Integrated Circuits for Communication
Berkeley

Transmitters: System Level Specifications

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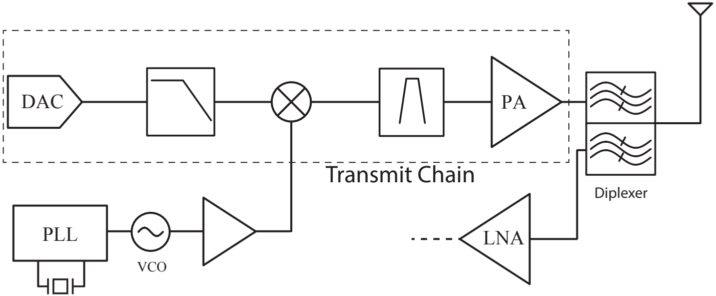
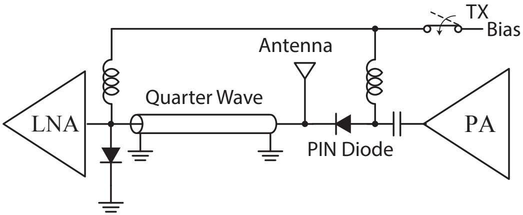
Simple Transmitter Block Diagram



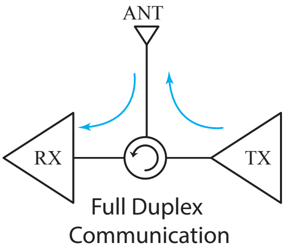
- Digital bits get converted to analog waveforms through DAC and filter.
- An transmit mixer or “modulator” takes the analog baseband waveform and up-converts it to the carrier frequency.
- An RF filter is used to limit out-of-band emissions (harmonics) and or the transmit noise into the receive band (frequency division duplex or FDD systems).

TR Switch



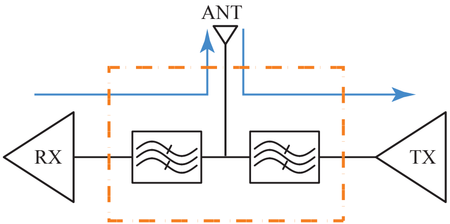
- Many communication systems use a transmit-receive switch to share an antenna between receive (Rx) and transmit (Tx) modes. This is known as half duplex communication.
- A pin diode can be used as a switch by forward or reverse biasing it in the signal path. A quarter wave line isolates the PA from the LNA and vice-versa.
- Note that the same spectrum can be used for Tx and Rx, but since information is flowing in one direction, the full capacity of the channel is not being used.

Full Duplex Communication



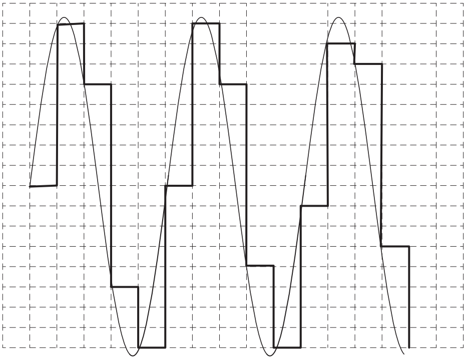
- Waves traveling in opposite directions do not actually interfere if we use a directionally senstiive block like a directional coupler or circulator.
- Full duplex communication systems require simultaneous transmit and receive. Rx and Tx bands can overlap, so a circulator is needed to isolate the transmit and receive signals in order to share an antenna. Note that separate antennas does not fully solve the problem, as the Tx signal will leak into the Rx antenna. Full duplex is rarely used.

FDD and TDD



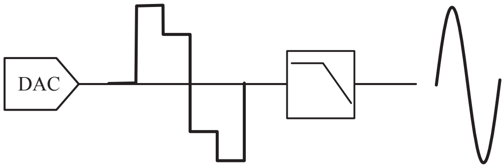
Frequency Division Duplex (FDD)

- In Frequency Division Duplex (FDD), simultaneous Rx/Tx operation is used, but the bands are separated and so a diplexer (bandpass filters) can be used to combine/separate the Rx and Tx bands in the frequency domain.
- In Time Division Duplex, or half duplex communication, only the Rx or Tx is operating, so switches can be used to share the antenna terminal.



- DAC converts digital bits into analog waveforms. Resolution (number of bits) is determined by the complexity of the modulation waveform and the tolerable quantization noise levels. The sampling rate must be at least twice as fast as the highest frequency of the waveform, but often a higher value is used to trade-off resolution or to relax the analog filtering.

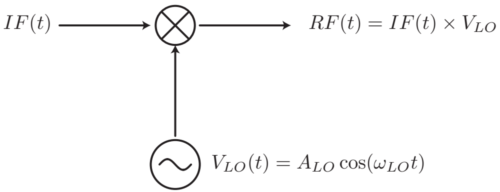
Tx Filter



- The "reconstruction filter" converts the abrupt sharp transitions from the DAC into a smooth analog waveform. Filter order and type determined by the amount of filtering performed in the digital domain (oversampling) and the out of band emission specifications.

Modulators

What's a Mixer?



- This is not an audio "mixer" (combiner), but more like a multiplier.
- Most mixers are not generic multipliers in the sense that they only have one input port that can be driven with a modulated signal. The other signal port is driven by the local oscillator (LO) with a string sinusoidal signal.

Complex Modulation

- Consider multiplying a waveform $f(t)$ by $e^{j\omega t}$ and taking the Fourier transform

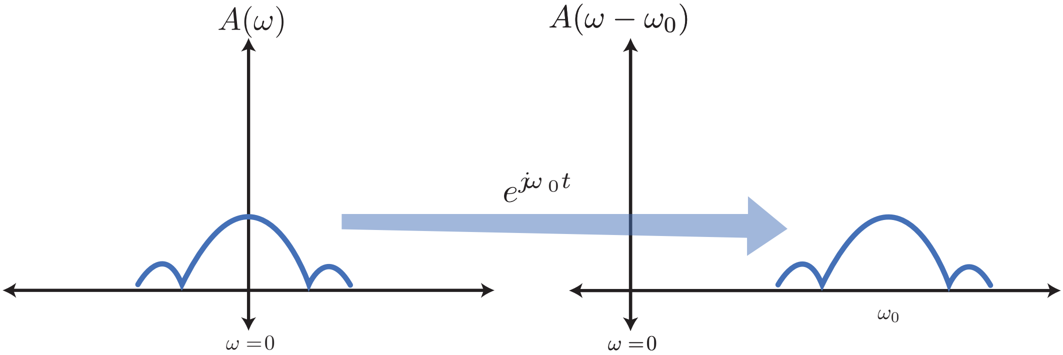
$$\mathcal{F}\left\{e^{j\omega_0 t} f(t)\right\} = \int_{-\infty}^{\infty} f(t) e^{j\omega_0 t} e^{-j\omega t} dt$$

- Grouping terms we have

$$= \int_{-\infty}^{\infty} f(t) e^{-j(\omega-\omega_0)t} dt = F(\omega - \omega_0)$$

- It is clear that the action of multiplication by the complex exponential is a frequency shift.

Complex Modulation



- Complex exponential multiplication shifts the spectrum of the waveform in one direction only.

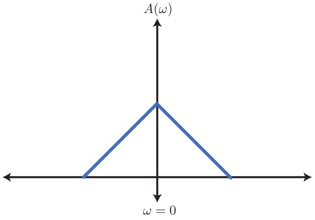
Real Modulation

- Now since $\cos(x) = (e^{jx} + e^{-jx})/2$, we see that the action of time domain multiplication is to produce two frequency shifts

$$\mathcal{F}\left\{\cos(\omega_0 t) f(t)\right\} = \frac{1}{2}F(\omega - \omega_0) + \frac{1}{2}F(\omega + \omega_0)$$

- These are the sum and difference (beat) frequency components.
- We can see that a multiplier, realized as an up-conversion mixer, is a natural amplitude modulator

Amplitude Modulation



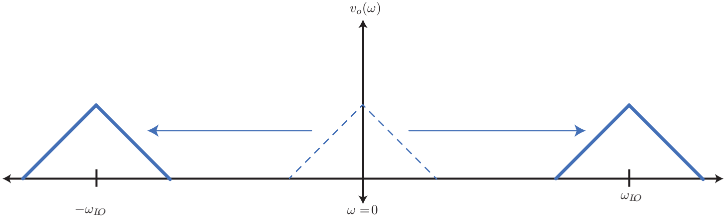
- If the input to the mixer is a baseband signal $A(t)$, then the output is an AM carrier

$$v_o(t) = A(t)\cos(\omega_{LO}t)$$

- Since $A(t)$ is a real waveform, it has identical positive and negative frequency components. The spectrum of A is frequency translated around the carrier.

$$v_o(\omega) = \frac{1}{2}A(\omega - \omega_{LO}) + \frac{1}{2}A(\omega + \omega_{LO})$$

Double-Sideband (DSB) Modulation



- It's interesting to note that the information in the upper and lower sidebands are redundant in that they are identical.
- In essence, we're wasting bandwidth by transmitting this waveform, but it's very easy to transmit and de-modulate.

Single-Sideband (SSB) Single Tone Modulation

- Consider a single tone ω_1 modulation with a cosine:

$$v_c = A_0 \cos(\omega_1 t) A_{LO} \cos(\omega_{LO} t)$$

$$= \frac{1}{2} A_0 A_{LO} (\cos((\omega_{LO} + \omega_1)t) + cos((\omega_{LO} - \omega_1)t)$$

- Consider a single tone ω_1, delayed by 90 degrees, and modulated with a sine:

$$v_s = A_0 \sin(\omega_1 t) A_{LO} \sin(\omega_{LO} t)$$

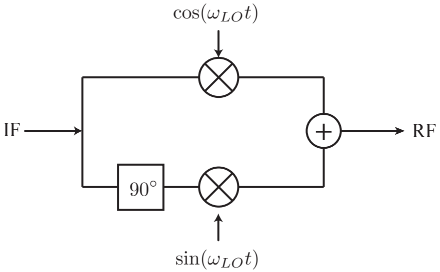
$$= \frac{1}{2} A_0 A_{LO} (-\cos((\omega_{LO} + \omega_1)t) + cos((\omega_{LO} - \omega_1)t)$$

- By summing these signals, we can generate a single sideband modulation, either above (USB) or below the carrier (LSB):

$$v_{USB} = v_c - v_s = A_0 A_{LO} \cos((\omega_{LO} + \omega_1)t)$$

$$v_{USB} = v_c + v_s = A_0 A_{LO} \cos((\omega_{LO} - \omega_1)t)$$

Single-Sideband (SSB) Modulation



- We can generalize this concept by phase shifting every frequency component of the baseband signal by 90° and modulate with sin and cos.
- This produces a SSB modulation. If you're not convinced, hold that thought. We'll return to this topic in the context of Image Reject mixers ...

Phase Modulation

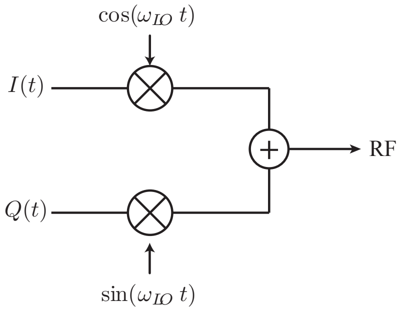
- How do we modulate the phase? A PLL is one way to do it, but suffers from limited bandwidth.
- This SSB modulator structure is actually a hint on how we can modulate phase. Let's expand a sinusoid that has AM and PM

$$v_o(t) = A(t)\cos(\omega_0 t + \phi(t))$$

$$= A(t)\cos\omega_0 t\cos\phi(t) - A(t)\sin\omega_0 t\sin\phi(t)$$

$$= I(t)\cos\omega_0 t + Q(t)\sin\omega_0 t$$

IQ Modulator



- By using two mixers and two quadrature phases of the LO, we can modulate both the amplitude and the phase of a carrier signal. The I and Q signals are typically baseband modulations.
- The I path is the in-phase path, and the Q path is the quadrature path.

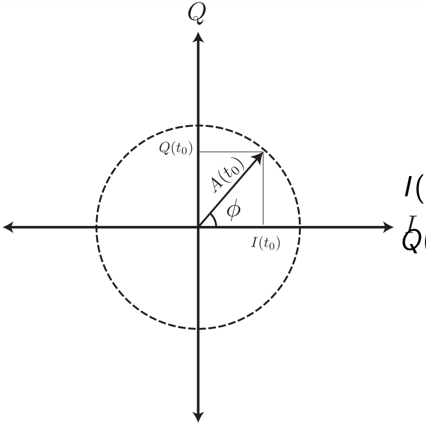
Orthogonality of I/Q

- The I and Q modulated components of the signal are orthogonal since $\sin \omega_0 t$ and $\cos \omega t$ are orthogonal when we integrate over a symbol duration T_s:

$$\int_{T_s} I(t) \cos \omega_0 t \times Q(t) \sin \omega_0 t dt = IQ \int_{T_s} \cos \omega_0 t \sin \omega_0 t = 0$$

- Note that I and Q are constant during a symbol duration, and hence we bring them out of the integral. Also we assume T_s is an integer number of carrier cycles.
- This orthogonality let's us think of I and Q as orthogonal vectors that can be independently analyzed, increasing or decreasing I has no impact on Q and vice versa.

I-Q Plane



$$I(t) = A(t)\cos\phi(t)$$
$$Q(t) = A(t)\sin\phi(t)$$

- We can draw a trajectory of points on the I-Q plane to represent different modulation schemes.
- The amplitude modulation is given by

$$I^2(t) + Q^2(t) = A^2(t)(\cos^2\phi(t) + \sin^2\phi(t)) = A^2(t)$$

General Modulator

- The phase modulation is given by

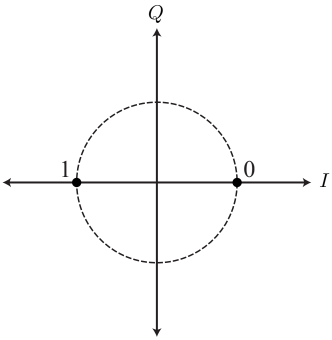
$$\frac{Q(t)}{I(t)} = \frac{\sin\phi(t)}{\cos\phi(t)} = \tan\phi(t)$$

  or

$$\phi(t) = \tan^{-1}\frac{Q(t)}{I(t)}$$

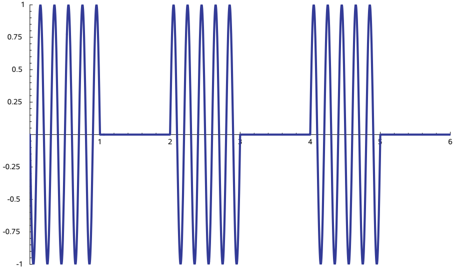
- The IQ modulator is a universal modulator. We can draw a set of points in the IQ plane that represent symbols to transmit. For instance, if we transmit $I = 0/A$ and $Q = 0$, then we have a simple ASK system (amplitude shift keying).

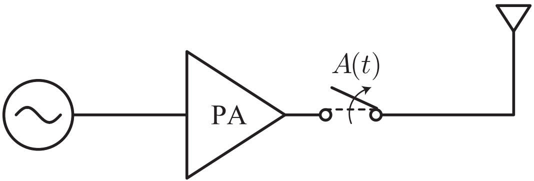
Digital Modulation: BPSK/QPSK



- For instance, if we transmit $I(t) = \pm 1$, this represents one bit transmission per cycle. But since the I and Q are orthogonal signals, we can improve the efficiency of transmission by also transmitting symbols on the Q axis.
- If we select four points on a circle to represent 2 bits of information, then we have a constant envelope modulation scheme.

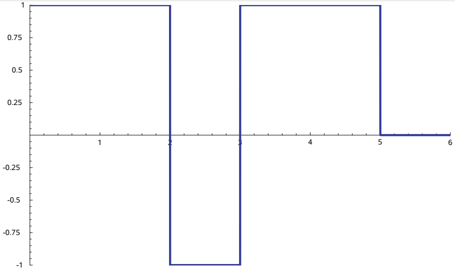
Modulation Waveforms: OOK

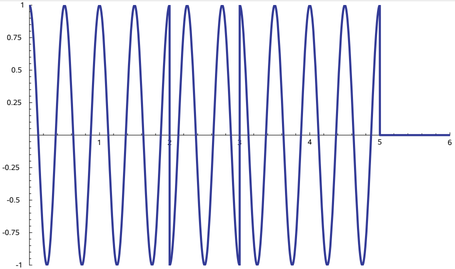




- The plot shows a simple on/off keying scheme. The advantage of this modulation is simplicity. We just turn on/off (to transmit a 1 or 0) the power amplifier (or VCO) and we impart modulation.
- This saves power as well, since on average the transmitter is on only half the time.
- What's the trade-off? To understand the downside, let's compare it to BPSK, or bi-polar phase shift keying.

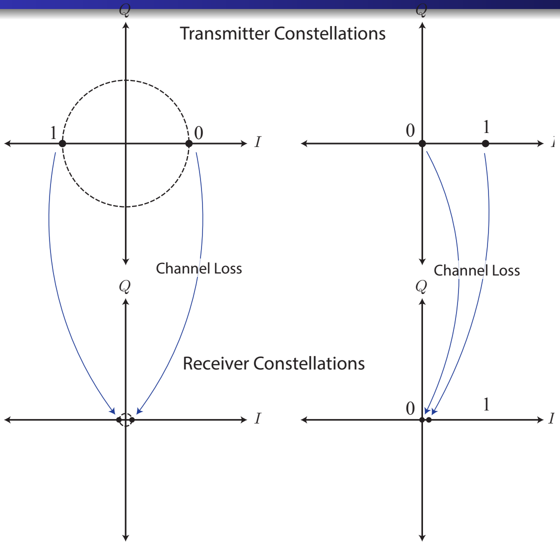
Modulation Waveforms: BPSK





- The data wave form (left) is modulated onto a carrier (right). With binary phase shift keying, or BPSK, we multiply the carrier by ± 1, rather than turn it on-off like BPSK.
- At first this may not seem as good because it seems that both a "1" and a "0" look the same, but there is in fact a 180° phase transition that allows the receiver to easily distinguish between the two. We'll explain how this works later but the important point is that this bipolar scheme is actually better because it's even easier to detect in the presence of noise.

Channel Loss

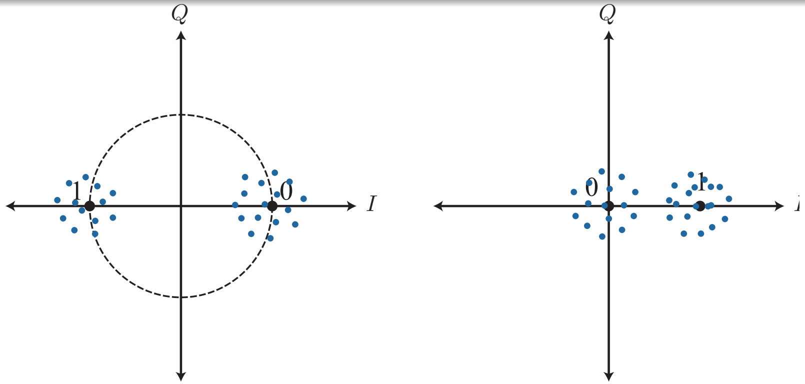


- Due to channel propagation and loss, the received constellation is a scaled copy of the transmitted constellation.
- Note that the radius of the transmitted constellation is determined by the output power limits of the transmitter power amplifier so we cannot arbitrarily transmit larger and larger amplitude signals.

Here the channel is modeled by a scalar $h < 1$.[1]

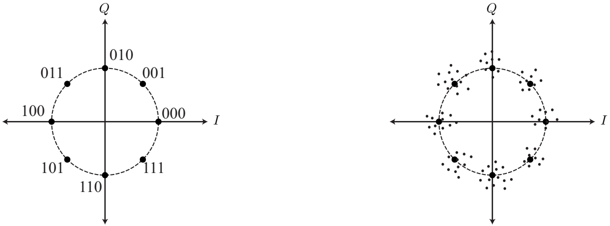
[1] For simplicity we are ignoring the rotation of the constellation due to the phase shift of the channel.

BPSK vs OOK



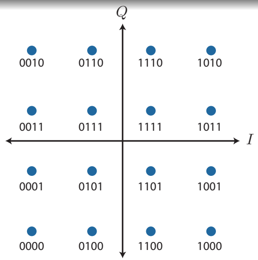
- Now it's clear that the presence of noise will limit the range of communication since eventually the constellation points will overlap. The size of the constellation is determined by the variance of the symbol position, which varies due to noise.
- Since BPSK symbols are twice the distance as OOK symbols, with the same transmit power limit, it is twice as efficient from a detection perspective.

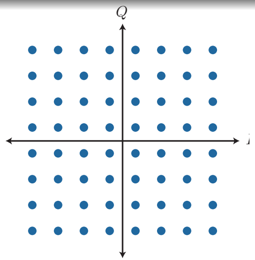
More Bits Per Cycle



- Eventually, the *constellation* points get very close together. Because of noise and distortion, the received spectrum will not lie exactly on the constellation points, but instead they will form a cluster around such points.
- If the clusters run into each other, errors will occur in the transmission.
- We can increase the radius but that requires more power.

QAM Modulation

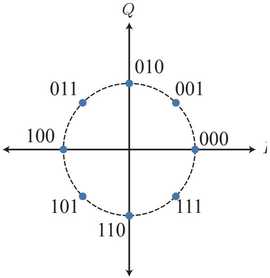




- To transmit more bits per given symbol duration (bandwidth), we could increase the number of constellation points. We transmit $b = \log_2 N_c$ bits for N_c constellation points.
- Here we show 16-QAM and 64-QAM, two popular modulation schemes. For 16-QAM we are sending 4-bits per symbol and for 64-QAM we are sending 6 bits.
- The bits are assigned to each constellation point so that neighboring points have only 1-bit change (Gray Coding).
- Compared to QPSK, the amplitude of the transmitted signal will vary, which requires a linear power amplifier (which has lower efficiency).

Higher-Order PSK and FSK Modulation

- Low power and power efficient schemes prefer a constant-envelope modulation scheme.
- If we simply limit our constellation points to lie on a circle, the resulting waveform will be constant amplitude.

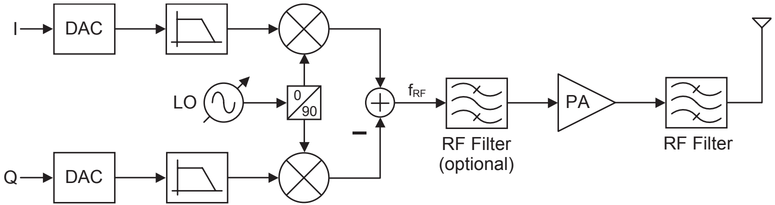


- Alternatively, we can simply shift between two (or more) frequencies to modulate the signal and use simple filters to detect transmitted tones.
- Abrupt frequency/phase changes cause amplitude ripples when we filter the signal, and to avoid this, various schemes have been devised to move smoothly between constellation points. The most popular, Gaussian Minimum Phase Shift Keying (GMSK), is used by Bluetooth, 2G GSM cellular radios, and other low power standards.

Bandwidth Utilization

- QPSK modulation modulates two independent data streams onto the same carrier without expanding the bandwidth.
- The reason this works is that sin and cos can be demodulated independently and so the I and Q waveforms can be individually recovered without distortion even though they lie right on top of each other at RF (occupy the same bandwidth).
- 16-QAM quadruples the data-rate while 64-QAM gives us $6\times$ the data-rate of simple BPSK, essentially using the same bandwidth.
- For this reason, we generally transmit the most complex modulation scheme given the constraints of noise, power, linearity, phase noise and other limits (dispersion). OFDM modulation is used to overcome channel dispersion.

Transmitter Block Diagram

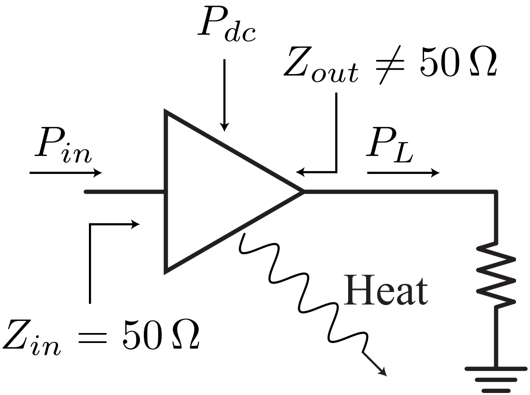


- Most direct conversion (DC→RF) transmitters are realized using the I/Q mixer discussed. Two I and Q DACs are folkowed by reconstruction filters, driving two mixers, and the output is summed and drives the PA stages.
- The LO frequency is tuned to the desired RF channel, usually with a voltage-controlled oscillator locked to a reference inside a phase-locked loop (PLL).

Transmitter Specifications

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. When we hit sensitivity limits, the only way to increase the range is to increase the Tx power.
- The peak power is specified at the 1-dB compression point or the maximum output power – the "clipping" point (makes a big difference).
  - $\sim$1W for cellular handsets (1 km distance)
  - $\sim$100mW for W-LAN (100 m)
  - $\sim$10mW for W-PAN (Bluetooth) (1-10 m)
  - $\sim$1mW for body area networks.
- In practice, the average power transmitted may be much lower than the peak output power due to "back-off", to obtain linearity for the amplitude modulation (fast time scale) or for power control (slow 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 drain
- drain efficiency (η_d), or for a BJT, the "collector" efficiency, 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 10mW), the power of the entire transmitter chain is important and should be taken into consideration.

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

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

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

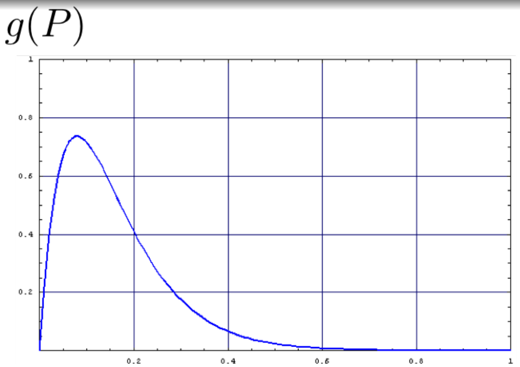
$$\eta_{PAE} = \eta_c(1 - G_p^{-1})$$

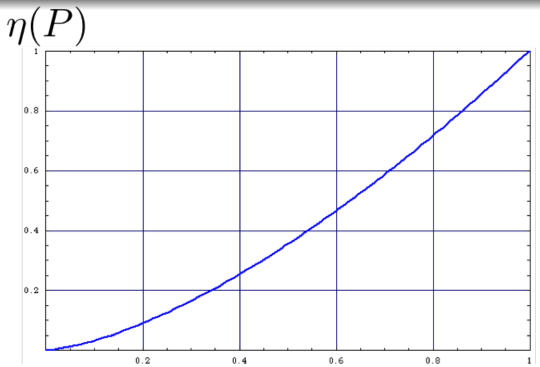
$$\approx \eta_c$$

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 error communication with the base station.
- Thus the actual average efficiency depends on how the efficiency varies with output power

Power Statistics

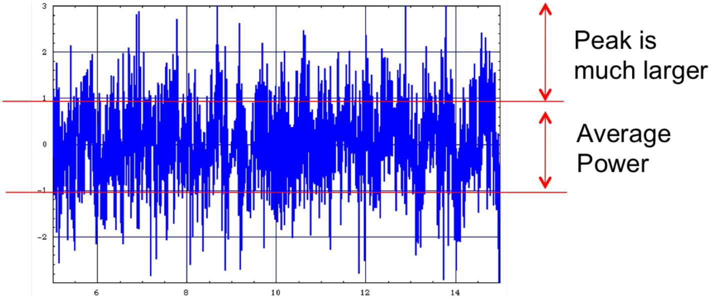




$$\eta_{av} = \int_{-\infty}^{\infty} \eta(P) g(p) dP$$

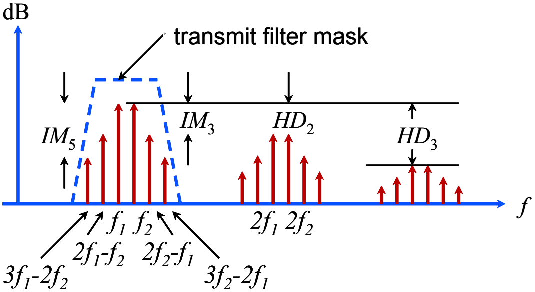
- Given the distribution of power levels, or the PDF $g(P)$, we can calculate the expected value of the efficiency
- Unfortunately, for most PAs the efficiency drops at low power.

Envelope Statistics



- 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

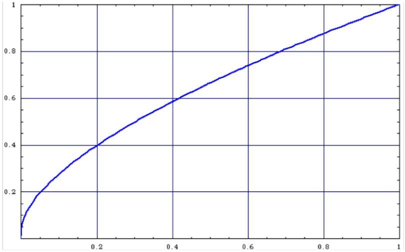


- The traditional way to characterize narrowband system linearity is with IM3. Since the system may be driven into a strongly non-linear regime, all odd order harmonics should be carefully taken into account to ensure that excessive spectral leakage does not occur.

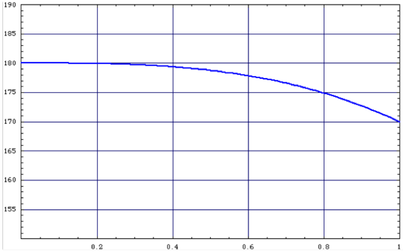
Sources of Non-Linearity

- PAs exhibit nonlinear distortion in amplitude and phase. For a modulated 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 g_m non-linearity before clipping
- AM-to-PM conversion dominated by non-linear capacitors (phase delay)

AM-AM and AM-PM Non-Linearity



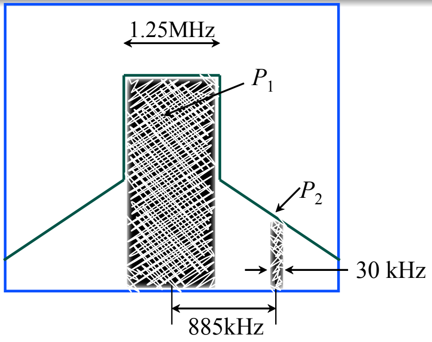
AM-AM Curve



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

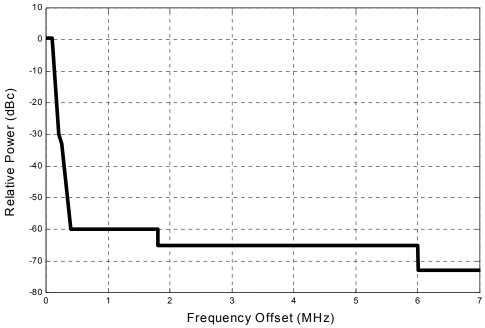
Adjacent Channel Power (ACP)

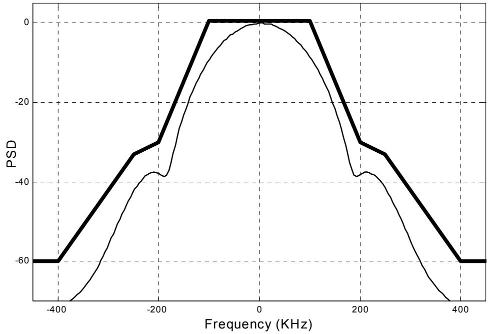


ACP=P_1(dBm)-P_2(dBm)

- For modern communication systems, the IM specifications leave a lot to be desired since they are only based on two-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 specified.

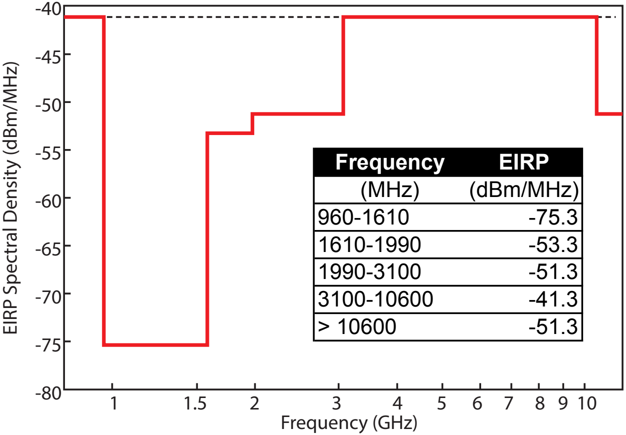
Transmit Mask Specs





- Every standard therefore has a transmit mask specification that must be met. This limits spectral regrowth, noise, and other spurious transmissions in the band and in nearby bands. Above examples are for GSM.

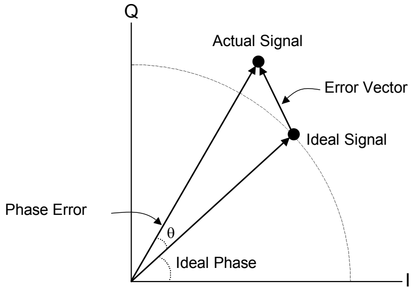
FCC Limts

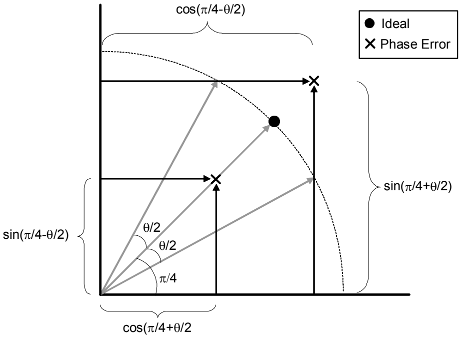


Frequency (MHz)	EIRP (dBm/MHz)
960-1610	-75.3
1610-1990	-53.3
1990-3100	-51.3
3100-10600	-41.3
> 10600	-51.3

- While the transmit mask is standard specific, every transmitter must comply with FCC limits (in the US). The above mask is for an unlicensed device meeting part 15 requirements.

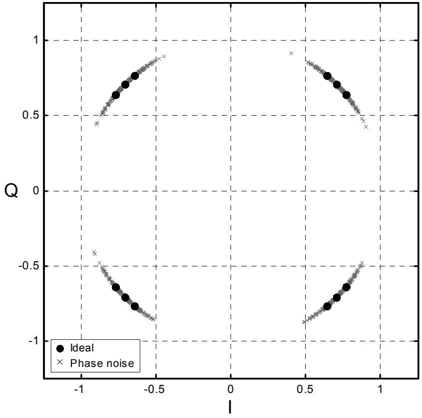
Error Vector Magnitude

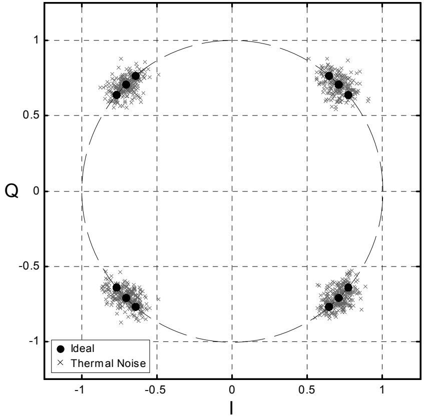




- While the ACP is a good way to measure how much the PA signal will deteriorate a neighboring channel signal, the EVM is a measure of how much the PA interferes with itself.
- The EVM measures the systematic deviation of the constellation points from the ideal positions due to amplifier non-linearity.

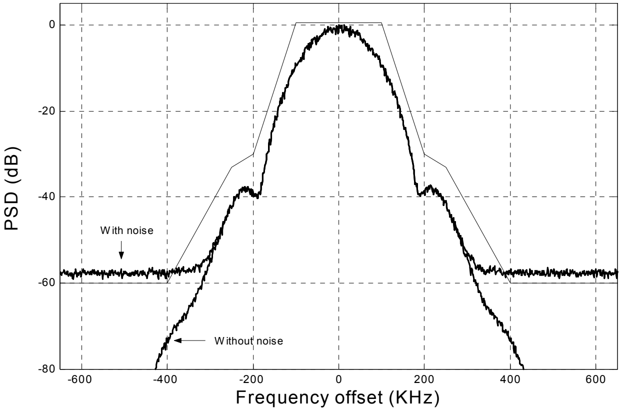
Example: GSM Transmitter Non-Ideality





- The first example shows the impact of phase noise whereas the second plot shows the impact of noise (both amplitude and phase).

Transmitter Noise



- Transmitter noise is important for two reasons. First the noise level should not significantly impact the EVM/BER of the transmitter itself. More importantly, the noise leaking into other bands must meet specs. This is especially problematic in FDD systems that transmit and receive at the same time.

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 $\Rightarrow$ 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 ratio (PAR)
  - QPSK (CDMA base station) has 10dB of PAR, OQPSK (CDMA handset) has 3dB of PAR
  - 802.11g OFDM at 54 Mbps (52 sub-carriers) has about 6-8 dB of PAR

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	—

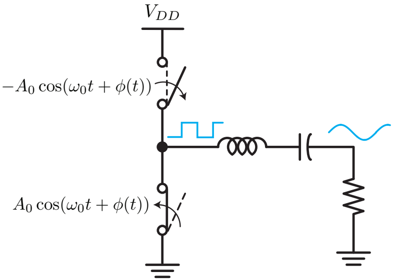
- Key specifications are the peak-to-average radio, the peak power, and the power control range.
- Constant modulation schemes much easier (GSM, AMPS).
- WiFi uses OFDM, which is the hardest ! LTE up-link uses a single carrier to ease the PA back-off requirements.

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. Typically (not strictly), 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

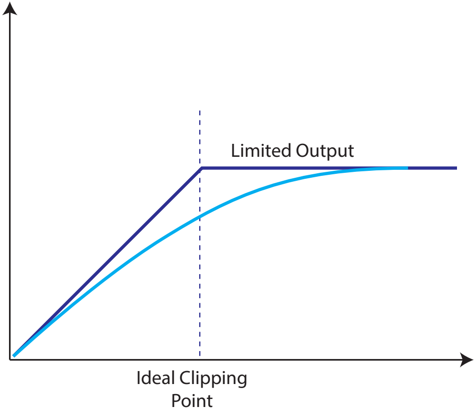
$$v_i(t) = A(t)\cos(\omega t + \phi(t))$$

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



Clipping: A "Linear" PA is Impossible

- All amplifiers eventually clip, that is the output cannot be higher than some multiple of the power supply. Note that the peak amplifier output can be arbitrarily large, but the average output power will limit.
- 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 802.11g system that 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 should be allowed to clip. A 6-7dB back-off is typical.

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. In GSM the output power can be off by $\pm$2dB.
- in CDMA systems, the noise level is actually set by this interference so all users are required to back-off to make the system as a whole more efficient.

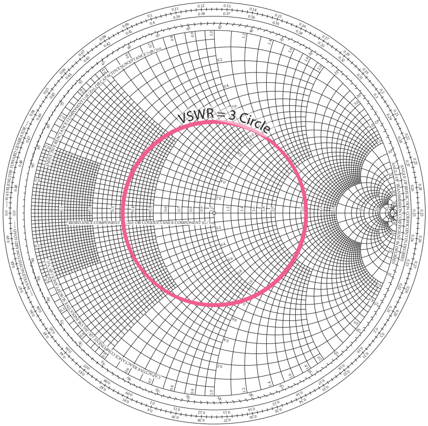
Closed Loop Power Control

- 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.

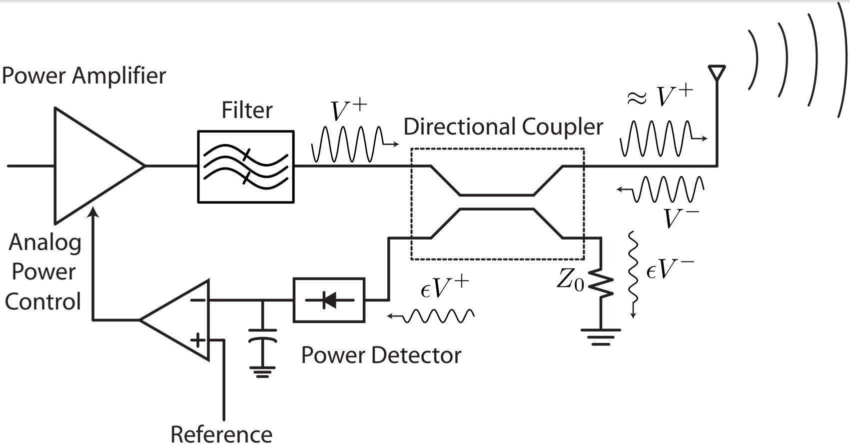
Stability over VSWR

- 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 $3 \times 50\Omega$ or as small as $50\Omega \div 3 = 17\Omega$.
- On the Smith Chart any load lying on a constant VSWR circle is a valid load, or any impedance such that

$$SWR^{-1} \leq |x + jy| \leq SWR^{+1}$$

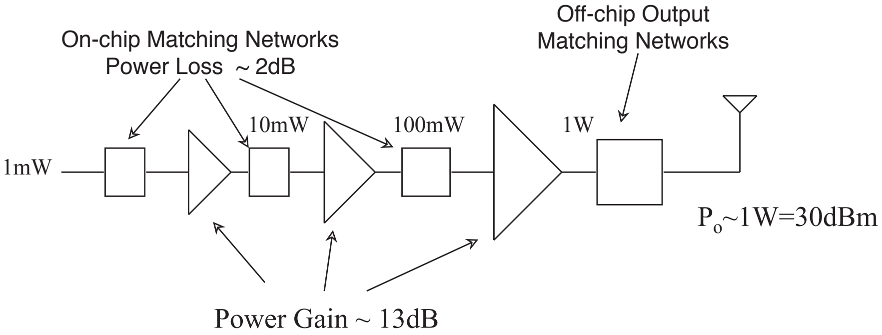


Power Control Loops



- 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.

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
- If you cannot afford loss at output stage, must off-chip components (preferably in the package to keep them close and parasitics minimal).

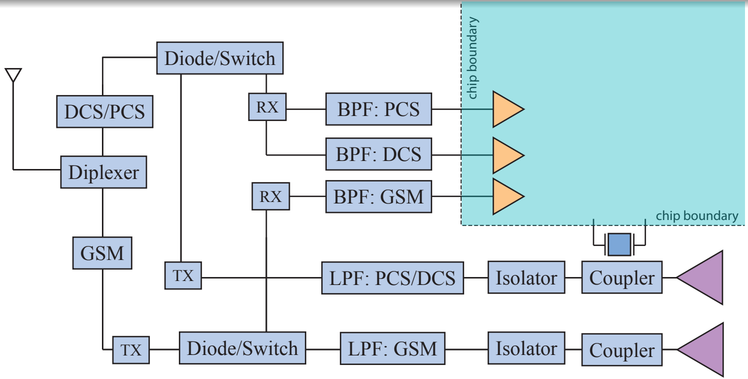
Count your dBs

- 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%!

dB	Linear
0.1	0.977
0.3	0.933
0.5	0.891
0.7	0.851
0.9	0.813
1.0	0.794
1.2	0.759
1.4	0.724
1.6	0.692
1.8	0.661
2.0	0.631

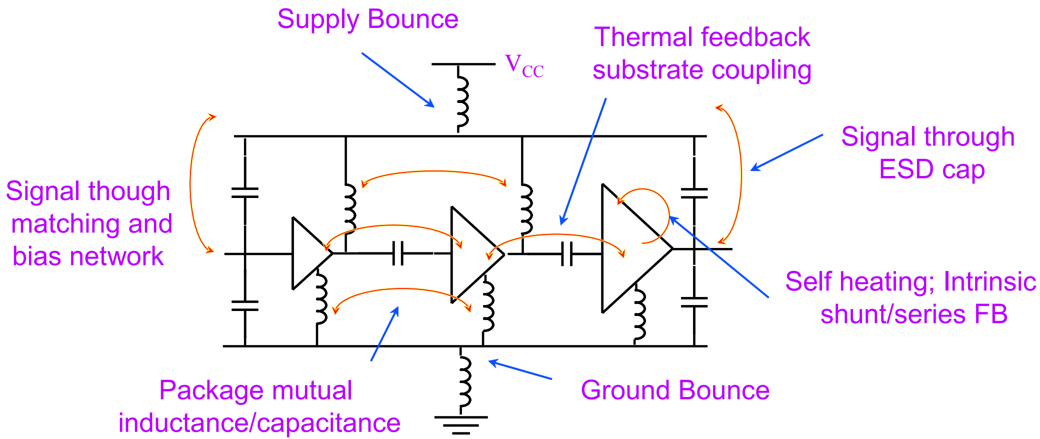
PA Package and Interface Issues

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 0.5W to the antenna (LTE). Due to loss in output matching network, coupler, duplexer/diplexer, and SAW filter, need

Parasitic Coupling



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

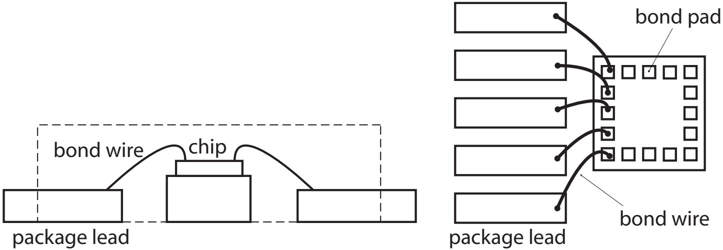
Ground Bounce

- 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

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

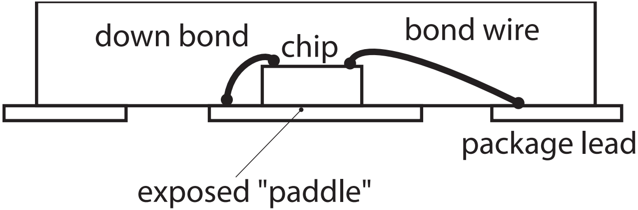
- Besides limiting the voltage swing (efficiency), for on-chip signals referenced to the internal ground, this is not a big issue. But for any external signals referenced to the clean board ground, this ground bounce is a problem (it can subtract or add from the input signal, for instance)
- For this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

Packaging Issues



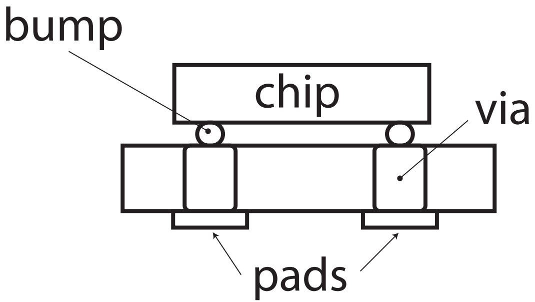
- The emitter/source inductance is a major problem as it limits the device swing, reducing the efficiency of the amplifier. It also is a big source of ground bounce that can lead to instability.
- Use as many bondwires to reduce this inductance. If possible, use a package with an exposed paddle to reduce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

Downbond



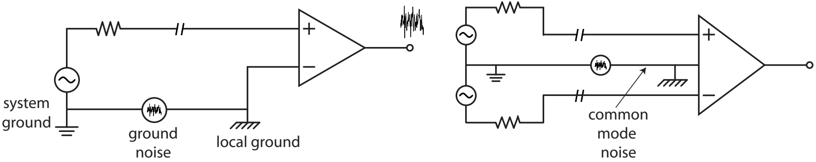
- To reduce the inductance to “gnd”, we can use an exposed paddle style package, where the chip is glued to a ground plane which is directly soldered to the board.
- The bond wire to ground is a downbond, and it is shorter and thus the overall inductance for the ground can be reduced substantially.
- Leadless packages are also preferred (such as QFN).

Flip-Chip Package



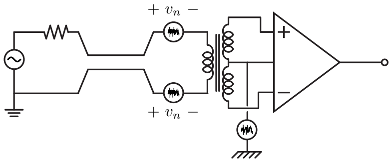
- Flip chip packages are more expensive but allow very low inductance bumps (< 100pH) to the package ground. This eliminates both the bond wire inductance and the package lead inductance.
- Another option, the entire PA can be constructed with lumped components in the package by utilizing high quality passives. This is more of a module than an integrated PA.

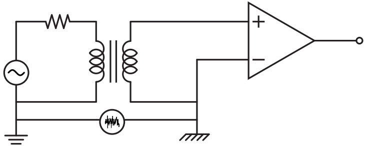
Stability Issues



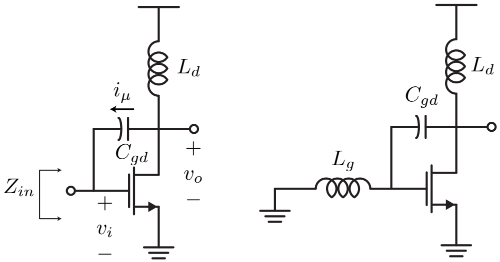
- The input signal comes from an off-chip source (driver amp or VCO buffer). The local ground is bouncing due to the PA output stage. To reduce the effects of this ground bounce, a fully differential source can be employed. If not available, a transformer can help isolate the two grounds.

Balanced/Differential Operation





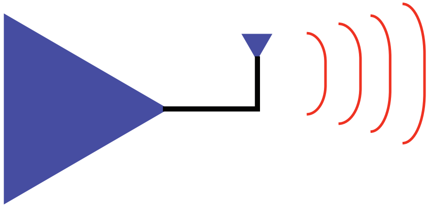
- Go differential / balanced to reduce common mode coupling.
- Transformer at input helps to isolate input/output.
- Watch out for parasitic oscillations (see next slide).
- Bypass capacitors (big and small) to cover multiple frequency bands. Big caps are usually MOS varactors.
- Plan the package layout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



- 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.

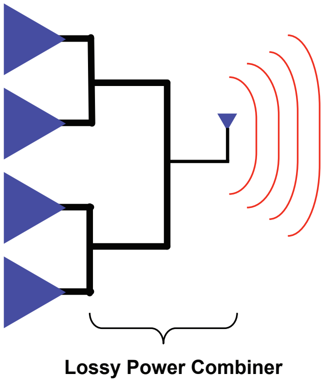
Power Combining

How Big?



- The amount of power that we can extract from a PA device is limited by the output impedance 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