EECS 242:
Power Amplifiers for Communications

Professor Ali M Niknejad

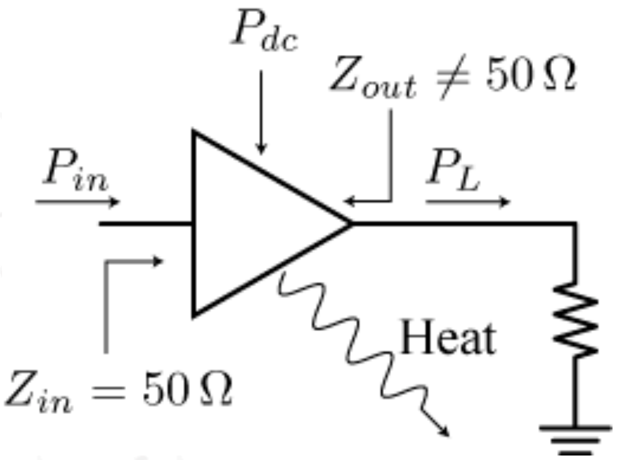
Advanced Communication Integrated Circuits

University of California, Berkeley

Power Amplifier Lecture Outline

- PA system level specifications
- Power devices (briefly) and compact models (EECS 231)
- Power amplifiers (EECS 142/242)
- Linearization techniques
- Matching networks (EECS 217)
- Power combining (EECS 217)

Power Amplifier Specifications



- Peak Output Power
- Efficiency
- Power Gain
- Amplifier Linearity
- Stability over VSWR
  - Ability to transmit into an unknown/varying load
- Power Control
  - Step size, range
  - High efficiency at back-off

Peak Output Power

- The peak output power determines the range for two-way communications.
- The peak power is often specified at the 1-dB compression point.
- Need about ~1W 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.
- In practice, the average power transmitted may be much lower than the peak output power due to power control (slow time scale) or the amplitude modulation (fast time scale)

Peak Efficiency

- Power Added Efficiency (PAE) is a popular metric. P_{out} is the output power, P_{in} is the input power, and P_{dc} is the DC power consumption of the PA
- For high power gain systems (G_p), the efficiency approaches the "collector" (drain) efficiency η_c, or simply the efficiency of the last stage
- The efficiency of the PA is an important measure of the battery life of the wireless transceiver. Since the PA power dwarfs the power consumption in the receiver, it is usually the most important specifications.
- For lower power systems (below 10 mW), the power of the entire transmitter chain is important and should be taken into consideration.

$$\eta_{PAE} = \frac{P_{out} - P_{in}}{P_{dc}}$$

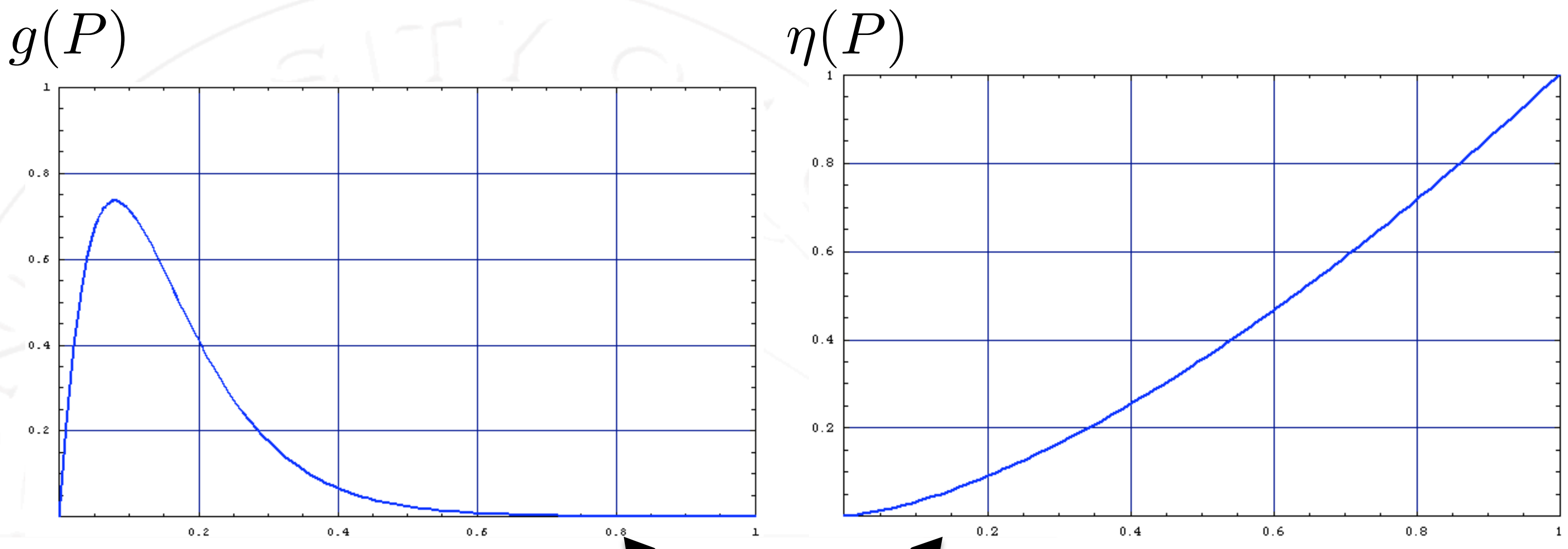
$$\eta_{PAE} = \frac{P_{out} - \dfrac{P_{out}}{G_p}}{P_{dc}} = \frac{P_{out}}{P_{dc}}(1 - G_p^{-1})$$

$$\eta_{PAE} = \eta_c(1 - G_p^{-1}) \approx \eta_c$$

Average Efficiency with Power Control

- For a constant envelope signal (phase/frequency modulation), the average efficiency is equal to the average efficiency at peak power.
- Due to power control, though, we must take into account the statistics of the transmitted signal. Modern systems use power control to minimize the impact of a transmitter on nearby systems (interference) and hence only use as much power as needed to achieve low data rate communication with the base station.
- Thus the actual average efficiency depends on how the efficiency varies with output power

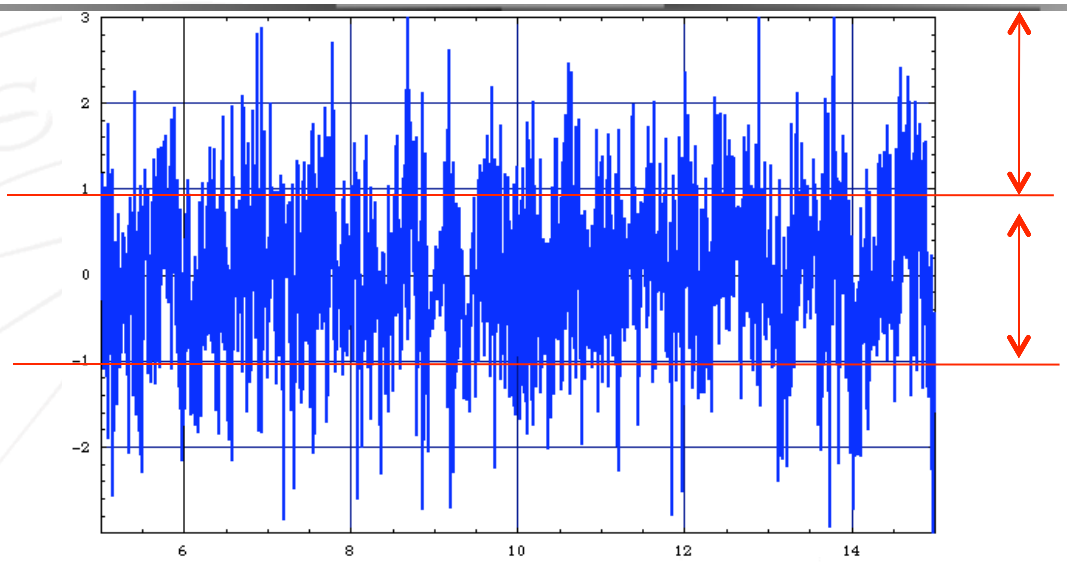
Power Statistics



$$\eta_{av} = \int_{-\infty}^{\infty} \eta(P) g(p) dP$$

- Given the distribution of power levels, or the PDF $g(P)$, we can calculate the expected value of the efficiency
- Unfortunately, for most PAs the efficiency drops at low power.

Envelope Statistics

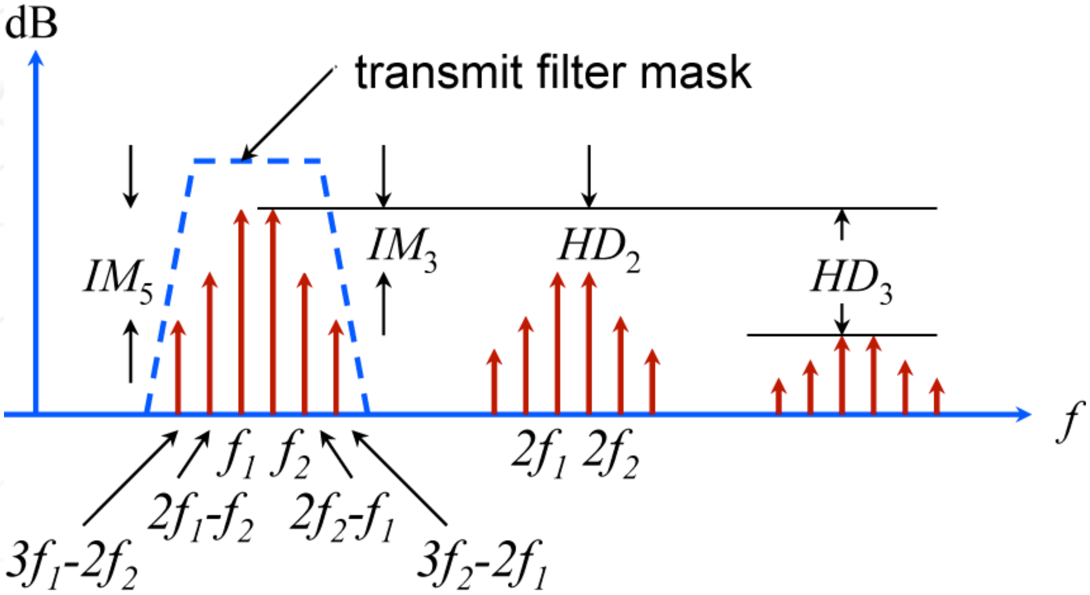


Peak is
much larger

Average
Power

- For signals with amplitude modulation, the average efficiency depends not only on the desired power level, but also on the statistics of the envelope.
- The amount of power variation is usually captured by the PAR, or the Peak-to-Average Radio.
- The PAR is a strong function of the type of modulation. Systems with the highest PAR are OFDM systems employing multiple carriers.

Linearity



- The traditional way to characterize narrowband system linearity is with IM3. Since the system may be driven into a strongly non-linear regime, all odd order harmonics should be carefully taken into account to ensure that excessive spectral leakage does not occur.

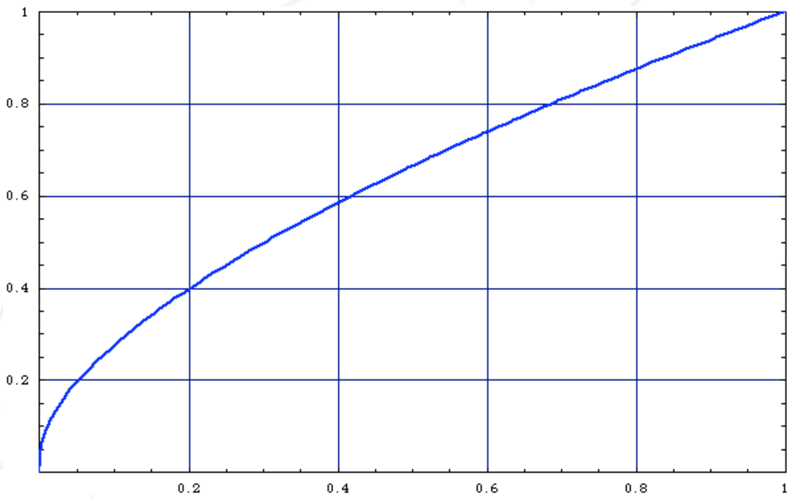
Sources of Non-Linearity

- PAs exhibit nonlinear distortion in amplitude and phase. For a mulated signal, both sources of distortion are significant.
- The dominant sources are AM-to-AM and AM-to-PM.
- Amplitude distortion: AM-to-AM conversion
- Phase distortion: AM-to-PM conversion
- For input: $x(t) = A(t)\cos(\omega t + \phi(t))$
- Corresponding output:

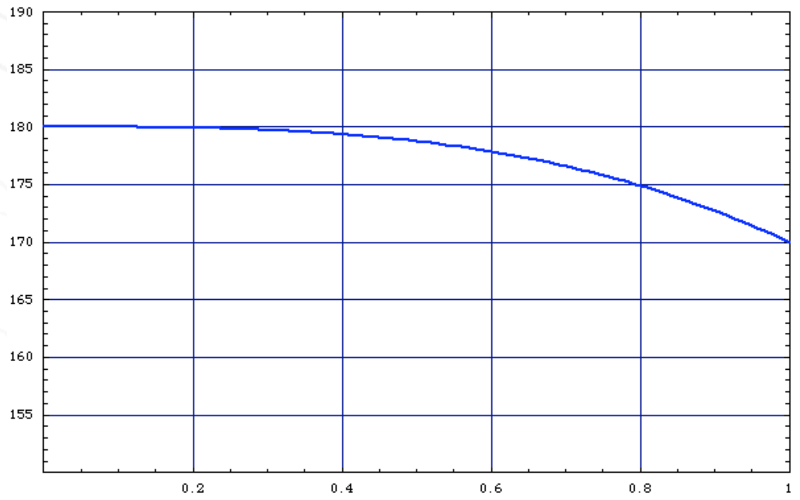
$$y(t) = g[A(t)]\cos(\omega t + \phi(t) + \psi[A(t)])$$

- AM-to-AM conversion dominated by gm non-linearity
- AM-to-PM conversion dominated by non-linear capacitors

AM-AM and AM-PM Non-Linearity



AM-AM Curve

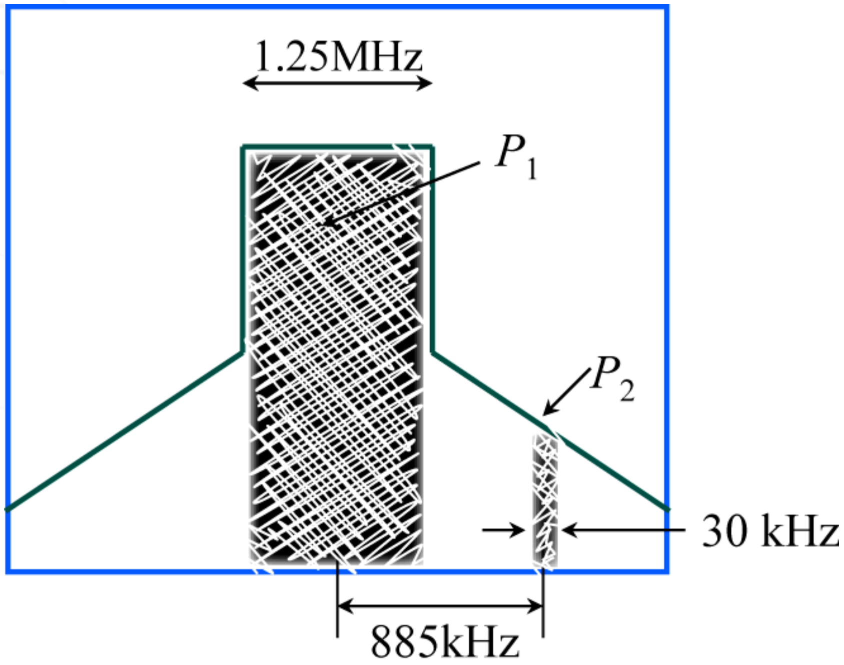


AM-PM Curve

- For a narrowband signal, we can partition the non-linearity into an amplitude-amplitude (AM-AM) component and an amplitude-phase (AM-PM) component
- This behavioral model can be used to run system level simulations to see the effect of non-linearity on a modulated waveform

Adjacent Channel Power (ACP)

- For modern communication systems, the IM specifications leave a lot to be desired since they are only based on multi-tone excitation. Increasingly, the actual modulation waveform needs to be tested with the PA.
- To ensure proper etiquette, the amount of power leaking into an adjacent channel is carefully specificed.



ACP=P_1(dBm)-P_2(dBm)

Error Vector Magnitude

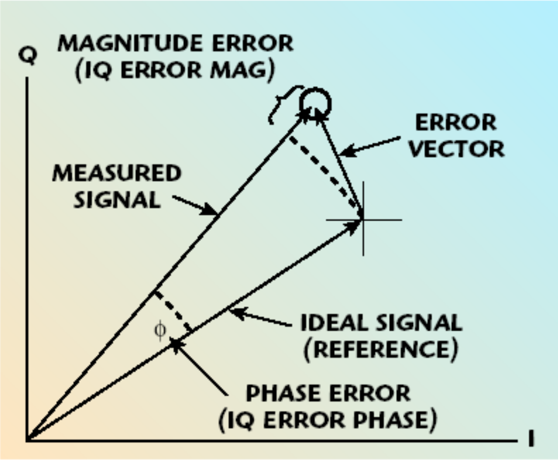


Fig. 1 Error vector magnitude and related quantities.[6]

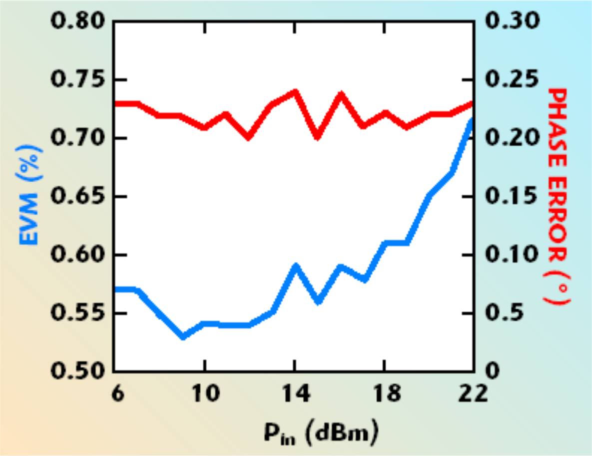


Fig. 2 EVM measurement (reference).

- Figures from Microwave Journal (April 2005), "DESIGN OF LINEAR S-BAND POWER AMPLIFIERS WITH HIGH POWER-ADDED EFFICIENCY," by Y.W. Yeap and T. W. Chua

- While the ACP is a good way to measure how much the PA signal will deteriorate a neighboring channel signal, the EVM is a measure of how much the PA interferes with itself.
- The EVM measures the systematic deviation of the constellation points from the ideal positions due to amplifier non-linearity.

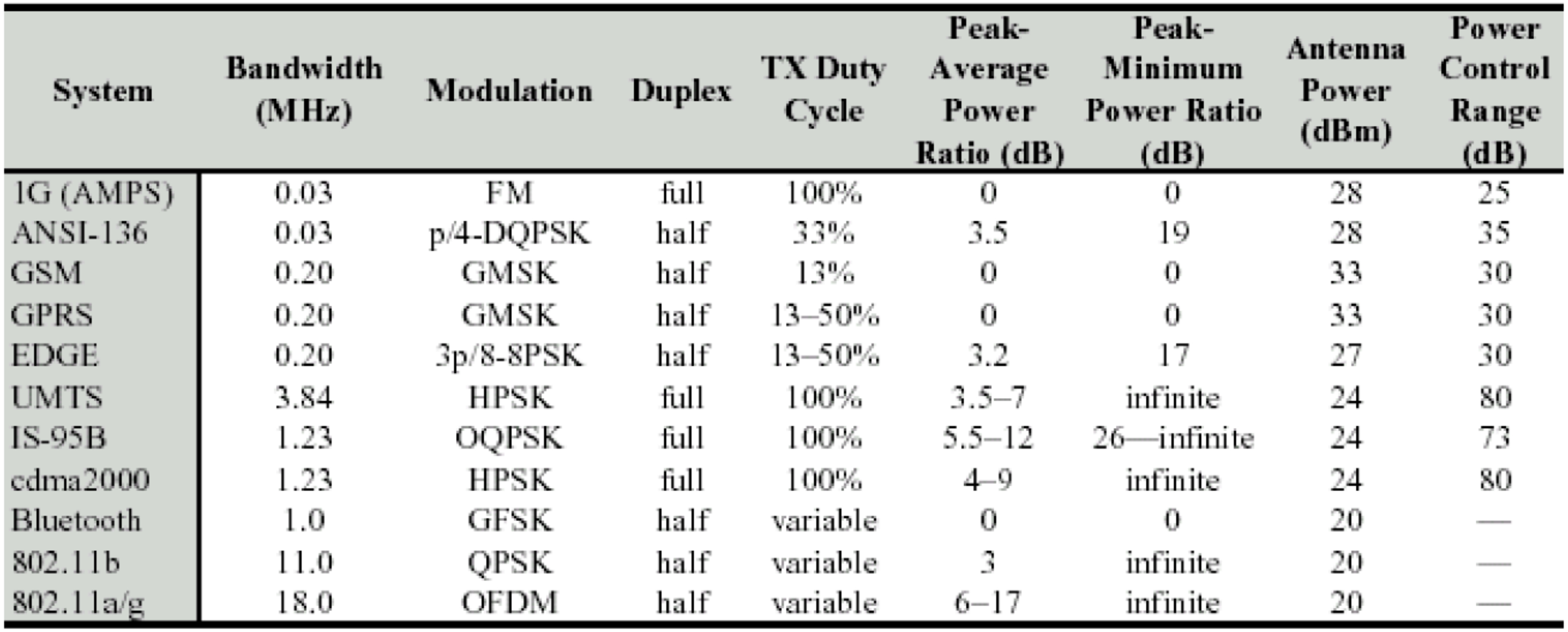
Digital and Analog Modulation

- Both digital and analog modulation schemes involve amplitude and/or phase modulation:

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

- Linearity specs of PA determined by envelope variation
- Most spectrally efficient modulation schemes have large envelope variations
- Analog FM (AMPS) uses constant envelope => can use efficient non-linear power amplifiers (60%-70%)
- GMSK (GSM) uses constant envelope as well
- pi/4 DQPSK (IS54/136) has 3dB peak to average envelope fluctuation (PAEF)
- QPSK (CDMA base station) has 10dB of PAEF
- OQPSK (CDMA handset) has 3dB of PAEF

Modulation Schemes

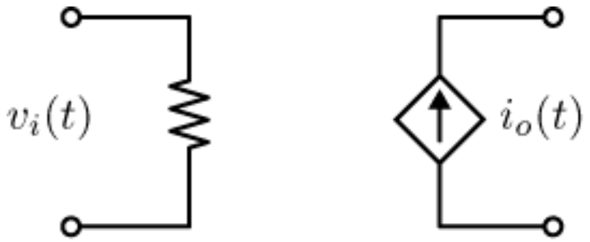


System	Bandwidth (MHz)	Modulation	Duplex	TX Duty Cycle	Peak-Average Power Ratio (dB)	Peak-Minimum Power Ratio (dB)	Antenna Power (dBm)	Power Control Range (dB)
1G (AMPS)	0.03	FM	full	100%	0	0	28	25
ANSI-136	0.03	p/4-DQPSK	half	33%	3.5	19	28	35
GSM	0.20	GMSK	half	13%	0	0	33	30
GPRS	0.20	GMSK	half	13–50%	0	0	33	30
EDGE	0.20	3p/8-8PSK	half	13–50%	3.2	17	27	30
UMTS	3.84	HPSK	full	100%	3.5–7	infinite	24	80
IS-95B	1.23	OQPSK	full	100%	5.5–12	26—infinite	24	73
cdma2000	1.23	HPSK	full	100%	4–9	infinite	24	80
Bluetooth	1.0	GFSK	half	variable	0	0	20	—
802.11b	11.0	QPSK	half	variable	3	infinite	20	—
802.11a/g	18.0	OFDM	half	variable	6–17	infinite	20	—

- Key specifications are the peak-to-average radio, the peak power, and the power control range.
- Constant modulation schemes much easier (GSM, AMPS).
- OFDM very hard !

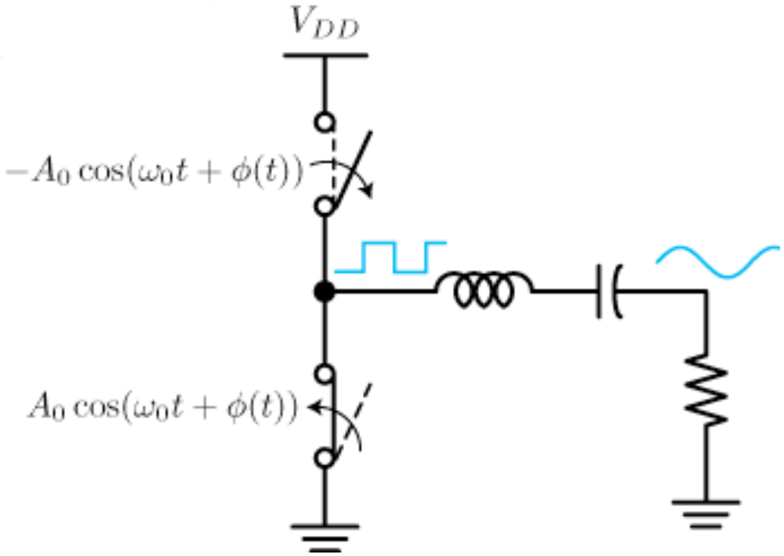
Switching versus “Linear” PA

- Two general classes of PA: Linear and Non-Linear
- “Linear Pas” preserve amplitude and phase information while “Non-linear PAs” only preserve phase mod. Linear PAs employ transistors as current sources (high Z), Non-linear PAs employs transistors as switches (low Z)
- Linear PAs can drive both broadband and narrowband loads. Non-linear PA usually drive a tuned circuit load
- Amplitude information in a non-linear PA can be recovered by:
    - Oversampling, duty cycling, or varying the supply voltage



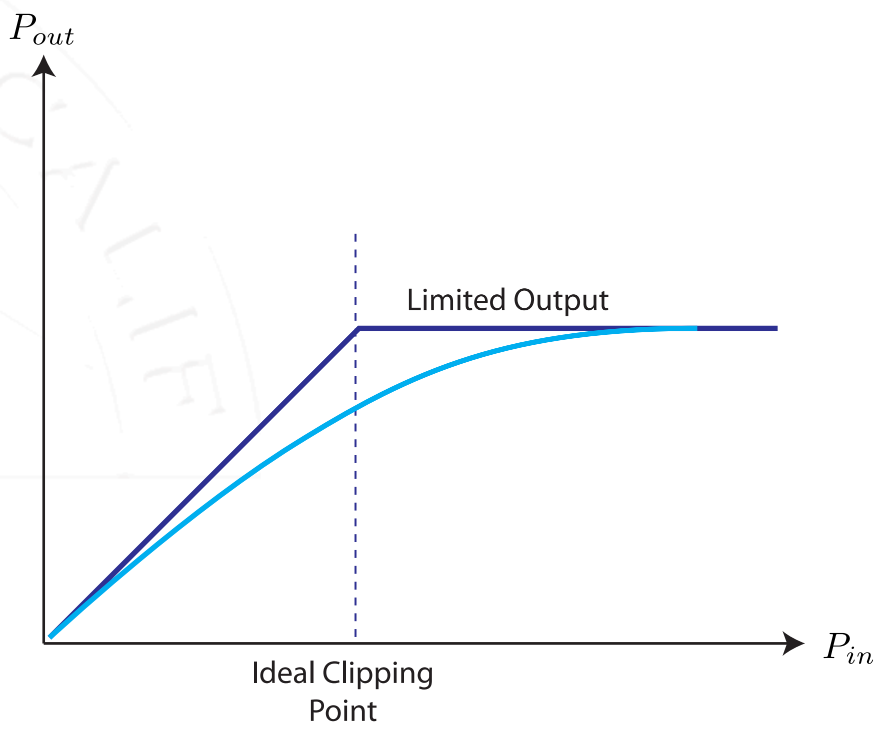
$$v_i(t) = A(t)\cos(\omega t + \phi(t))$$

$$i_o(t) = G_m A(t)\cos(\omega t + \phi(t))$$



Clipping: A “Linear” PA is Impossible

- All amplifiers eventually “clip”, that is the output cannot be some multiple of the power supply.
- If we “back-off” sufficiently from the peak so that the amplifier never clips, then we compromise the efficiency.
- We can generally make a compromise and choose sufficient back-off to meet the EVM specs



Power Back-off

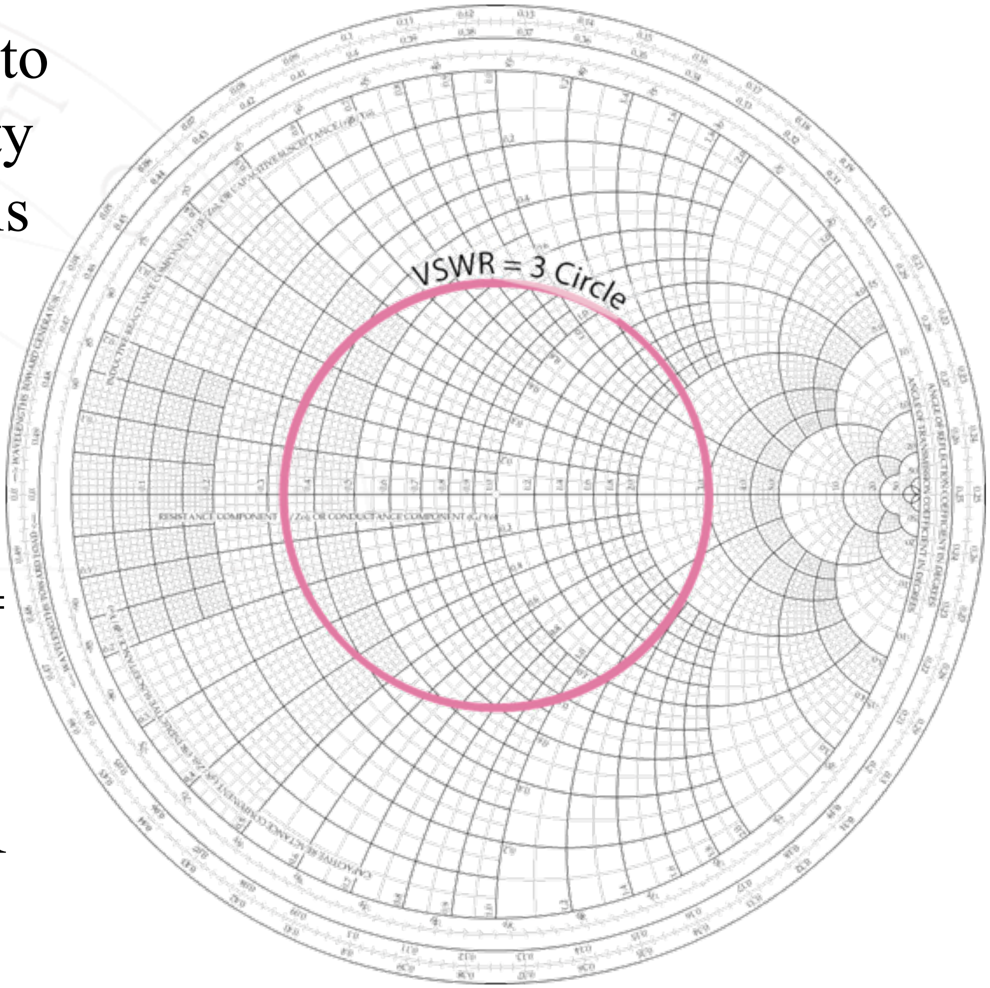
- In applications requiring a linear PA due to PAR, we must back-off from the peak power point to avoid clipping the waveform.
- For 10 dB of PAR that means operating the PA at 10 dB lower power (or power back-off).
- An OFDM 802.11 g system needs 20 dBm at antenna and has a PAR of about 17 dB. That means to transmit 20 dBm average power, the PA should be capable of transmitting 37 dBm !!! In practice the peak amplitude is a rare event and the PA will clip.

Power Control

- Most wireless systems have power control. Power control is important to limit transmit power to the lowest possible setting. This saves battery power and limits the amount of interference to other nearby users.
- There are two power control loops to consider: (1) Mobile power control loop and (2) Basestation to mobile power control loop
- The mobile unit must transmit a given output power with a certain resolution. Say in GSM the output power can be ±2 dB.
- The mobile power control loop can be a closed loop or open loop system. In an open loop system, the power of the output power of the hand-held is measured and calibrated for each DAC setting. Then an open loop system is used estimated based on a one-time calibration.
- In a closed-loop system, the output power is estimated using a directional coupler, a voltage measurement, or a current measurement.

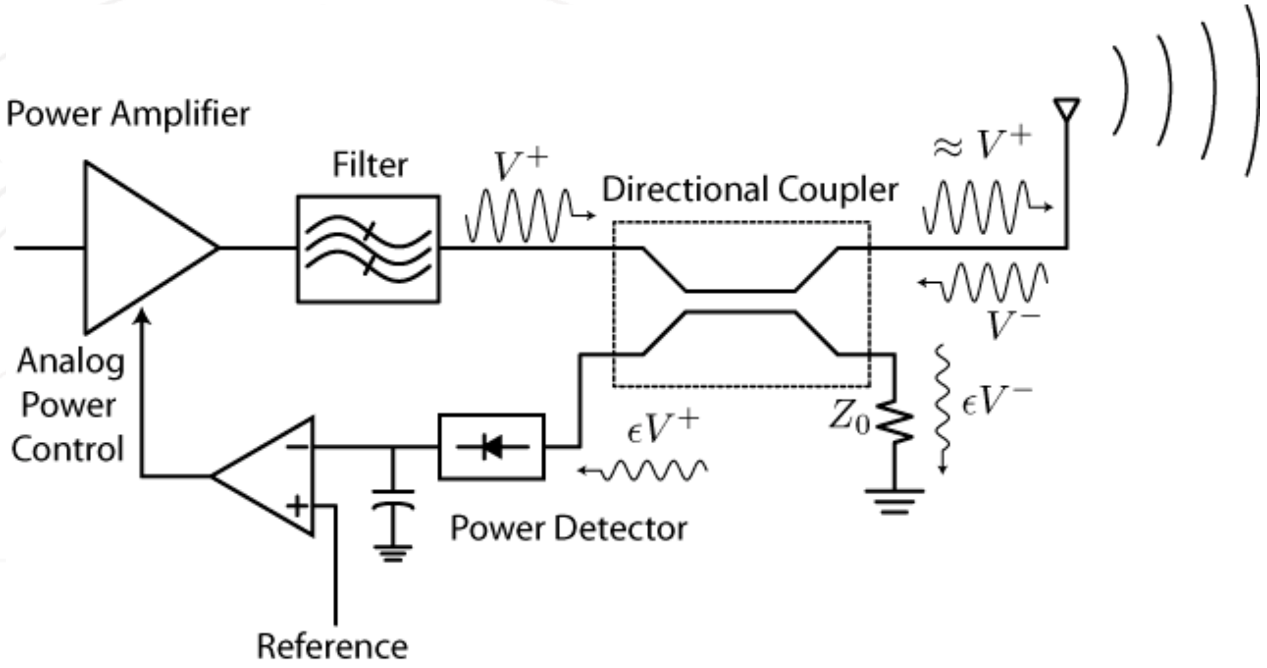
Stability over VSWR

- The PA generally must be able to drive a varying load. The ability to drive a given range of loads is specified as the VSWR, e.g. a VSWR of 3:1
- A system with a VSWR of 3:1 can drive any load with magnitude as large as 3*50 Ω = 150 Ω or as small as 50Ω/3 =17Ω. On the Smith Chart *any* load lying on a constant VSWR circle is a valid load, or any impedance such that



$$swr^{-1} \leq |x + j\,y| \leq swr^{+1}$$

Power Control Loops



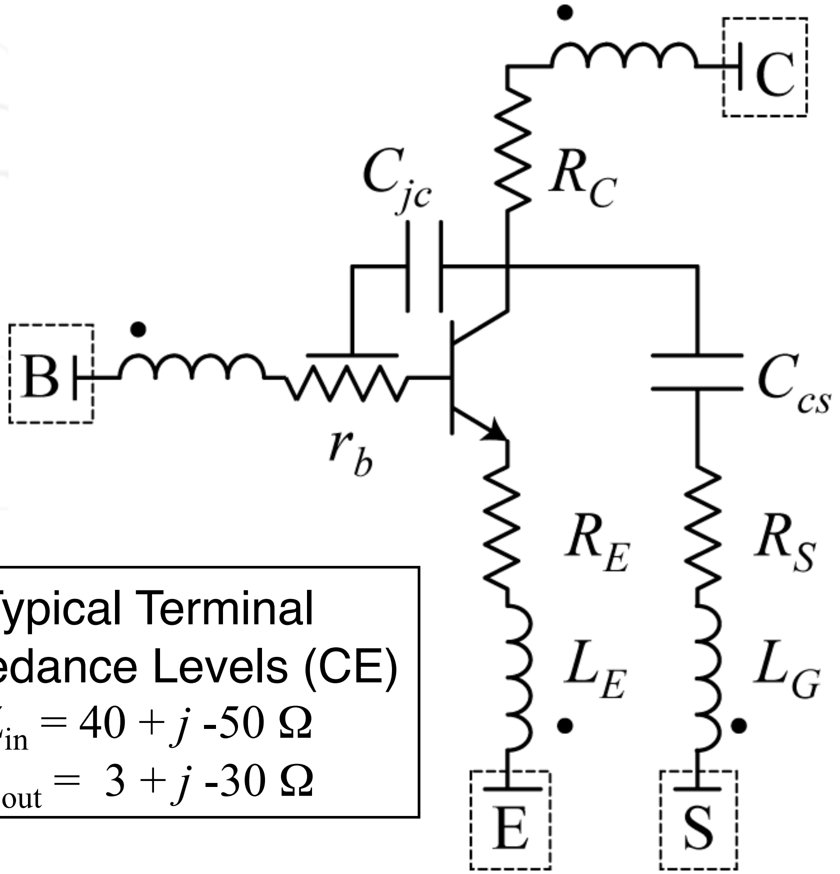
- A directional coupler is one of the more accurate methods to measure the power delivered to the load (antenna). The power reflected from the antenna due to a mismatch is not computed. But the directionality of the coupler is key.

RF Power Transistors

- In a BJT there is a direct trade-off between the breakdown voltage and the f_T of the device. Some people define this as a metric for the transistor.
- Thus we should employ the lowest tolerable f_T device for our PA. That's because such a device can swing the largest voltage.
- Unfortunately, the trend in technology is the opposite, mostly for digital and RF applications, giving us over 100 GHz f_T and only 1-2 volts to operate with. This is good for digital.
- CMOS devices also require a large C_{ox} (gate control) for short channels, and thus gate oxide breakdown is a big issue. Punchthrough is another breakdown mechanism.

BJT Device Power Gain

- For 300mA of current need ~ 20,000 mm^2 of Si area
- Operating at frequencies ~ f_T / 10 (say 2.5 GHz in 25 GHz process)
- Device parasitics dominate impedance levels. Don't forget Temp!!!
- Package parasitics limit gain by providing feedback
- Gain determined by (M. Versleijen et. al.):



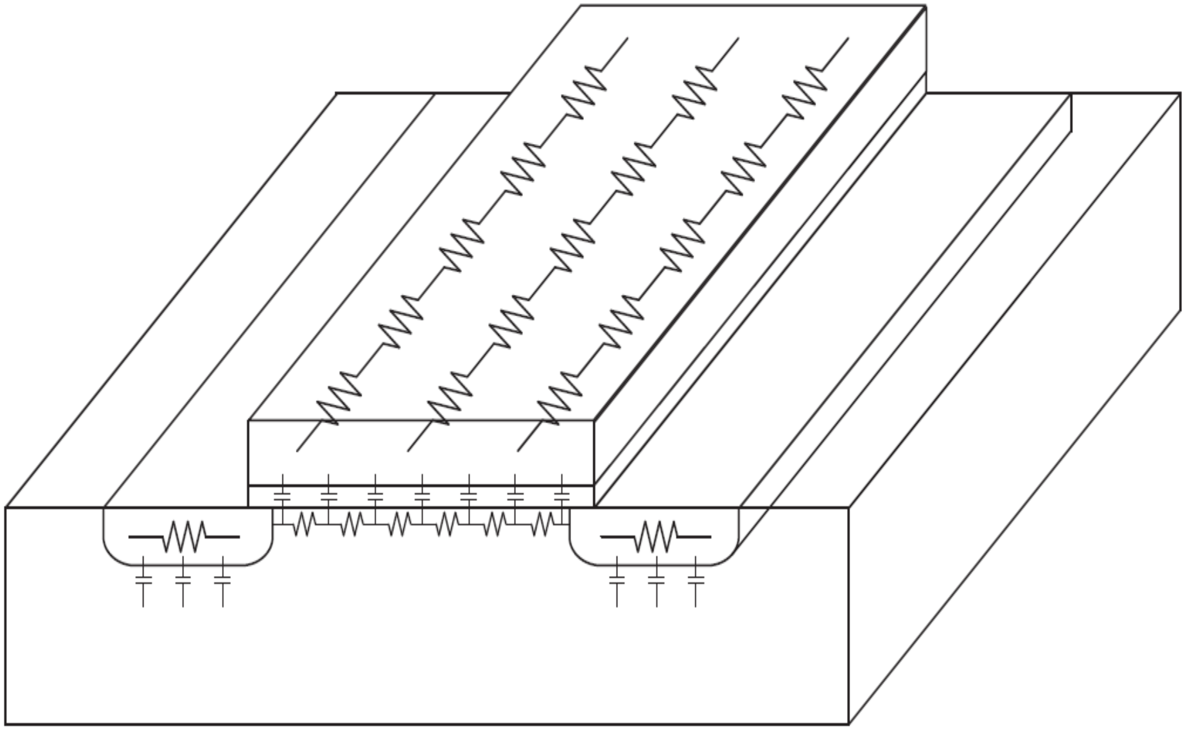
Typical Terminal Impedance Levels (CE)

$Z_{in} = 40 + j\,\text{-}50\ \Omega$

$Z_{out} = 3 + j\,\text{-}30\ \Omega$

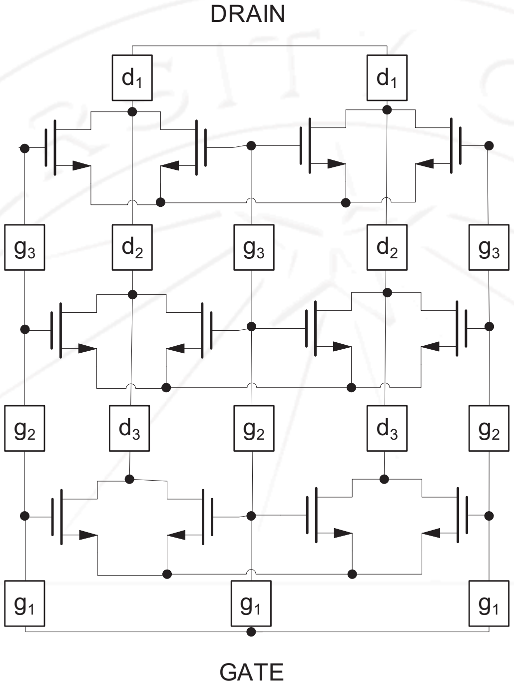
$$G_P = \left(\frac{\omega_T}{\omega}\right)^2 \frac{1}{1+\omega_T R_L C_{BC}} \frac{R_L}{\omega_T L_E + R_E + R_B(1+\omega_T R_L C_{BC}^{\text{int}})} \approx \frac{\frac{1}{C_{BC} L_E}}{\omega^2}$$

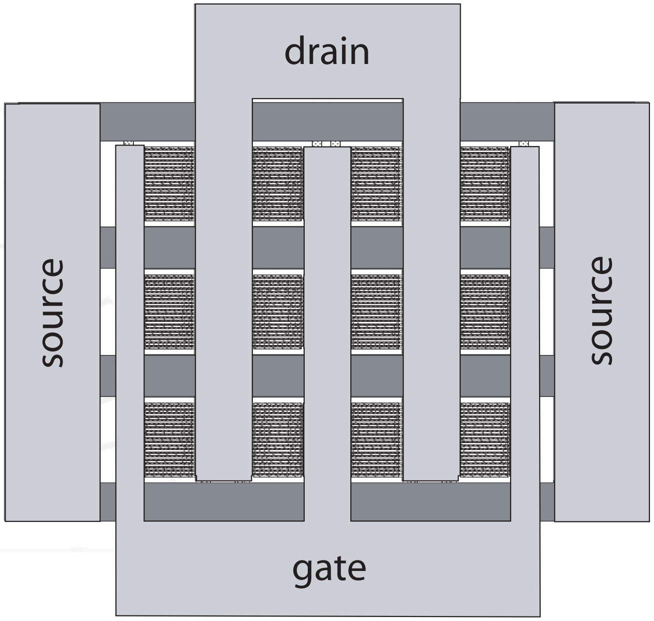
CMOS Device Losses



- For each "finger" of the CMOS device, we must carefully extract the capacitance and resistive parasitics. The layout will have a large impact on these parasitics.

Power FET Layout

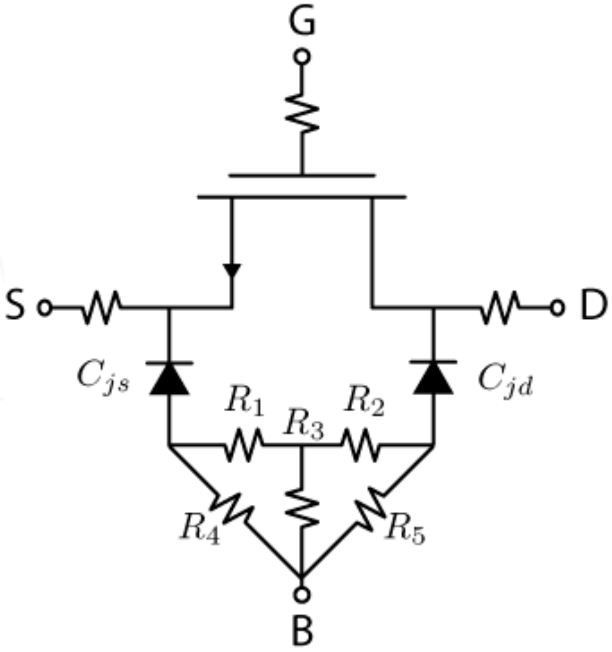




- Power FETs are typically very large (millimeter size) and the layout is broken into sub-cells. Each sub-cell is broken into multi-fingered transistors and the gate/drain lines are delay equalized.
- The layout metals introduce significant resistance and capacitance, which needs to be carefully modeled.

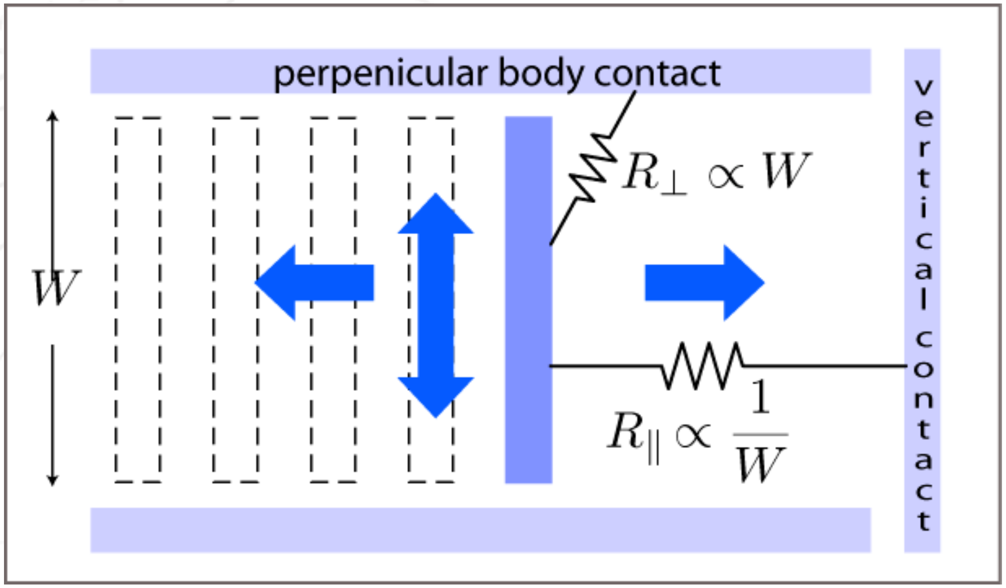
CMOS Device Power Gain

- Need a good model of device, especially resistive paraistics. To predict power gain need to know the gate/source/drain resistance, including the interconnect parasitics (vias, metal, poly), and the gate induced parasitics.
- Substrate parasitics will also limit power gain and needs to be extracted accurately.
- Include inductance for high frequencies or very large "distributed" device.
- Note that the point the device looks distributed depends on the slow wave velocity due to large gate and drain cap.



Don't forget the temp *T* of device !!!

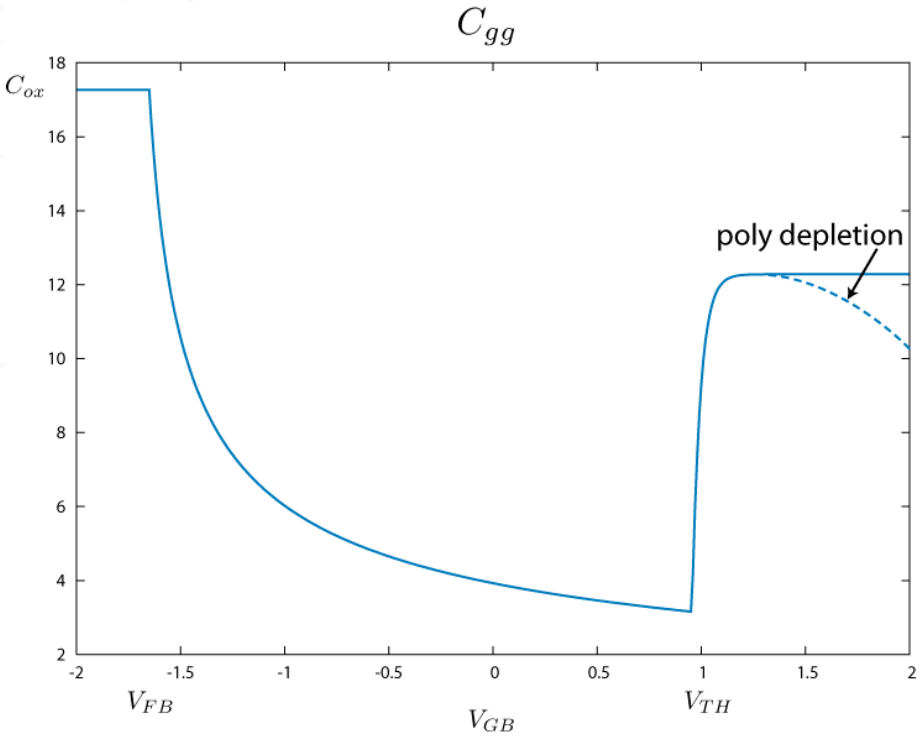
Substrate Parasitics



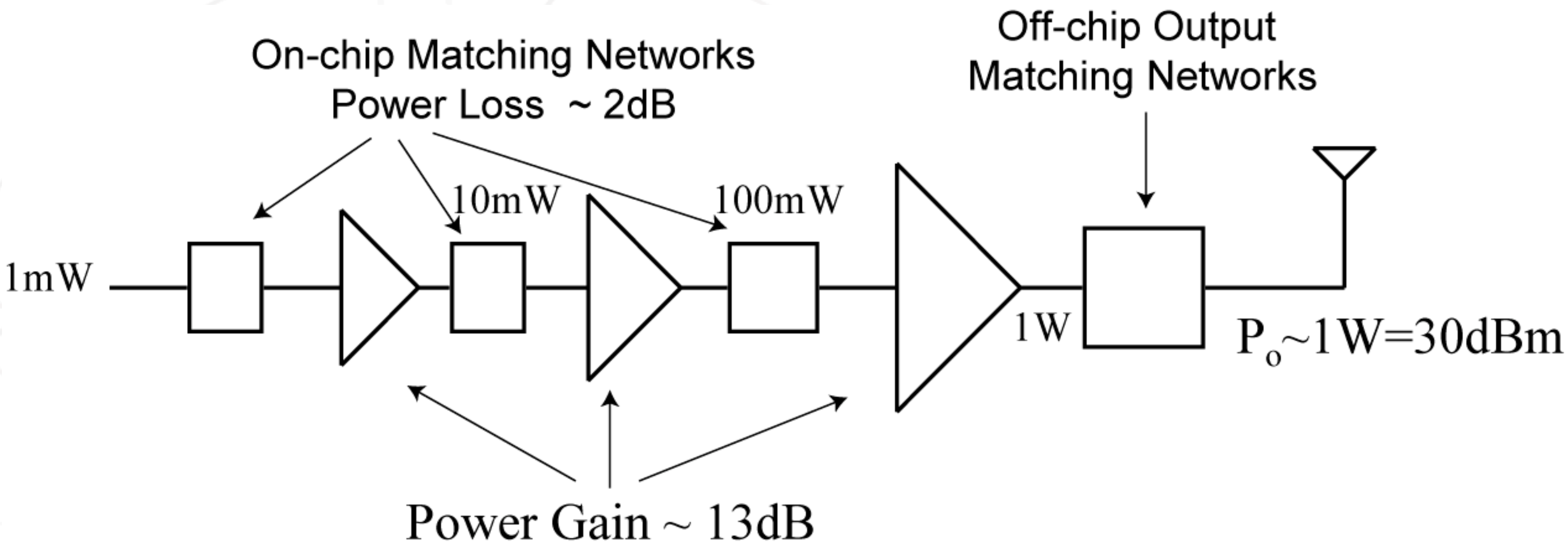
- Notice that the placement of the substrate contacts has an important impact on the overall substrate loss (the output impedance of the device). Increasing the device finger width W will decrease the "parallel resistance" but increase the "perpendicular resistance".

MOS CV Curve

- Capacitors need to be large signal accurate over voltage swing. Voltage swings maybe negative and move device into accumulation (due to inductors).
- Make sure the CV model is accurate (BSIM capmod=2). Include quantum effects and poly depletion.



Typical Multi-Stage PA



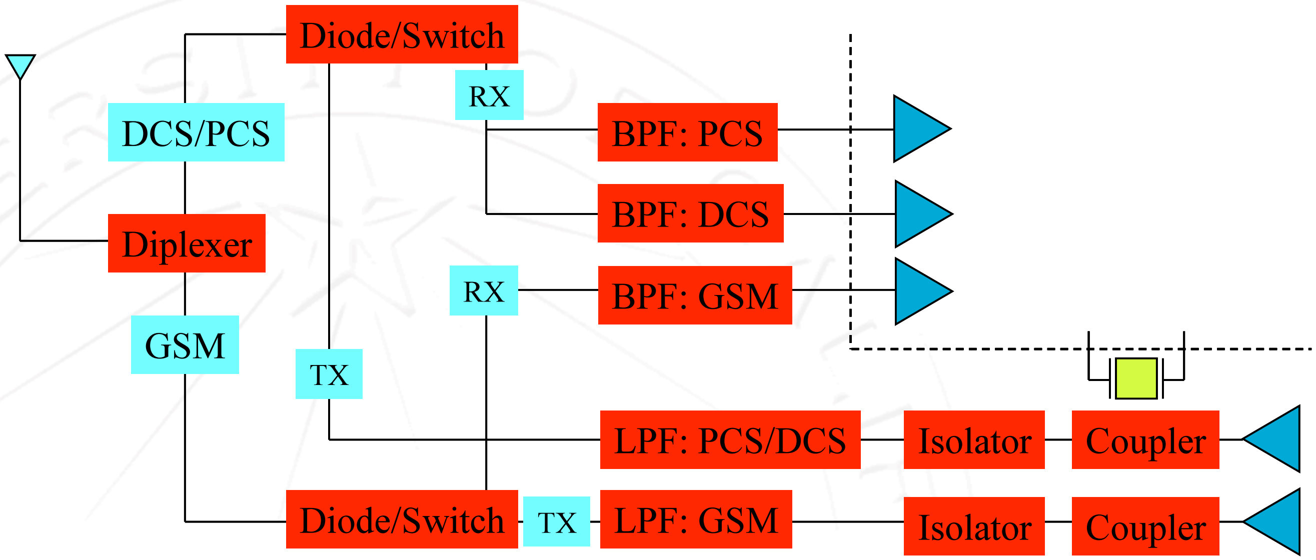
- Need 1W at antenna and about 30 dB of power gain
- Each amplifier stage has about 13 dB of power gain
- Interstage matching networks have an insertion loss of about 2 dB
- Cannot afford loss at output stage so must use off chip components.

Count your dB's

- In RF receiver design we throw around a lot of dB's without giving it much thought. For instance, you may put in a margin 3dB in your design. But for a PA, this is not so easy ! 3dB is a factor of 2 in power !!
- Likewise, any loss in the signal path can hurt the PA efficiency considerably.
- Consider designing a 1W PA with an efficiency of 65%. But due to a customer demand, you have to budget up to 1dB of extra loss at the output.
- That means your PA efficiency can potentially drop to 52%!

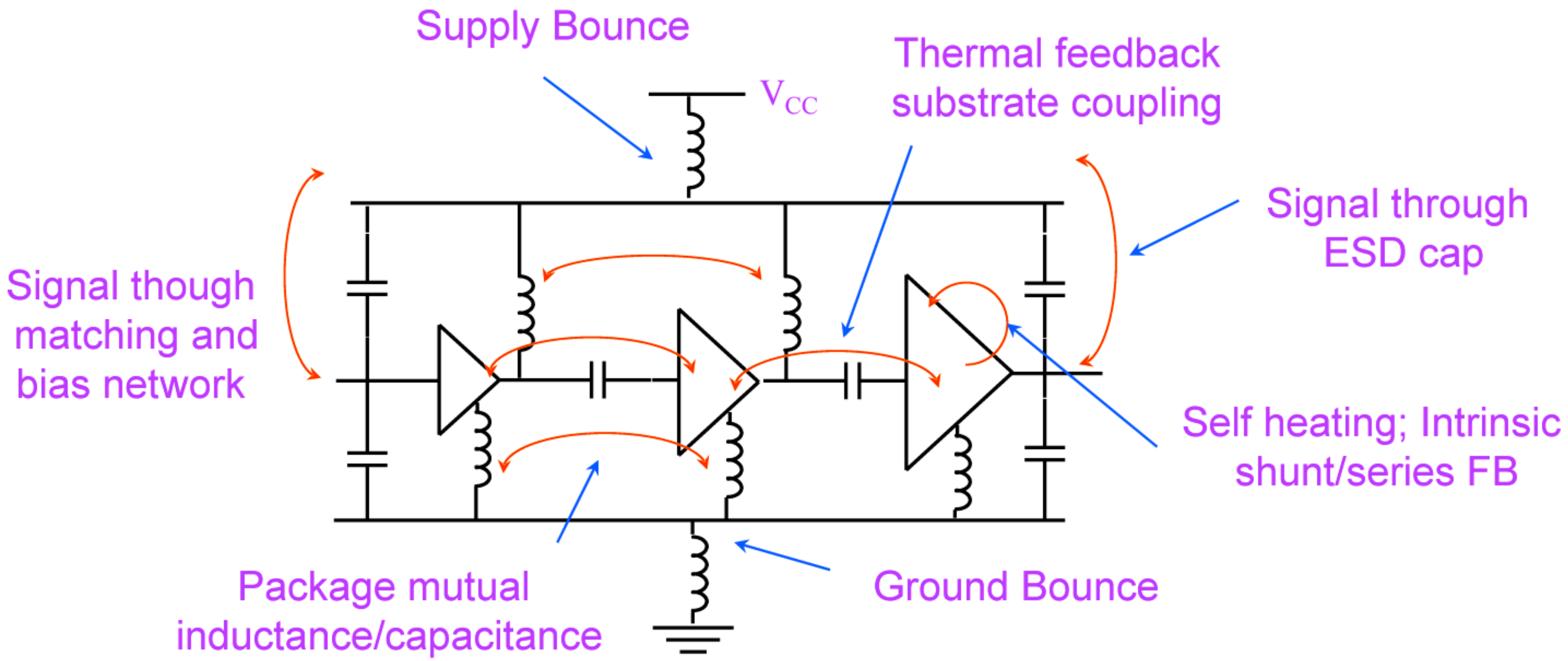
0.1	0.977
0.3	0.933
0.5	0.891
0.7	0.851
0.9	0.813
1	0.794
1.2	0.759
1.4	0.724
1.6	0.692
1.8	0.661
2	0.631

What PA Needs to Drive



- Need SAW filter to eliminate out of band emissions. Directional coupler measures output power.
- In a half duplex system, a switch is used for RX and TX. In a full duplex system, a duplexer is used to isolate the TX and RX. In the extreme case, a circulator can be used as well.
- Typical cell phone PA that needs to put out 1W to the antenna. Due to loss in output matching network, coupler, duplexer/diplexer, and SAW filter, need to put out an additional 3 dB.

Parasitic Coupling



- Package: ESD, bias, pins, bond wires
- Substrate: Devices (passive and active), thermal
- Maximum safe power gain ~ 30 dB

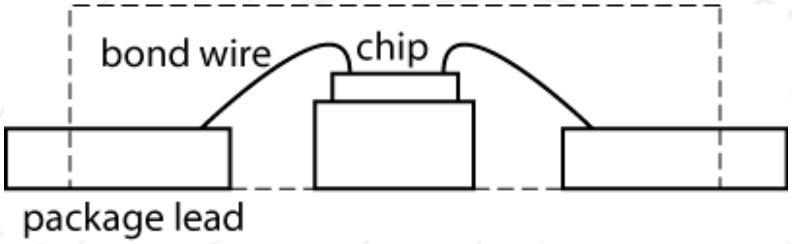
Ground Bounce

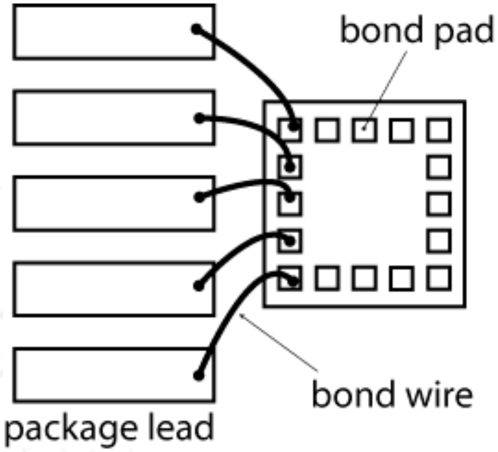
- Since the load current is large (amps), and it flows out of the chip to the external load, there is considerable "bounce" in the ground and supply lines

$$V_{bounce} \propto L\frac{dI}{dt}$$

- Besides limited the voltage swing (efficiency), for on-chip signals referenced to the internal ground, this is not a big issue. But for any external signals referenced to the clean board ground, this ground bounce is a problem (it can subtract or add from the input signal, for instance)
- For this reason, the output stage ground is often separated to mitigate this coupling effect.

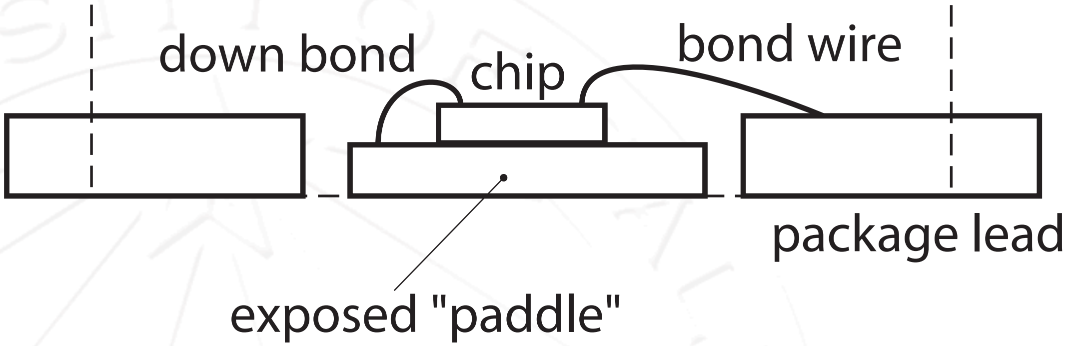
Packaging Issues





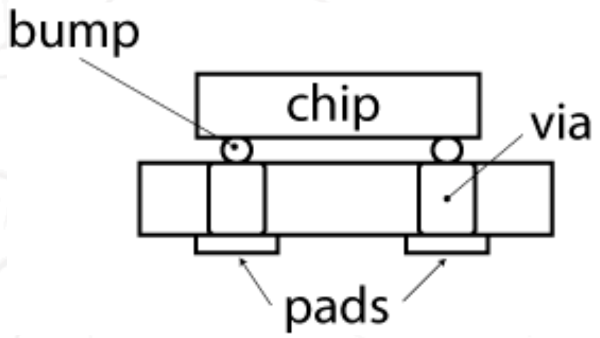
- The emitter/source inductance is a major problem as it limits the device swing, reducing the efficiency of the amplifier. It also is a big source of ground bounce that can lead to instability.
- Use as many bondwires to reduce this inductance. If possible, use a package with an exposed paddle to reduce the bondwire length.

Downbond GND versus Bonded Lead



- To reduce the inductance to gnd, we can use an exposed "paddle" style package, where the chip is glued to a ground plane which is directly soldered to the board.
- The bond wire to ground is a "downbond", and it is shorter and thus the overall inductance for the ground can be reduced substantially.

Flip-Chip Package

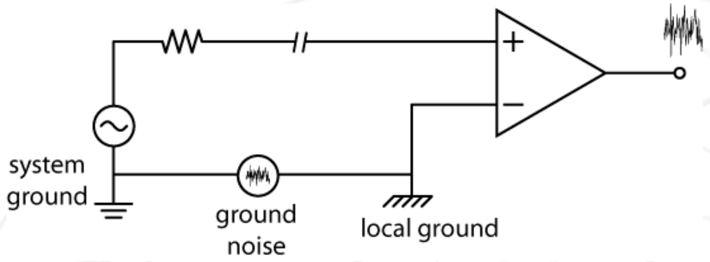


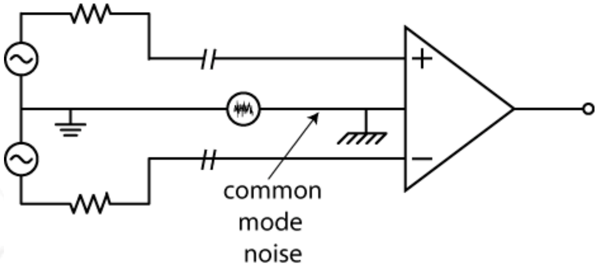
- Flip chip packages are more expensive but allow very low inductance “bumps” (< 100 pH) to the package ground. The entire PA can be constructed with lumped components in the package by utilizing high quality passives. This is more of a “module” than an integrated PA.

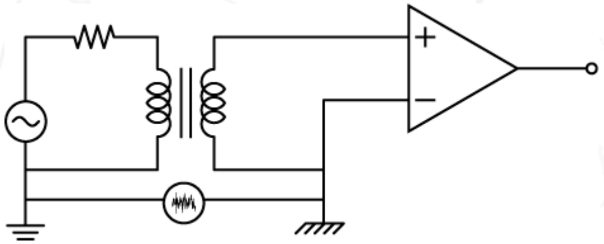
Stability Issues

- Go differential / balanced to reduce common mode coupling.
- Transformer at input helps to isolate input/output.
- Watch out for parasitic oscillations (see next slide).
- Bypass capacitors (big and small) to cover multiple frequency bands. Big caps are usually MOS varactors.
- Plan the package layout early in design.
- Spend at least as much time on ground/VDD/bypass issues as the circuit design !!

Balanced/Differential Operation

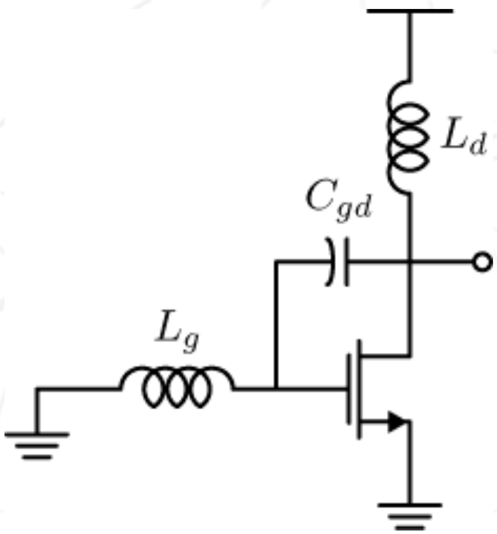






- The input signal comes from an off-chip source (driver amp or VCO buffer). The local "ground" is bouncing due to the PA output stage. To reduce the effects of this ground bounce, a fully differential source can be employed. If not available, a transformer can help isolate the two grounds.

Parasitic Oscillator



$$A_v = -g_m Z_L = -g_m j\omega L_d$$

$$i_\mu = j\omega C_{gd}(v_o - v_i) \approx -j\omega C_{gd} v_i (g_m j\omega L_d + 1)$$

$$i_i = -i_\mu + j\omega C_{gs} v_i \approx j\omega C_{gs} v_i + j\omega C_{gd}(g_m j\omega L + 1) v_i$$

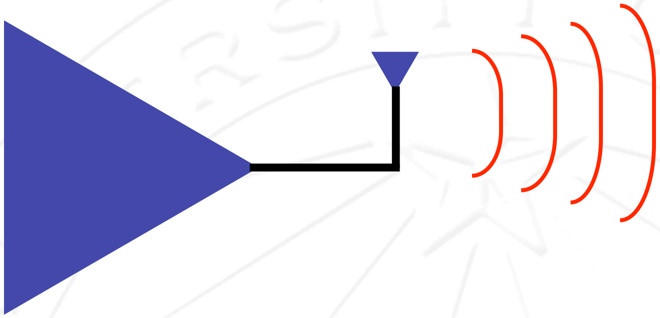
$$Y_{in} = j\omega(C_{gs} + C_{gd}) - g_m \omega^2 C_{gd} L$$

- Consider the medium frequency equivalent circuit for output stage. Due to the large device size, the gate-to-drain capacitance is substantial. The gate inductance is for biasing or to tune out the input cap.

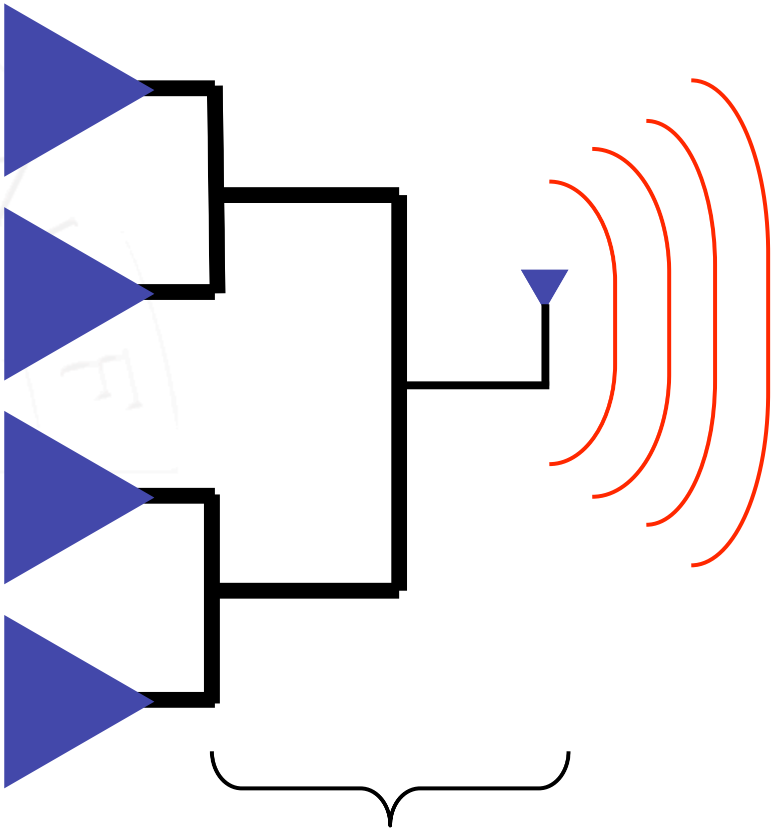
How Big?

- The amount of power that we can extract from a PA device is limited by the output imepdance of the device. As the device is made larger to handle a higher DC current (without compromising the f_T), the lower the output impedance.
- For a "current source" style of PA, eventually the device is so large that power is lost in the device rather than the load. This is the attraction of a switching PA.

Power Combining (cont)



- But for a non-switching PA we must perform some power combining to use more than one device. This way we can transform the load into a higher impedance seen by each PA.
- The power combining networks are lossy and large. We'll come back to them later.



Can we "wire" PAs together?

- Note that we cannot simply "wire" PAs together since the impedance seen by each PA increases by N if we connect N in parallel:

$$R_{PA} = \frac{V_L}{I_L/N} = NR_L$$

- This means that each PA delivers less power for a fixed swing

$$P_{PA} = \frac{V_{swing}^2}{2R_{PA}}$$

- There is also "load pulling" effects if the sub-PAs are not perfectly in phase