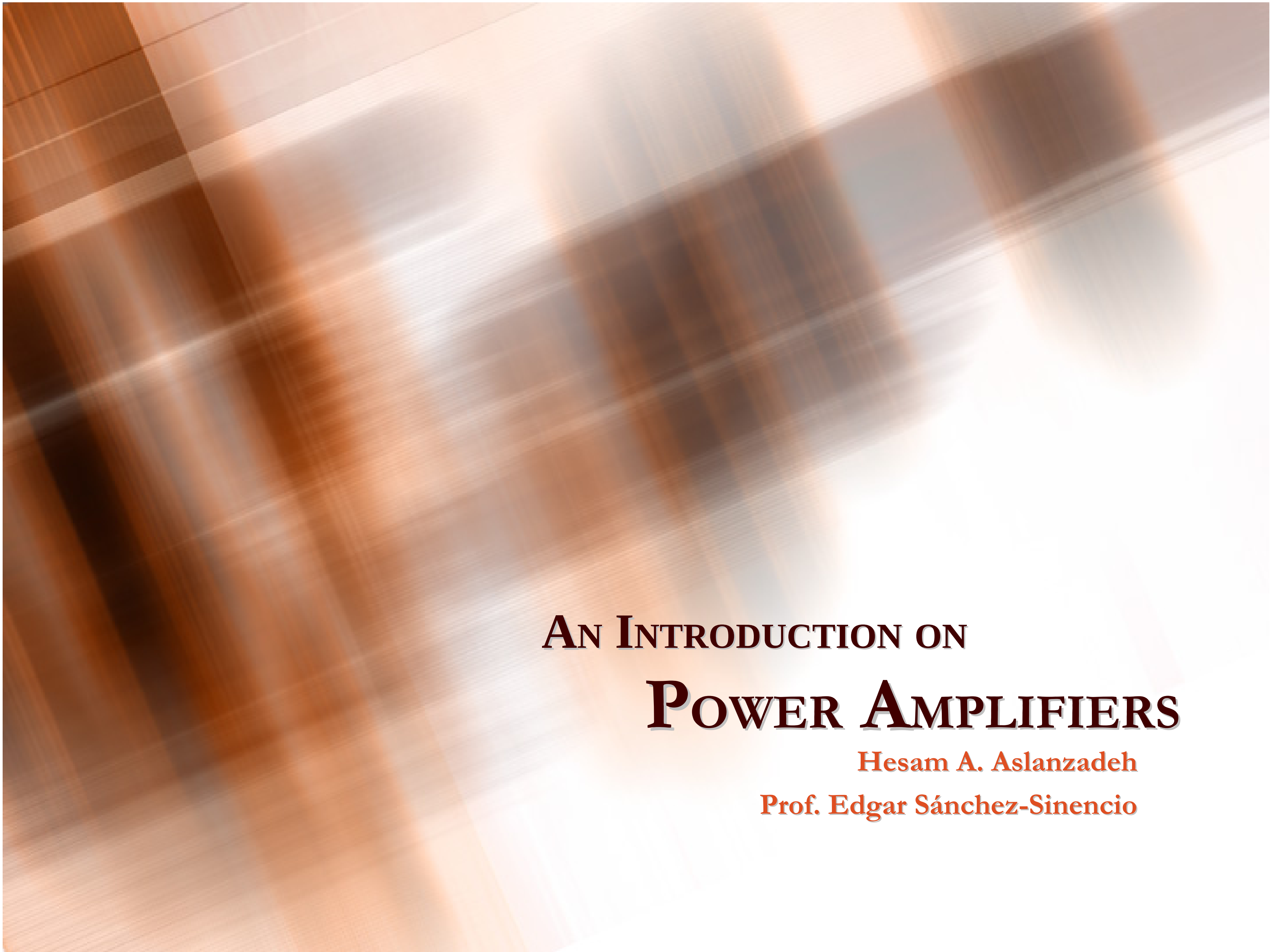


AN INTRODUCTION ON

POWER AMPLIFIERS

Hesam A. Aslanzadeh

Prof. Edgar Sánchez-Sinencio

Outline

- Introduction
- Power Amplifier Classes
  - Linear PAs
  - Switching PAs
- Lineariziation techniques
  - Input
  - Output
  - Supply

Introduction

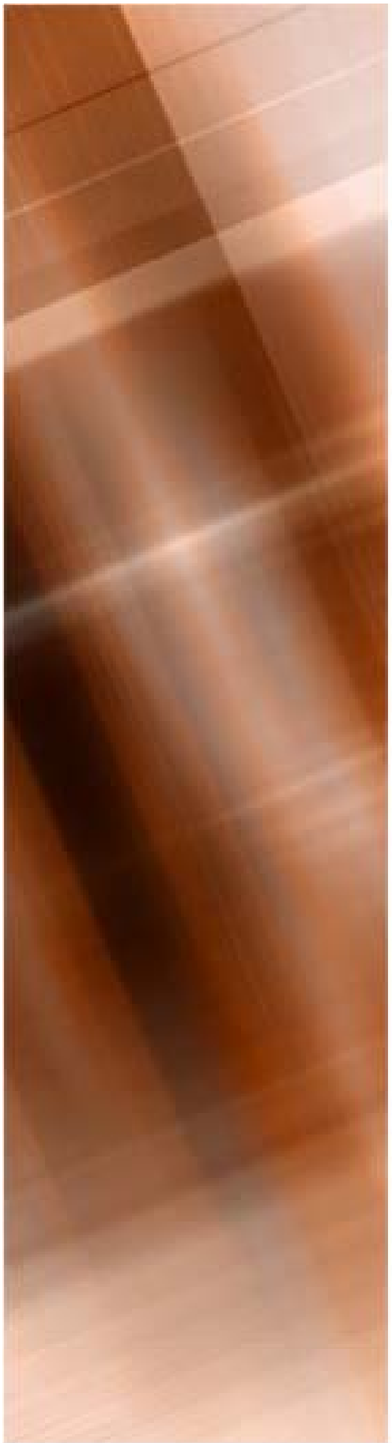
Performance Metrics

Why Power Amplifiers?

- RF Power Amplifier’s vast applications
  - Wireless and wireline communications
- Output transmitted power is relatively large portion of the total power consumption.
- Power efficiency of PAs can greatly influence overall power efficiency.

Power Amplifier performance metrics

- Metrics *defined* in standards
  - Output Power
  - Spectral Mask
  - ACPR (Adjacent Channel Power Ratio)
  - Signal Modulation
- Metrics *not defined* in standards
  - PAE (Power Added Efficiency)
  - Drain Efficiency
  - Power Gain
  - IIP3
  - $P_{1\text{-dB}}$



Output Power

- Power delivered to the load within the band of interest.
- Load is usually an antenna with Z_0 of 50Ω
- Doesn’t include power contributed by the harmonics or any unwanted spurs

- Sinusoidal $\longrightarrow$ $P_{out} = \dfrac{V_{out}^2}{2R_L}$
- Modulated Signal $\longrightarrow$ $P_{out/avg} = \int_0^\infty \varphi(p)\,dp = \dfrac{1}{T}\int_0^T v(t)\,dt$

Probability profile of Modulation: *Prob (P_{out}=p)*

Output Power

- Maximum output power varies drastically among different standards

Standard	Modulation	Max. P_{out}
AMPS	FM	31 dBm
GSM	GMSK	36 dBm
CDMA	O-QPSK	28 dBm
DECT	GFSK	27 dBm
PDC	π/4 DQPSK	30 dBm
Bluetooth	FSK	16 dBm
802.11a	OFDM	14-19 dBm
802.11b	PSK-CCK	16-20 dBm

Efficiency

- *Power Added Efficiency*; Most common efficiency metric

$$DC \xrightarrow{\qquad} RF \qquad \boxed{PAE = \frac{P_{out} - P_{in}}{P_{DC}} \times 100\%}$$

- Shows how efficiently supply DC power is converted to RF power
- Drain efficiency is often used to indicate the efficiency of a single power amplifier stage

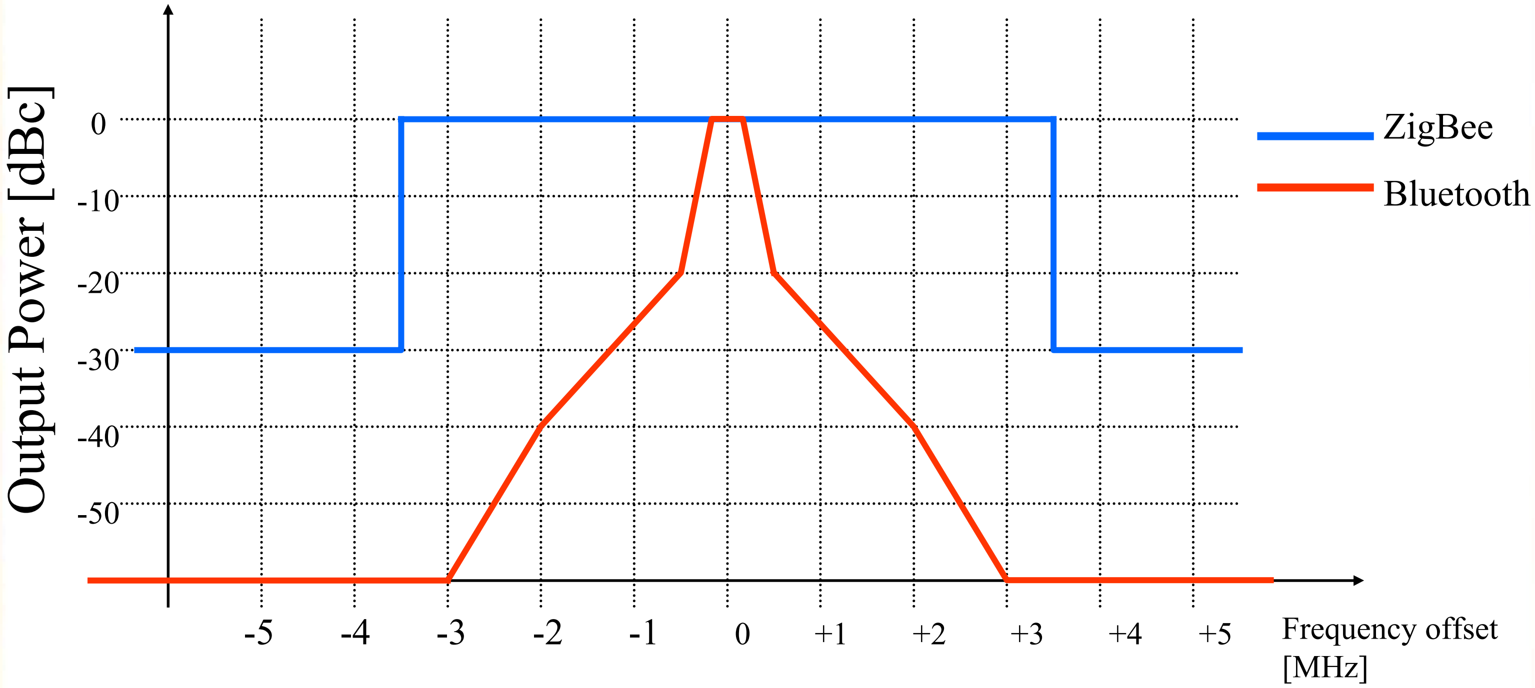
$$\eta_{drain} = \frac{P_{delivered}}{P_{DC}} \times 100\%$$

Linearity measures

- Linearity Requirement can be different based on modulation
  - Variable Envelope
    - Information is carried in the amplitude
    - $\pi/4$ $DQPSK$ and $OQPSK$
  - Constant Envelope
    - Information is carried in the phase
    - $GFSK$ and $GMSK$
- AM-to-AM, AM-to-PM distortion and $P_{1\text{-dB}}$
- Spectral Mask
- ACPR (Adjacent Channel Power Ratio)
- IP3

Linearity measures

- Power mask is an indication of how much spectrum regrowth is allowed

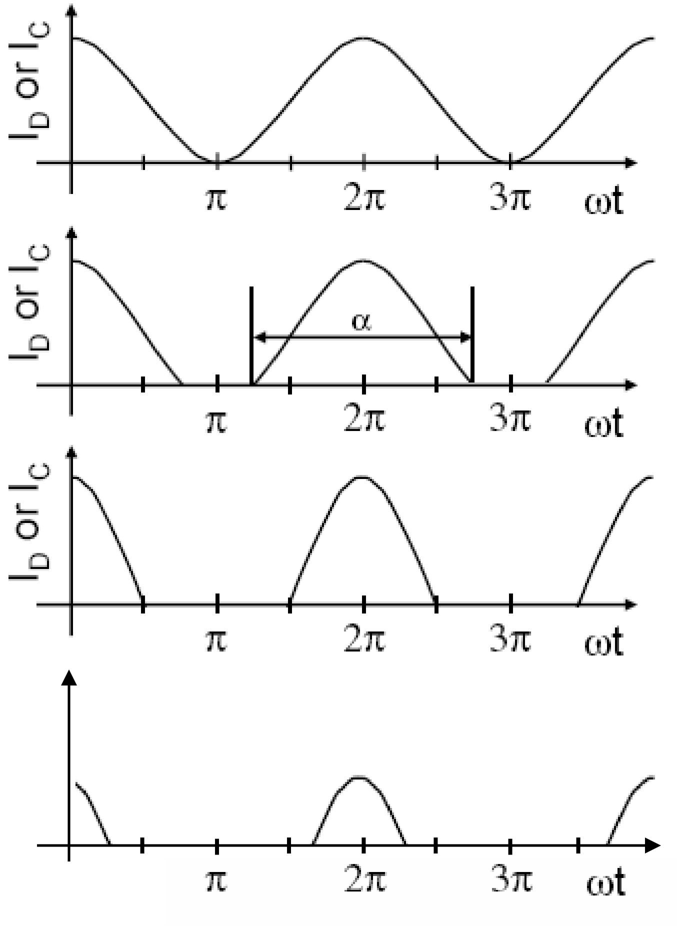


Introduction

Power Amplifier Class Types

PA Class types; Linear PAs

Conduction Angle:



Class A: $\alpha = 2\pi$

Class AB: $\pi < \alpha < 2\pi$

Class B: $\alpha = \pi$

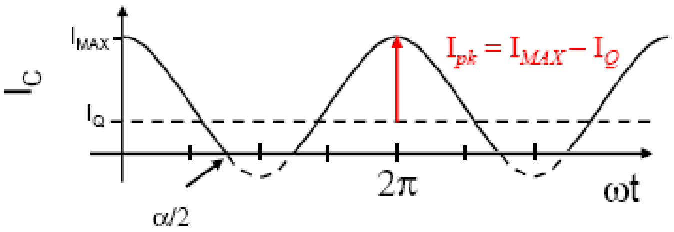
Class C: $\alpha < \pi$

Efficiency and conduction angle

- To calculate power efficiency, power of main harmony and DC current should be calculated

$$I_{dc} = (1/2\pi)\int_{-\alpha/2}^{\alpha/2} I_Q + I_{pk}\cos(\omega t)\, d\omega t$$ ← DC part of current

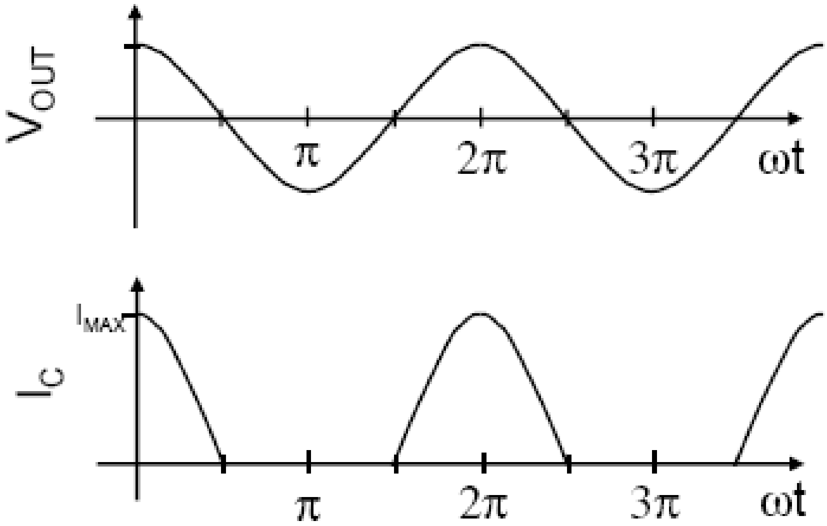
$$I_n = (1/\pi)\int_{-\alpha/2}^{\alpha/2} I_{pk}\cos(\omega t)\cos(n\omega t)\, d\omega t$$ ← n^{th} harmonic of current



$$\boxed{\cos(\alpha/2) = -\frac{I_Q}{I_{pk}} = -\frac{I_Q}{I_{MAX} - I_Q}}$$ ← Conduction angle

Output voltage shape

- If load tank filters out all harmonics, output voltage is pure sinusoidal even when there is current discontinuity



Efficiency

$$\boxed{\eta = \frac{P_1}{P_{dc}} = \frac{I_{1,rms}.V_{1,rms}}{I_{dc}.V_{dc}}}$$

Class A: $$\begin{cases} I_1 = \dfrac{I_{MAX}}{2}, \; I_{dc} = \dfrac{I_{MAX}}{2} \\ \eta = \dfrac{\left(\dfrac{I_{MAX}/2}{\sqrt{2}}\right)\left(\dfrac{V_{DD}}{\sqrt{2}}\right)}{\left(\dfrac{I_{MAX}}{2}\right).V_{DD}} = 50\% \text{ max}. \end{cases}$$

Efficiency

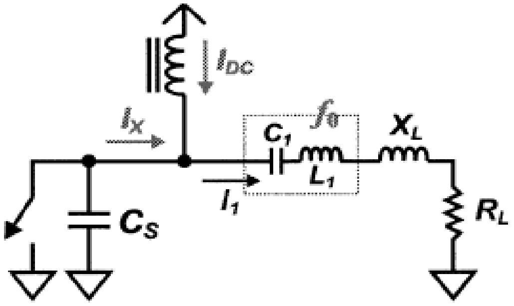
Class B:

$$\begin{cases} I_1 = \dfrac{I_{MAX}}{2}, \quad I_{dc} = \dfrac{I_{MAX}}{\pi} \\ \eta = \dfrac{\left(\dfrac{I_{MAX}/2}{\sqrt{2}}\right)\left(\dfrac{V_{DD}}{\sqrt{2}}\right)}{\left(\dfrac{I_{MAX}}{\pi}\right).V_{DD}} = 78\% \text{ max}. \end{cases}$$

- Class C efficiency depends on α and ideally can reach 100% but at that point output power also reaches zero!

Class E

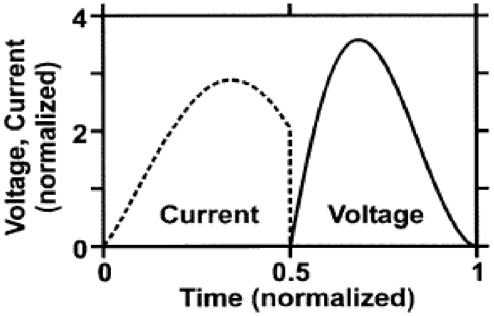
- Loading network is carefully designed so that before switch turns on (Soft switching) :
  - $V_s = 0$ **ZVS** ☺
  - $\frac{\partial V_s}{\partial t} = 0$



- Non-overlapping voltage and current minimize switch power consumption ☺

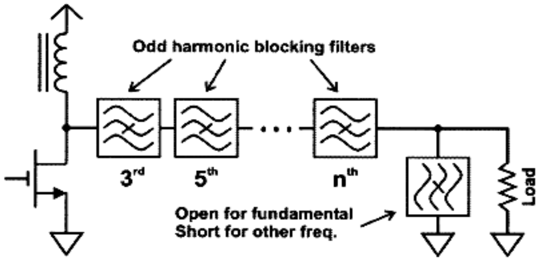
$\max(V_D) = 3.6V_{DD}$ ☹

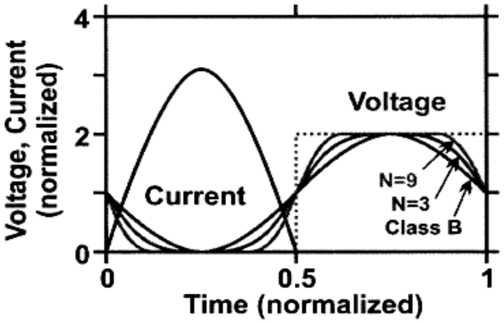
- So low-voltage operation is neede for reliability



Class F

- By adding odd harmonics :
  - Drain voltage starts to increasingly resemble square wave
  - Decreasing the voltage across transistor during conduction time and hence increasing efficiency





- **All-harmonics-tuned=>class D**
- $\max(V_D) = 2V_{DD}$ ☺
- Not ZVS operation ☹

Linearization Techniques

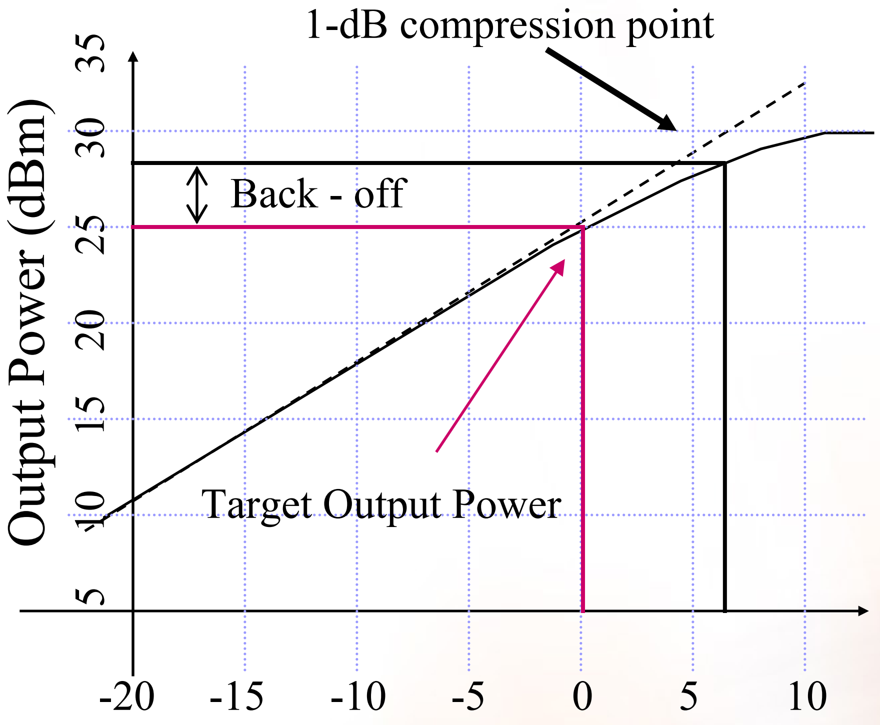
How to linearize highly efficient PAs?

Linearization Techniques

- Non-linear power amplifier can reach great efficiencies
- But they lack linearity
- Linearization techniques can be applied to non-linear PAs to get a *good* linearity and a *modest* efficiency
- Control is applied at
  - **Input**
    - Back-off
    - Pre-distortion
    - Cartesian feedback
    - Polar feedback
  - **Output**
    - Feed-forward
    - LINC (Linearization using Nonlinear Components)
  - **Supply**
    - EER (Envelope Elimination and Restoration)

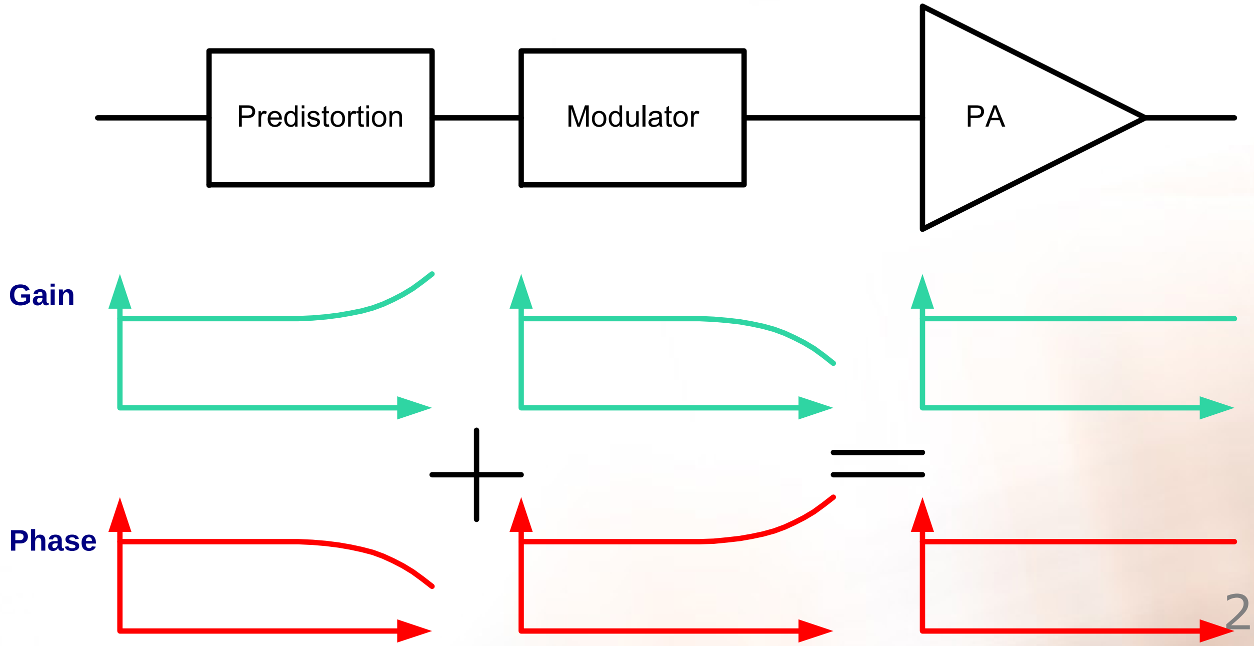
Input: Back-off

- Simplest and most common linearization
- PAE is greatly reduced ☹



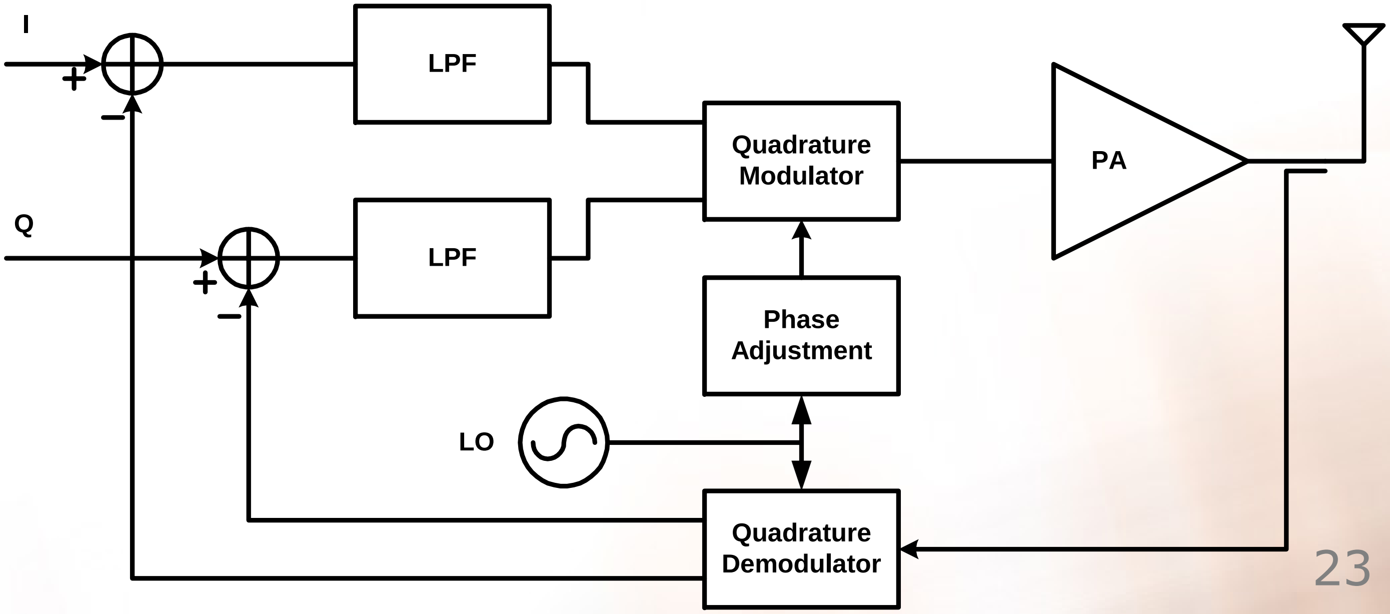
Input: Pre-distortion

- Tracking gain and change variations of amplifier is very challenging using analog techniques
- Digital Look-up tables often used
- PA gain and phase response varies with bias, temperature and supply changes ☹

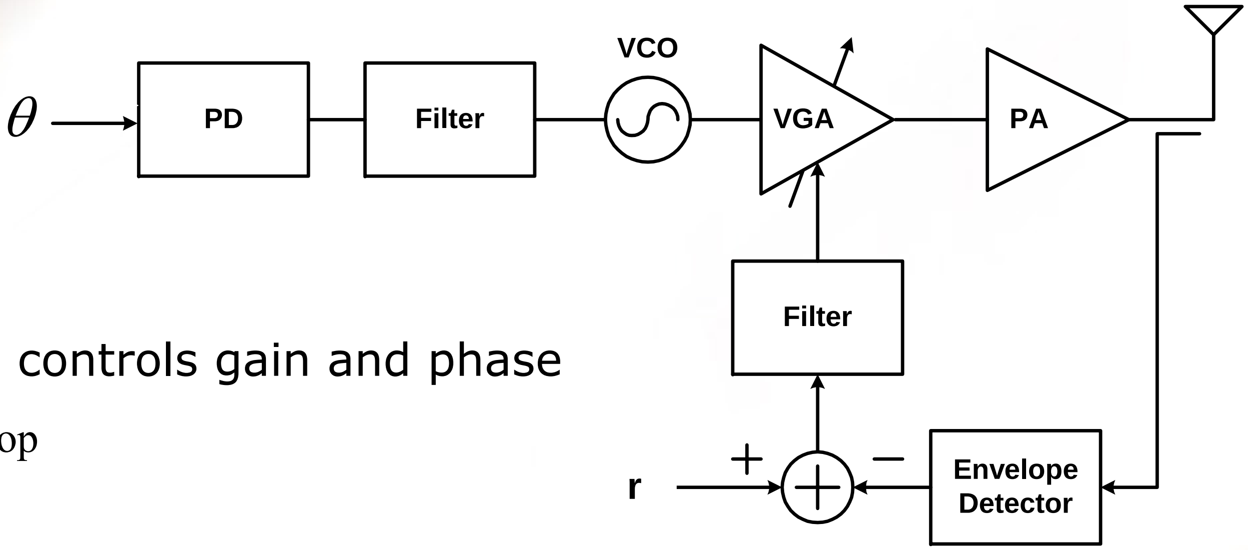


Input: Cartesian Feedback

- Feedback is used to increase linearity
- Large loop gain is needed to improve linearity; very difficult to achieve at RF frequencies
- Down-converting alleviates this problem
- Stability is a big challenge



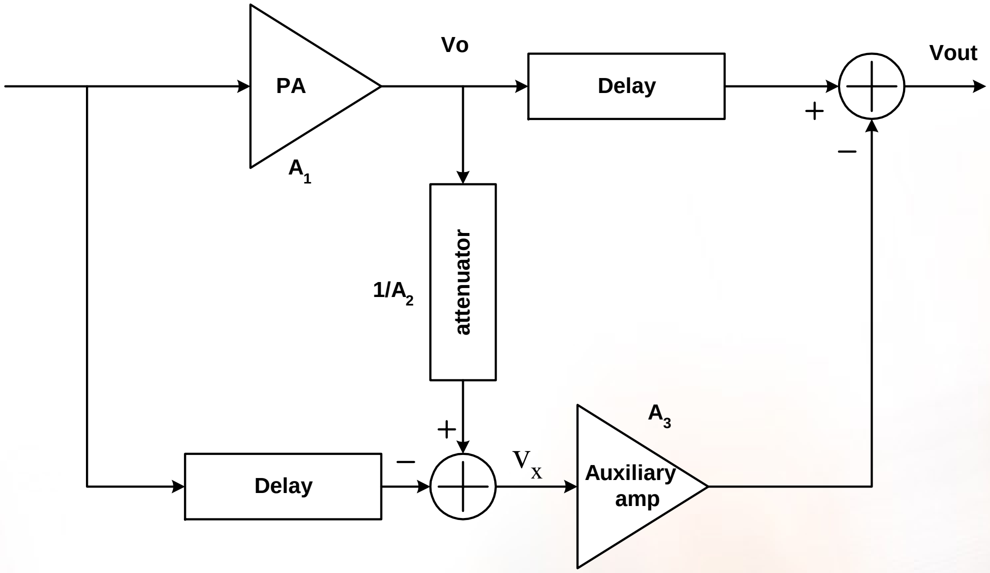
Input: Polar feedback



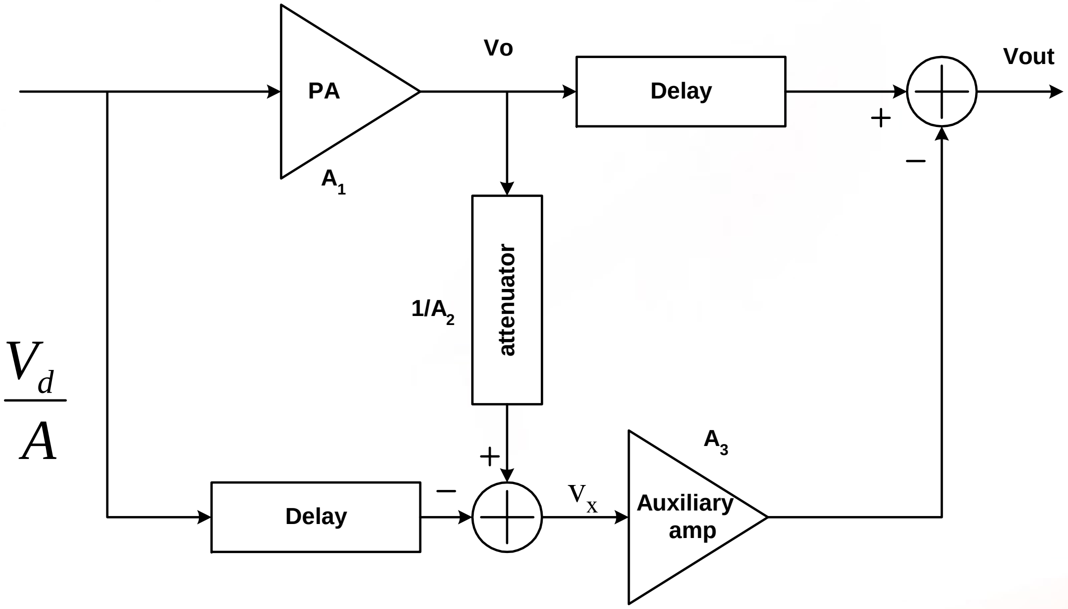
- Two loop controls gain and phase
  - Gain loop
  - PLL
- Doesn't require up/down conversion
- If AM/PM distortion of PA is not severe, phase feedback is not needed
- Stability challenging
- Polar feedback loops should operate at wider bandwidth compared to Cartesian feedback

Output: Feed-forward

- Distortion is calculated and subtracted from output:
  - Precise matching of A1, A2, A3 needed
  - Tracking over process, time and temp is tough
  - Constant analog Delay is challenging
  - Stability is not a problem
- Operates at the bandwidth of carrier frequency rather than base band hence applicable in multi-carrier systems



Output: Feed-forward Analysis



$$V_o = AV_{in} + V_d, \qquad V_x = \frac{V_o}{A} - V_{in} = \frac{V_d}{A}$$

$$\Rightarrow V_{out} = V_o - A\left(\frac{V_d}{A}\right) = \boxed{AV_{in}}$$

- Gain and phase mismatch can degrade linearity of power amplifier [*]:

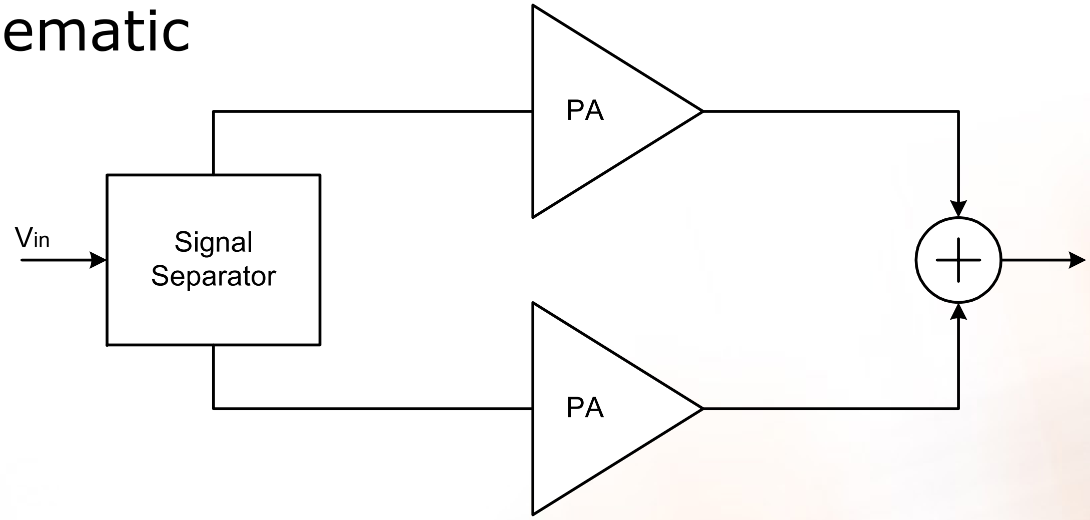
$$\Delta IP3 = \sqrt{1 - 2\left(1 + \frac{\Delta A}{A}\right)\cos\Delta\phi + \left(1 + \frac{\Delta A}{A}\right)^2}$$

[*] B. Razavi, *RF Microelectronics*

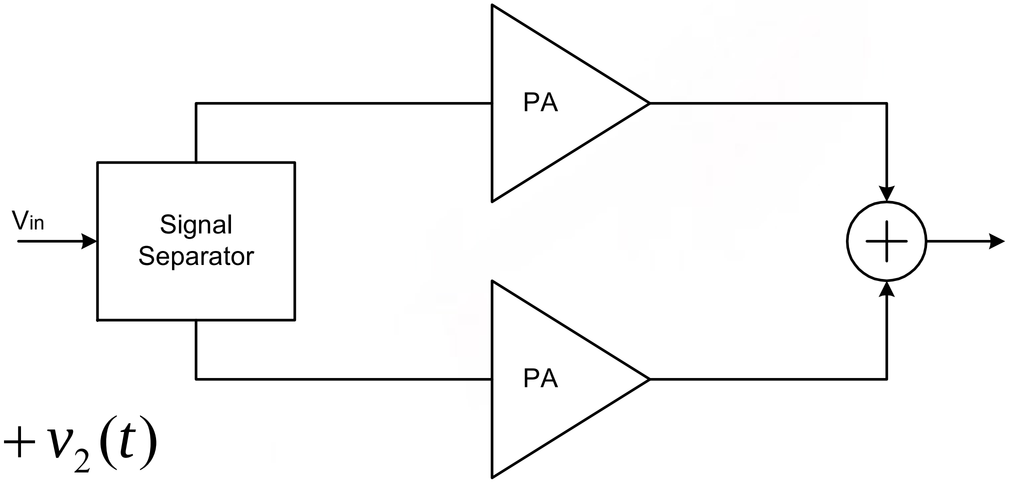
Output: LINC

(Linear Amplification using Nonlinear Components)

- Theoretically any non-constant envelope signal on a carrier can be split into two constant-envelope signals
- A complex conversion at RF is very challenging task
- Signal combination at output is practically problematic



Output: LINC Analysis



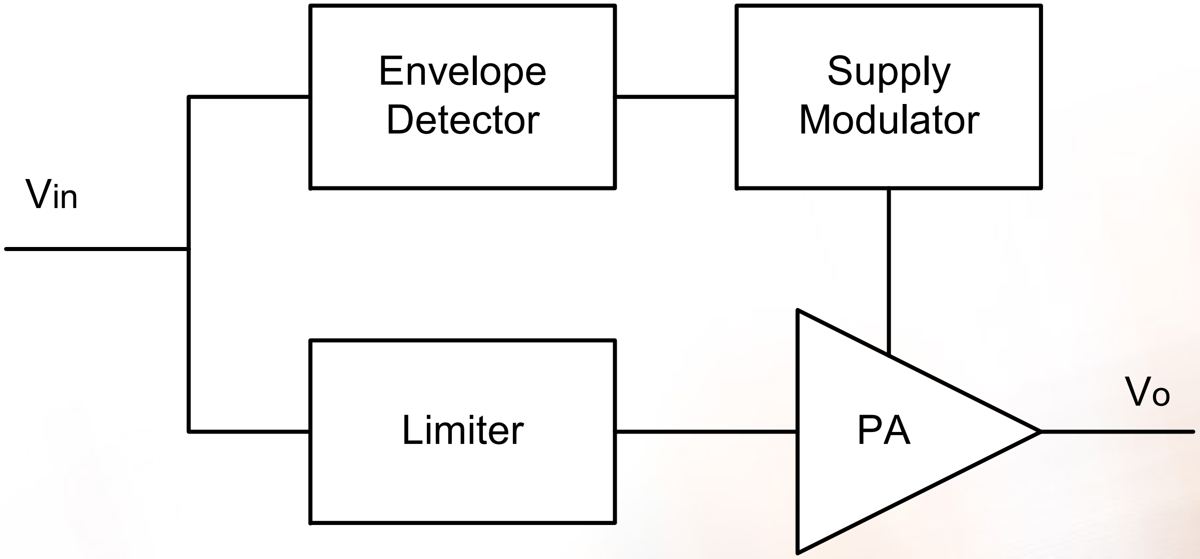
$$v_{in} = a(t)\cos[\omega_c t + \varphi(t)] = v_1(t) + v_2(t)$$

$$\begin{cases} v_1(t) = \frac{1}{2}V_0 \sin[\omega_c t + \varphi(t) + \theta(t)] \\ v_2(t) = -\frac{1}{2}V_0 \sin[\omega_c t + \varphi(t) - \theta(t)] \end{cases}$$

$$\theta(t) = \sin^{-1}\left[\frac{a(t)}{V_0}\right]$$

Supply: EER
(Envelope Elimination and Restoration)

- Amplitude and phase are amplified separately
- Amplitude information is fed at the output by supply
- Substantial power could be dissipated in the supply modulation circuitry providing the whole current of PA
- Dc-to-dc can be used but still delivered current is quite large
- Delay mismatch between two paths introduces distortion



For more information:

- Power Amplifier notes of MIT OpenCourseWare
- Steve C. Cripps, *Advanced Techniques in RF Power Amplifier Design*, Artech House Publishers
- Mohammed Ismail and Mona Hella, *RF Cmos Power Amplifiers: Theory, Design and Implementation*
- Several Thesis on PAs

Some Research Ideas

- Design a non-linear Power Amplifier for output power of 10 dBm delivered to the load of 50Ω antenna at the operating frequency of 2.4 GHz. Optimize the efficiency. Measure linearity (IIP3). Then use one linearization technique to increase IIP3 to 30 dBm. Efficiency will be decreased as a result of overhead circuits. Can we come up with a different kind of linearization technique to reduce complexity and power consumption of overhead?
- Design a signal separator at 2.4 GHz to be used in LINC technique.