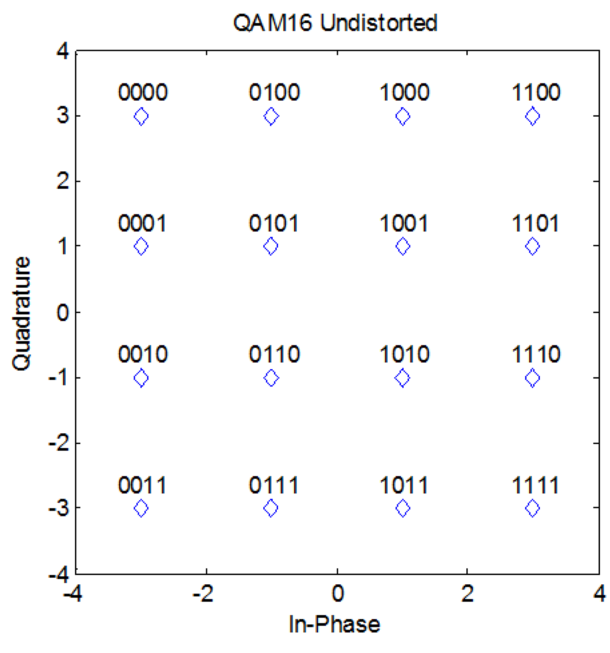
Why bother with class AB?

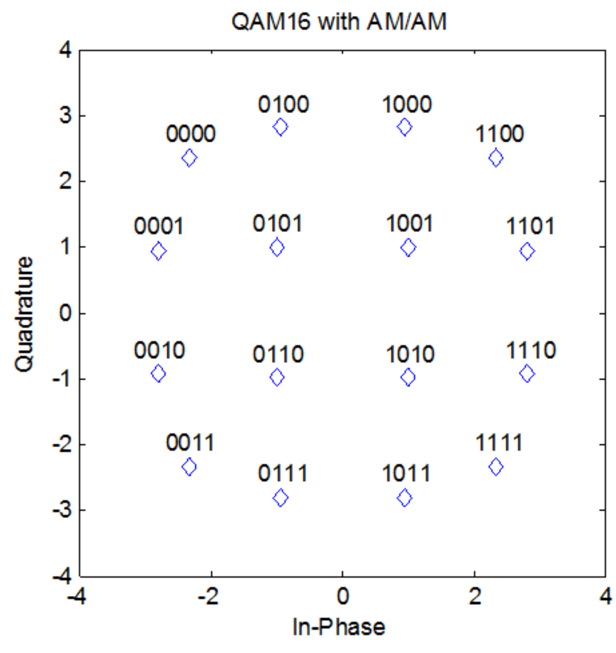


- Efficiency is best when amplifier gain is compressed
- But what happens due to non-constant gain?

Gain Changes w/ Amplitude In-band Distortion

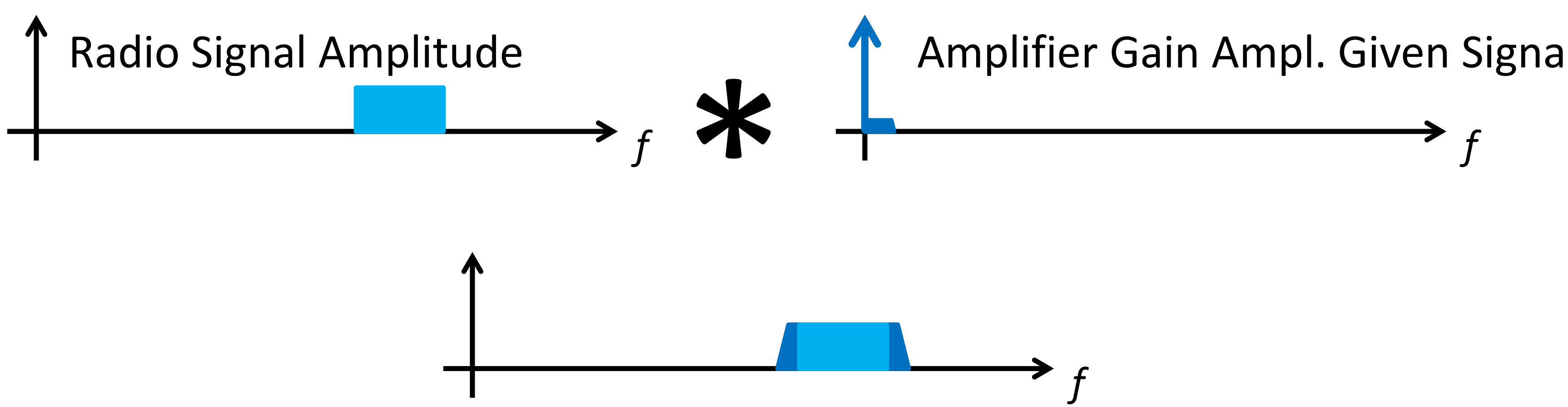
- If amplifier has non-linearity
  - QAM Constellation gets distorted
  - Error Vector Magnitude (EVM) increases





Gain Changes w/ Amplitude

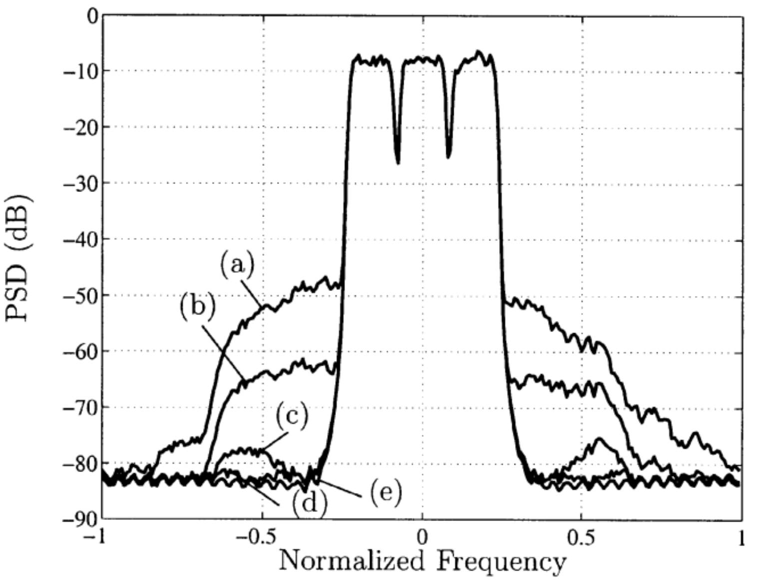
- PA gain is a now time-varying function
  - Thus it has some frequency spectrum
  - Convolve with original modulation spectrum
  - Resultant spectrum is wider (spectral leakage)



Spectrum is Broadened … Some energy leaks into Adjacent Channels

Frequency Spreading

- Amplifier non-linearity causes spectral spreading,
- **Adjacent Channel Power Ratio:**
  - **ACPR =** $\frac{\text{Power Leaked into Adjacent Channel}}{\text{Power Transmitted in Your Channel}}$
- **Determines the number of channels you can have within a band of (expensive) frequencies**
- A person standing near your transmitter, operating on "Normalized Frequency = -0.5" can actually have their signal overwhelmed by the leakage from your nearby transmitter in scenario (a).



Can we avoid the problem?

- In the “old days”, modulate only phase.
  - **GSM** phones do this to get efficiency
  - Data rate per bandwidth suffers
- Transition period:
  - **EDGE** had a small amount of amplitude modulation. Largely avoided the non-linear gain.
- Now:
  - OFDM in WiFi/WiMAX/LTE has a significant amplitude modulation.

Introduce a new component.

- How do we correct for a time-varying gain?
- **With a nonlinear time-varying filter called the predistorter.**
- The gain also changes with your transmitter’s power supply level and temperature, so you must do it ***adaptively*** in your transmitter. Cannot pre-determine the filter.

Design Target

- Introduce a new component in the transmitter that attempts to cancel the gain changes

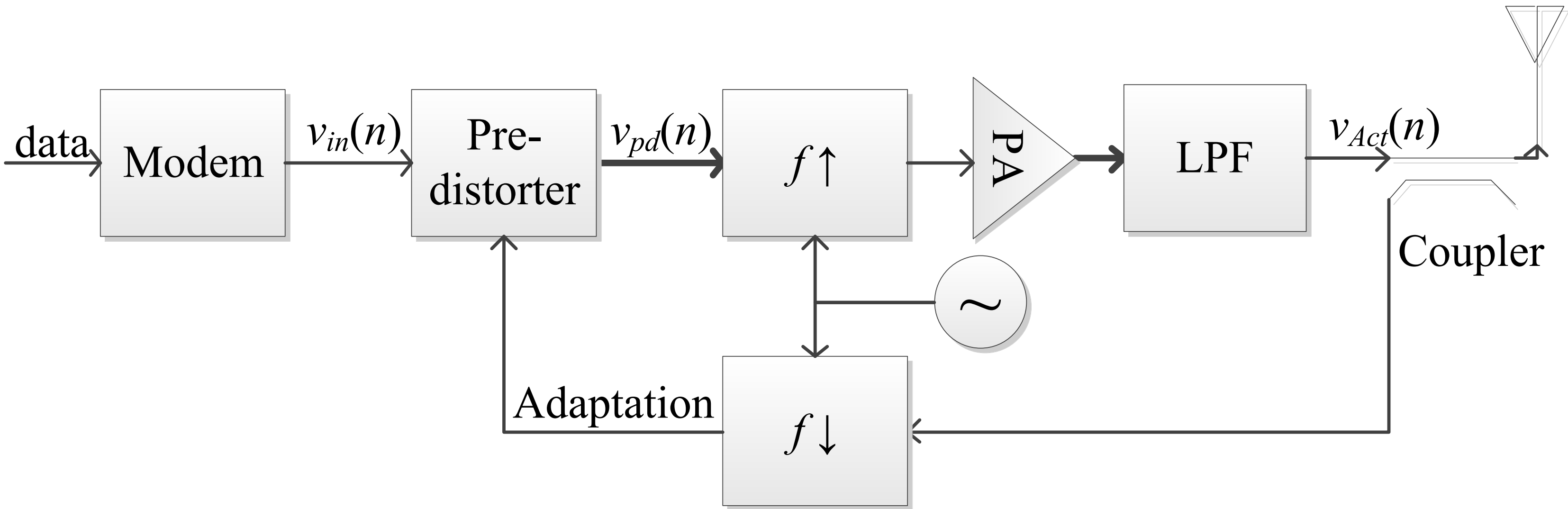
- New component (predistorer) has:

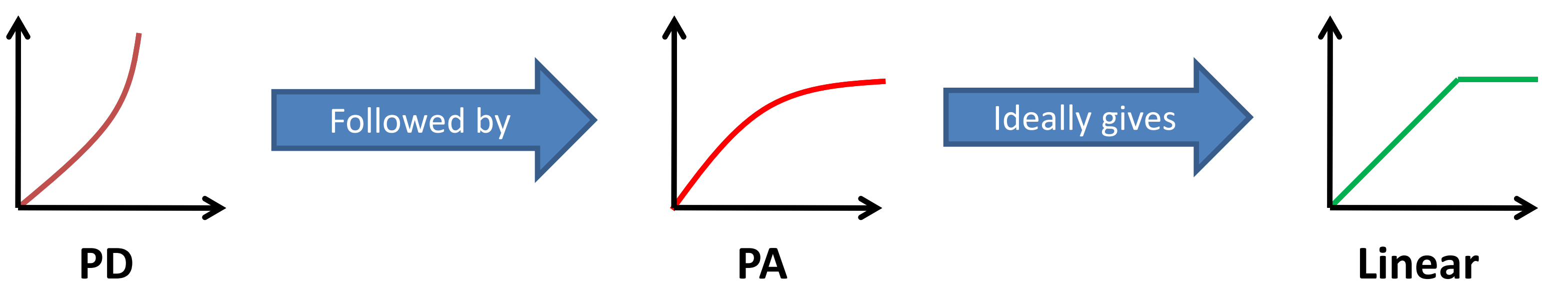
  “gain expansion” with increasing amplitudes
- To cancel amplifier’s

  “gain compression” with increasing amplitudes
- Total system thus is:

  “gain constant” with increasing amplitude

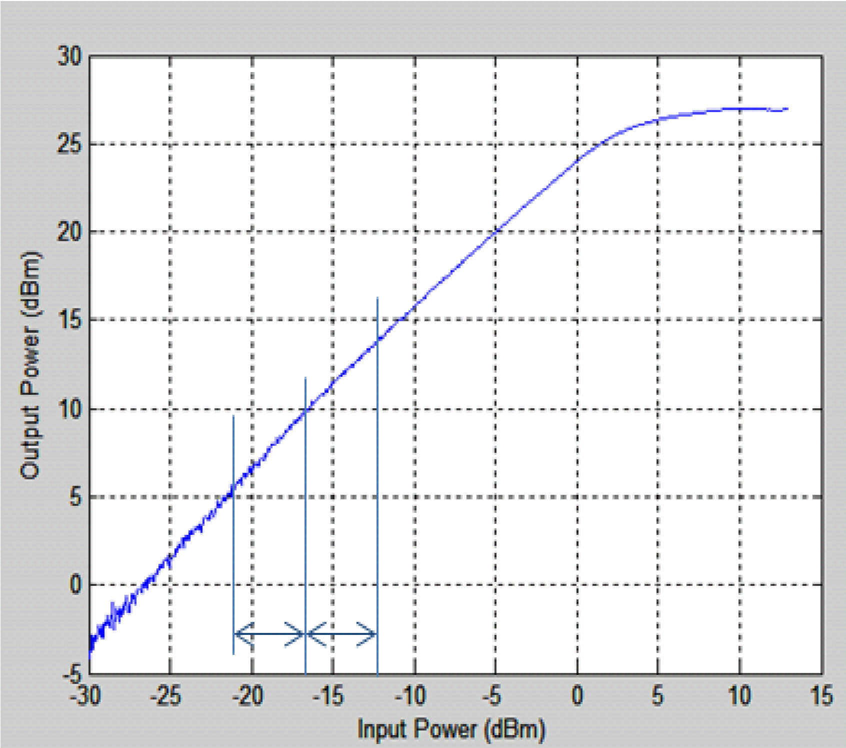
Predistorted Transmitter Topology





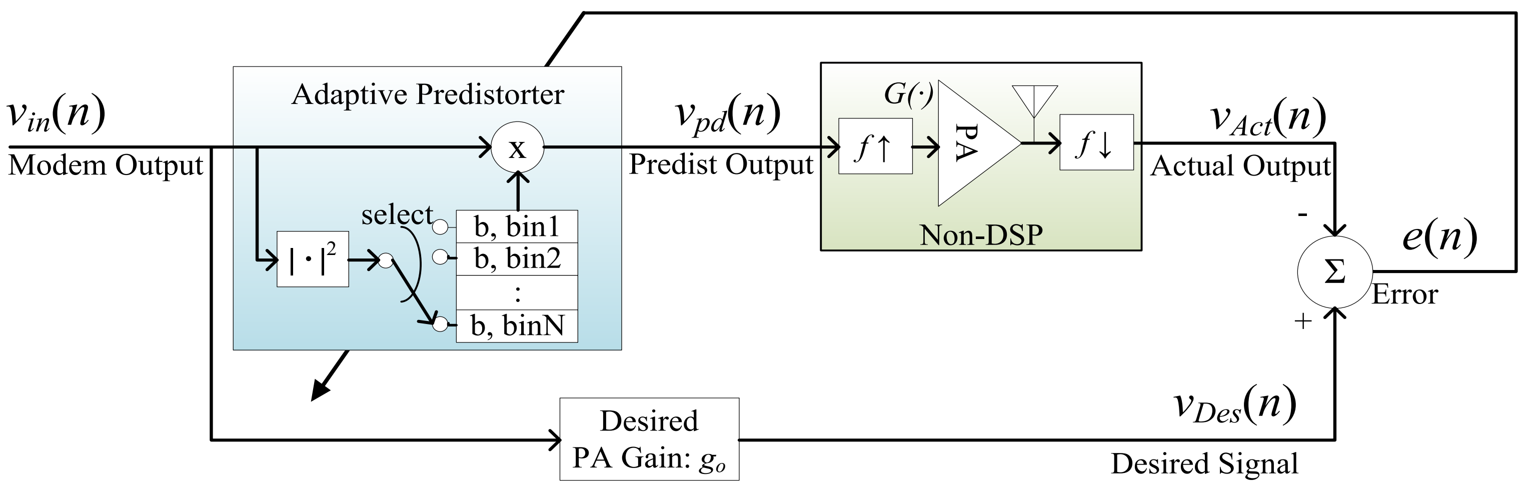
Gain-Based Predistorter Overview

- Split the input power range into “bins” of similar power points
- Within the narrow range, PA is approximately linear
- Develop a correction factor for gain in that bin
- Apply correction prior to feeding input to the PA
- Monotonicity is assumed
  - inputting more power to amplifier boosts its output



Gain-Based LUT Predistortion

- Split the gain curve into regions and correct each region's gain via an adaptive algorithm



- LMS:

$$b_{selected}(n+1) = b_{selected}(n) + 2\mu e(n)\, v_{in}^{*}(n)$$

Cavers, J.K., "A linearizing predistorter with fast adaptation," Vehicular Technology Conference, 1990 IEEE 40th , vol., no., pp.41-47, May 1990.

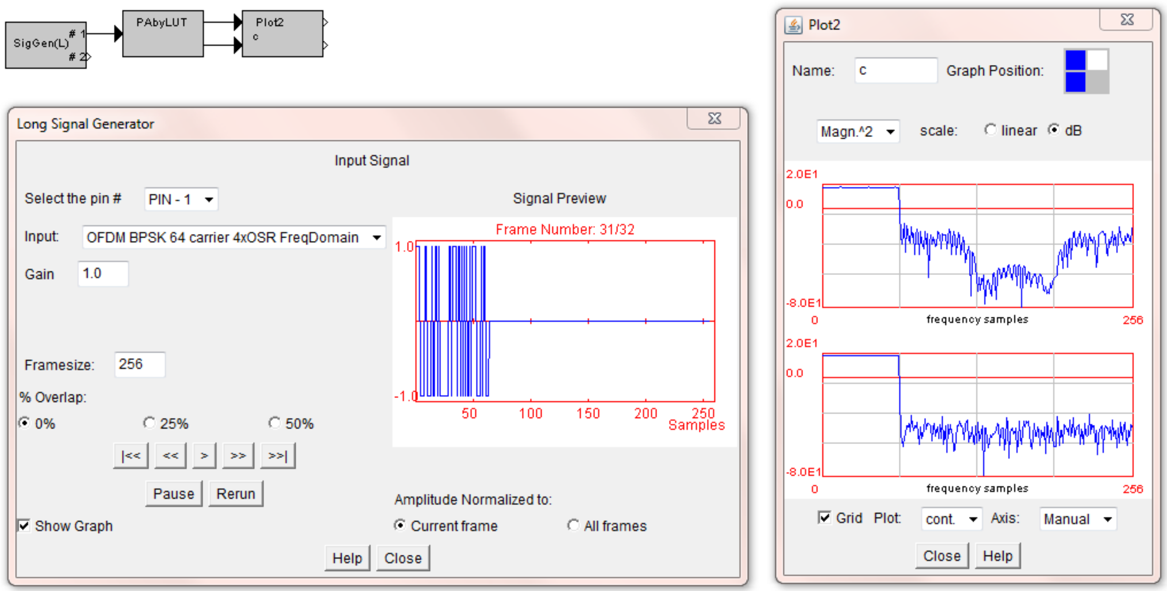
Design Tradeoffs

- **Number of bins (LUT Size)**
  - More bins: Better Accuracy (good),
  - More bins: More Training Required (bad)
- **LMS Learning factor (μ)**
  - Higher: Correction factors learned more quickly.
  - Lower: Correction factors are more accurate.
- **Power Back off**
  - Higher: Lower efficiency (bad), better linearity (good)
- **We will demonstrate these tradeoffs using JDSP.**

Conclusion

- **Amplifier designers must face a tradeoff**
  - Amplifiers operate most efficiently when in “compression”
  - “Compression” introduces non-linearity
  - Time-varying non-linear gain
- **Non-linear gain causes spectral broadening, distortion**
- ***Introduce a new filter in DSP to correct for Nonlinear PA***
  - Time-varying non-linear filter
  - Gain Expansive characteristic to compensate for gain compressive amplifier
  - **Predistortion**

JDSP Demonstration



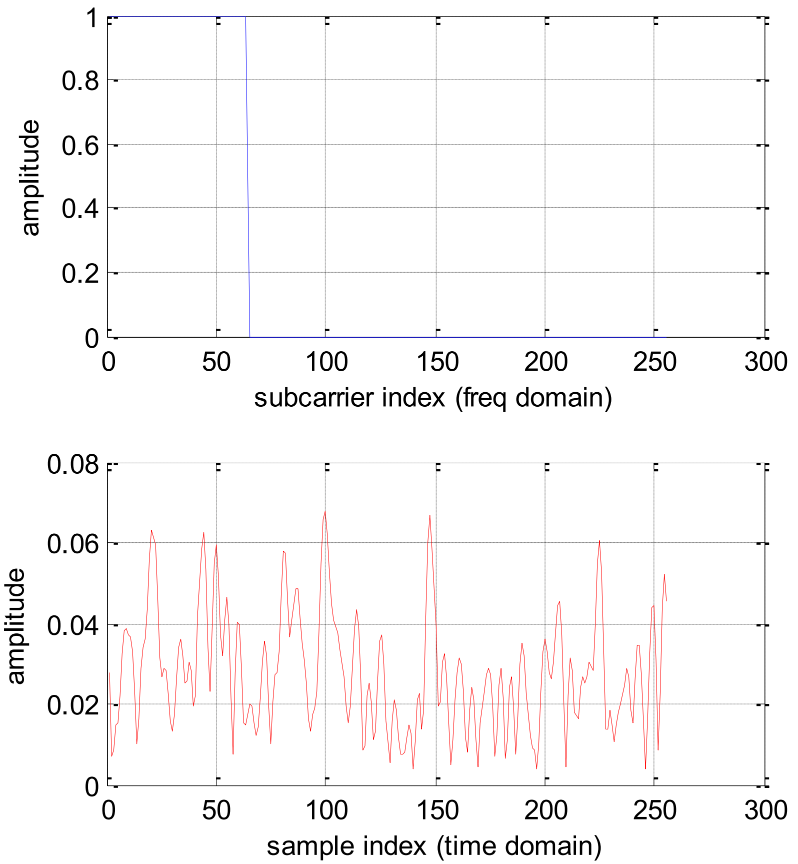
Backup

OFDM

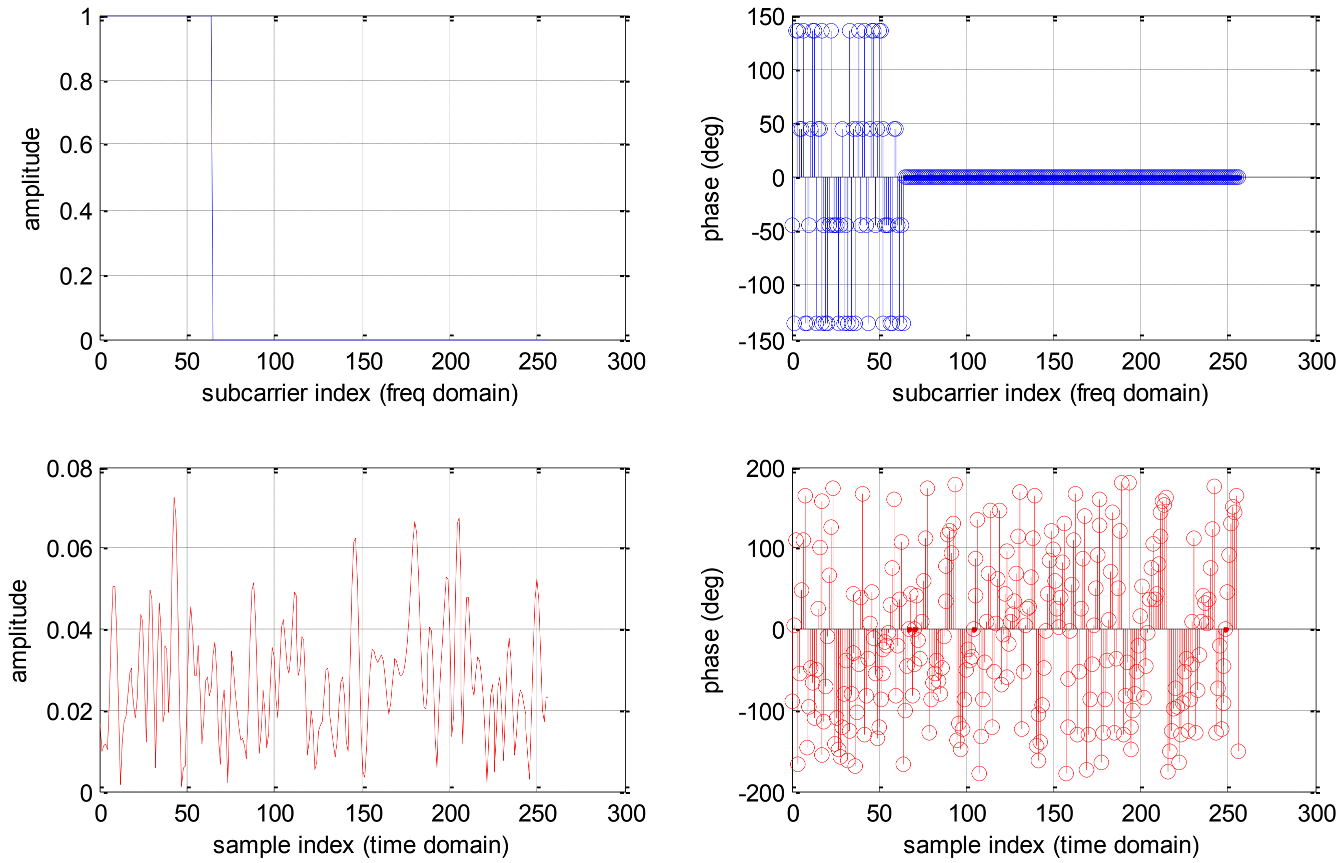
- A transmitted signal may take multiple paths to get to a receiver.
  - Line of sight, reflected off buildings, etc.
- If we transmitted a sequential series of symbols as fast as possible, the order at which they arrive at the receiver after travelling different paths can be jumbled.
- Instead, split your available frequency band into a series of subcarriers which each transmit a single slow symbol in parallel. Placing enough in parallel makes the symbol long enough in duration that arrival time is a non-issue.

What does an OFDM symbol look like?

- In the frequency domain, each subcarrier holds a given symbol. These can be independently modulated.
- Transmitters are still operate in the time-domain. They are fed by a DAC that generates a series of analog inputs to a mixer and amplifier.
- So you need to take IFFT.
- The independent sinusoids in frequency domain result in a random combine

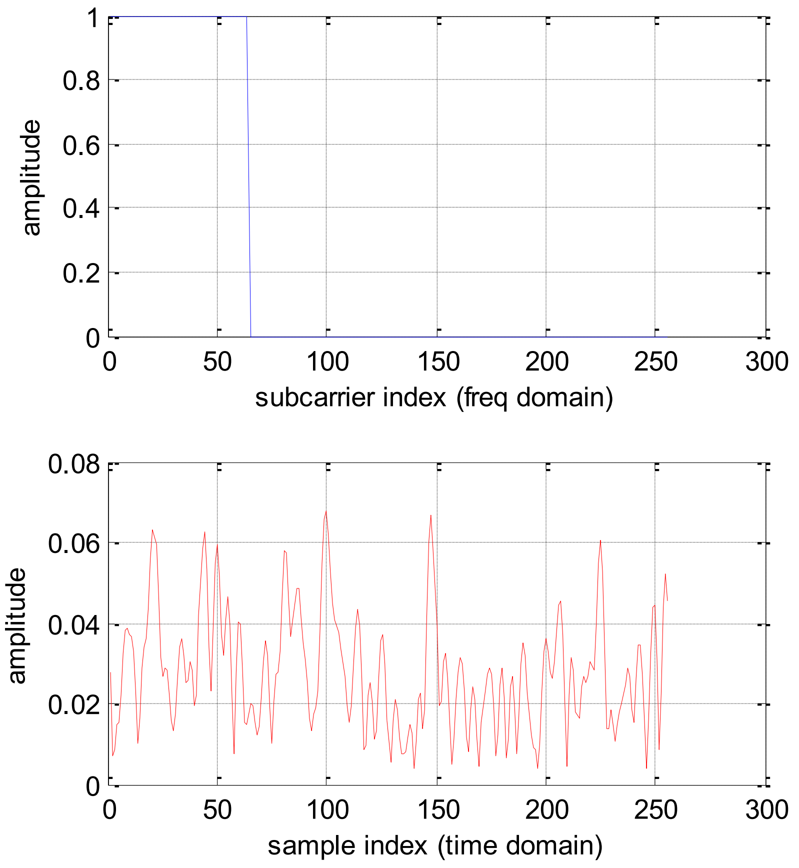


Simple case: Information carried by subcarrier phase only



An Additional Benefit

- OFDM allows you to have very steep attenuation outside of your desired operating frequency
- Allows use of adjacent band of frequencies bands or “channels” with very little gap
- Why is it important to place channels close together?



Review what we have:

- A modulation scheme that works well in a multiple path of propagation environment
- Signal that is transmitted has significant peaks and valleys in its amplitude

Another Pre-distortion Block Diagram