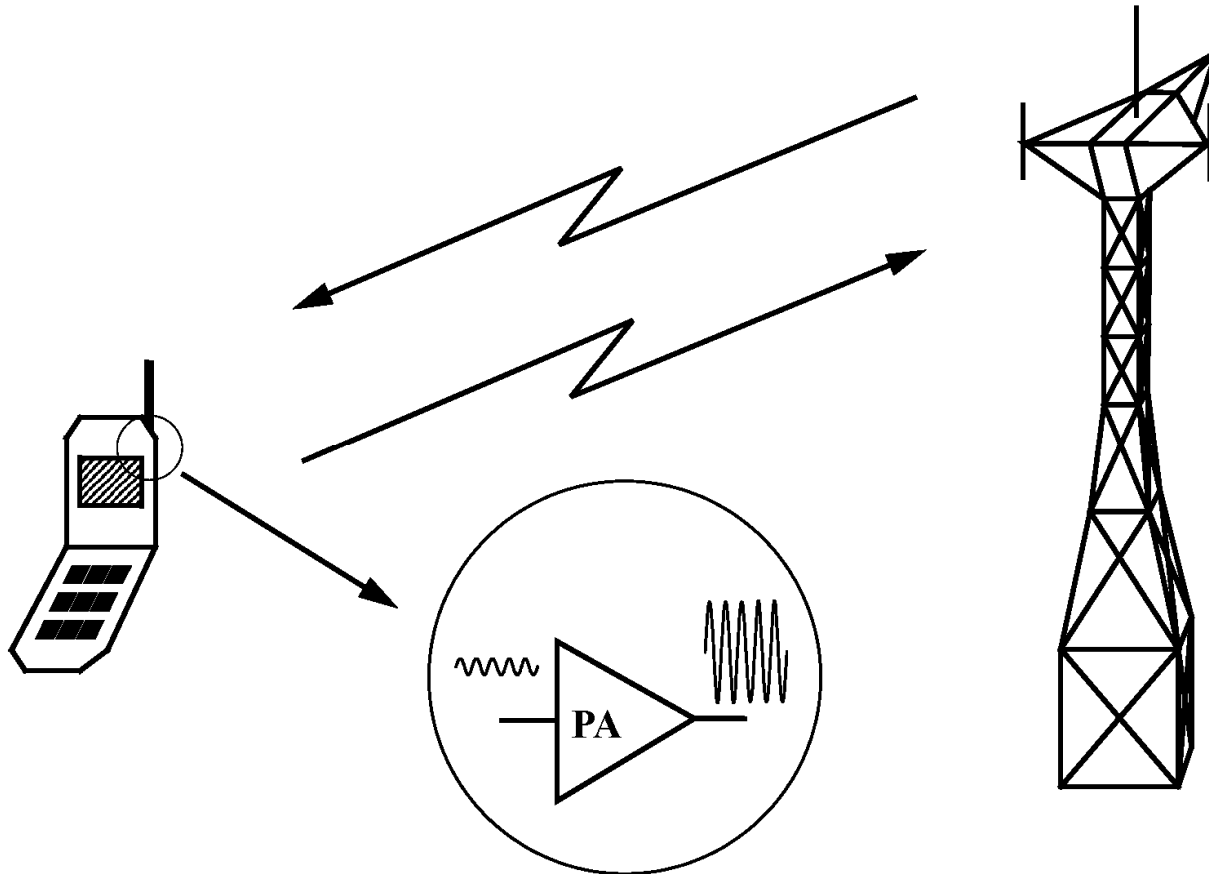




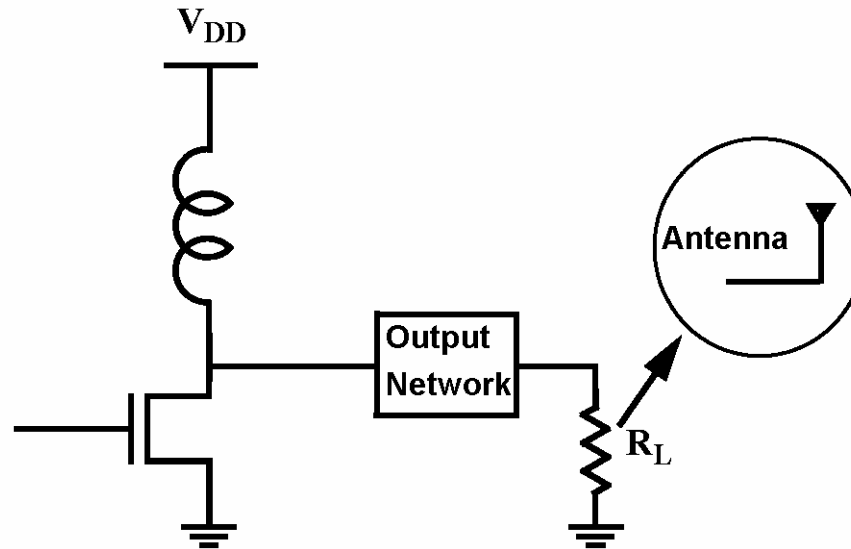
RF POWER AMPLIFIERS

Alireza Shirvani
SCV SSCS RFIC Course

Mobile and Base Stations in a Wireless System



RF Power Amplifiers

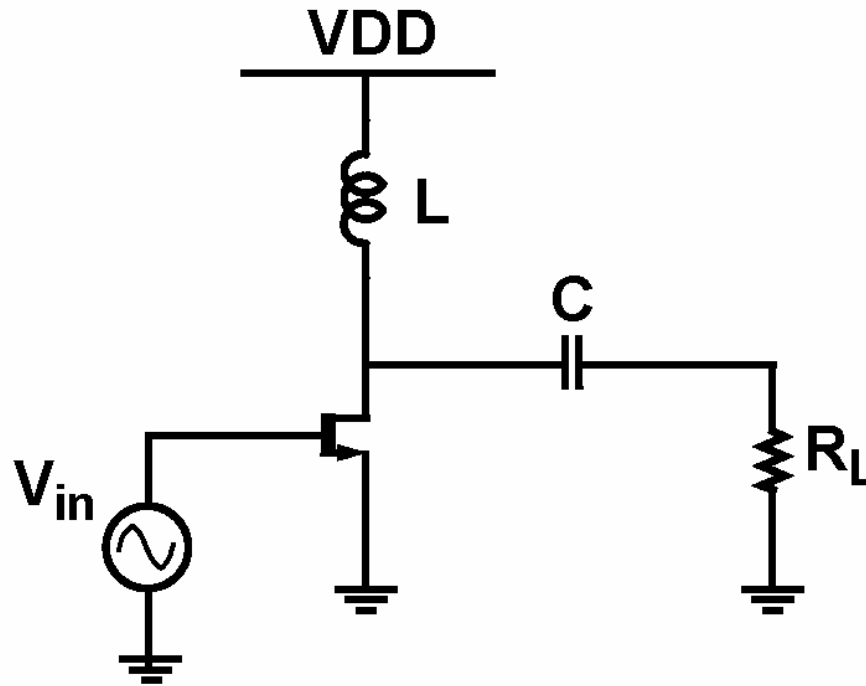


- **Function: Delivering RF Power to the Antenna**

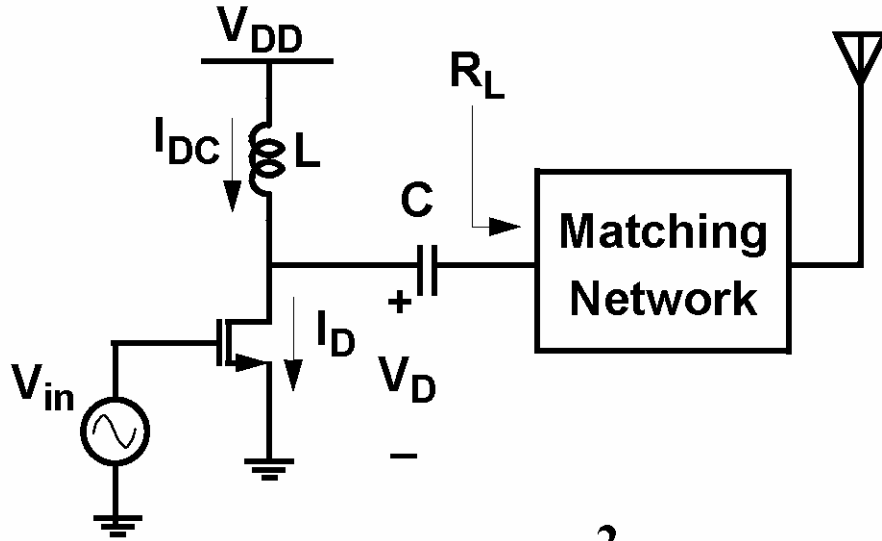
Performance Metrics

- **Output Power**
 - Usually ranges from 10mW to 4W (10 to 36 dBm)
- **Efficiency**
 - Usually ranges from 15% to 55%.
- **Linearity**
 - Requirements depend on the modulation scheme, should meet modulation accuracy and spectral emissions requirements.
- **Power Gain**
 - Usually is on the order of 20 - 30 dB.

Class A Power Amplifiers



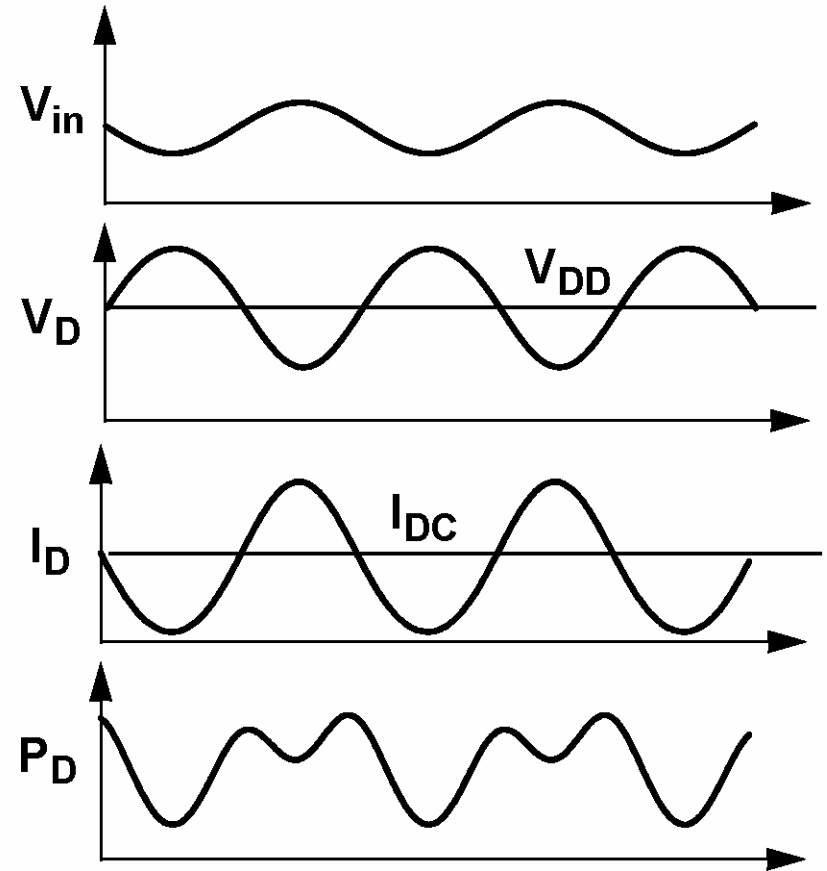
Efficiency of Class A Power Amplifiers



$$P_{out} \leq \frac{V_{DD}^2}{2R_L}$$

$$P_{supply} = I_{DC} \times V_{DD} = \frac{V_{DD}^2}{R_L}$$

$$\eta = \frac{P_{out}}{P_{supply}} \leq 50\%$$

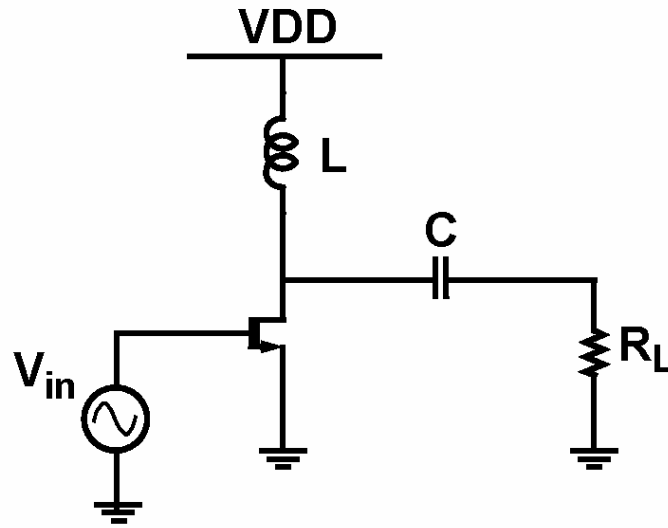


Output Power of Class A Power Amplifiers

$$V_{\text{out}} = -g_m R_L V_{\text{in}}$$

$$P_{\text{out}} = \frac{V_{\text{out}}^2}{2R_L} \leq \frac{V_{\text{DD}}^2}{2R_L}$$

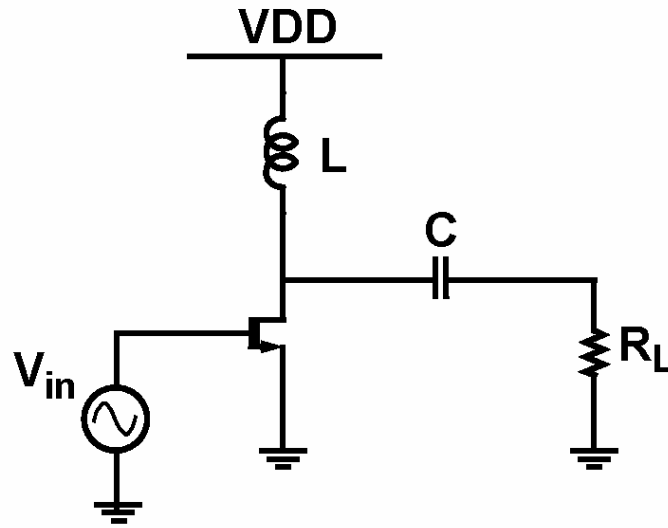
Class B Power Amplifiers



$$V_{in} = -V_B + v_{in}$$

$$P_{out} = \frac{V_{out}^2}{2R_L}$$

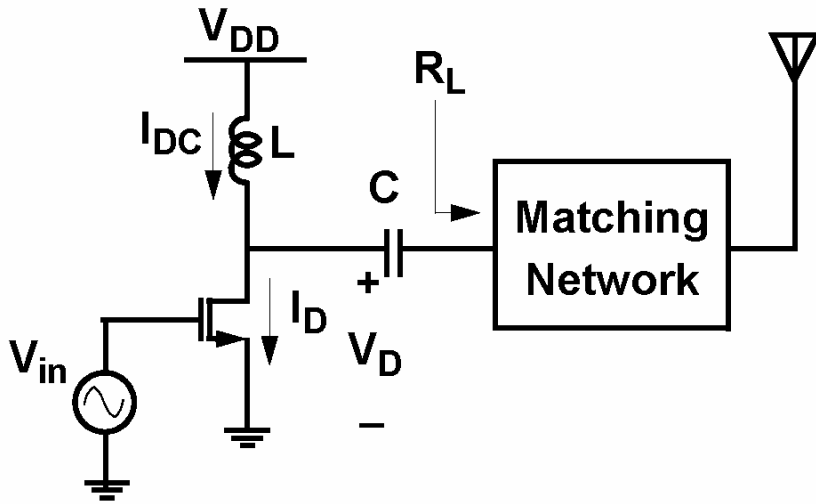
Class B Power Amplifiers



$$V_{in} = -V_B + v_{in}$$

$$P_{out} = \frac{V_{out}^2}{2R_L}$$

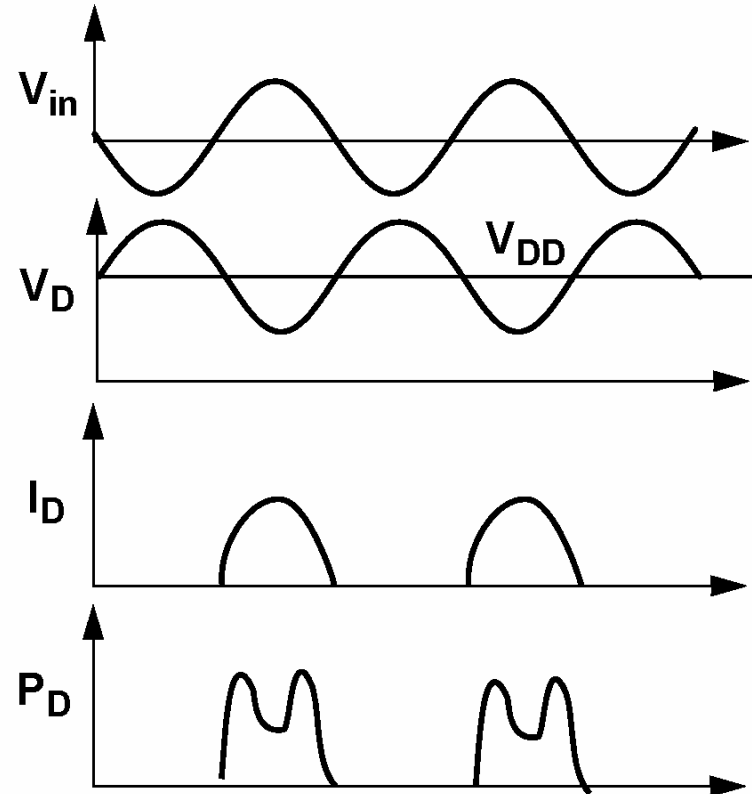
Efficiency of Class B Power Amplifiers



$$I_{\text{supply}} = \frac{1}{\pi} \frac{V_{\text{out}}}{R_L}$$

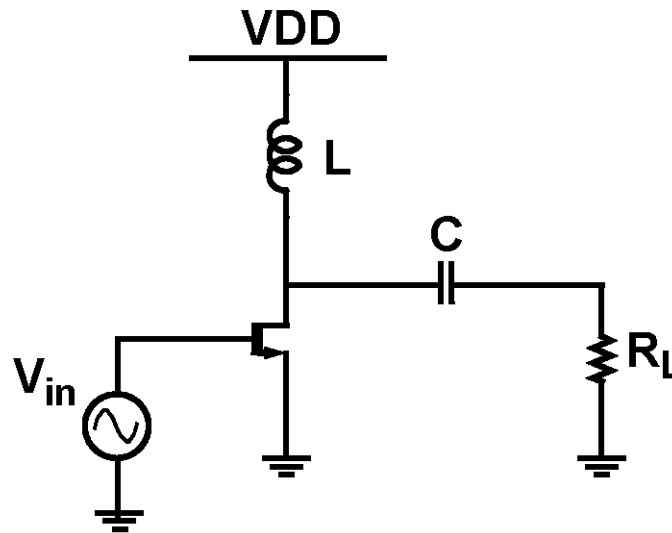
$$P_{\text{supply}} = I_{\text{DC}} \times V_{\text{DD}} = \frac{2}{\pi} \frac{V_{\text{DD}}}{R_L} V_{\text{out}}$$

$$\eta = \frac{P_{\text{out}}}{P_{\text{supply}}} \leq \frac{\pi}{4} (78\%)$$



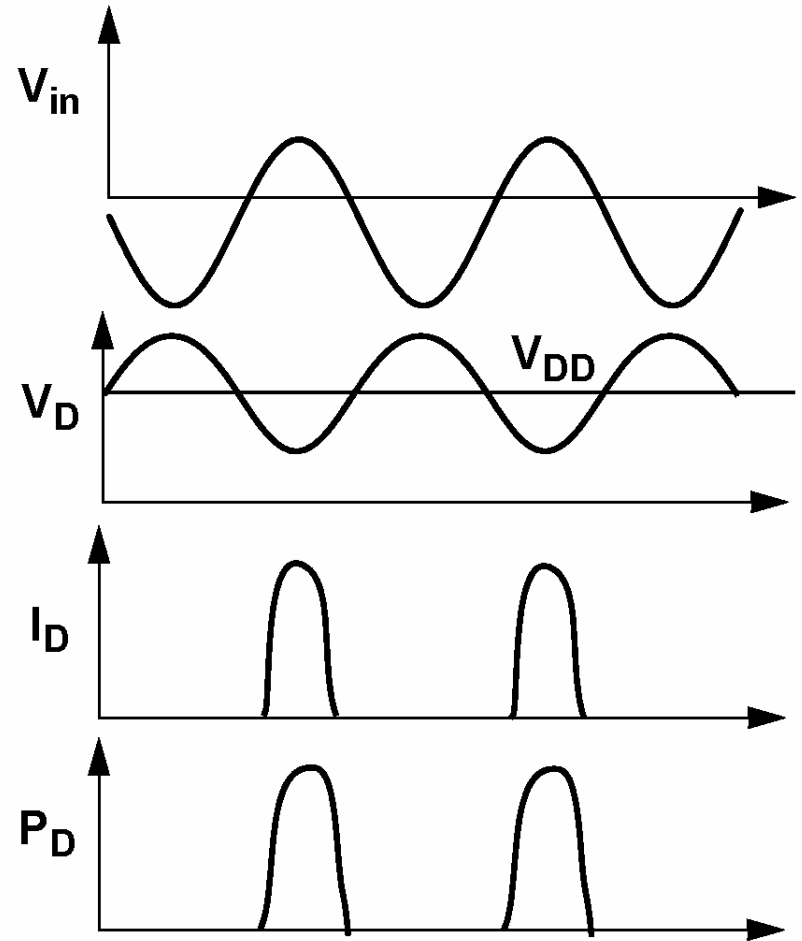
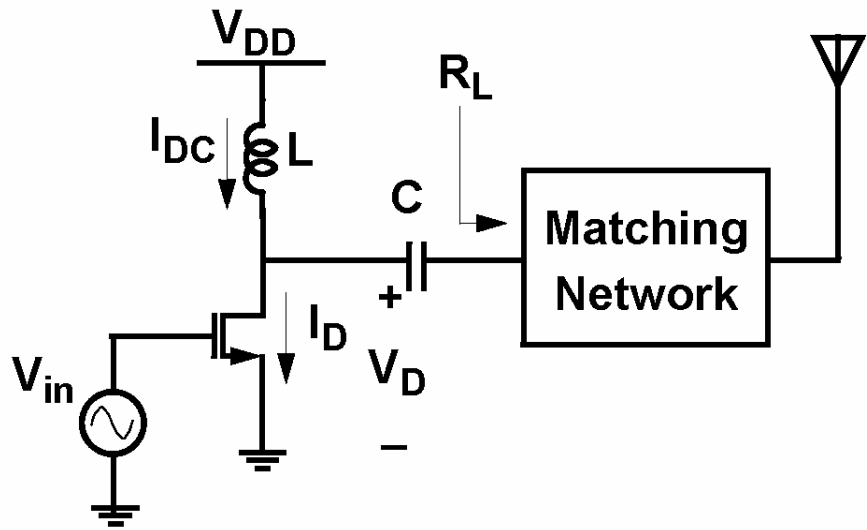
Conduction Angle = 180

Class C Power Amplifiers

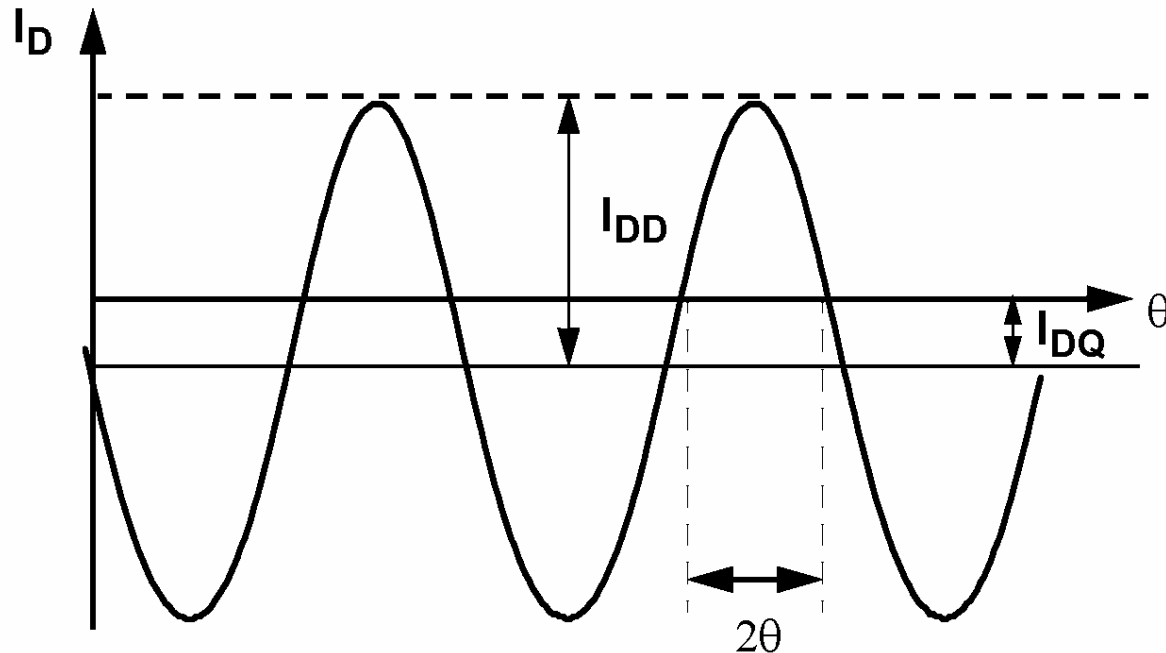


$$V_{in} = -V_B + v_{in}$$

Class C Power Amplifiers (cont'd)



Class C Power Amplifiers (cont'd)

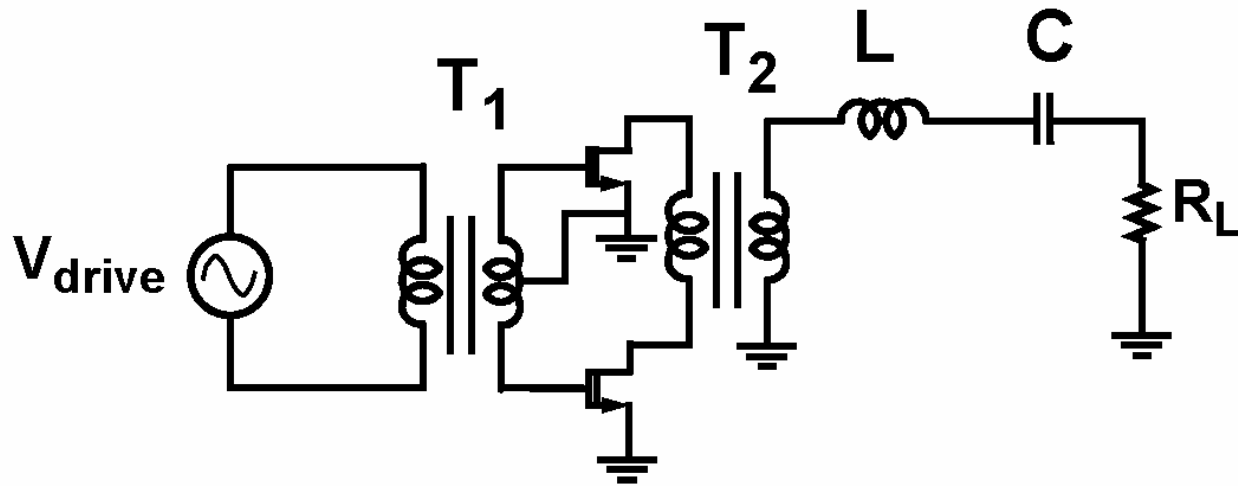


$$V_{\text{out}} = \frac{I_{DD} R_L}{2\pi} (2\theta - \sin 2\theta)$$

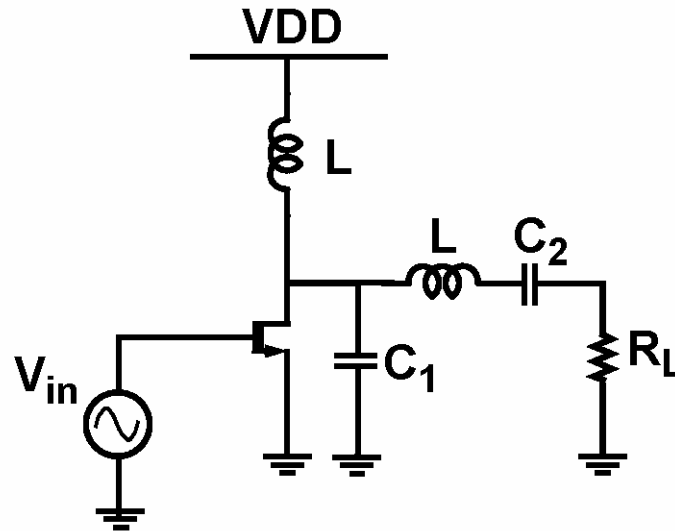
$$\eta = \frac{1}{4} \frac{(2\theta - \sin 2\theta)}{(\sin \theta - \theta \cos \theta)}$$

$$\lim_{\theta \rightarrow 0} \eta = 100\%$$

Class D Power Amplifiers



Class E Power Amplifiers



$$L = \frac{QR_L}{\omega}$$

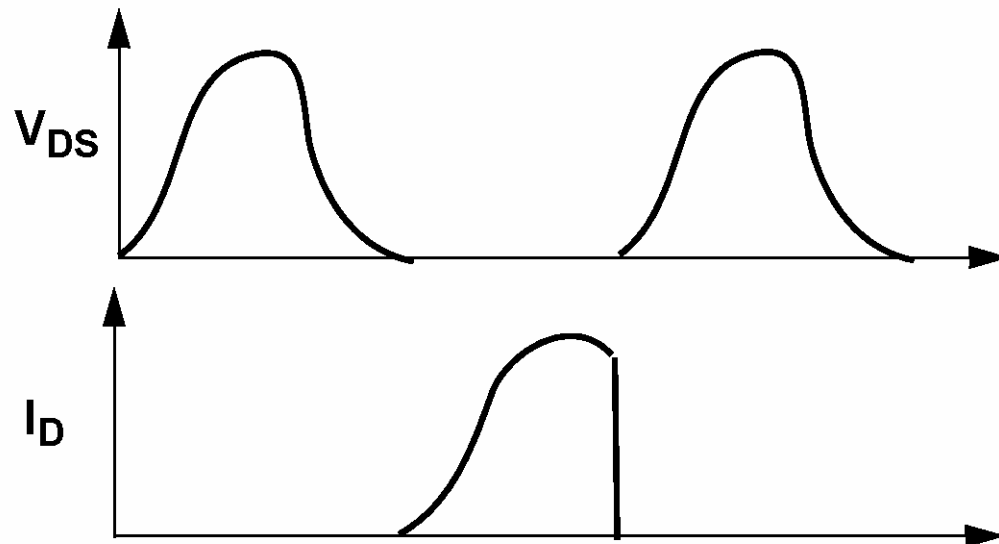
$$C_1 = \frac{1}{\omega R_L \left(\frac{\pi^2}{4} + 1 \right) \left(\frac{\pi}{2} \right)} = \frac{1}{5.447 \omega R_L}$$

Class E Power Amplifiers (cont'd)

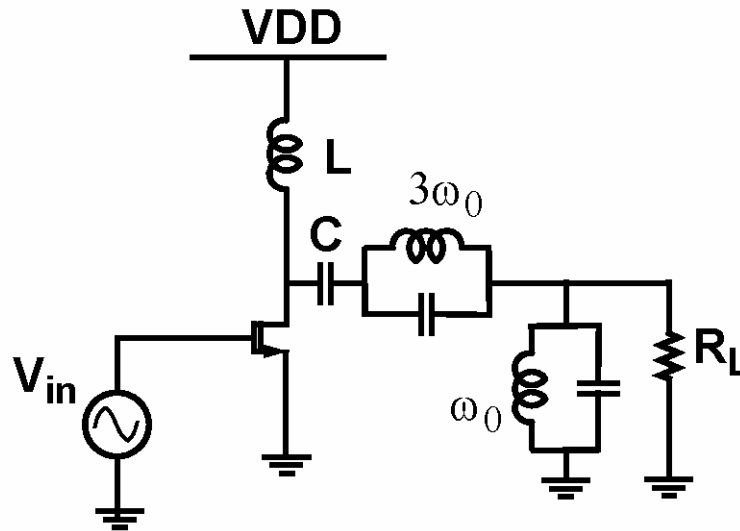
$$C_2 \cong C_1 \left(\frac{5.447}{Q} \right) \left(1 + \frac{1.42}{Q - 2.08} \right)$$

$$P_{\text{out}} = \frac{2}{1 + \frac{\pi^2}{4}} \cdot \frac{V_{\text{DD}}^2}{R_L} \cong 0.577 \cdot \frac{V_{\text{DD}}^2}{R_L}$$

$$\frac{P_{\text{out}}}{v_{\text{DS,pk}} \cdot i_{\text{D,pk}}} \cong 0.098$$

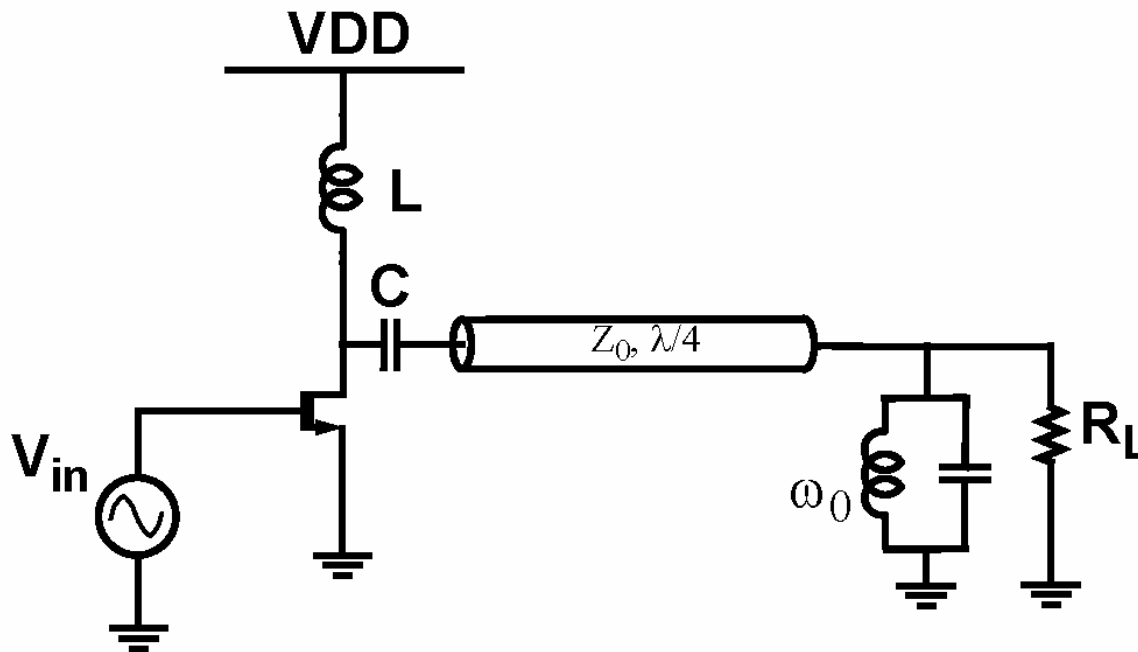


Class F Power Amplifiers

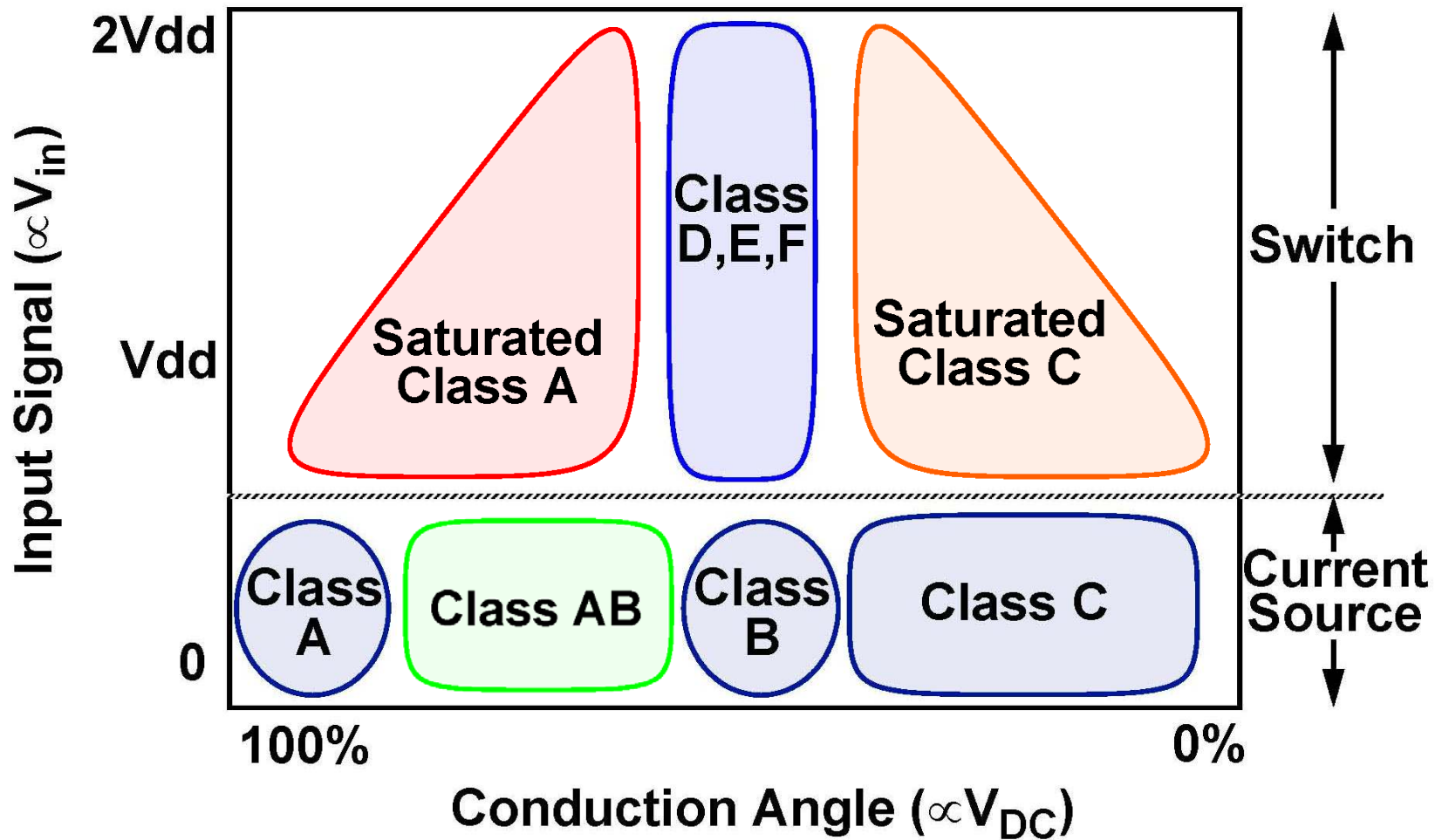


$$\frac{P_{out}}{v_{DS,pk} \cdot i_{D,pk}} \cong 0.16$$

Class F Architecture with Multiple Harmonic Terminations



Power Amplifier Classification



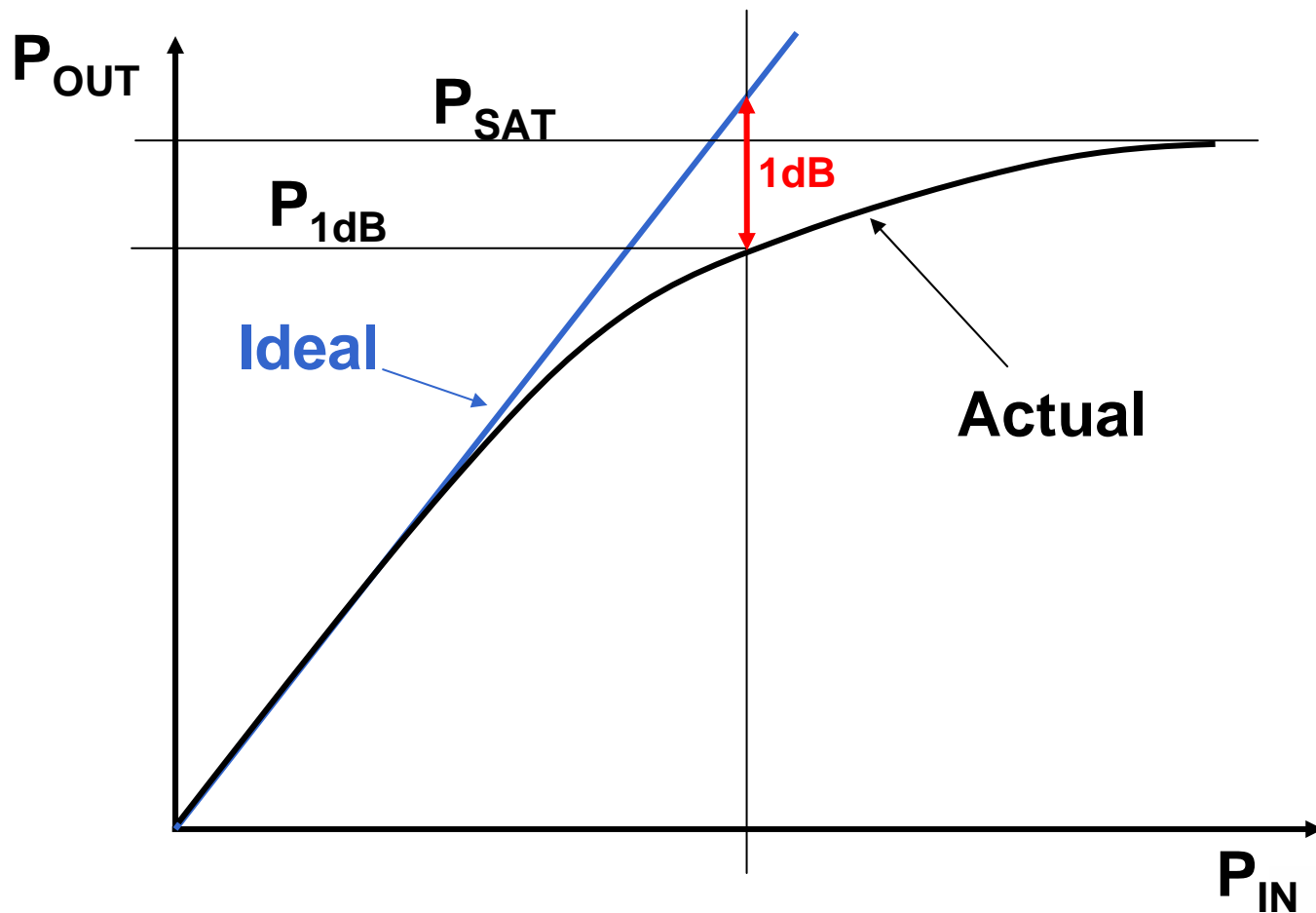
Power Amplifier Classification (cont'd)

| Class | Mode | Maximum Efficiency | Linearity |
|--------------|--------------------------|---------------------------|------------------|
| A | Trans-conductance | 50% | Good |
| B | | 78.5% | Moderate |
| C | | 100% | Poor |
| D | Switch | 100% | Poor |
| E | | 100% | Poor |
| F | | 100% | Poor |

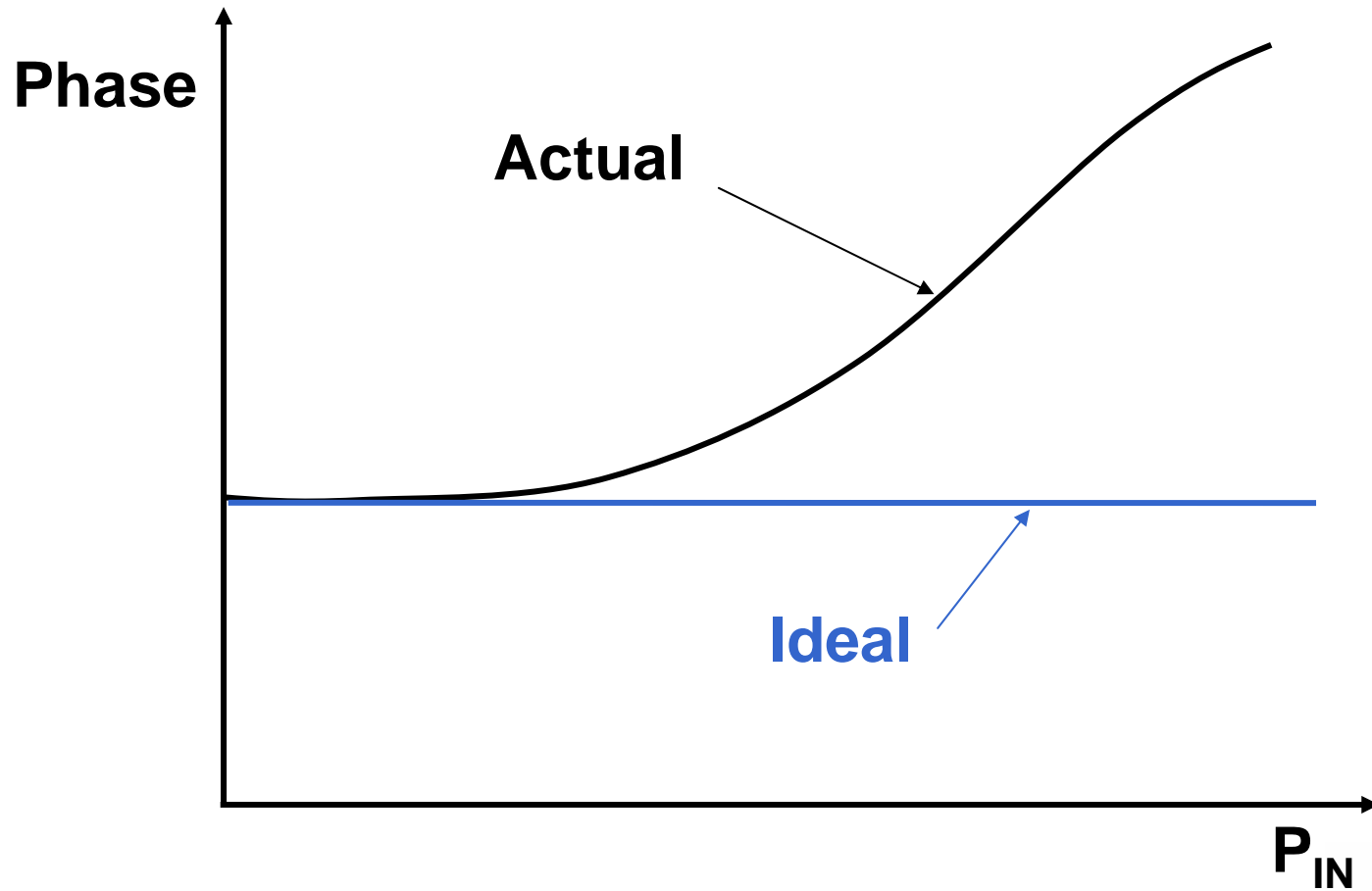
Power Amplifier Model

- **Simple Memoryless Nonlinearity**
 - **Taylor Series**
 - **Rapp – Proc. 2nd European Conf on Satellite Commun., Oct 1991. (AM-AM)**
 - **Saleh – IEEE Trans Commun., Nov 1981 (AM-AM; AM-PM)**
- **Memory Effects**
 - **Signal/temperature dependent AM/AM and AM/PM**
 - **Volterra Series (Baytekin, Meyer, JSSC Feb. 2005)**

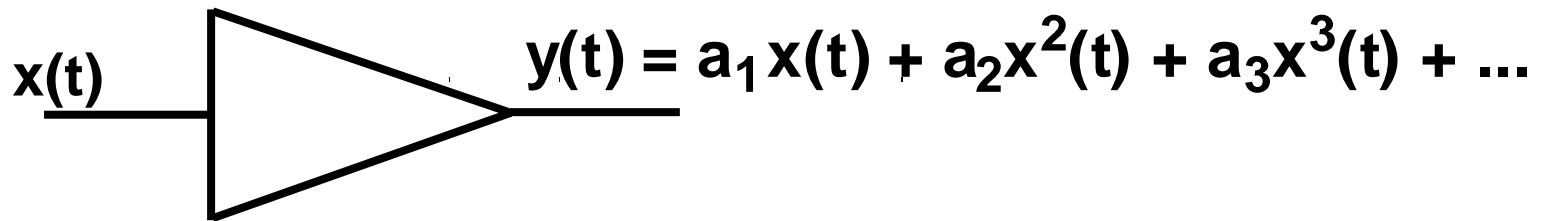
Amplitude Distortion (AM-AM)



Phase Distortion (AM-PM)



Taylor Series PA Model



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

$$y(t) = a_1 A \cos \omega t + a_2 A^2 \cos^2 \omega t + a_3 A^3 \cos^3 \omega t + \dots$$
$$= K_0 + K_1 \cos \omega t + K_2 \cos 2 \omega t + K_3 \cos 3 \omega t + \dots$$

Where

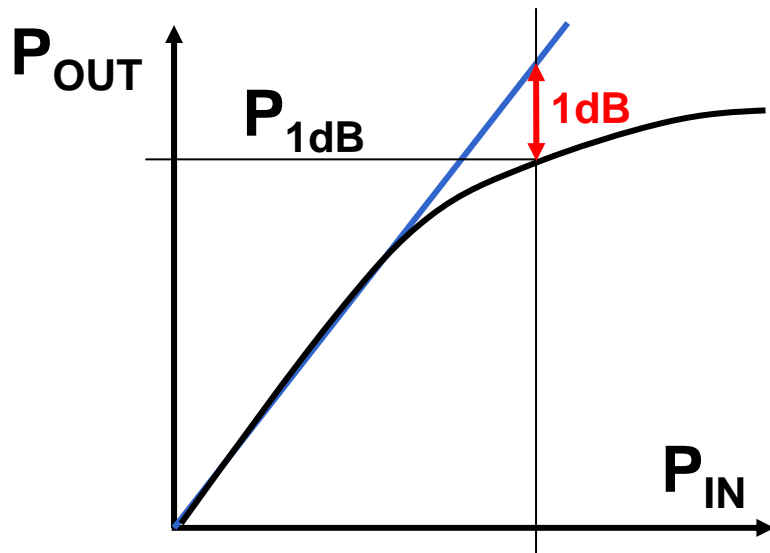
$$K_0 = a_2 A^2 / 2;$$

$$K_2 = a_2 A^2 / 2;$$

$$K_1 = (a_1 A + 3/4 a_3 A^3);$$

$$K_3 = a_3 A^3 / 4;$$

Output 1dB Compression Point



Ideal Input = $A \cos \omega t$

Ideal Output = $a_1 A \cos \omega t$
Actual Output = $K_1 \cos \omega t$
(Fundamental)

At P_{1dB} , Ideal-Actual=1dB

$$20\log|a_1 A \cos \omega t| - 20\log|K_1 \cos \omega t| = 1 \text{ dB}$$

$$\text{OR Output } P_{1dB} = 20\log | a_1 \text{ SQRT}(0.115 |a_1 / a_3|)|$$

Maximize Data Rate

Modern digital modulation attempts to transmit at highest data rate within a given signal bandwidth.

1. Nonlinear PA:

Information in phase only. Transmit with constant envelope for power efficiency – GSMK, FSK

2. Modestly Linear PA:

Information in phase only. Reduce signal bandwidth with non-constant envelope signal – $\pi/4$ QPSK, OQPSK

3. Linear PA:

May encode information in both amplitude and phase. Non-constant envelope; high SNR – 64 QAM

Digital Cellular Systems

NADC(IS-136)
 $\pi/4$ QPSK
30kHz BW

GSM
GMSK
200kHz BW

EDGE
8PSK
200kHz BW

WCDMA-HSDPA
QPSK/16QAM
5MHz BW

LTE

CDMAOne
QPSK/OQPSK
1.25MHz BW

**CDMA2000(1xRTT,
1xEV-DO, 1xEV-DV)**
QPSK/16QAM
1.25MHz BW

Nonlinear PA

Modestly Linear PA

Linear PA

Wireless PAN

Bluetooth 1.2
GFSK
1MHz BW
1Mbps

Bluetooth 2.1 (EDR)
8PSK
1MHz BW
3Mbps

Bluetooth ??
OFDM?

Nonlinear PA

Modestly Linear PA

Linear PA

Wireless LAN

**802.11
GFSK
20MHz BW
1-2Mbps
FHSS**

**802.11b
CCK-QPSK
20MHz BW
11Mbps**

**802.11a/g
OFDM-64QAM
20MHz BW
54Mbps**

**802.11n
OFDM-64QAM
+MIMO
40MHz BW
300Mbps
(2 streams)**

Nonlinear PA

Modestly Linear PA

Linear PA

Power Amplifier Specifications

General Specifications

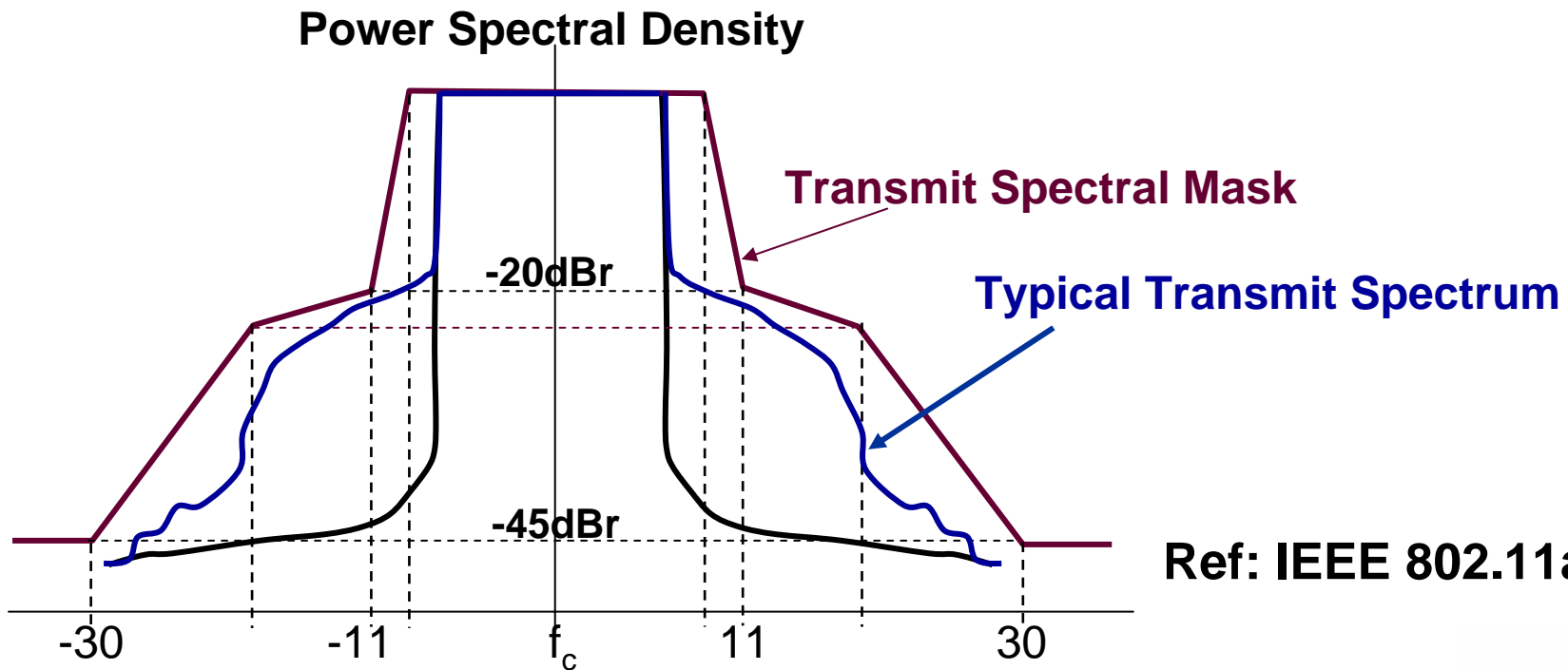
- **Output power: Saturated power, P1dB**
- **Efficiency**
- **Linearity: OIP3/IM3, Harmonics**
- **Stability/Robustness: VSWR**

Digital Communications

- **Transmit Spectral Mask**
- **Error vector magnitude (EVM)**

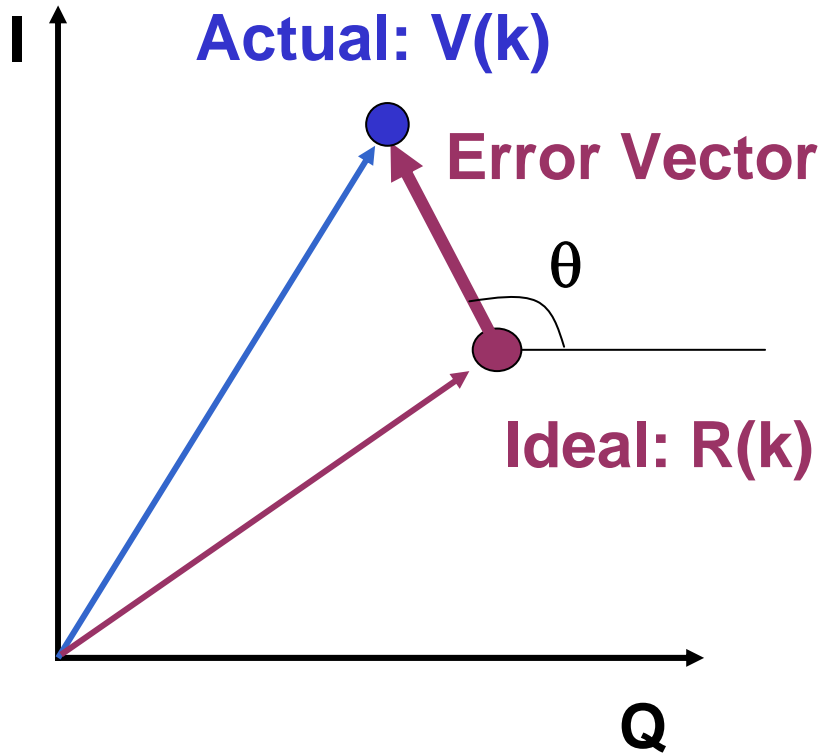
Transmitter Spectral Mask

Nonlinearity \rightarrow Spectral Regrowth / ACPR
(Adjacent/Alternate channel power rejection)



Ref: IEEE 802.11a Spec.

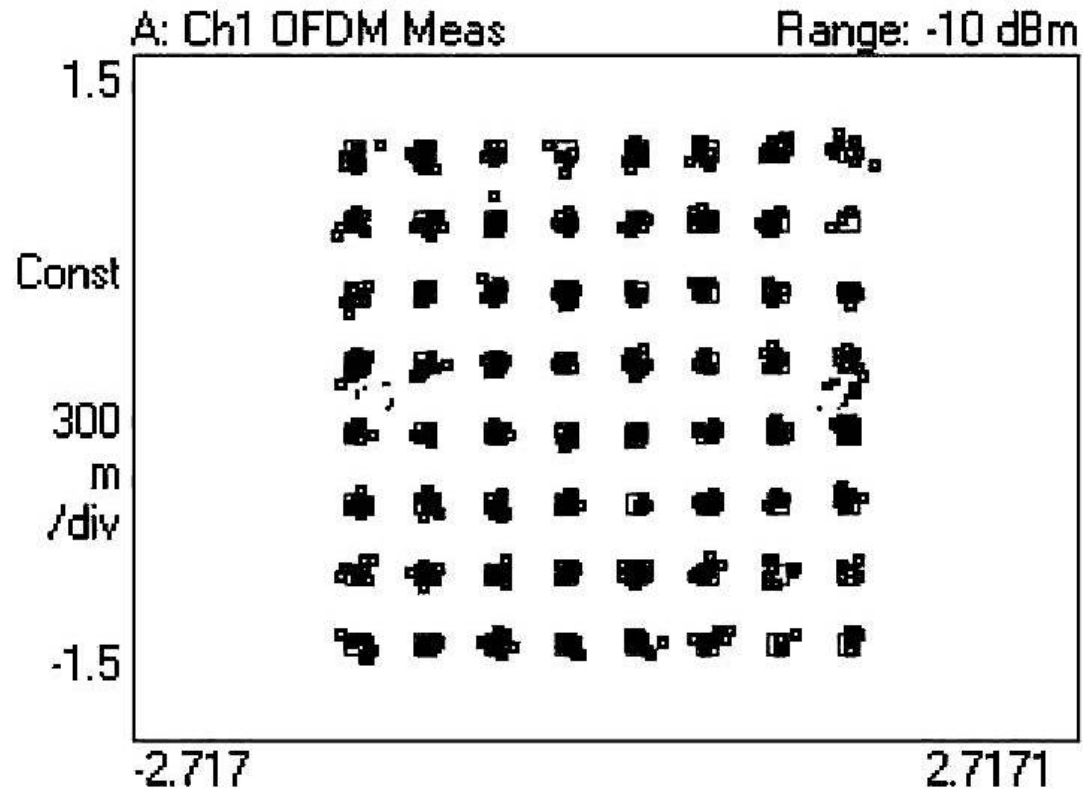
Transmit Modulation Accuracy



Error Vector Magnitude (EVM)

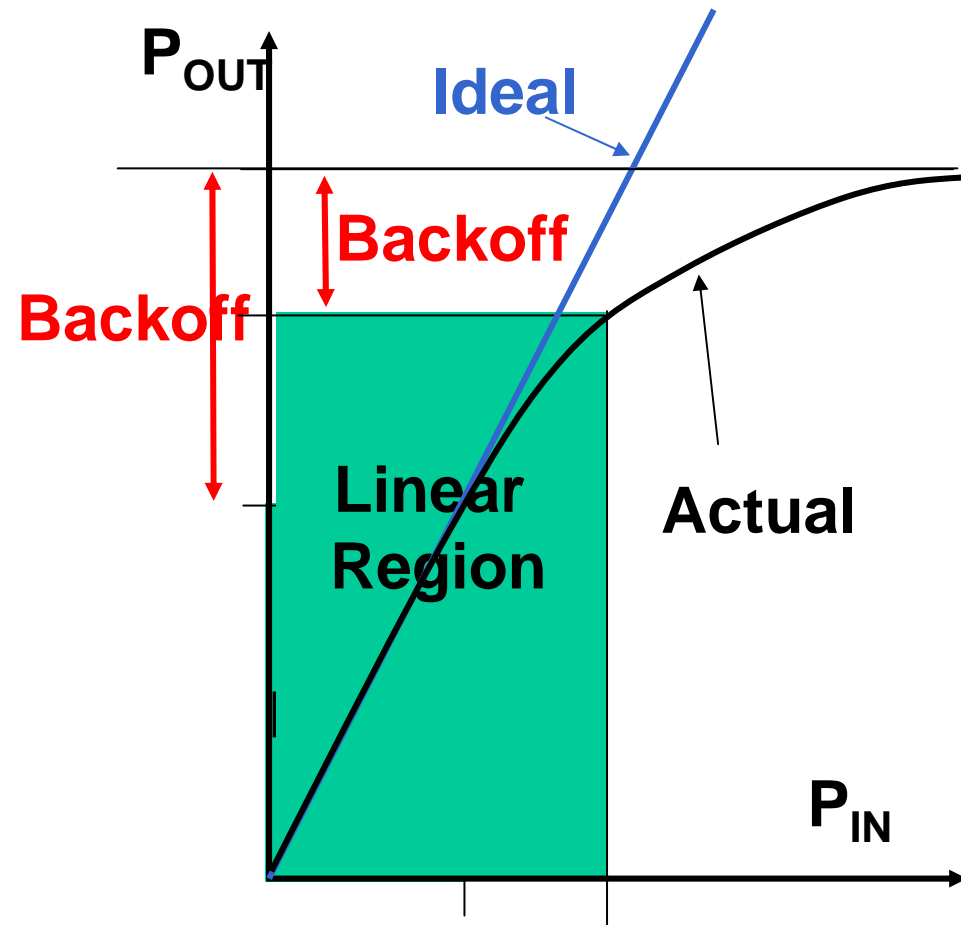
$$\text{EVM} = \sqrt{\frac{\sum_{k=1}^M \|V(k) - R(k)\|^2}{\sum_{k=1}^M \|R(k)\|^2}}$$

Transmitter EVM



Modulation: OFDM (with 64QAM)
Measured EVM: -27.4dB

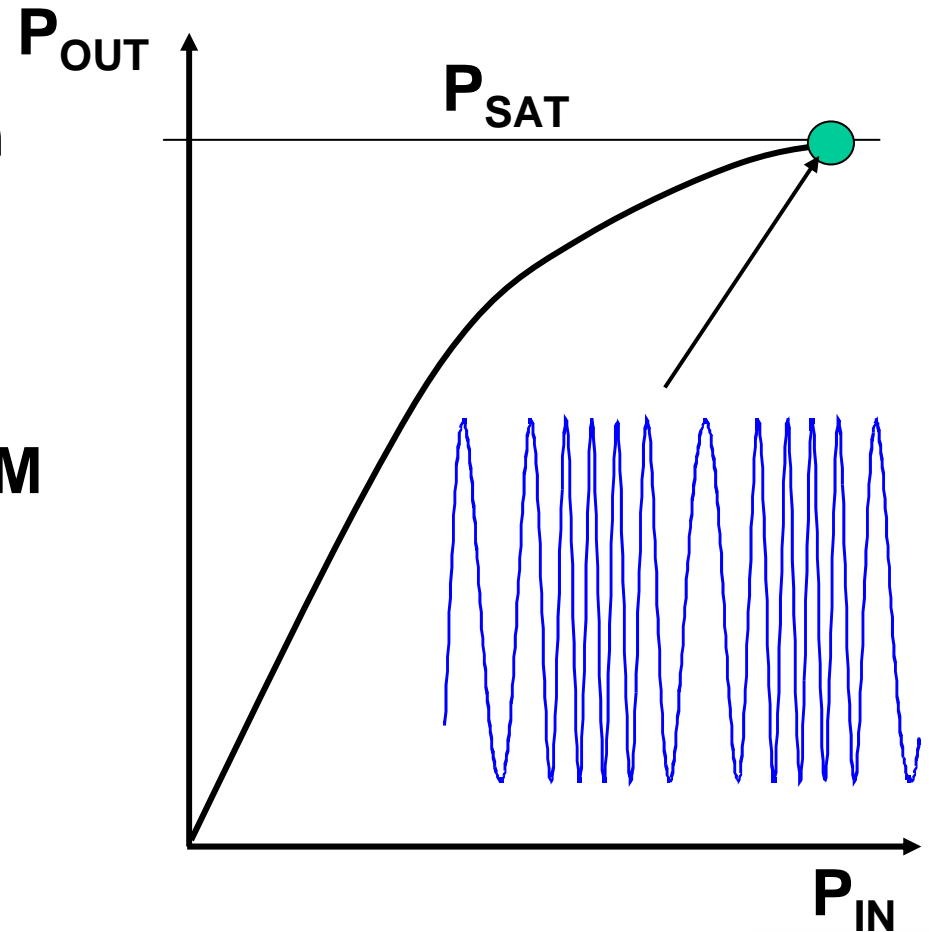
(1) Large Signal to Noise Ratio



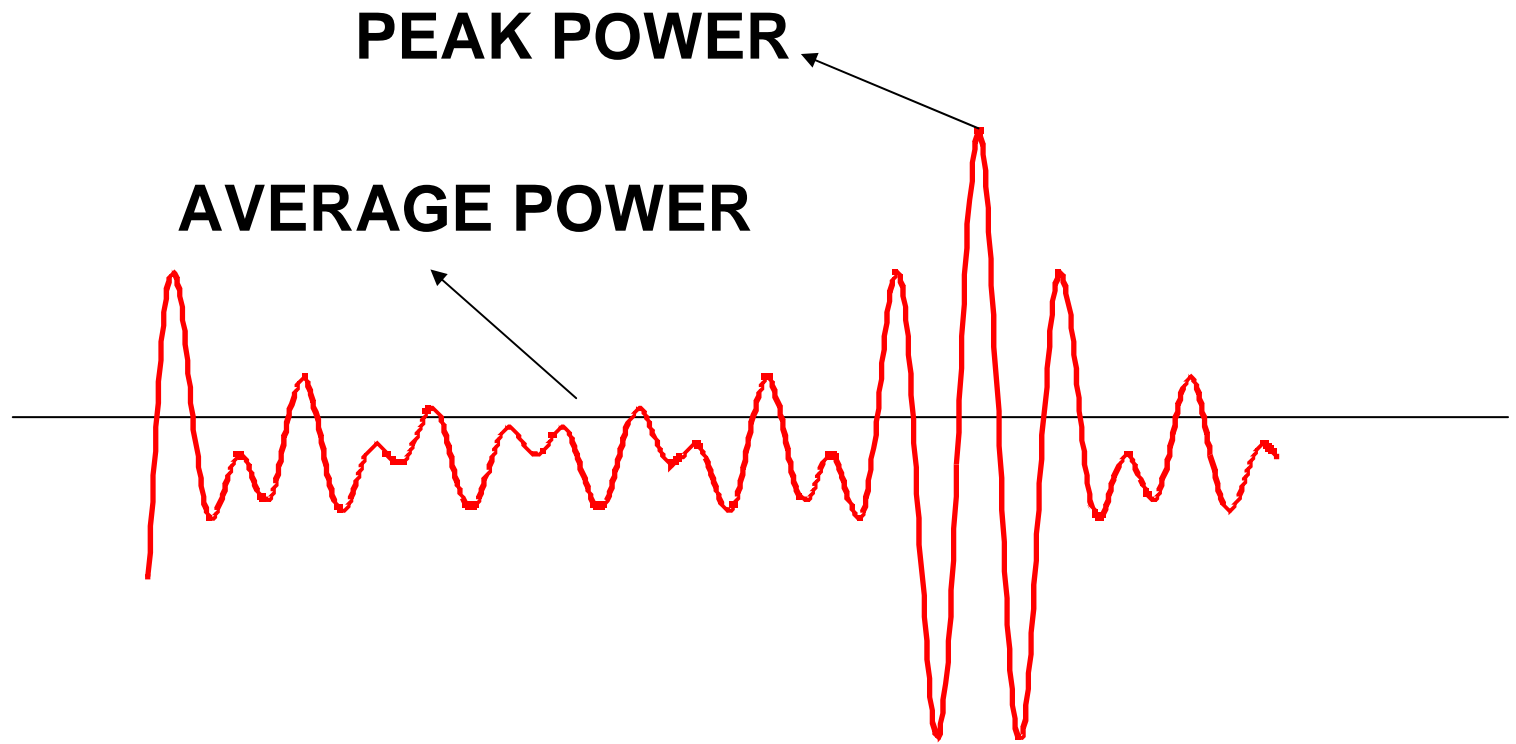
- Small SNR \rightarrow small backoff
- 64QAM OFDM modulation requires SNR \sim 30dB
- That is, needs to operate in linear region. Needs large power backoff to avoid distortion.

Constant Envelope Modulation

- Information encoded in phase/frequency only
 - GMSK, FSK, ...
 - Applications: 802.11 FHSS, BT FHSS, GSM
 - Power efficient amplification but spectrally inefficient



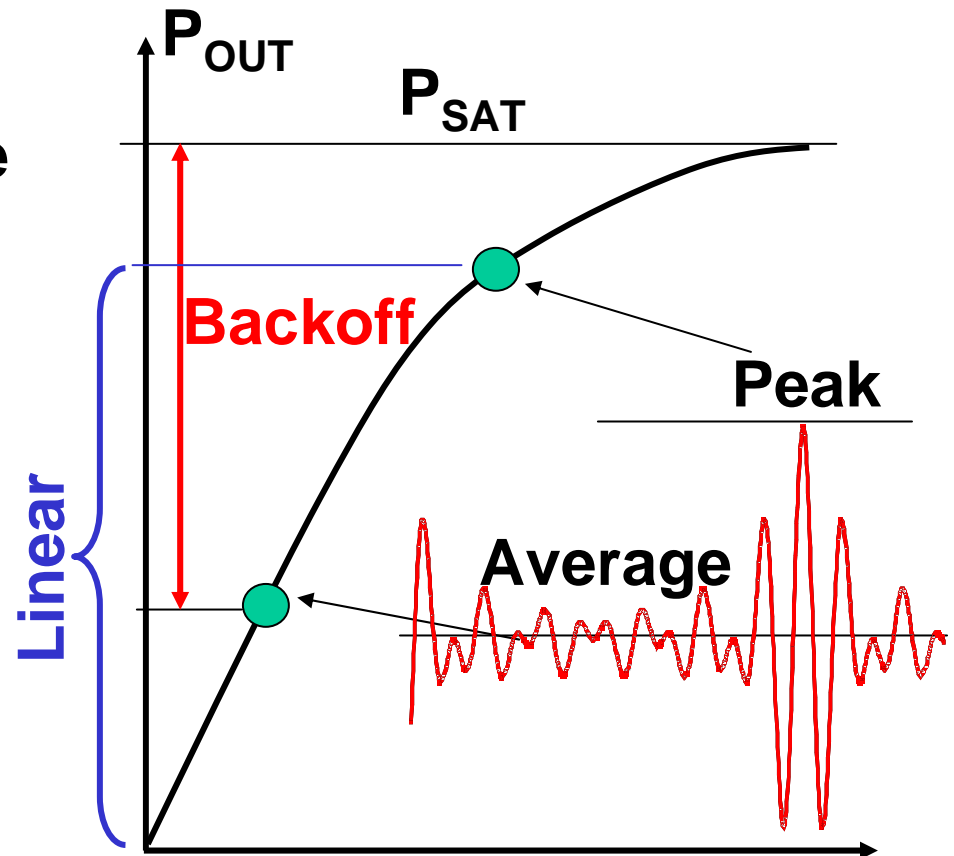
Peak to Average Power Ratio



$$\text{Peak to Average Power Ratio (Crest Factor)} = \frac{\text{Peak Power}}{\text{Average Power}}$$

Non-Constant Envelope Modulation

- Information encoded in both amplitude and phase
 - QPSK, QAM, CDMA, OFDM, ...
 - Applications: CDMA, 802.11a/b/g/n, Bluetooth EDR, EDGE
- Spectral efficient but power inefficient



(2) Large PAR for OFDM

- OFDM has a large peak to average ratio (PAR) of ~17dB
- Signal peaks are infrequent: 0.25dB SNR degradation when PAR reduced to 6dB for 16-QAM.
- Implications:
 - Poor power efficiency
 - With 6dB PAR, to obtain 40mW (16dBm) requires P_{sat} of ~22dBm or 160mW $\rightarrow \eta < 25\%$
 - With 17dB PAR, to obtain 40mW (16dBm) requires P_{sat} of ~33dBm or 2W $\rightarrow \eta < 2\%$

Simulated Power Backoff vs Data Rate

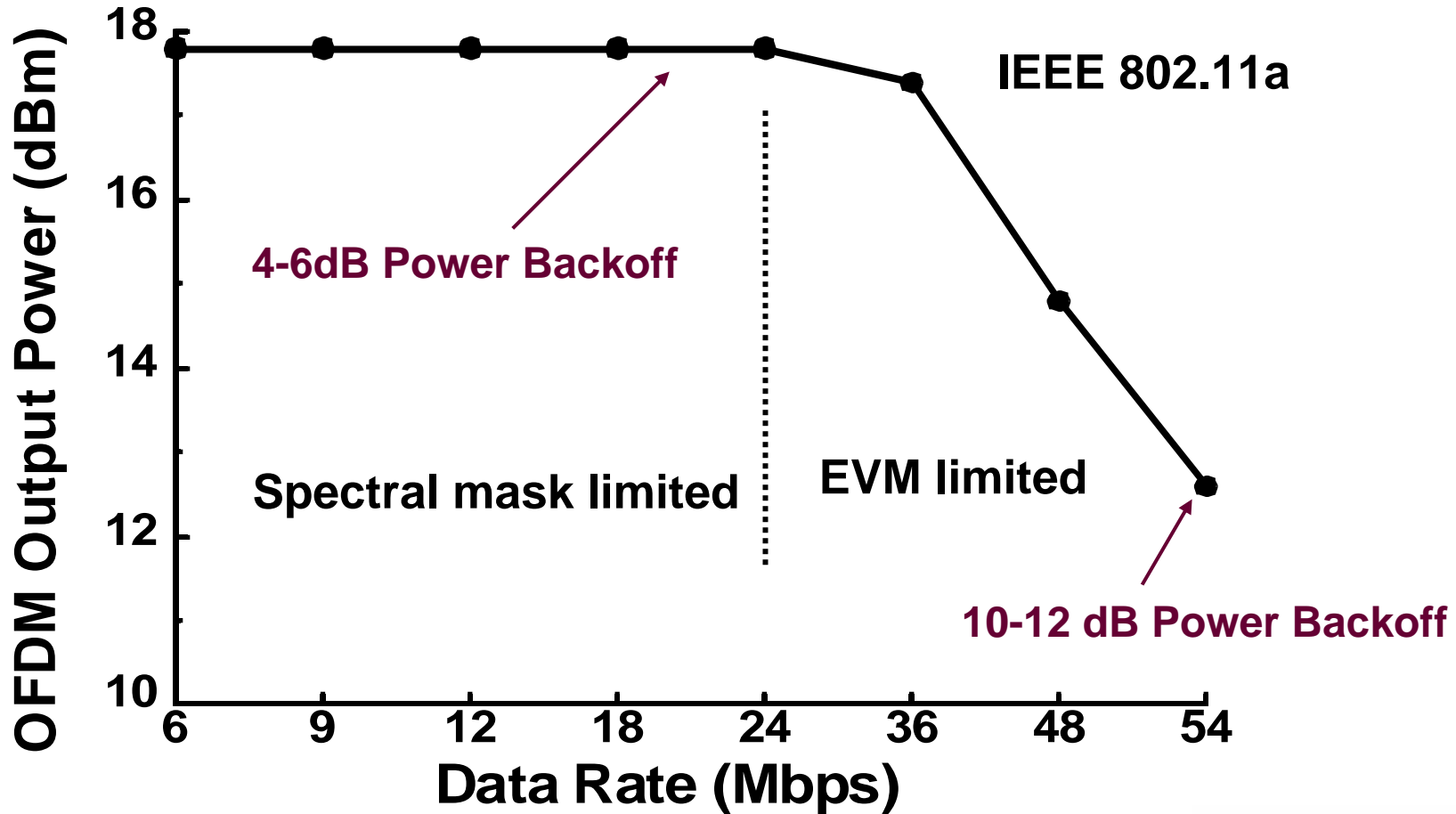
- Rapp Model:

$$V_{out} = \frac{V_{in}}{(1 + V_{in}^{2R})^{\frac{1}{2R}}}$$

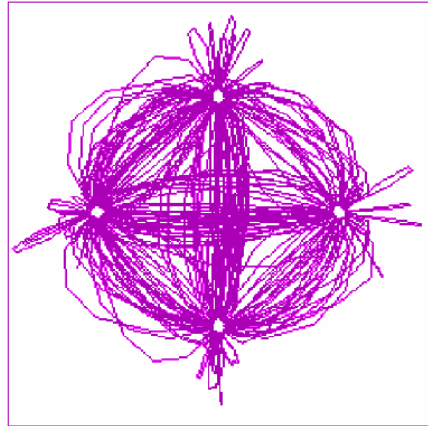
| R (Rapp Coeff) | 6-24Mbps | 36Mbps | 48Mbps | 54Mbps |
|------------------|----------|--------|--------|--------|
| 1 | 5 dB | 6.4 dB | 7.9 dB | 9.1 dB |
| Infinite (Ideal) | 3.4 dB | 4 dB | 4.8 dB | 5.4 dB |

Ref: McFarland et al, 2002 IEEE GaAs Symposium

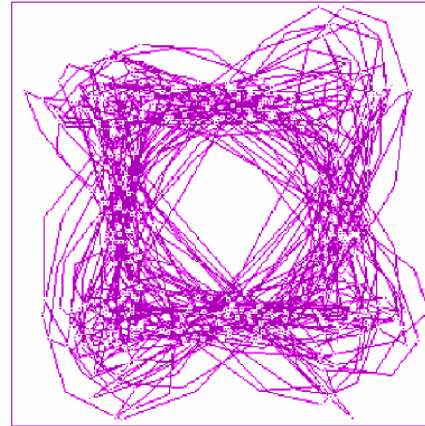
EVM vs Output Power



(3) Probability of Zero-Crossing



QPSK



OQPSK

Ref: Agilent AN 1334

- **No zero crossing: OQPSK, $\pi/4$ -QPSK**
- **Zero crossing: QPSK, HPSK, 8PSK, ...**
- **Lower probability \rightarrow Lower Peak to average ratio**

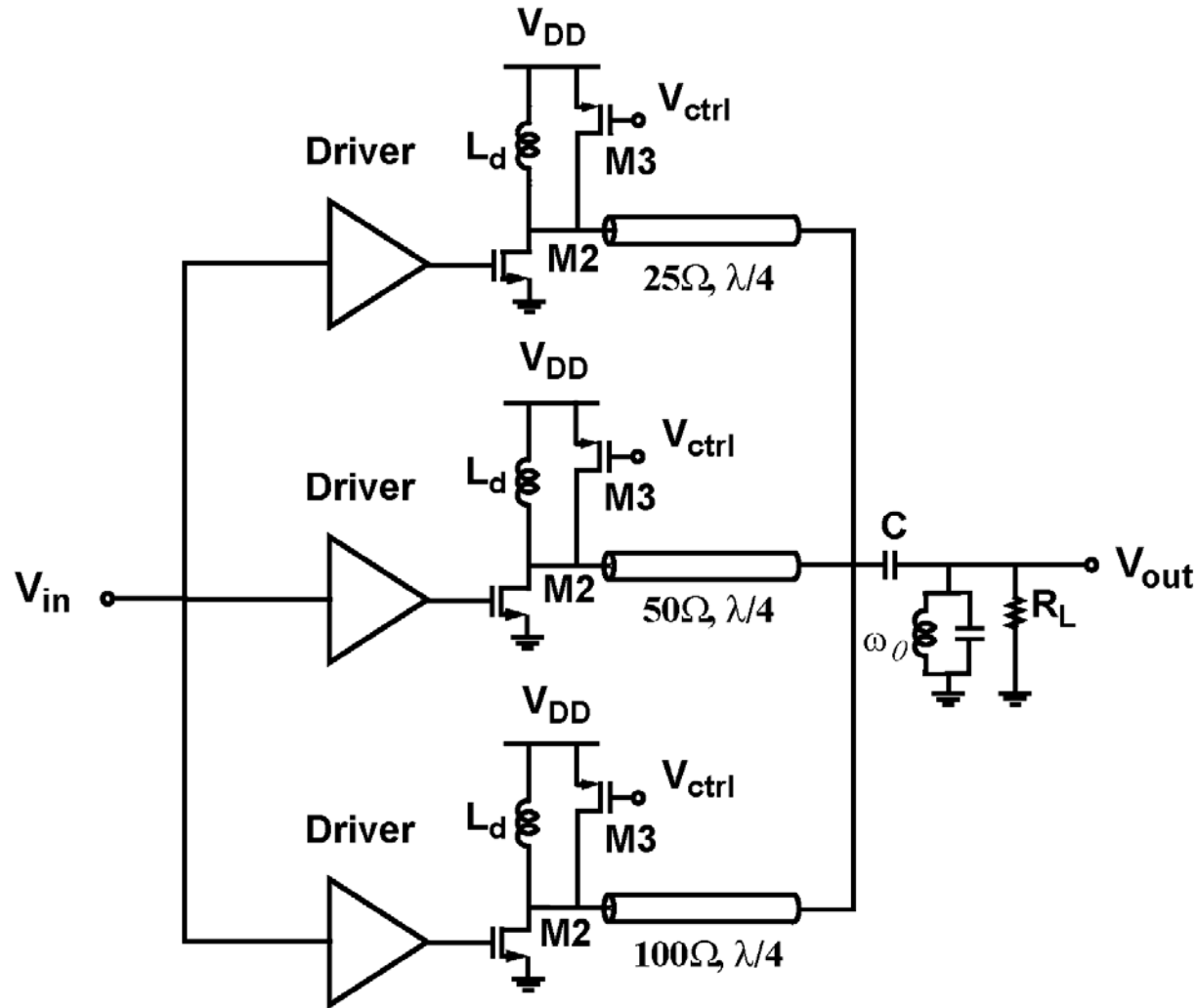
(4) Large Signal Bandwidth

- **Signal bandwidth:**
 - **Low bandwidth: 30kHz to 200kHz**
 - **Mid bandwidth: 1.25MHz**
 - **High bandwidth: 20MHz – 40MHz**
 - **Ultra High bandwidth: UWB...**
- **Large signal bandwidth has implications for linearization approaches such as polar, cartesian, ...**

PA Linearization

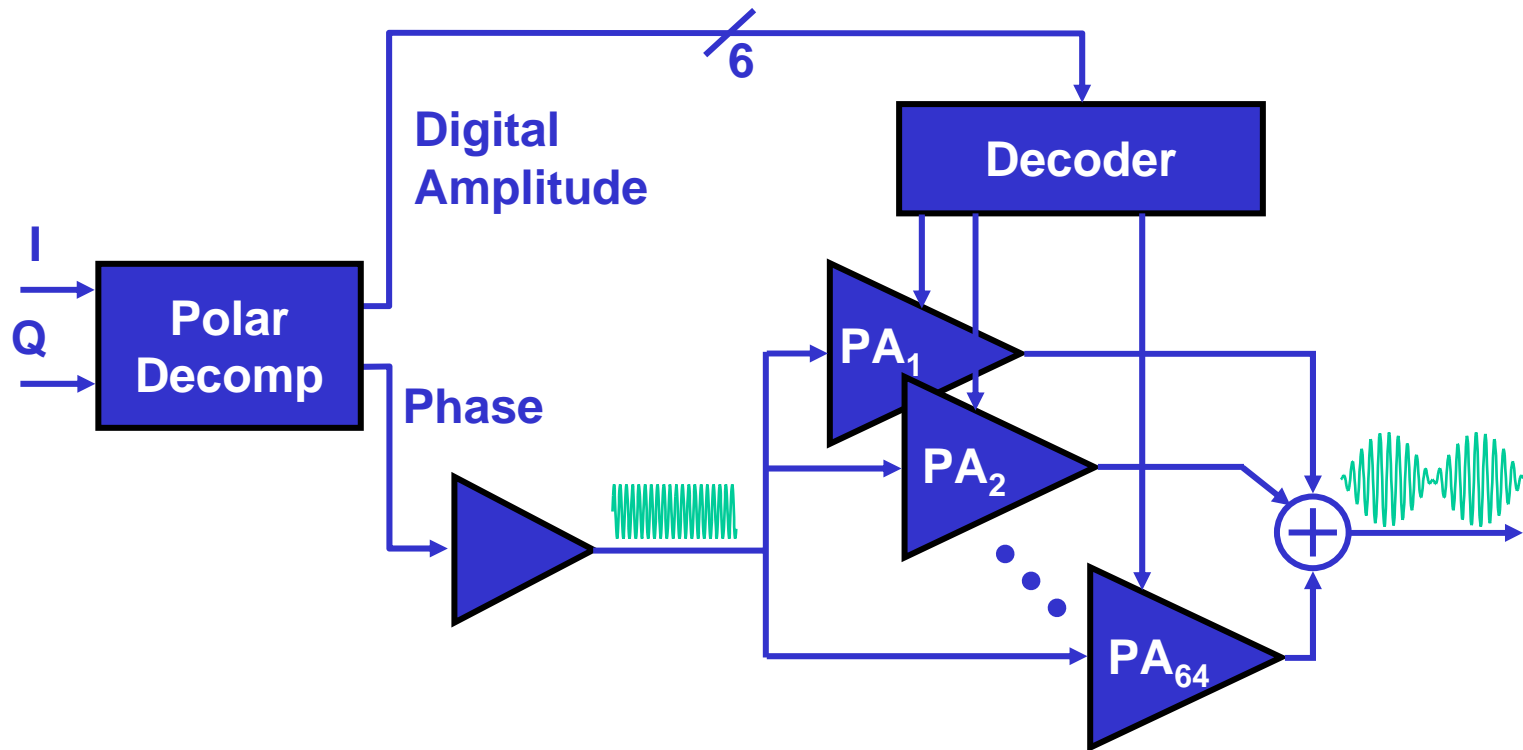
- **Concept:**
 - **Use efficient nonlinear PAs for amplification**
 - ***Techniques* to improve linearity**
- **An active research area for over half a century!**
 - **Polar (phase-magnitude); EER**
 - **Predistortion**
 - **Outphasing (Phase-Phase); LINC**
 - **Feedforward**
 - **Cartesian feedback**
 - **Doherty**

Parallel Amplification



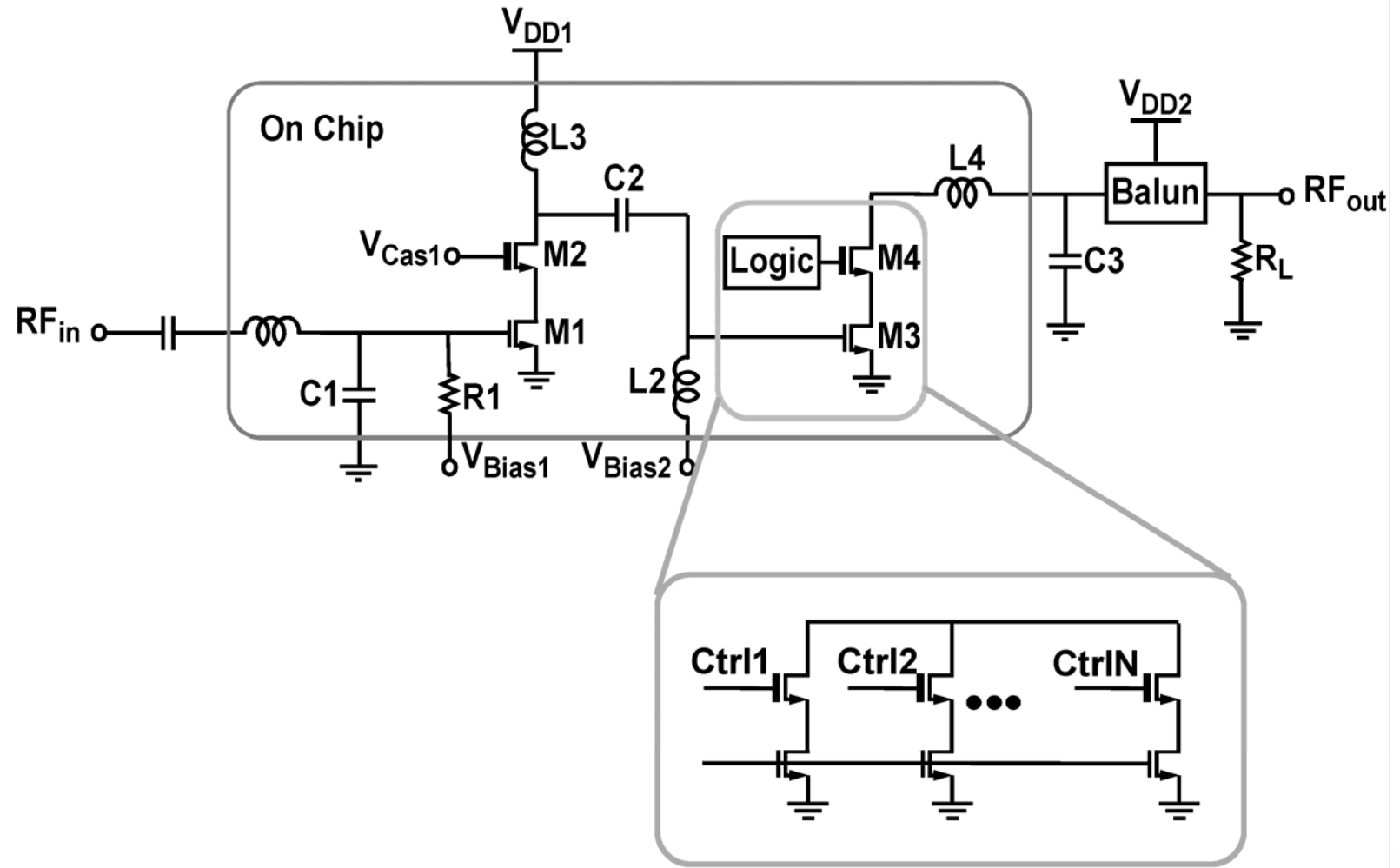
Ref: Shirvani et al, IEEE JSSC, June 2002

Polar Modulation for OFDM



Ref: Kavousian et al, ISSCC 2007

Polar Modulation for OFDM (cont'd)



Ref: Kavousian et al, ISSCC 2007

Conclusion

- **Digital wireless communication system is evolving from:**
 - **constant envelope → non-constant envelope**
 - **small signal bandwidth → large signal bandwidth**
- **Major PA linearity specifications:**
 - **Spectral mask limit**
 - **EVM limit**
- **Design of Efficient and Linear PA is still an area of active research**

Acknowledgements

- I would like to thank Dr. David Su and Dr. Pouya Kavousian for contributing to this presentation.