Sharif University of Technology

Power Amplifier

Instructor:

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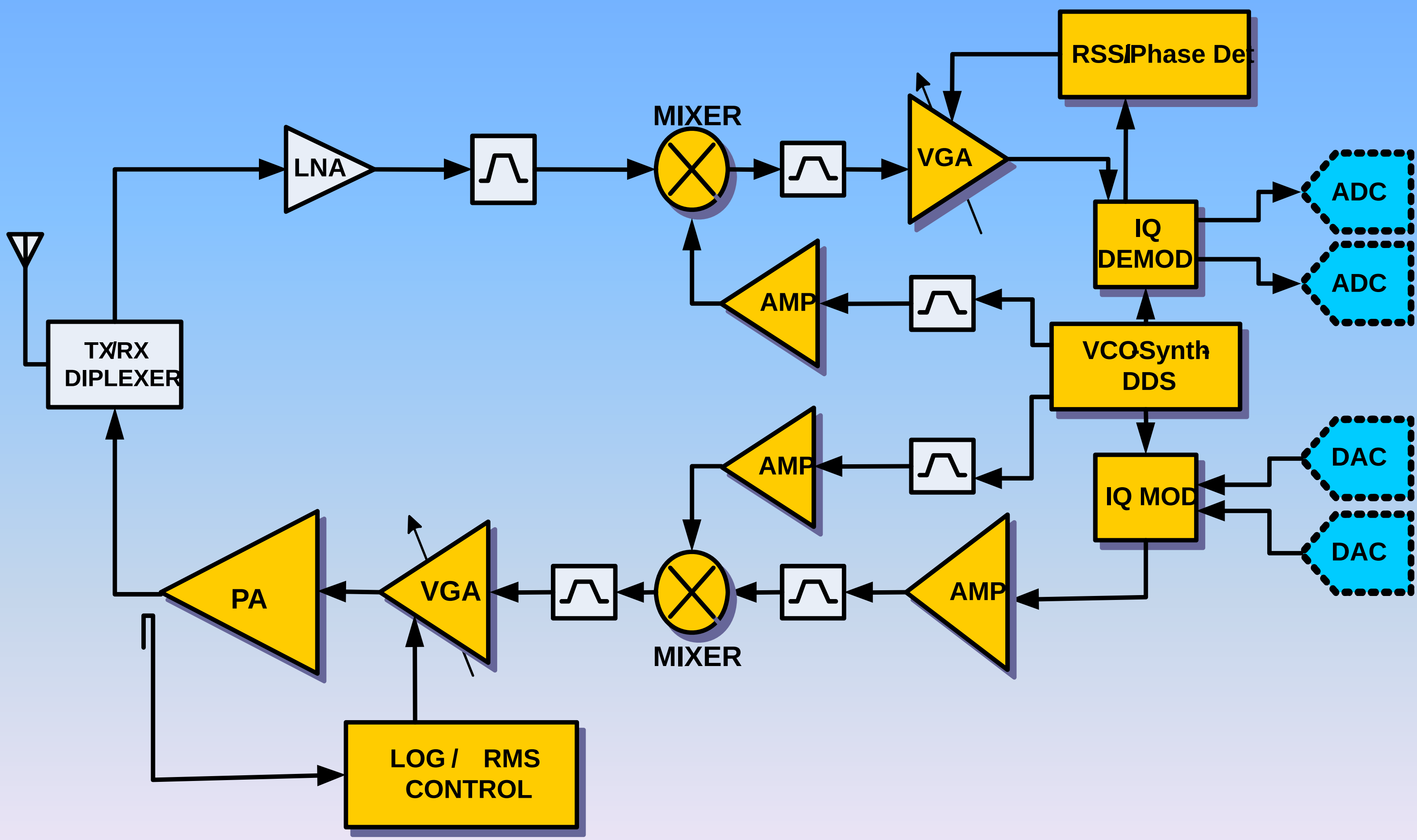
Outline

- **Introduction**
- **Some Important Definitions**
- **PA Classes**
  - **Linear**
  - **Non-linear**
- **Linearization Techniques**
- **Conclusion**

System Schematic



PA Specifications

- Gain (Gain Flatness)
- Power consumption
- Linearity
- Signal peak to mean ratio
- Bandwidth
- Frequency band (transmit and receive)
- Power delivered
- Permissible in-band emission
- Permissible out-of-band emission
- Stability over VSWR
  - Ability to transmit into unknown/varying load
- Efficiency
  - Minimize any lose in the form of heat & noise
- Size
  - Find the minimum size as much as possible

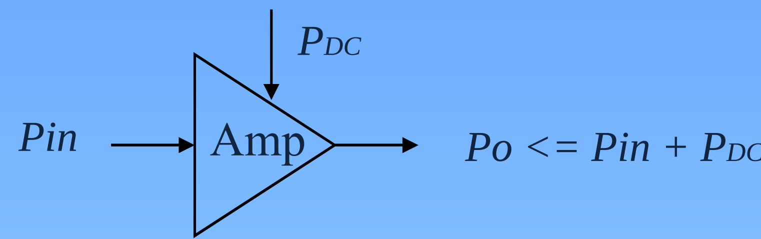
Peak Output Power

- **Determines the range for two-way communications**
- **Often specified at the 1-dB compression point**
- **Some examples:**
  - **Need about 1-2 W for cellular handsets (~1 km distance)**
  - **Need about 100mW for W-LAN (100 m)**
  - **Need about 10mW for W-PAN (Bluetooth) (1-10 m)**
  - **Need about 1mW for UWB and sensor networks**
- **The average power transmitted may be much lower**
  - **Power control (slow time scale)**
  - **Amplitude modulation**

Efficiency

- Remember- COST is major driving factor!
- The associated power supply and heat sink can be <u>incredibly</u> expensive
- For lower power systems, (below 10mw) ,power consumption of other block is important too

Efficiency Measurement



- **Drain Efficiency**
  - **P_{OUT} includes harmonics power**

$$\eta_D = \frac{P_{out}}{P_{dc}}$$

- **Power Added Efficiency**
  - **Account drive power**
  - **Could be negative for low gain!**

$$\eta_{PA} = \frac{P_{OUT} - P_{IN}}{P_{DC}} = \eta_D \cdot \left(1 - \frac{1}{G}\right)$$

- **Total efficiency**

$$\eta_{total} = \frac{P_o}{P_{DC} + P_{in}}$$

- **When power gain is high**

$$\eta_{PAE} \approx \eta_c \approx \eta_{total}$$

High PAPR

- There are some ways ,such that…
  - Drain modulation
  - Load modulation
  - RF PWM
    - In low frequency
    - BUT, broadband
- Some linearization schemes may reduce the overall efficiency!!!

Signal Types

- There are two categories including:
  - Constant-envelope
    - Data is in phase or frequency
    - Non-linear PA can be used
    - Abrupt frequency or phase transitions
      - Sinc-function spectrum
        - » Spreads signal energy over a wide BW
        - » Data rate will be reduced
  - Non-constant envelope
    - Linear PA should be used
    - Data is in envelope, too
    - Higher data rate

Constant Envelope Modulation

- Information encoded in phase/frequency only
  - GMSK,FSK
- Power efficient amplification

BUT, spectrally inefficient

Non-Constant Envelope Modulation

- **Information encoded in both amplitude and phase**
  - **QPSK,QAM,CDMA**
- **Spectral efficient ,**

BUT power inefficient!

PAPR

- **Peak to average Power Ratio**
  - **Peak power over average power**

- **PAPR is a strong function of the type of modulation**

Average Efficiency

- **Important for non-constant envelope**
  - **There is time-varying instantaneous efficiency**

$$\eta_{AVG} = \frac{P_{outAVG}}{P_{inAVG}}$$

- **Modern systems uses power control**
  - **Uses as low as possible power**

Basics of non-Linearity

- Large signal behavior of the semiconductor devices is nonlinear
  - Power amplifiers are nonlinear systems
- Nonlinearity leads to
  - Generation of Harmonics
  - Intermodulation Distortion / Spectral Regrowth
  - SNR (NPR) Degradation
  - Constellation Deformation

Linearity Measurment

- **Some ways to measure non-linearity:**
  - **ACPR (Adjacent Channel Power Ratio)**
  - **EVM (Error Vector Magnitude)**
  - **Spectral Mask**
  - **P_{1dB}**
  - **C/I**
  - **NPR (Noise-Power Ratio)**

AM-AM distortion

System transfer function:

$$y(t) = \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t) + \ldots$$

Input signal:

$$x(t) = A(t)\cos(\omega t + \phi(t))$$

Output signal:

$$y(t) = g[A(t)]\cos(\omega t + \phi(t) + \psi[A(t)])$$

- **AM/AM conversion is dominated by g_m non-linearity**

AM-PM Distortion

- Phase shift associated with the signal amplitude
- Introduction of unwanted phase modulation into the output signal
- Phase modulation observed
  - Depending of the input amplitude
- AM-PM is often the result of voltage dependent capacitors

AM-PM Conversion

$$V_{out} = B(t)Cos(\omega t + \varphi(t))$$

$$C = C[V_{out}(t)] \Rightarrow \overline{C} \approx \overline{C[B(t)]}$$

$$\varphi(t) = \tan^{-1}(RC[B(t)]\omega)$$

$$\overline{\varphi} \approx \tan^{-1}(R\overline{C}\omega)$$

$\overline{C}$ **= Average capacitor value at the fist harmonic**

$\overline{\varphi}$ **=Average phase at the fist harmonic**

TX Spectrum Mask

ACPR

- **Adjacent (Alternate) Channel Power Ratio**
  - **Is the ratio of the power in a specified band outside the signal bandwidth to the rms power in the signal**
  - **Widely used with modern shaped pulse digital signals such as NADC and CDMA**

EVM

- **Error Vector Magnitude**
  - **A convenient measure of how nonlinearity interferes with the detection process**
  - **the distance between the desired and actual signal vectors, normalized to a fraction of the signal amplitude**
    - **both peak and rms errors are specified**

$$EVM = \sqrt{\frac{\sum_{k=1}^{M} \left\| V(K) - R(K) \right\|^2}{\sum_{k=1}^{M} \left\| R(K) \right\|^2}}$$

$$EVM = \sqrt{\frac{\sum_{k=1}^{M} \left\| V(K) - R(K) \right\|^2}{\sum_{k=1}^{M} \left\| R(K) \right\|^2}}$$

Constellation Deformation

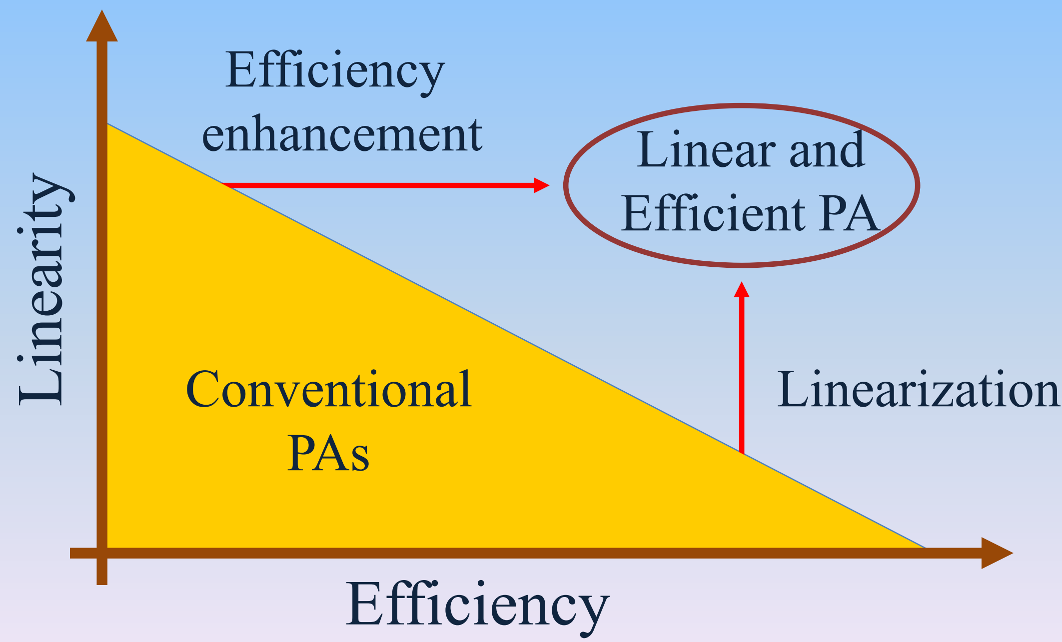
Input Signal

Output Signal of Nonlinear Amplifier
(with Gain- and Phase-Distortion)

PA Design Challenges

Power Amplifier design challenges:

- **Long talk time** → High efficiency
- **High data rate** → High linearity



C/I Measure

- Carrier-to-Intermodulation ratio
  - The PA is driven with two or more carriers (tones) of equal amplitude
  - IMD will be produced
    - Corresponding to sums and differences of multiples of the carrier frequencies
  - A typical linear PA has a C/I of 30 dB or better

PA Classes

- **Linear operation**
  - **Classes A,B,AB and C**
  - **Amplitude modulation**
  - **Multi-carrier signals**
  - **Transistor works as a transducer**
  - **The RF output power is proportional to the RF input power**
  - **Narrow band and broadband applications**
- **Switching mode (Non-linear)**
  - **Classes D,E,F**
  - **Constant-envelope operation**
  - **Transistor operates as a switch**
  - **Narrow band applications**

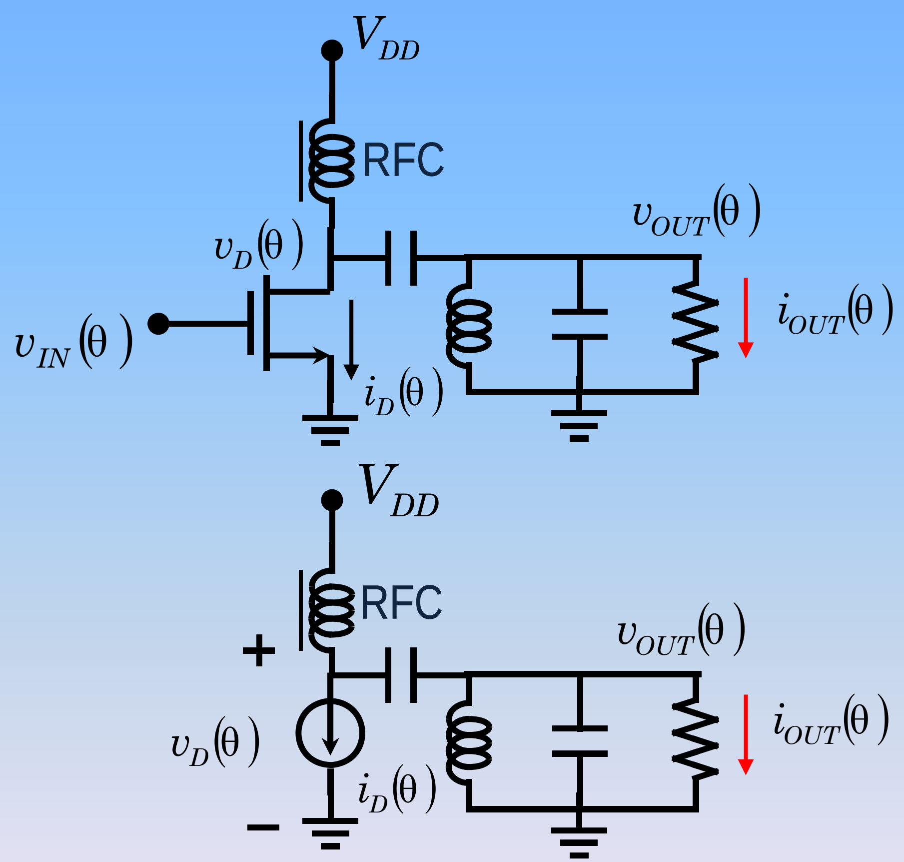
How preserve Linearity?

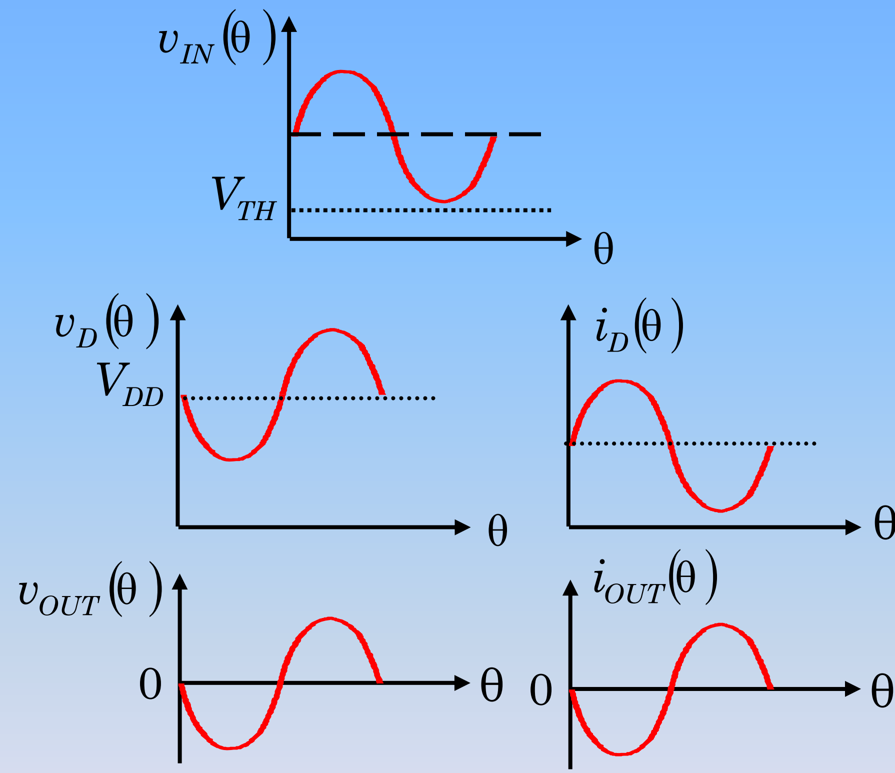
- Backed-Off Operation of PA
  - Simplest Way to achieve Linearity
- Linearity improving Concepts
  - Predistortion
  - Feedforward
  - EER
  - ...

Basic Linear PA Circuit

ISSCC 2007 GiRaFe Forum

Class A RF Power Amplifier





$$P_{RFout} = \frac{V_{om}^2}{2R} \le \frac{V_{DD}^2}{2R}$$

$$\eta_{Drain} = \frac{P_{RFout}}{P_{DC}} = \frac{V_{om}^2 / 2R}{V_{DD}^2 / R} = \frac{V_{om}^2}{2V_{DD}^2} \le \frac{1}{2}$$

Class A Characteristics

- There is no harmonic
  - Can be used at frequencies near f_{max} of the transistor
- Applications:
  - High linearity
  - High frequency operation
  - High gain
  - Broadband operation

Some Practical Considerations

- Used as low-level driver for efficient PAs
- Used for laboratory equipments
  - Very low-distortion amplifiers
- LC circuit is not necessarily
  - Can operate over a wide frequency range
- No difference between small signal and class A PA
- BJTs have V_{sat} ➔ limits voltage swing

Class A Specifications

- High linearity
- Low drain efficiency of 20-30%
- Power added efficiency of 20%
- Capable of working at higher frequencies relative to f_T, up to ½-1/3 of f_T
- Can amplify non-constant envelope signals
- Capable of broadband amplification

Class A Considerations

- **Typical efficiency is lower than 40% for "linear" operation**
  - **Efficiency actually drops down when the signal level is lower.**
- **Output power capability (transistor utilization factor)**

$$P_N = \frac{P_o}{V_{\max} I_{\max}} = \frac{\frac{1}{2}\frac{V_{\max}}{2}\frac{I_{\max}}{2}}{V_{\max} I_{\max}} = \frac{1}{8}$$

- **Dynamic class A is attractive**

CLASS A RFPA Performance

Class B

- Lower dc current
  - Lower power dissipation
  - Lower f_t

Push-Pull Class B

- **Two devices are driven 180 degrees out-of-phase**
- **They are alternately active or cut-off**

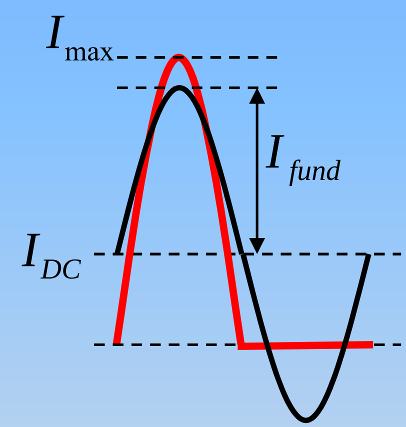
Class B

- **All harmonics exist**

harmonic termination:
open @ w, and short @ 2w, 3w,…

$$I_{fund} = \frac{I_{\max}}{2} = I_{CQ,A}$$

$$I_{DC} = \frac{I_{\max}}{\pi} < I_{DC,A}$$



$$P_{out,\max} = \frac{1}{2}\left(V_{CEQ} - V_{\min}\right)\left(I_{fund}\right)$$

$$\eta_{c,\max} = \frac{P_{out,\max}}{P_{DC}} = \frac{\frac{1}{2} V_{CC} \frac{I_{\max}}{2}}{V_{CC} \frac{I_{\max}}{\pi}} = 78.5\%$$

pure sinusoidal waveform
of current flow

$$P_N = \frac{1}{8} \quad \text{(same as class A)}$$

Class AB Characteristics

- **Conduction angle is between 0 degree and 180 degree**

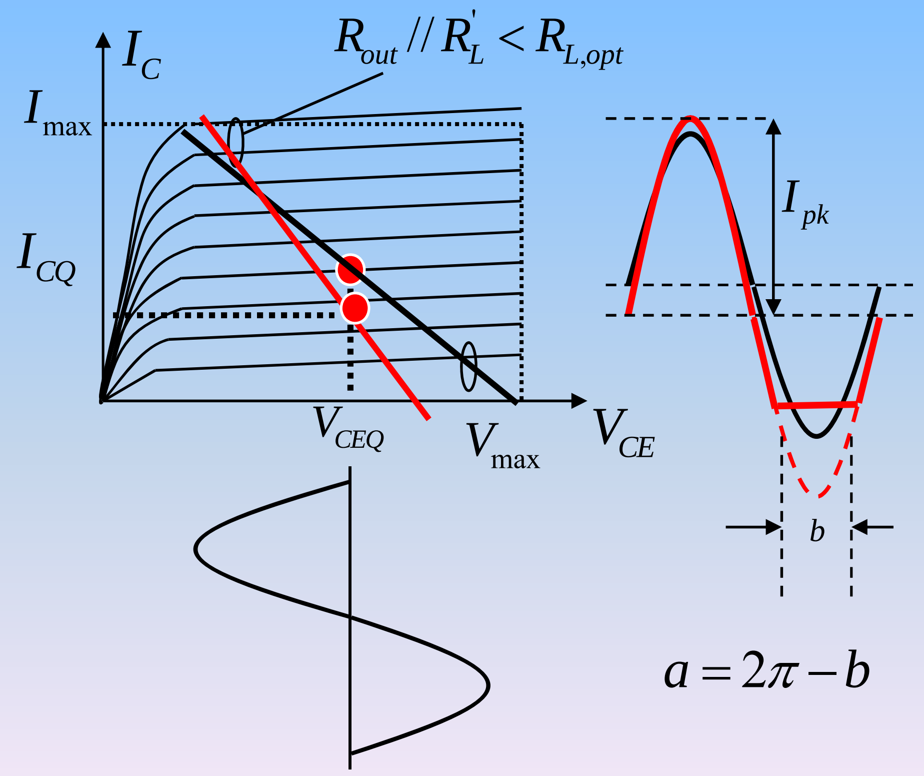
$$\text{Let } \theta \equiv \omega_o t$$

$$I(\theta) = \begin{cases} I_{CQ} + I_{pk}\cos\theta & -\frac{a}{2} \le \theta \le \frac{a}{2} \\ 0 & \text{theother} \end{cases}$$

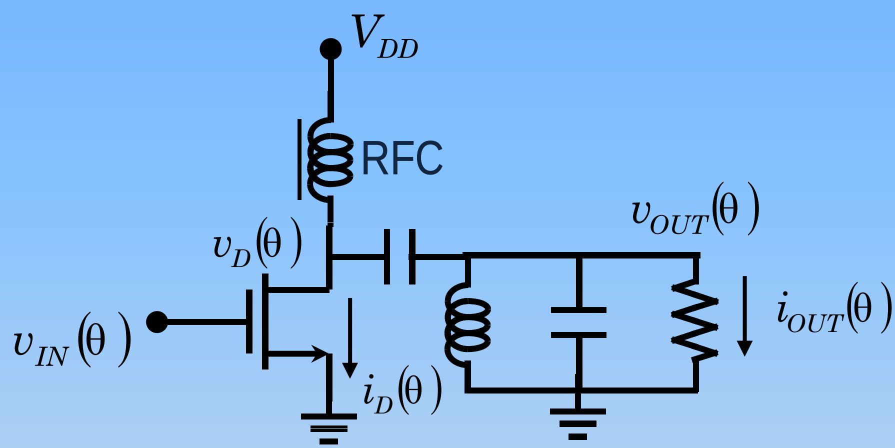
$$\text{From } I_{CQ} + I_{pk}\cos\frac{a}{2} = 0 \Rightarrow \cos\frac{a}{2} = -\frac{I_{CQ}}{I_{pk}}$$

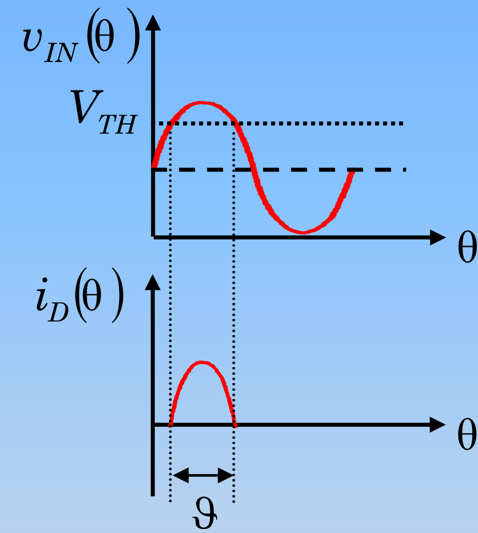
$$\Rightarrow I_{pk} = I_{\max}\frac{1}{1-\cos\frac{a}{2}}, I_{CQ} = I_{\max}\frac{-\cos\frac{a}{2}}{1-\cos\frac{a}{2}}$$

$$\Rightarrow I(\theta) = I_{\max}\frac{\cos\theta - \cos\frac{a}{2}}{1-\cos\frac{a}{2}}$$



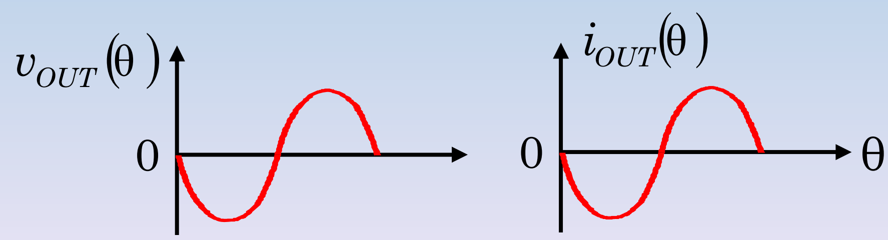
Class C Amplifier Waveforms





$$P_{RFout} \propto \frac{\vartheta - \sin\vartheta}{1 - \cos(\vartheta/2)}$$

$$\eta_{Drain} = \frac{P_{RFout}}{P_{DC}} = \frac{1}{4}\,\frac{\vartheta - \sin\vartheta}{\sin(\vartheta/2) - \vartheta/2\,\cos(\vartheta/2)}$$



Class C Amplifier

- Biased such that conduct less than 50% of time
- Specifications
  - Efficiency achieved
  - Large device is needed
  - Impractical for solid-state circuit

Class C Considerations

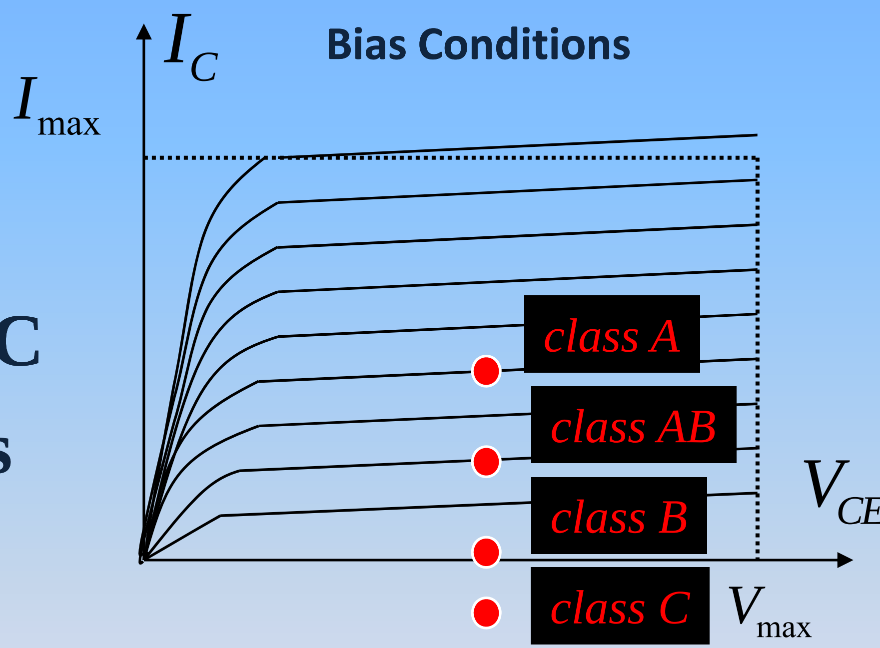
- **Higher efficiency, BUT lower output power**
- **Lower output power capability**
  - **Maximum @ 245.2 degrees ➔ C_p=0.1341**
- **The choice of conduction angle is trade off between**
  - **Output power**
  - **Efficiency**
  - **Power gain**

Types of Class C

- There are 3 types
  - Current-Source Class C Amplifiers
    - Transistor never saturates
    - Acts as controlled-current source
  - Saturated Class-C Amplifiers
    - Transistor acts in saturation region in a portion of conduction
  - Class C Mixed Mode Amplifiers

Comparison

- **From class A to C bias current will be decrease**
  - **– Lower f_t from class A to C**
  - **– BUT, efficiency increases**



Comparison

Comparison

COMPARISON

- **Numerical value of PA under different operation**

	Class A	Mid-Class AB	Class B	Mid-class C	Class C
b	0	90	180	270	360
I_{CQ}	Imax/2	0.41*Imax	0	0	0
I_{DC}	Imax/2	0.44*Imax	Imax/π	0.16*Imax	0
I_{fund}	Imax/2	0.53*Imax	Imax/2	0.31*Imax	0
$\eta_{c,max}$	50%	60%	78.5%	~100%	(~100%)

SMPA

- **Major part of power dissipation is due to transistors**
- **Single pole-single through switch is used**

SMPA

Voltage and current waveforms in a switching-mode amplifier

SMPA

SMPA IDEA

- **Filter is used**
  - **Parallel LC shunt**
  - **Series LC tuned**
- **Filter increases the efficiency**

SMPA Idea

- **Parallel LC filter**

SMPA Idea

- **Series LC tuned filter**

General SMPA switching conditions

A

B

- **Two models:**
- **Model A is better**

$$P_{C,Loss} = \frac{1}{2} \cdot C \cdot V_c^{\,2} \cdot f \qquad P_{L,Loss} = \frac{1}{2} \cdot L \cdot I_L^{\,2} \cdot f$$

- **Minimzation of losses at RF requires:**
  - **V_c = 0 when switch closes at t = 0**
    - **Zero voltage switching condition (ZVS)**
  - **Even better: dV_c/dt = 0**

Class D Power Amplifier

- Transistors act as to pole switch
- Suffers from losses
  - Saturation
  - Switching speed
  - Drain capacitor
    - Dissipation occurs
      - Proportional with F
      - Limited to VHF

Other Categories

- **Complementary Voltage Switching (CVS) Circuit**
- **Transformer-Coupled Voltage Switching (TCVS) Circuit**
- **Transformer-Coupled Current Switching (TCCS) Circuit**

CVS Class D

- Parallel LC can not be used
- In ideal condition
  - Zero saturation voltage
  - Zero saturation resistance
  - Infinite OFF resistance
  - Instantaneous and lossless switching

CVS Waveforms

- Switch capacitance limits efficiency in high frequency applications

Class-D and Class-D^{-1} Amplifiers

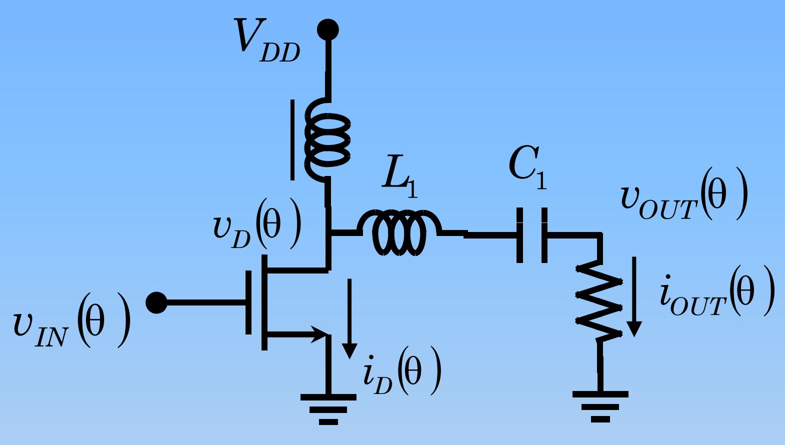
TCVS

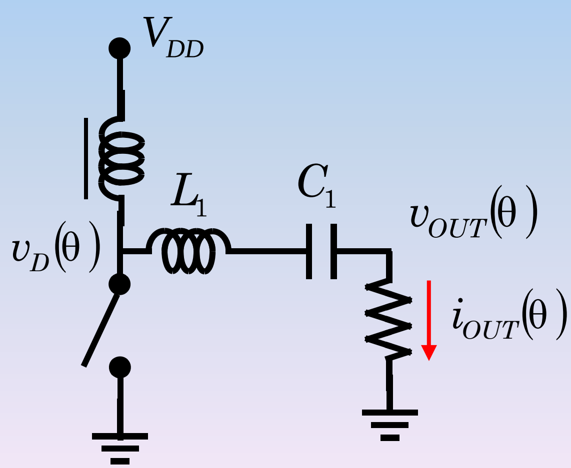
TCCS

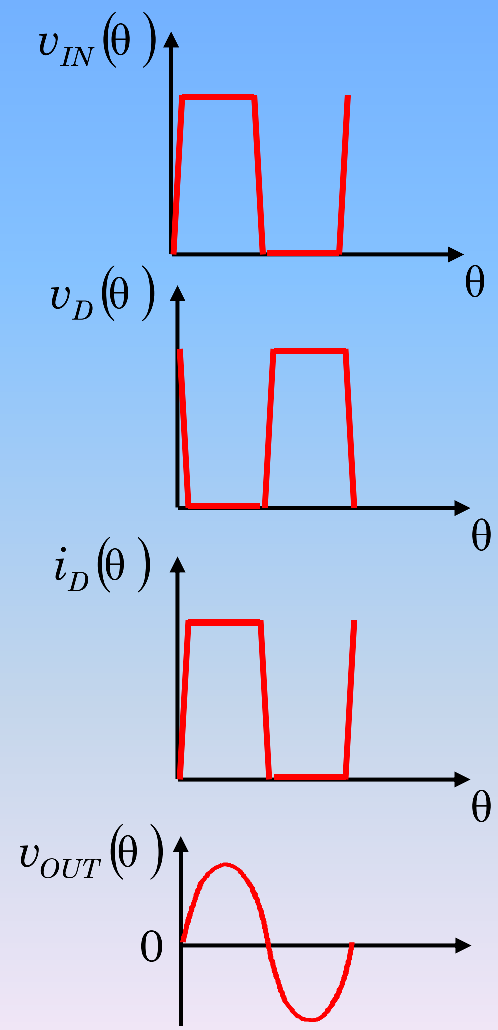
Class D Specifications

- Very low linearity
  - Can not amplify non-constant envelope signals
- High drain efficiency (60%)
- Moderate power added efficiency(40%)
- Can only be used for narrow-band amplification
- Proper for low frequency operation

Class E Power Amplifiers







Class E

- Transistor acts as a switch
- Conditions
  - Turn on
    - The drain voltage drops to zero
    - Zero voltage slope
      - Transistor current is zero @ off ➔ on
      - Helps to minimize transition time
  - Turn off
    - Zero current
    - Zero current slope

Class E

- **Trade-off between efficiency and output harmonic content**

$$L = \frac{QR_L}{\omega} \qquad C_1 = \frac{1}{5.447 \cdot \omega R_L}$$

$$C_2 = \frac{1}{\omega^2 L}\left(1 + \frac{1.42}{Q_L - 2.08}\right)$$

$$P_N \approx 0.098$$

Important Considerations

- Shunt capacitance is important
  - It does not allow a fast rise of the collector voltage
- Shunt capacitance is voltage dependent
  - One of non-idealities
- No current jump at turn-on transition
  - Reduce the power loss

Practical Considerations

- Real transistor has
  - Non-zero switching time
  - Parasitic reactance
  - Non-zero ON resistance
    - Saturation voltage for BJTs
- No pure sine wave current @ the output
- Finite Q-factor of reactive components
- Maximum Drain voltage is “3.6*VDD”

Class E Amplifier Design and Efficiency

- **Non-idealities of class E**
  - **ON resistance**
  - **Off-transients**
    - **Efficiency will be reduced**
- **Normalized Output Power Capability**

$$v_{DS,\max} \approx 3.6V_{DD}, i_{D,\max} \approx 1.7\frac{V_{DD}}{R}$$

$$P_{L,\max} = \frac{2}{1+\frac{\pi^2}{4}} \approx 0.577.\frac{V_{DD}^{\ \ 2}}{R} \Rightarrow P_N = \frac{P_{L,\max}}{v_{DS,\max}.i_{D,\max}} \approx 0.098$$

Class F Amplifiers

- **Harmonic manipulation is used to shape voltage and current signals**

Class F Schematic

Class F Operation

Class F Operation

- **A Parallel LC resonator is used instead of Quarter-wave length transmission line.**

Class F Power Amplifier Analysis

$$v_{fund} = \frac{4}{\pi}.V_{DD}$$

Power delivered to the load:

$$P_L = \frac{v_{fund}^2}{2R} = \frac{8V_{DD}^2}{\pi^2 R}$$

$$i_{D,\max} = \frac{4}{\pi}.\frac{2V_{DD}}{\pi R}, v_{DS,\max} = 2V_{DD}$$

$$P_N = \frac{v_{fund}^2}{2R} = \frac{8V_{DD}^2}{\pi^2 R} / \left(2V_{DD}.\frac{8V_{DD}}{\pi R} \right) = \frac{1}{2\pi} \approx 0.16$$

Other Type of Class F

Waveforms in a second-harmonic peaking Class F1 amplifier

Class F Efficiency

- **In theory, if you can control an infinite number of harmonics, efficiency approaches 100%**

Class F Disadvantages

- **Output capacitance of device not naturally absorbed into network ➔need inductor to tune it out**
- **Difficult to control more than 5th harmonic … resonators are lossy and additional losses present diminishing returns on efficiency.**

Comparison

- **Achievable Efficiencies of PAs**

PA CLASSIFICATION

Traditional PA Classification

Summary of a few basic PA measures for classes A-F

Linearization Techniques

Linearization Techniques

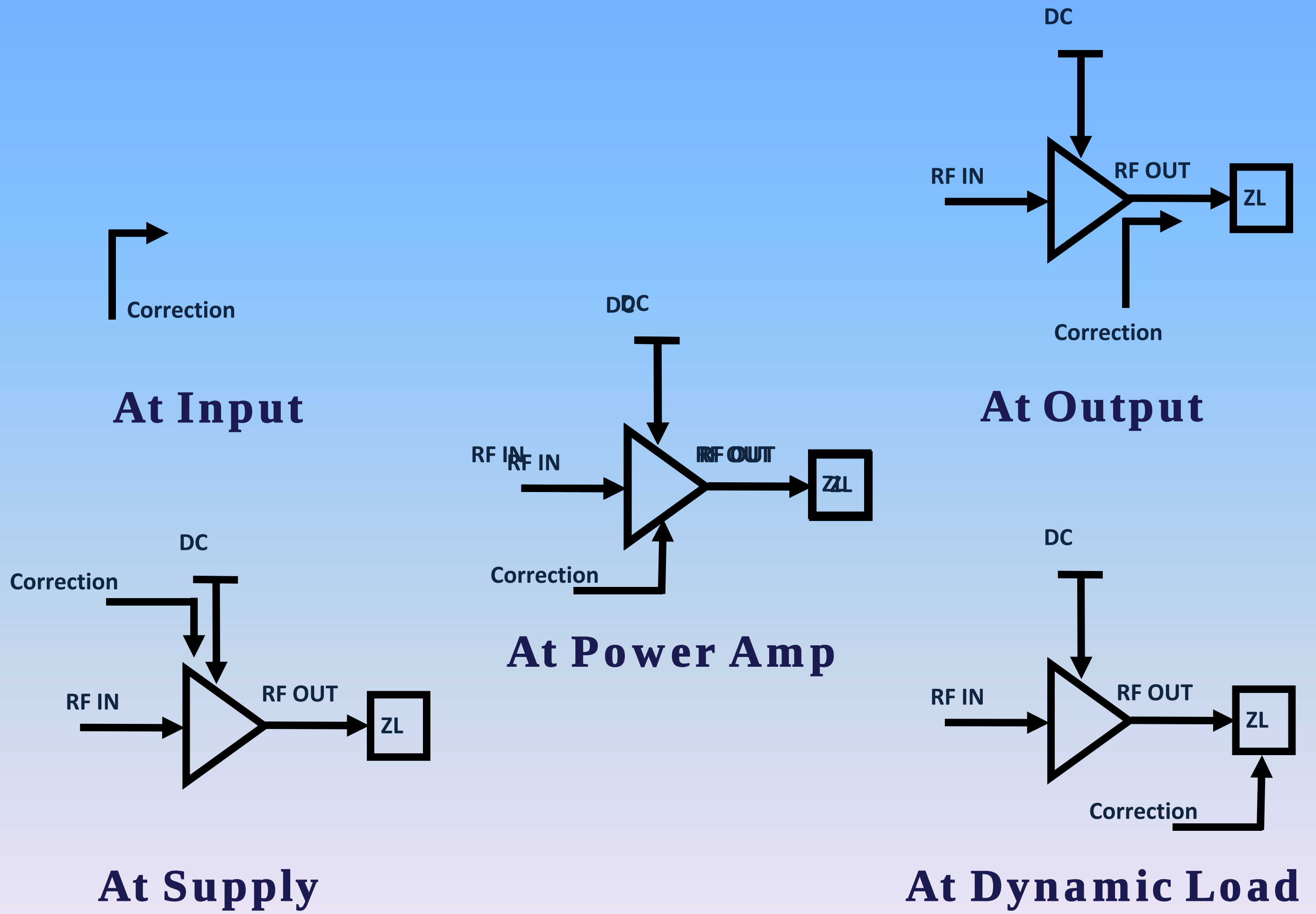
- **Linearization techniques:**

  "… utilized in complex , expensive RF and microwave systems, but they have not yet found their way into low-cost portable terminals." B. Razavi, *RF Microelectronics*.

- **Most linear PAs in portable phones**

  ➔ class A stages with "backed off"

Linearization Schemes

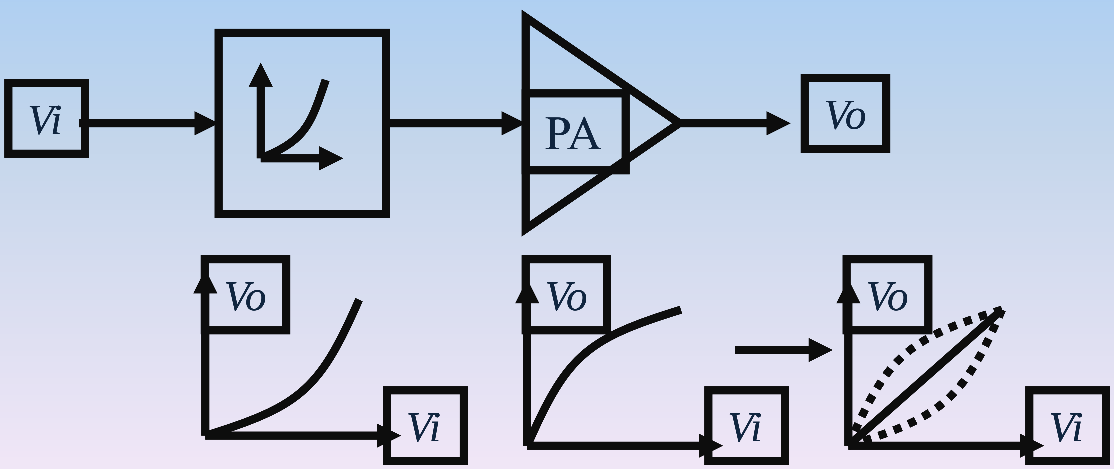


Correct Nonlinearity at Input

- **Predistortion**
  - **Close loop(Adaptive PreDistortion)**
  - **Open loop**
- **Feedback**
  - **Direct Feedback**
  - **Cartesian**
  - **Polar**

PreDistortion

- **RF/ IF/ base band**
- **Insertion a nonlinear element before PA**
- **Amplitude and/or phase correction.**
- **Improvement in ACPR by 10 dB is typical.**



AM/AM & AM/PM Distortion

Open Loop PreDistortion

- Require Characteristics of PA
- Lookup table for base-band or RF
- Difficulties in
  - Resolution
  - Tolerances
  - Long term drift in characteristics

Table Based Predistortion

- **Polar Predistortion by Amplitude**

Table Based Predistortion

- **Full Cartesian Predistortion**

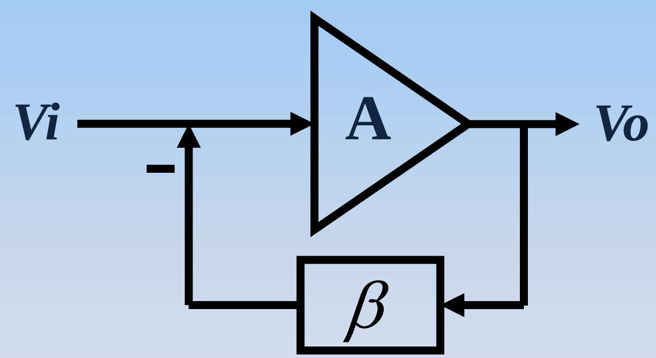
Closed Loop PreDistortion

- **Difficulties in Resolution**
- **Corrects for long term drift and slowly changing amplifier behaviors /temperature /etc.**

PreDistortion Example

Direct Feedback

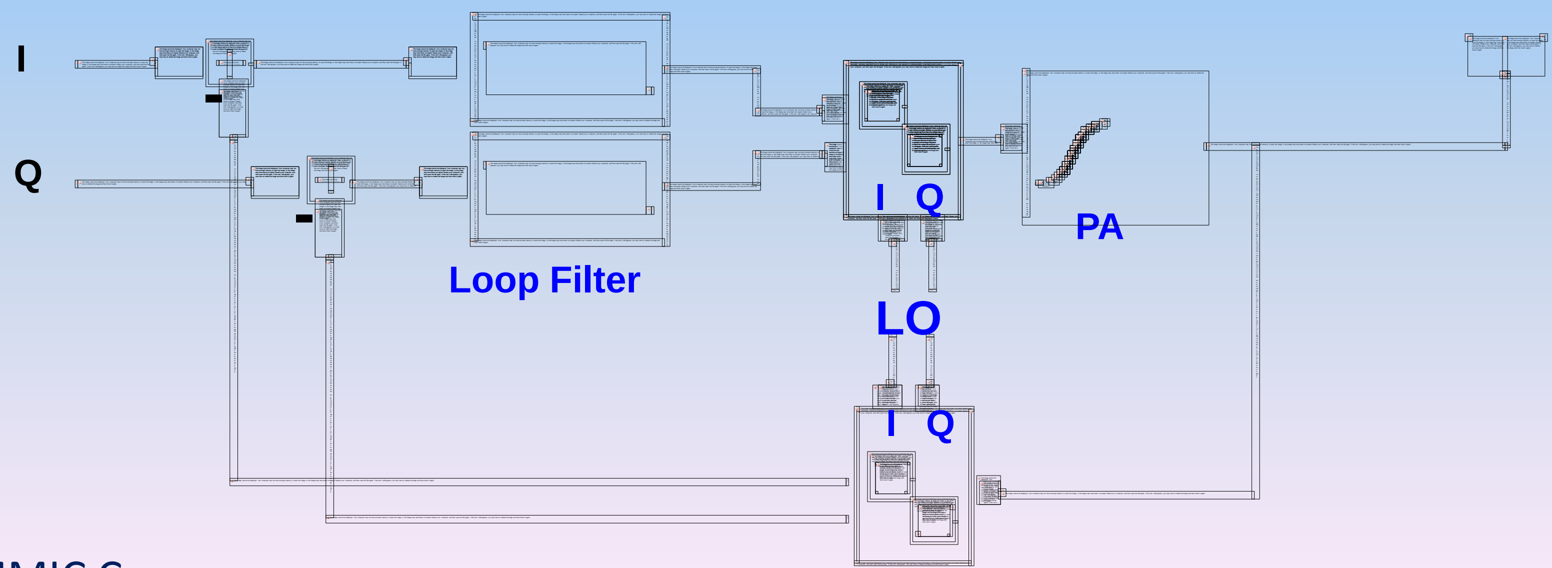
- Basic negative feedback technique to improve linearity
- High loop gain yields to better linearity
- Signal gain drop and excess phase shift
- Stability Check



$$G = \frac{V_o}{V_i} = \frac{A}{1+\beta A}$$

Cartesian Feedback

- **W: Bandwidth Limitation**
- **W: Stability concerns**
- **S: Low-Complexity & power efficient**
- **S: Highly resistant to drift and aging**
- **Ss: Robust to poor characterization of PA**



Polar Feedback

- **W: Bandwidth Limitation & Stability concerns**
- **S: Low-Complexity**
- **S: Highly resistant to drift and aging**
- **Ss: Robust to poor characterization of PA**

Correct Nonlinearity at Supply

- **Envelope Elemination And Restoration(EER)**
- **Dynamic Supply/ Envelope Tracking**

Envelope Elimination and Restoration (EER)

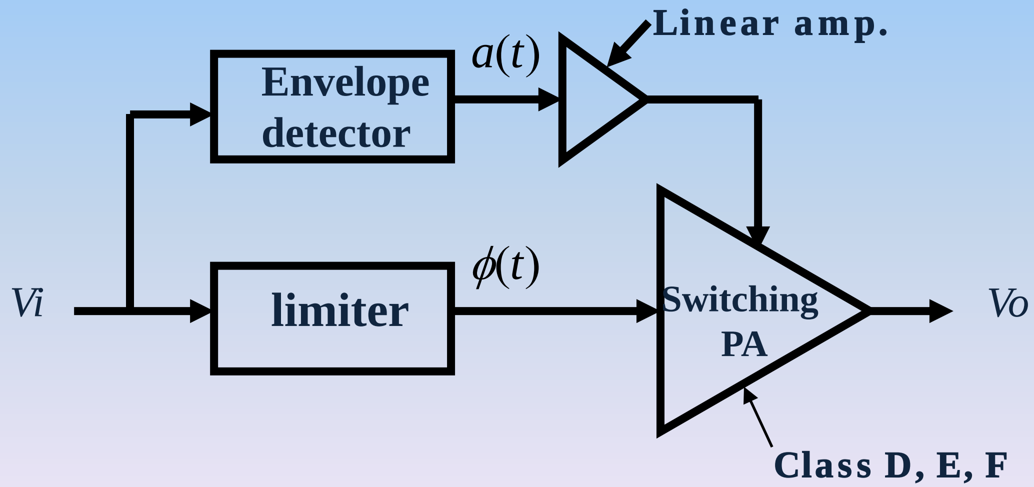
- **Decompose a bandpass signal into an envelope signal and a phase signal**

$$v(t) = a(t)\cos[\omega_c t + \phi(t)]$$

$\rightarrow a(t)$

$\rightarrow \phi(t)$

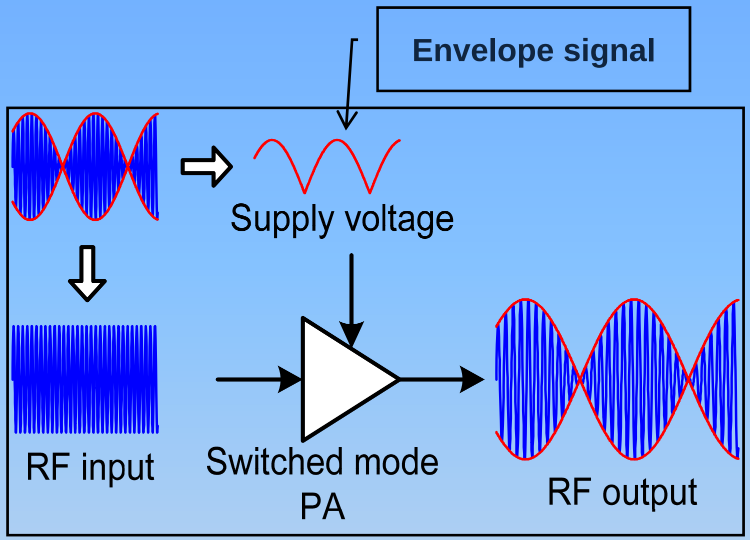
- **Require no linearity in PA stage.**



$k \cdot a(t)$

$\phi(t)$

Envelope Signal



Closed-Loop EER Implementation

Envelope Detector

- **Non Ideal Diode → Using this circuit**

Envelope Amplifier

- High efficiency envelope amplifier is required
  - Bandwidth: > 20 MHz for 5 MHz signal
  - High Current
  - Efficiency: >>50%
- Problems
  - Complicated circuit
  - Limited bandwidth

Influence of time alignment

- **Misalignment between amplitude and phase paths**
  - **Leads to severe signal distorton**
  - **Alignment requirements in the order of a few psec.**

Influence of time alignment

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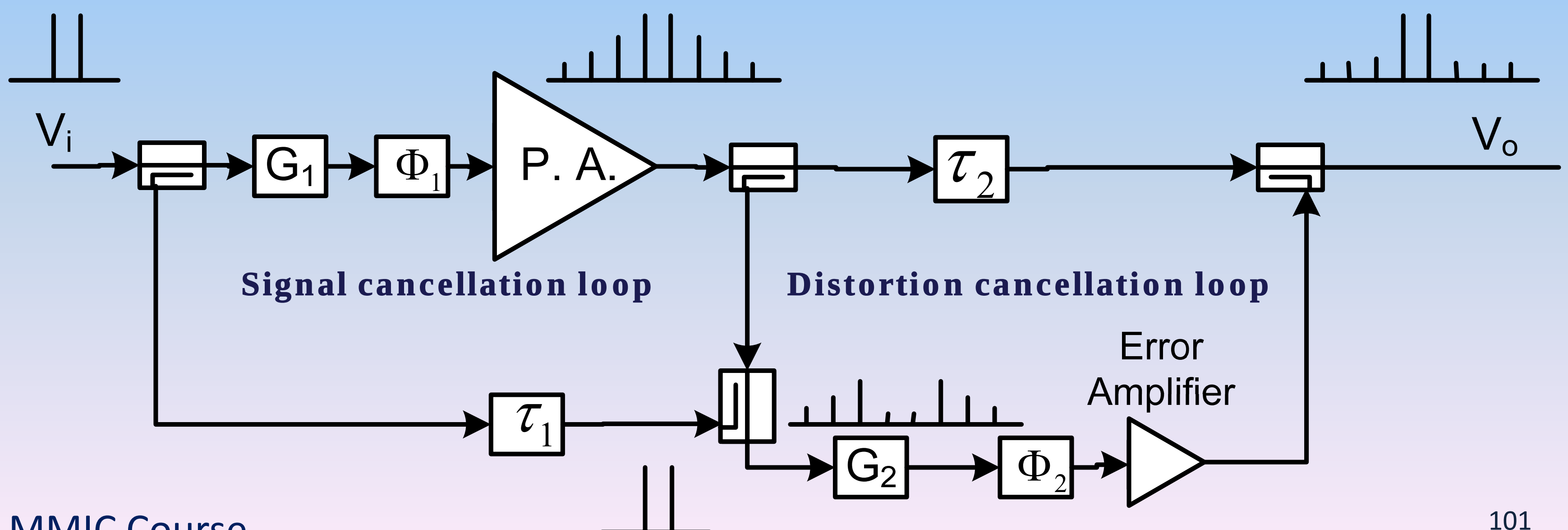
  - **Leads to severe signal distorton**
  - **Alignment requirements in the order of a few psec.**

EER Issues

- Require Envelope amplifier (drain DC supply)
- Mismatch of gain and phase between two paths
- Limiter exhibits AM/PM Distortion
- Efficiency of Switching Power Supply
- Band Width of Switching Power Supply
- Time alignment between the supply and RF paths

Feed Forward

- Correct non-linearity at output
- Two loops
  - Signal Cancellation loop
  - Distortion Cancellation loop



Feed Forward

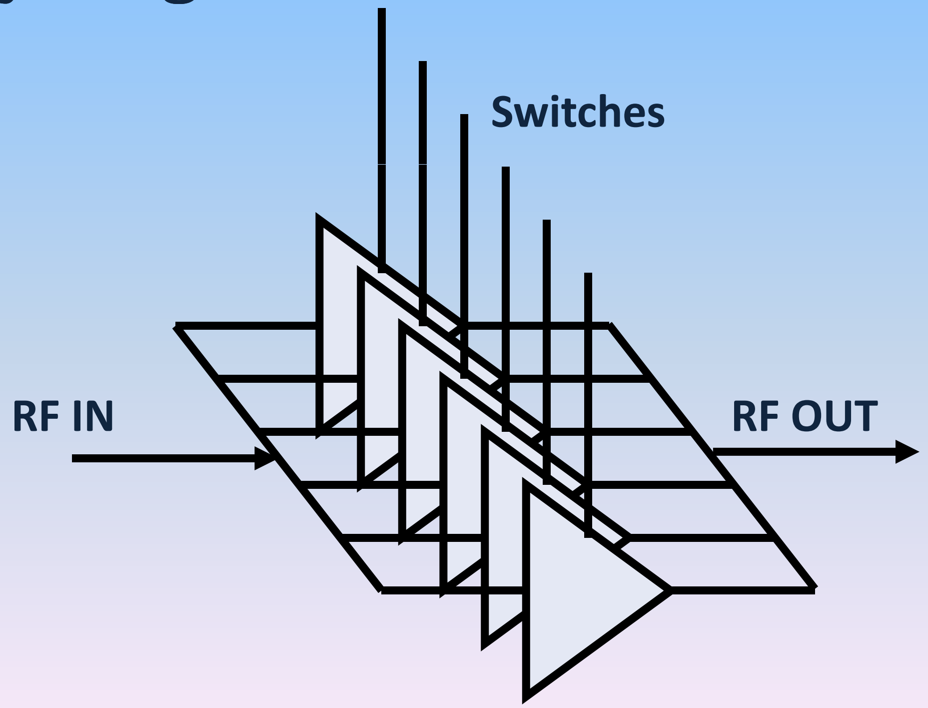
- **Advantages:**
  - Wide bandwidth
  - Good Cancellation performance
- **Issues:**
  - Difficult to build analog delay elements.
  - Requires low loss output “adder/coupler”.
  - Sensitive to amplitude and phase imbalance due to process and temperature variation..
  - High complexity

Adaptive Feed Forward

- Open loop → Close loop FF
- Robust to poor characterization of PA

Array of Power Amps

- Array of Power Amps are used
  - Similar
  - Binary weighted



Thanks for your time!