Introduction to RF Circuits

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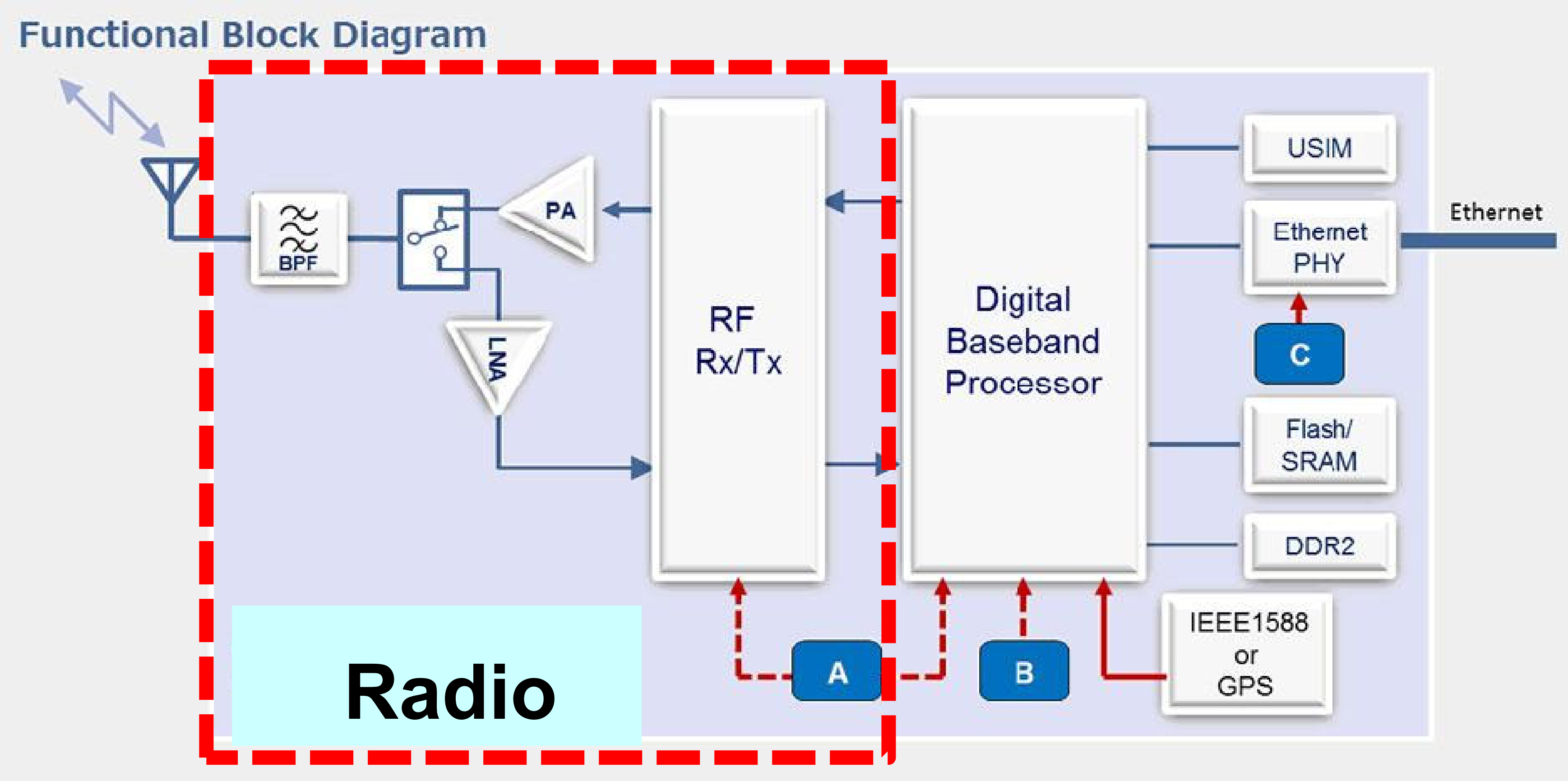
What is RF circuits?

- RF: Radio Frequency
- In some class, RF Circuits are regarded as High-Frequency Circuits, such as GSM (~900MHz), BLE (2.4GHz), WiFi (2.4GHz and 5GHz), Automobile: 24 GHz/77 GHz. Emerging bands: 60 GHz, 300 GHz, THz....However, this definition is NOT Correct!
- For example, NFC has a communication frequency of 13.56MHz and the signal on telephone wireline is less than 4kHz, which are low frequencies. But we also call the circuits “RF Circuits”
- Therefore, RF Circuits should be the Circuits processing wire/wireless communication signals.

[B. Razavi, RF Microelectronics]

A Cell Phone

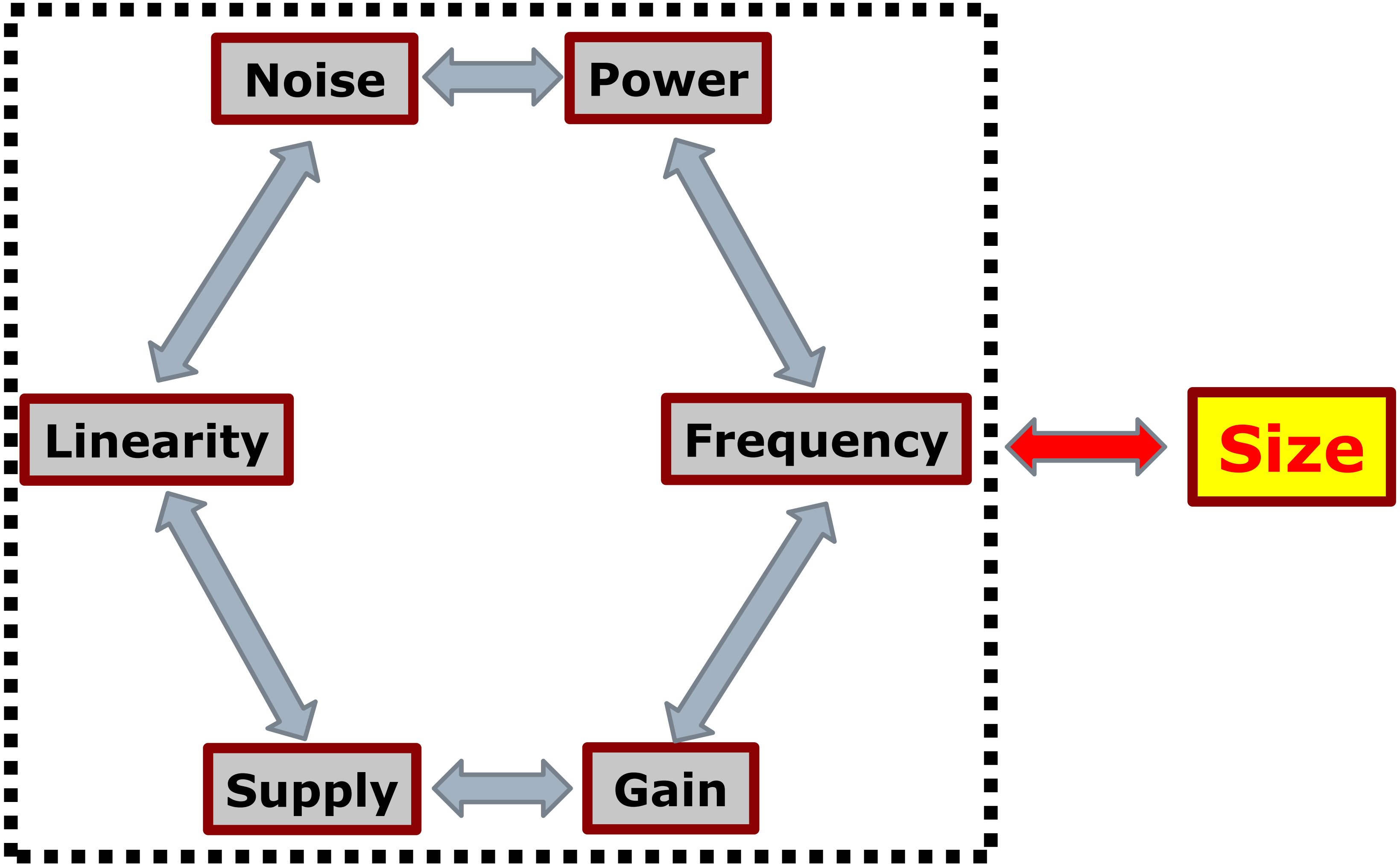


The radio circuit is Closest to antenna, Very sensitive, Powerful driver

[gimg2, Baidu]

Smartphone Dissection

Circuit Design "Hexagon"



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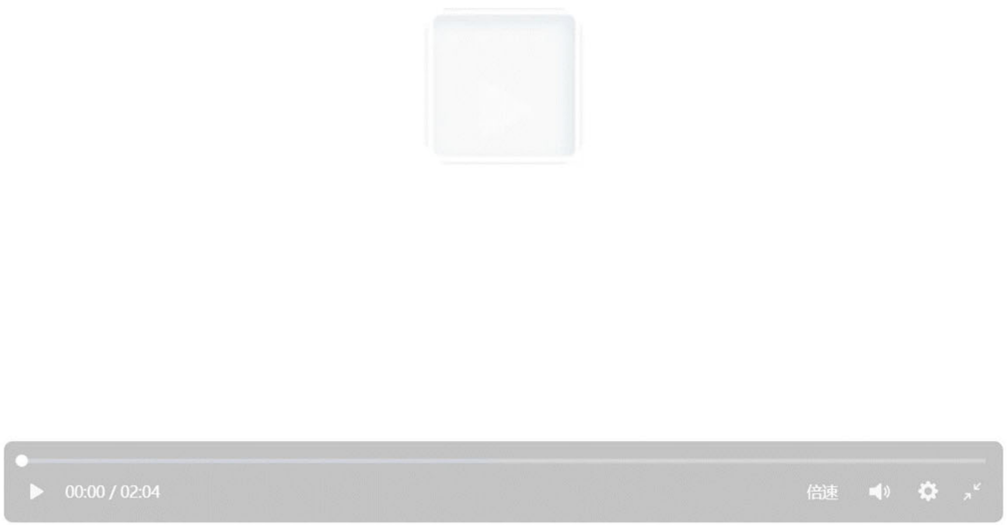
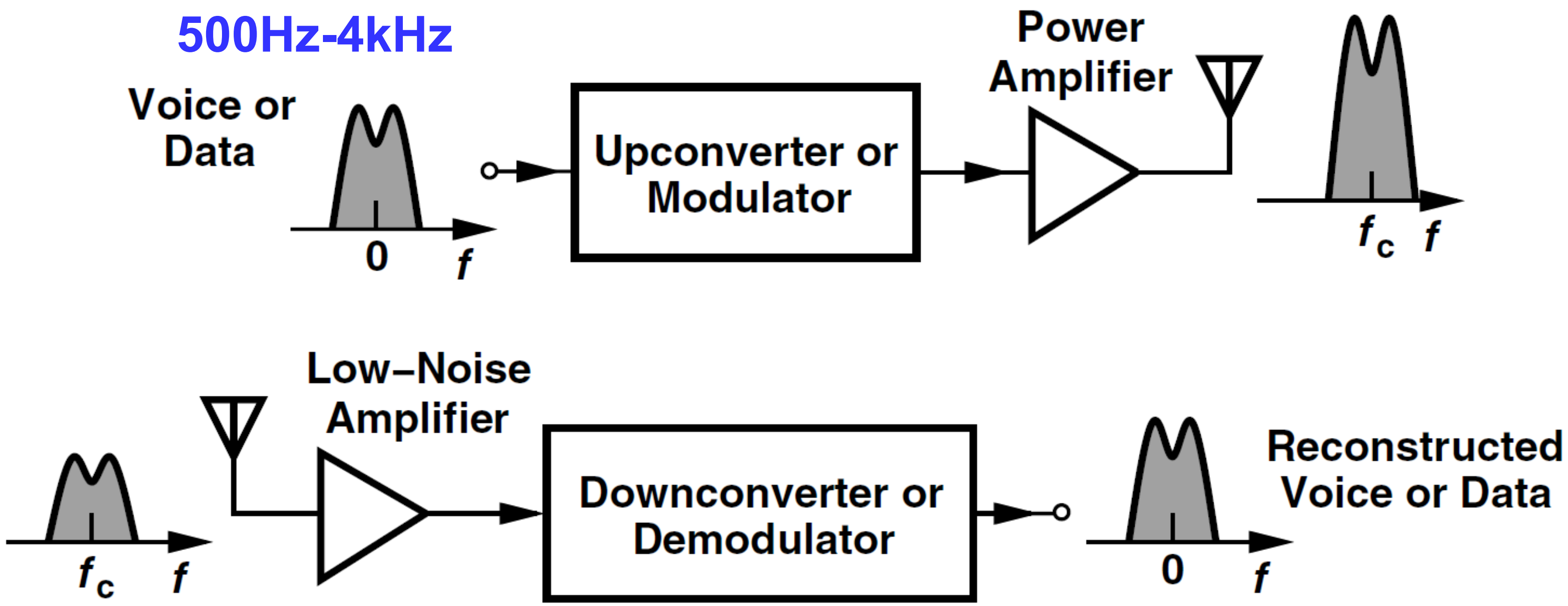
IC Fabrication



Simple View of A System

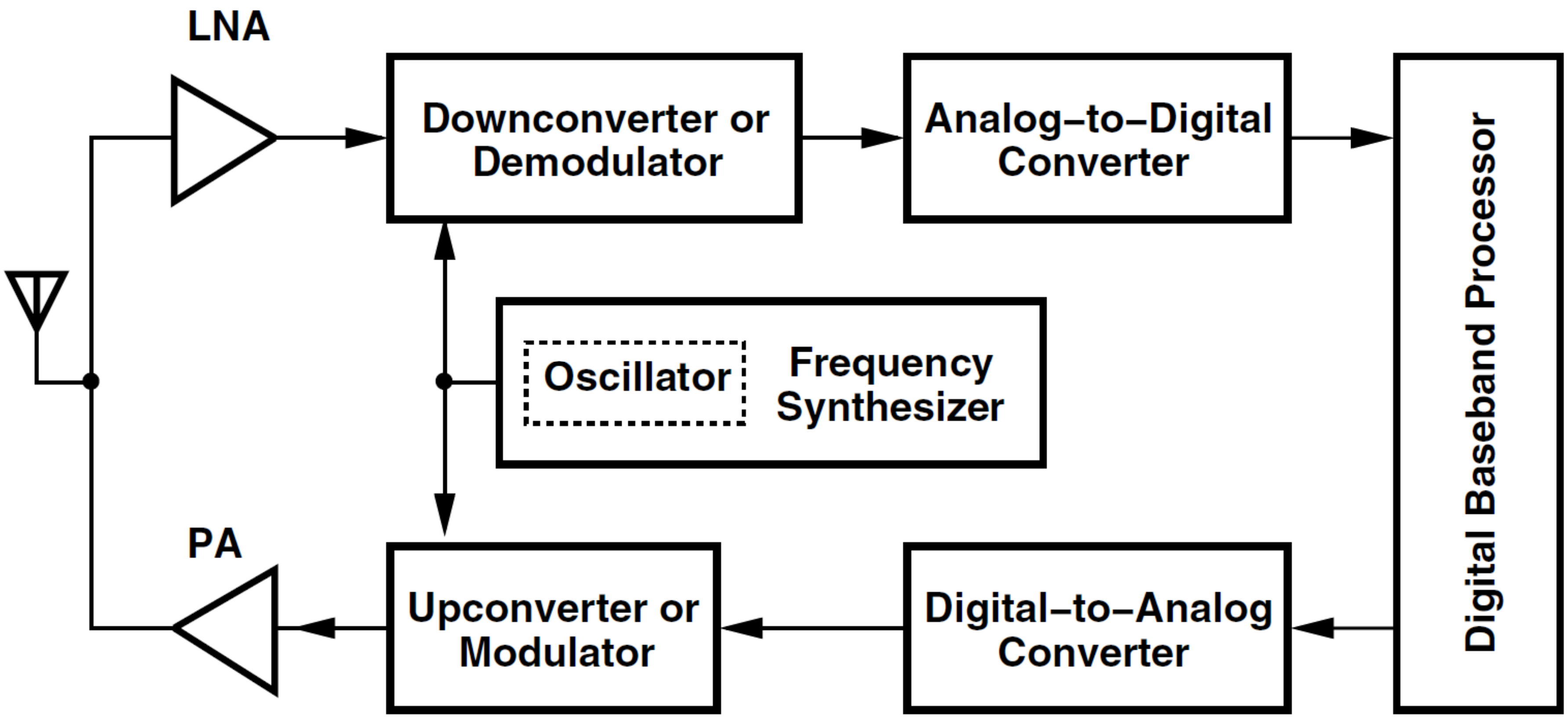


Why modulating and demodulating?

- Reduce the antenna size
- Distribute the signals to different channels

[B. Razavi, RF Microelectronics]

Block Diagram



- ❑The “Front-End” usually operates at a **RELATIVELY** high frequency
- ❑The upconversion and downconversion paths are driven by an oscillator, which is controlled by a “frequency synthesizer.”

[B. Razavi, RF Microelectronics]

Gain

- The voltage gain and power gain are expressed in dB:

$$A_V|_{\text{dB}} = 20\log\frac{V_{out}}{V_{in}}$$

$$A_P|_{\text{dB}} = 10\log\frac{P_{out}}{P_{in}}$$

- The power level is often expressed in dBm rather than Watts:

$$P_{sig}|_{\text{dBm}} = 10\log\left(\frac{P_{sig}}{1\text{ mW}}\right)$$

[B. Razavi, RF Microelectronics]

Nonlinearity

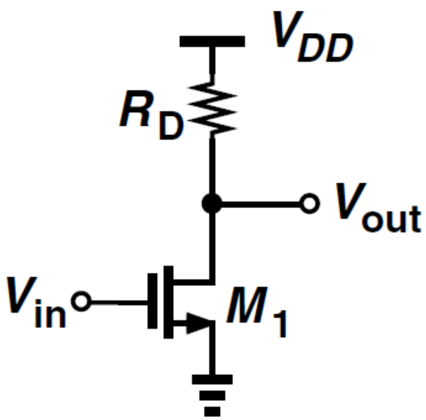
❑For a linear system, the input/output characteristic is given by:

$$y(t) = \alpha x(t)$$

❑For a nonlinear system, the input/output characteristic can be approximated as a polynomial:

$$y(t) = \alpha_0 + \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t) + \cdots$$

❑An amplifier based on single transistor is an example:



$$V_{out} = V_{DD} - I_D R_D$$
$$= V_{DD} - \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{in} - V_{TH})^2 R_D$$

[B. Razavi, RF Microelectronics]

Nonlinearity

- ❑Harmonic Distortion

- ❑Gain Compression

- ❑Desensitization (blocker)

- ❑Cross Modulation

- ❑Intermodulation

[B. Razavi, RF Microelectronics]

Harmonic Distortion

❑We approximate the nonlinear system to be:

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

❑If a sinusoid signal is applied to a nonlinear system:

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

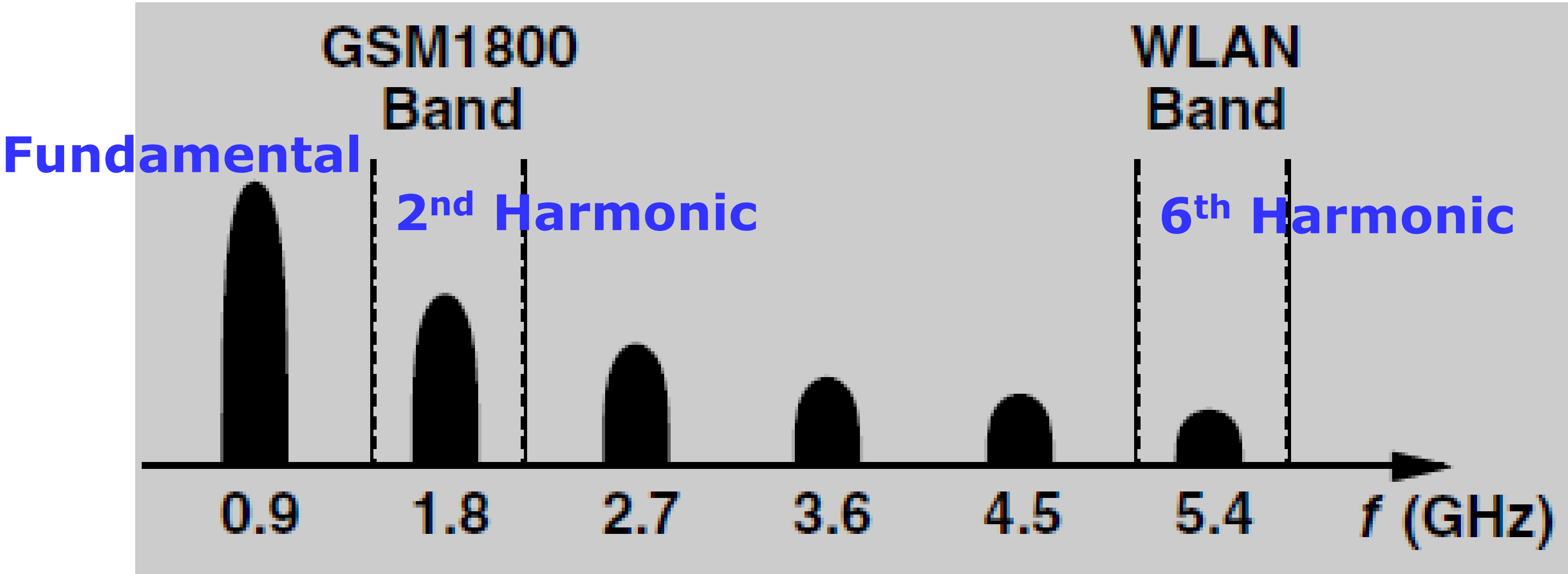
❑At the output, we have:

$$\begin{aligned} y(t) &= \alpha_1 A\cos\omega t + \alpha_2 A^2\cos^2\omega t + \alpha_3 A^3\cos^3\omega t \\ &= \alpha_1 A\cos\omega t + \frac{\alpha_2 A^2}{2}(1+\cos 2\omega t) + \frac{\alpha_3 A^3}{4}(3\cos\omega t + \cos 3\omega t) \\ &= \underbrace{\frac{\alpha_2 A^2}{2}}_{\text{DC}} + \underbrace{\left(\alpha_1 A + \frac{3\alpha_3 A^3}{4}\right)\cos\omega t}_{\text{1st Harmonic (Fundamental)}} + \underbrace{\frac{\alpha_2 A^2}{2}\cos 2\omega t}_{\text{2nd Harmonic}} + \underbrace{\frac{\alpha_3 A^3}{4}\cos 3\omega t}_{\text{3rd Harmonic}} \end{aligned}$$

[B. Razavi, RF Microelectronics]

Harmonic Distortion

❑For a 900-MHz GSM cellphone:



❑The second harmonic falls within another GSM cell phone band around 1800MHz. The sixth harmonic falls in the 5-GHz band used in wireless local area networks (WLANs), e.g., in laptops.

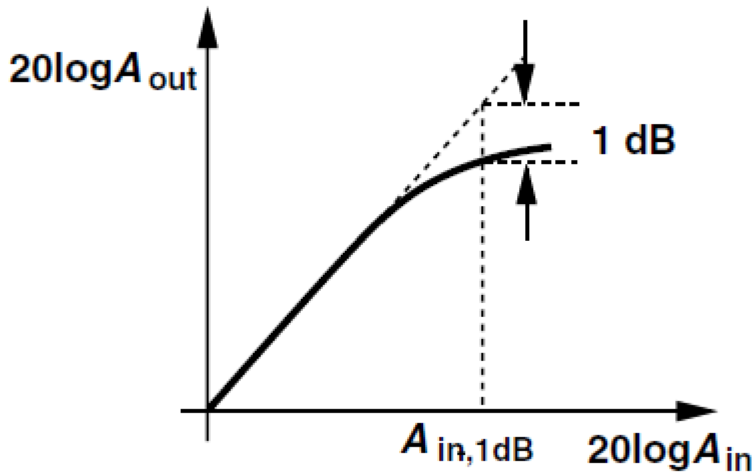
[B. Razavi, RF Microelectronics]

Gain Compression

- The fundamental component at the output:

$$x(t) = \mathrm{A}\cos\omega t \qquad y(t) = \left(\alpha_1 + \frac{3\alpha_3 A^2}{4}\right)\mathrm{A}\cos\omega t$$

- The gain varies appreciably as the input amplitude "A" becomes larger. In most cases, α_1 and α_3 have opposite signs, so the gain falls as the signal amplitude "A" rises.



We quantify this effect by the "1-dB compression point," defined as the input signal level that causes the gain to drop by 1 dB.

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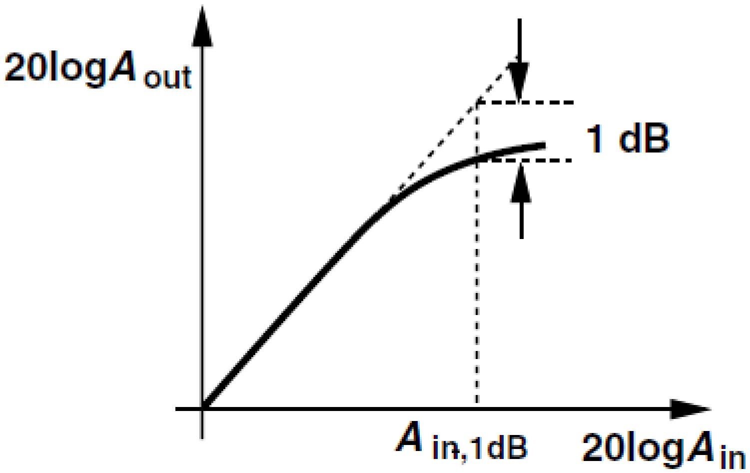
1-dB Compression Point



A higher 1 dB compression point means a better linearity

- To calculate the 1-dB compression point, we have:

$$20\log\left|\alpha_1 + \frac{3}{4}\alpha_3 A_{in,1dB}^2\right| = 20\log|\alpha_1| - 1\text{ dB}$$

$$A_{in,1dB} = \sqrt{0.145\left|\frac{\alpha_1}{\alpha_3}\right|}$$

[B. Razavi, RF Microelectronics]

Desensitization (Blocker)

❑If a large interferer accompanies the received signal:.

$$x(t) = \underbrace{\boxed{A_1 \cos \omega_1 t}}_{\text{Desired Signal}} + \underbrace{\boxed{A_2 \cos \omega_2 t}}_{\text{Interferer}}$$

$$y(t) = \left(\alpha_1 + \frac{3}{4}\alpha_3 A_1^2 + \frac{3}{2}\alpha_3 A_2^2 \right) A_1 \cos \omega_1 t + \cdots$$

❑For $A_1 << A_2$, the equation reduces to:

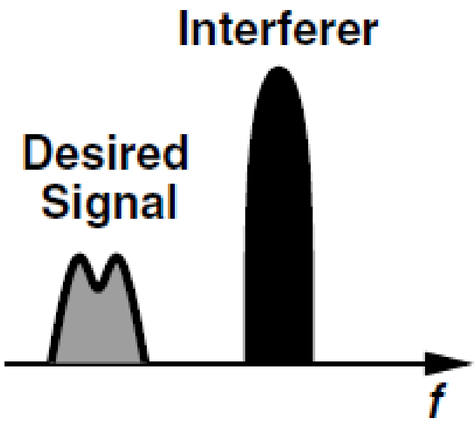
$$y(t) = \left(\alpha_1 + \frac{3}{2}\alpha_3 A_2^2 \right) A_1 \cos \omega_1 t + \cdots$$

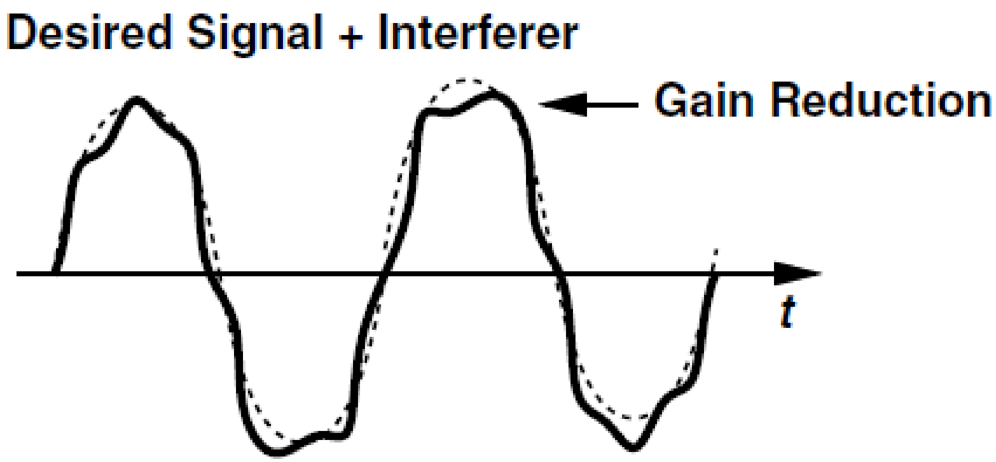
❑The gain experienced by the desired signal is a decreasing function of A_2 if $\alpha_1 \alpha_3 < 0$. In fact, for sufficiently large A_2, the gain drops to zero, and we say the signal is "blocked."

[B. Razavi, RF Microelectronics]

Desensitization (Blocker)

❑In the time domain, the small desired signal is superimposed on the large interferer. Consequently, the receiver gain is reduced by the large excursions produced by the interferer.





❑If the signal is received by a receiver, this phenomenon lowers the signal-to-noise ratio (SNR) at the receiver output.

[B. Razavi, RF Microelectronics]

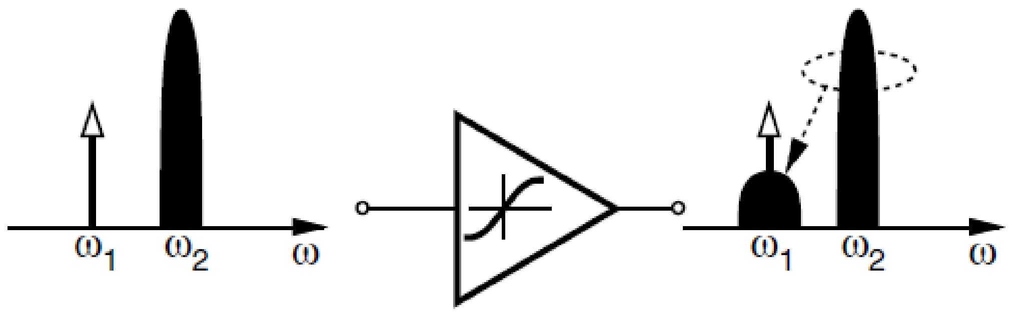
Cross Modulation

- when a weak signal and a strong interferer pass through a nonlinear system, and the interferer is an amplitude modulated signal: $A_2(1 + m\cos\omega_m t)\cos\omega_2 t$

- Then, the output of the nonlinear system will be:

$$y(t) = \left[\alpha_1 + \frac{3}{2}\alpha_3 A_2^2\left(1 + \frac{m^2}{2} + \frac{m^2}{2}\cos 2\omega_m t + 2m\cos\omega_m t\right)\right]A_1\cos\omega_1 t + \cdots$$

- The desired signal at the output suffers from amplitude modulation coming from the interferer



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Intermodulation

❑If there are two interferences: $x(t) = A_1 \cos \omega_1 t + A_2 \cos \omega_2 t$

$$y(t) = \alpha_1(A_1 \cos \omega_1 t + A_2 \cos \omega_2 t) + \alpha_2(A_1 \cos \omega_1 t + A_2 \cos \omega_2 t)^2 + \alpha_3(A_1 \cos \omega_1 t + A_2 \cos \omega_2 t)^3$$

❑Then, there will be intermodulation products:

$$\omega = 2\omega_1 \pm \omega_2 : \ \frac{3\alpha_3 A_1^2 A_2}{4} \cos(2\omega_1 + \omega_2)t + \frac{3\alpha_3 A_1^2 A_2}{4} \cos(2\omega_1 - \omega_2)t$$

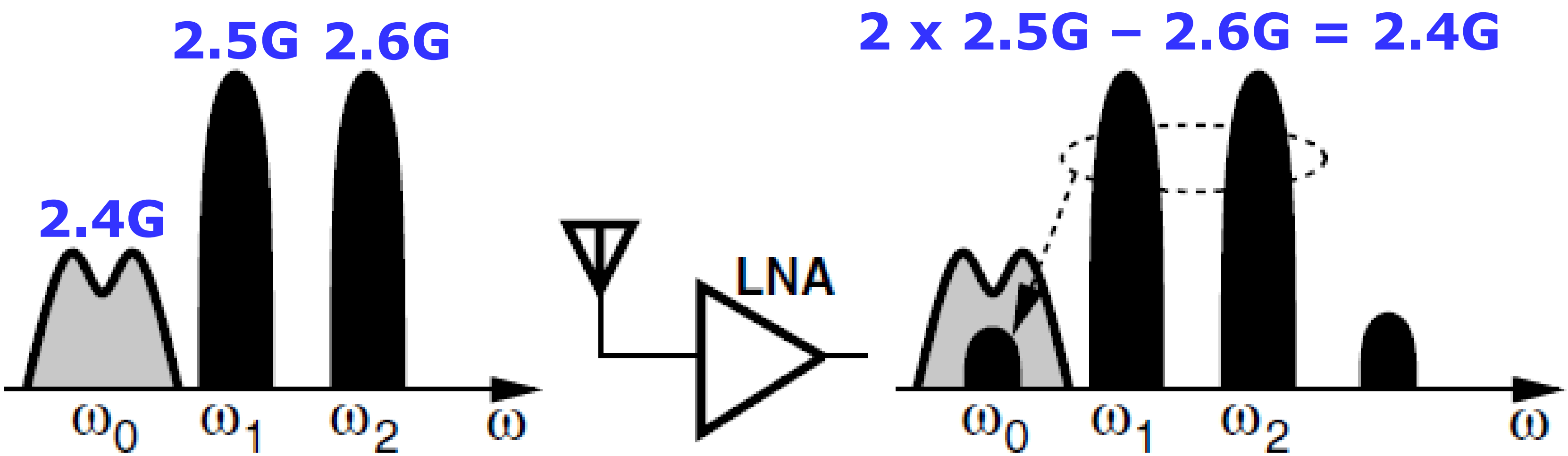
$$\omega = 2\omega_2 \pm \omega_1 : \ \frac{3\alpha_3 A_1 A_2^2}{4} \cos(2\omega_2 + \omega_1)t + \frac{3\alpha_3 A_1 A_2^2}{4} \cos(2\omega_2 - \omega_1)t$$

❑The third-order IM products at $2\omega_1$-ω_2 and $2\omega_2$-ω_1 are of particular interest. This is because, if ω_1 and ω_2 are close to each other, then $2\omega_1$-ω_2 and $2\omega_2$-ω_1 appear in the vicinity of ω_1 and ω_2

[B. Razavi, RF Microelectronics]

Intermodulation

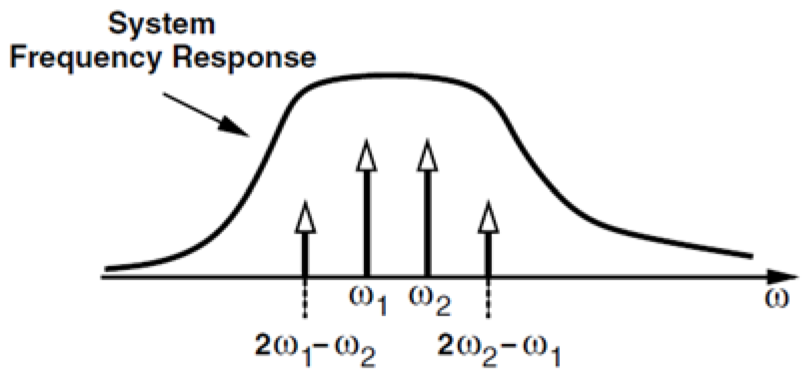
❑Suppose an antenna receives a small desired signal at ω_0 along with two large interferers at ω_1 and ω_2. In addition, the interferer frequencies happen to satisfy $2\omega_1-\omega_2=\omega_0$



❑Consequently, the intermodulation product at $2\omega_1-\omega_2$ falls onto the desired channel, corrupting the signal.

[B. Razavi, RF Microelectronics]

Intermodulation



- To measure the intermodulation performance, the two-tone test is versatile and powerful because it can be applied to systems with arbitrarily narrow bandwidths.

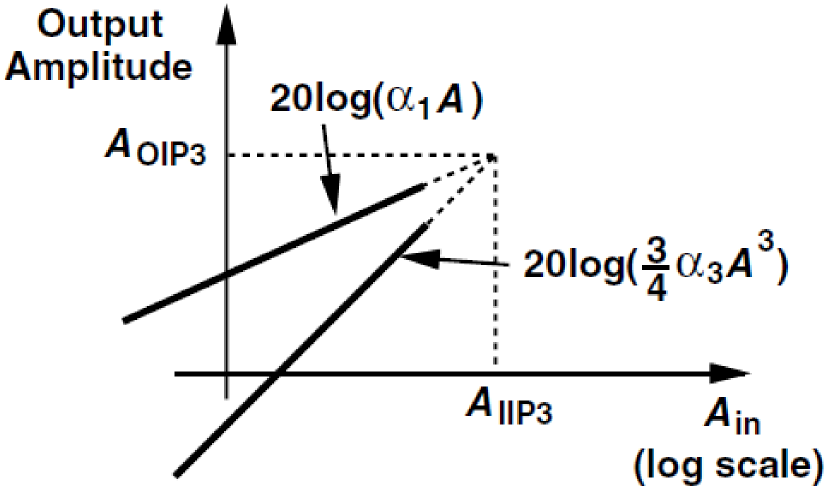
- A sufficiently small difference between the two tone frequencies ensures that the IM products also fall within the band, thereby providing a meaningful view of the nonlinear behavior of the system.

- A large difference between ω_1 and ω_2 results in an output-of-band $2\omega_2$-ω_1, leading to an wrong result in intermodulation measurement

[B. Razavi, RF Microelectronics]

Third Intercept Point

❑if the amplitude A of each tone rises, that of the output IM products increases more sharply ($\propto A^3$). Thus, if we continue to raise A, the amplitude of the IM products eventually becomes equal to that of the fundamental tones at the output



$$|\alpha_1 A_{IIP3}| = \left|\frac{3}{4}\alpha_3 A_{IIP3}^3\right|$$

$$A_{IIP3} = \sqrt{\frac{4}{3}\left|\frac{\alpha_1}{\alpha_3}\right|} \qquad A_{in,1dB} = \sqrt{0.145\left|\frac{\alpha_1}{\alpha_3}\right|}$$

$$\frac{A_{IIP3}}{A_{1dB}} = \sqrt{\frac{4}{0.435}} = 9.6 \text{ dB}$$

❑The input level at which this occurs is called the “input third intercept point” (IIP3). (We also have OIP3)

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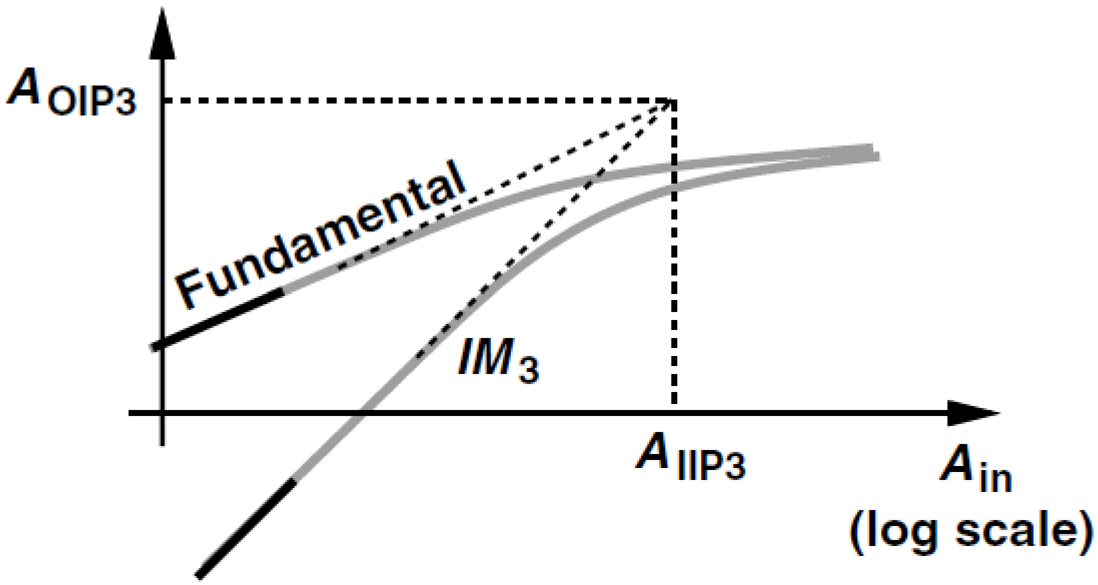
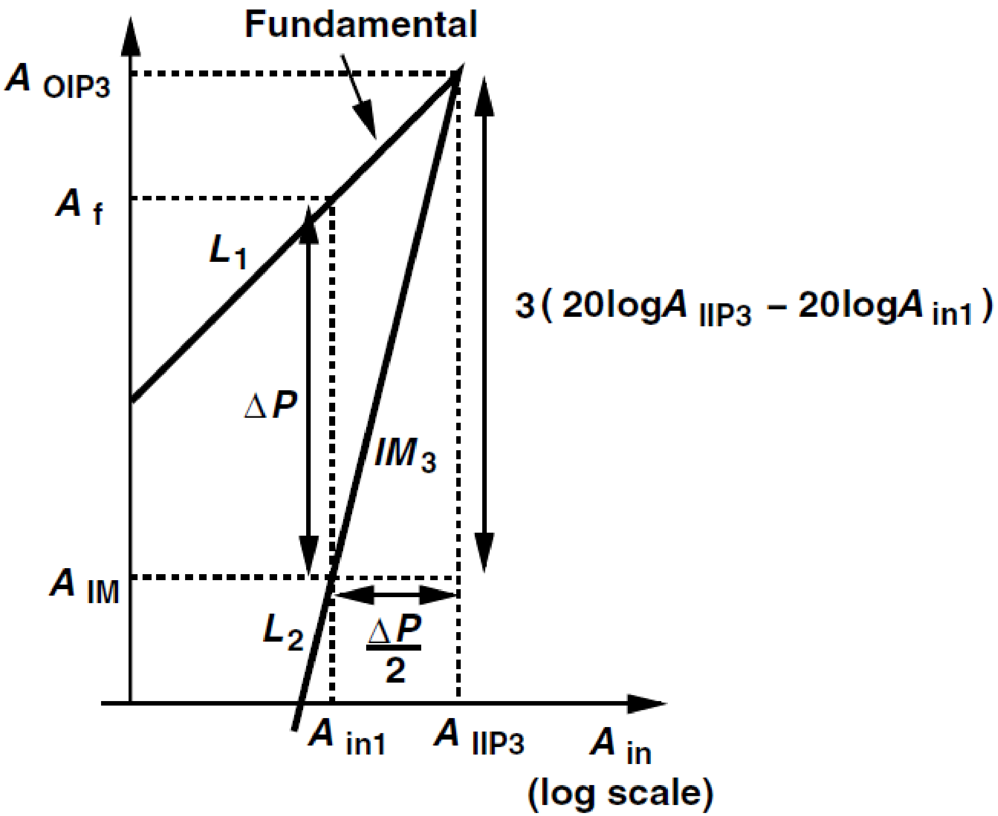
IIP3 Measurement

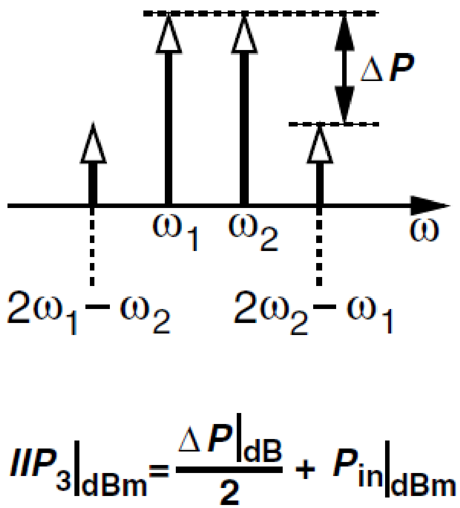


❑**We begin with a very low input amplitude, and then increase it, plot the amplitudes of the fundamentals and the IM products on a log-log scale, and extrapolate these plots according to their slopes to obtain the IIP3**

[B. Razavi, RF Microelectronics]

IIP3 Measurement





$$\Delta P = 20\log A_f - 20\log A_{IM} = 2(20\log A_{IIP3} - 20\log A_{in1})$$

$$20\log A_{IIP3} = \frac{\Delta P}{2} + 20\log A_{in1}$$

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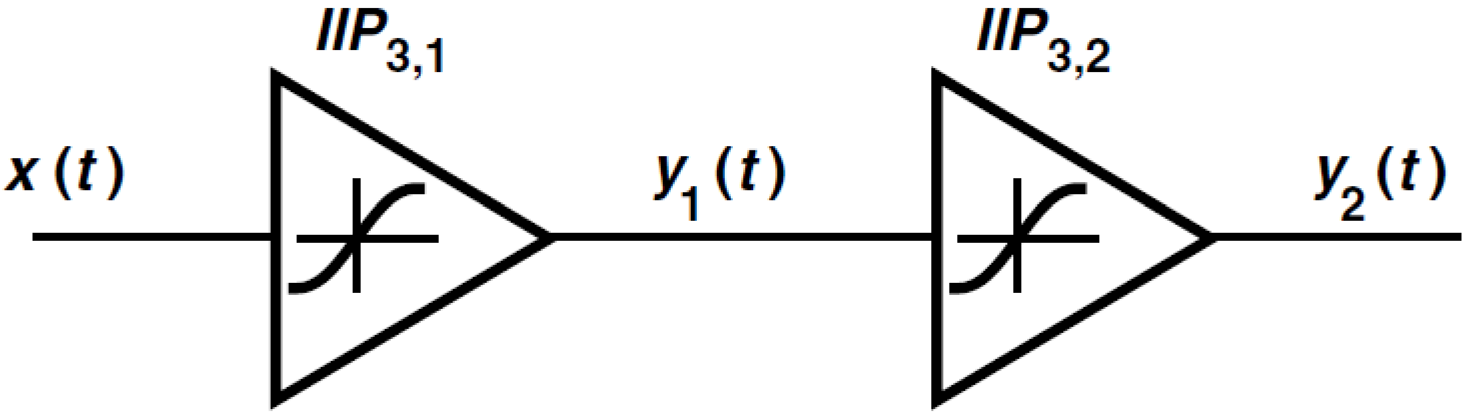
Cascaded Nonlinear Stages



$$\frac{1}{A_{IP3}^2} \approx \frac{1}{A_{IP3,1}^2} + \frac{\alpha_1^2}{A_{IP3,2}^2} \qquad \frac{1}{A_{IP3}^2} \approx \frac{1}{A_{IP3,1}^2} + \frac{\alpha_1^2}{A_{IP3,2}^2} + \frac{\alpha_1^2\beta_1^2}{A_{IP3,3}^2} + \cdots$$

- **If each stage in a cascade has a gain greater than unity, the nonlinearity of the latter stages becomes increasingly more critical because the IIP3 of each stage is equivalently scaled down by the total gain preceding that stage.**

[B. Razavi, RF Microelectronics]

AM-PM Conversion

❑In a system, for an input $V_{in}(t) = V_1 \cos \omega_1 t$, the fundamental output component is given by

$$V_{out}(t) = V_2 \cos[\omega_1 t + \phi(V_1)]$$

❑where $\varphi(V_1)$ denotes the amplitude-dependent phase shift.

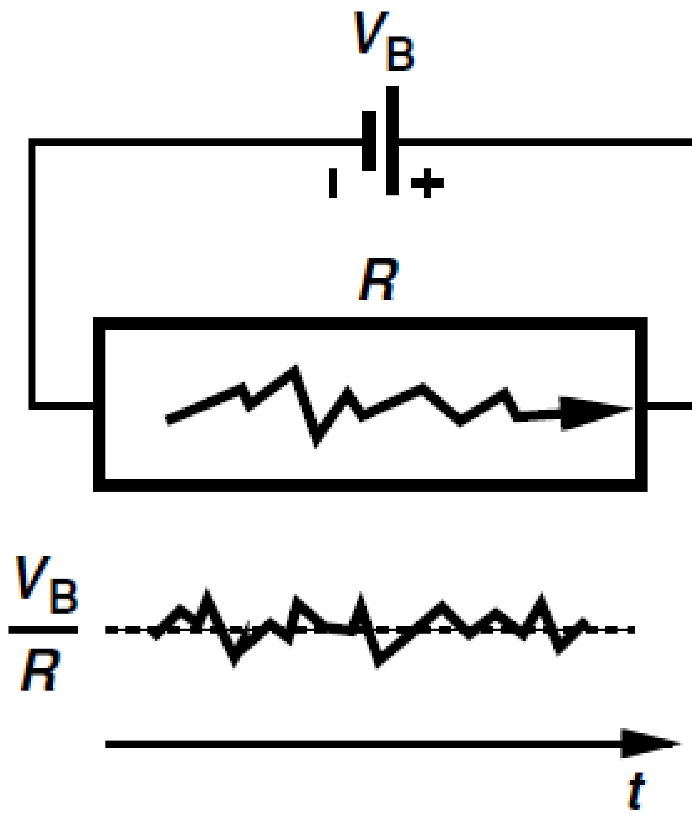
❑In the presence of AM-PM conversion, amplitude modulation (or amplitude noise) corrupts the phase of the signal.

❑Especially for the circuits where the phase is very important, such as PSK system, oscillator, etc.

[B. Razavi, RF Microelectronics]

Noise in Resistor

❑Noise is random !!!



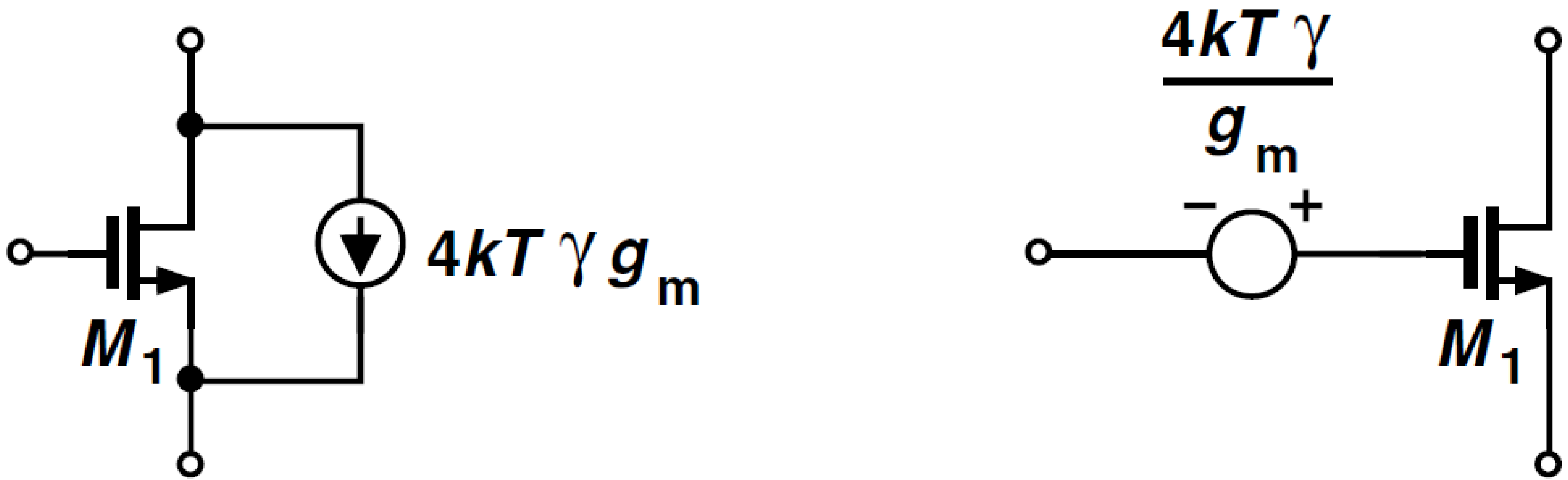
❑The average current remains equal to V_B/R but the instantaneous current displays random values.

❑The noise of a resistor is proportional to the temperature, which can be expressed by

$$\overline{V_n^2} = 4kTR$$

[B. Razavi, RF Microelectronics]

Noise in MOSFET



- The thermal noise of MOS transistors operating in the saturation region is approximated by a current source, which can be alternatively be modeled by a voltage source at the gate

- γ is the "excess noise coefficient" and g_m is the transconductance.

[B. Razavi, RF Microelectronics]

Noise in MOSFET

❑MOS devices also suffer from “flicker” or “1/f ” noise

$$\overline{V_n^2} = \frac{K}{WLC_{ox}} \frac{1}{f}$$

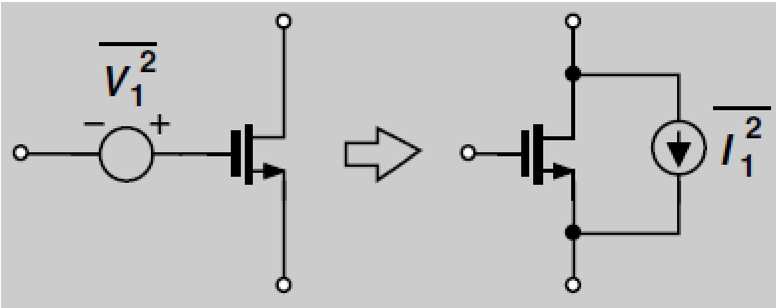
❑Where W and L represent the size of a transistor, C_{OX} is the gate-to-substrate capacitance of unit area, K is a process-depend constant.

❑In most CMOS technologies, K is lower for PMOS devices than for NMOS transistors.

[B. Razavi, RF Microelectronics]

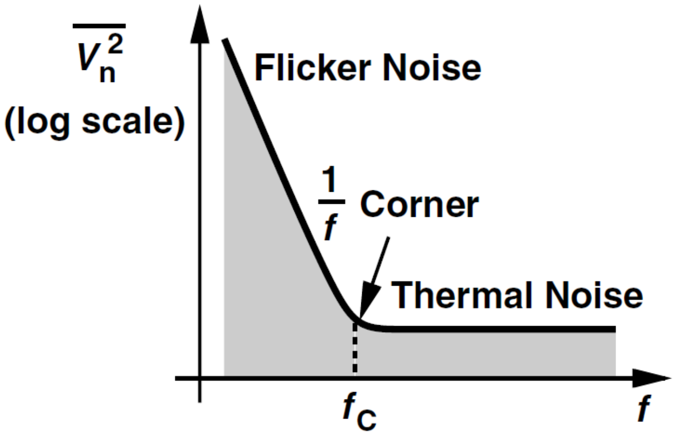
Noise Corner

❑The corner frequency f_C can be obtained by converting the flicker noise voltage to current (according to the above example) and equating the result to the thermal noise current:



$$\frac{K}{WLC_{ox}}\frac{1}{f_c}g_m^2 = 4kT\gamma g_m$$

$$f_c = \frac{K}{WLC_{ox}}\frac{g_m}{4kT\gamma}$$

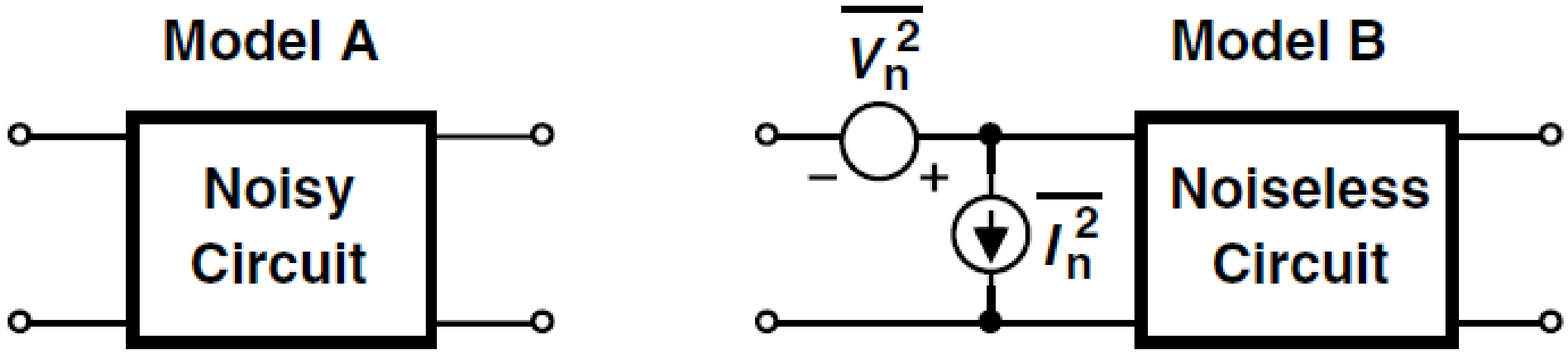


❑Note that the flicker noise can be translated into high frequency by nonlinear circuits.

[B. Razavi, RF Microelectronics]

Input-Referred Noise

❑The input-referred noise is modeled by a series voltage source and a parallel current source. The former is obtained by shorting the input port of models A and B and equating their output noises. Similarly, the latter is computed by leaving the input ports open and equating the output noises.



[B. Razavi, RF Microelectronics]

Noise Figure

❑The Noise Figure (NF) of an amplifier is a measure of the degradation of the SNR

$$F = \frac{SNR_i}{SNR_o}$$

$$NF = 10 \cdot \log(F) \text{ (dB)}$$

❑The noise figure is measured (or calculated) by specifying a standard input noise level through the source resistance R_S and the temperature

❑For RF communication systems, this is usually specified as R_S = 50 and T = 293 K.

[Ali Niknejad, EE142&EE242 of UC Berkeley]

Noise Figure of an Amplifier

- Suppose an amplifier has a gain G and apply the NF definition

$$SNR_i = \frac{P_{sig}}{N_s}$$

$$SNR_o = \frac{GP_{sig}}{GN_s + N_{amp,o}}$$

- The term $N_{amp,o}$ is the total output noise due to the amplifier in absence of any input noise.

$$SNR_o = \frac{P_{sig}}{N_s + \frac{N_{amp,o}}{G}}$$

[Ali Niknejad, EE142&EE242 of UC Berkeley]

Noise Figure of an Amplifier

- Let $N_{amp,i}$ denote the total input referred noise of the amplifier

$$SNR_o = \frac{P_{sig}}{N_s + N_{amp,i}}$$

- The noise figure is therefore

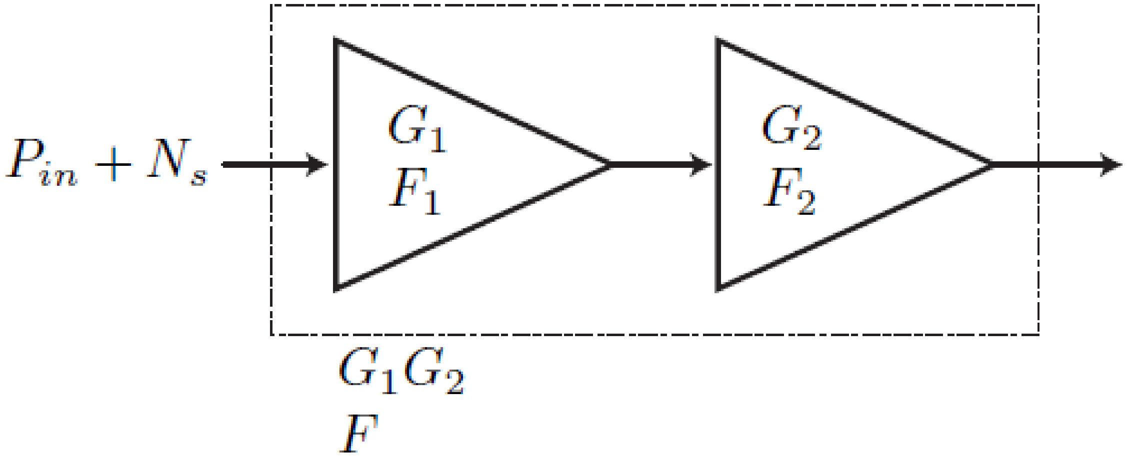
$$F = \frac{SNR_i}{SNR_o} = \frac{P_{\cancel{sig}}}{N_s} \times \frac{N_s + N_{amp,i}}{P_{\cancel{sig}}}$$

$$F = 1 + \frac{N_{amp,i}}{N_s} \geq 1$$

- All amplifiers have a noise figure ≥ 1. Any real system degrades the SNR since all circuit blocks add additional noise.

[Ali Niknejad, EE142&EE242 of UC Berkeley]

Noise Figure of Cascaded Blocks



❑If two blocks are cascaded, we would like to derive the noise figure of the total system.

❑Assume the blocks are impedance matched properly to result in a gain G = G_1G_2. For each amplifier in cascade, we have

$$F_i = 1 + \frac{N_{amp,i}}{N_s}$$

[Ali Niknejad, EE142&EE242 of UC Berkeley]

Total Noise for Cascade

❑By definition, the noise added by each amplifier to the input is given by

$$N_{amp,i} = N_s(F - 1)$$

❑where N_S represents some standard input noise. If we now input refer all the noise in the system we have

$$N'_{amp,i} = N_s(F_1 - 1) + \frac{N_s(F_2 - 1)}{G_1}$$

❑Which gives us the total noise figure of the amplifier

$$F = 1 + \frac{N'_{amp,i}}{N_s} = 1 + (F_1 - 1) + \frac{F_2 - 1}{G_1} = F_1 + \frac{F_2 - 1}{G_1}$$

[Ali Niknejad, EE142&EE242 of UC Berkeley]

Cascade NF

- If there are 3 blocks in cascade, we apply the formula to the last two blocks

$$F_{23} = F_2 + \frac{F_3 - 1}{G_2}$$

$$F = F_1 + \frac{F_{23} - 1}{G_1}$$

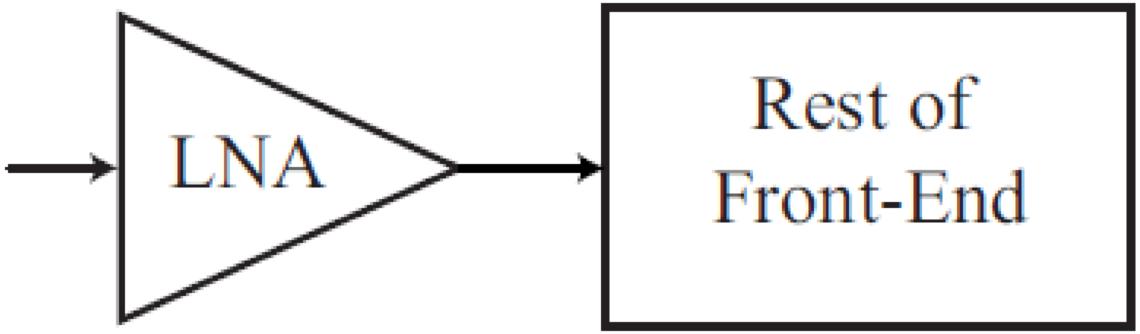
$$= F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2}$$

- The general equation is written by inspection

$$= F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \cdots$$

[Ali Niknejad, EE142&EE242 of UC Berkeley]

Cascade NF



❑We see that in a cascade, the noise contribution of each successive stage is smaller and smaller.

❑The noise of the first stage is the most important. Thus, every communication system employs a low noise amplifier (LNA) at the front to relax the noise requirements

❑A typical LNA might have a G = 20 dB of gain and a noise figure NF < 1.5 dB. The noise figure depends on the application.

[Ali Niknejad, EE142&EE242 of UC Berkeley]

The unit "dBm"

$$10 \cdot \log\left(\frac{P[\mathrm{mW}]}{1\,\mathrm{mW}}\right) = P[\mathrm{dBm}]$$

❑The power in communication systems is often measured in the dBm scale, or the log power measured relative to a 1 mW reference. E.g. a power level of 10 mW can be expressed as 10 dBm.

❑On your laptop or cellular phone, you can often see the signal strength expressed in dBm units.

❑Amplification of weak signals is a major goal of a communication system. Amplification is not easy since the signals are often only marginally larger than the intrinsic noise. Additionally, high gain for the interference signals can easily "rail" our amplifiers unless we carefully filter them out.

❑Say your WLAN on your laptop is receiving a signal with strength −70 dBm. This corresponds to a power of P = 1E-7 mW = 1E-10 W=100pW. The voltage on the antenna can be approximated by

$$P = \frac{V^2}{2Z_0} \qquad V = \sqrt{2Z_0 P} = \sqrt{2 \cdot 50 \cdot 10^{-10}} = 10^{-4}\,\mathrm{V} = 100\,\mu\mathrm{V}$$

[Ali Niknejad, EE142&EE242 of UC Berkeley]

Sensitivity

- In the presence of excessive noise, the sensitivity is defined as the minimum signal level that a receiver can detect with "acceptable quality"

$$NF = \frac{SNR_{in}}{SNR_{out}} = \frac{P_{sig}/P_{RS}}{SNR_{out}} \qquad P_{sig} = P_{RS} \cdot NF \cdot SNR_{out}$$

- where P_{sig} denotes the input signal power and P_{RS} the source resistance noise power, both per unit bandwidth.

- Since the overall signal power is distributed across a certain bandwidth B, then we have

$$P_{sig,tot} = P_{RS} \cdot NF \cdot SNR_{out} \cdot B$$

[B. Razavi, RF Microelectronics]

Sensitivity

❑Expressing the quantities in dB or dBm

$$P_{sen}|_{dBm} = P_{RS}|_{dBm/Hz} + NF|_{dB} + SNR_{min}|_{dB} + 10\log B$$

❑If the receiver is matched to the antenna, then

P_{RS}=kT=-174 dBm/Hz and

$$P_{sen} = -174\,\mathrm{dBm/Hz} + NF + 10\log B + SNR_{min}$$

❑Note that the sum of the first three terms is the total integrated noise of the system (sometimes called the “noise floor”).

[B. Razavi, RF Microelectronics]

Receiver Selectivity (Filtering)

❑A cell phone can sense very small signals, such as -100dBm or even -120dBm ($P_{IN}=10^{-12}$mW=10^{-15}W). For a 50 Ohm antenna, the equivalent input voltage of -120dBm is

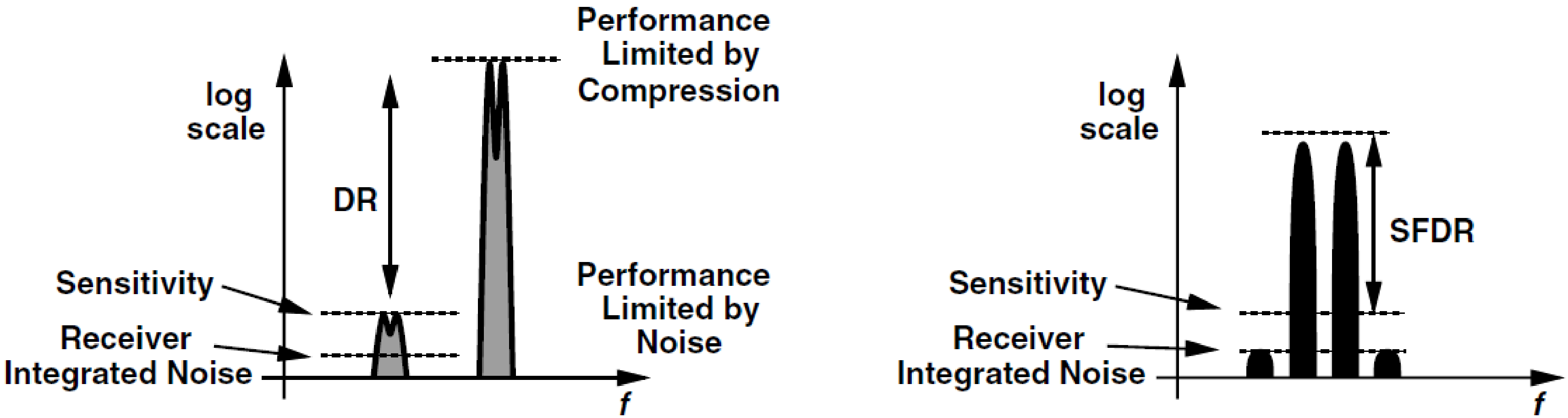
$$V_{IN}=\sqrt{10^{-15}*100}=0.3\text{uV}$$

❑This is indeed a tiny signal. We need a voltage gain of about 10^6 to bring this signal into the range for baseband processing.

❑Now imagine an interference signal of strength −40 dBm, or about 3mV. This may seem like a small signal, but it effectively limits the gain of our system to about 1000. Unless we employ a very high resolution ADC (expensive, bulky, power hungry), we must filter out this interference.

[Ali Niknejad, EE142&EE242 of UC Berkeley]

Dynamic Range (DR)



- **Dynamic Range: The maximum tolerable desired signal power divided by the minimum tolerable desired signal power (the sensitivity). This DR is limited by compression at the upper end and noise at the lower end.**

- **Spurious-Free Dynamic Range (SFDR): The upper end is defined as the maximum input level in a two-tone test for which the third-order IM products do not exceed the integrated noise of the receiver.**

[B. Razavi, RF Microelectronics]

SFDR

❑Recalling the equation: $P_{IIP3} = P_{in} + \frac{P_{out} - P_{IM,out}}{2}$

❑If the circuit exhibits a gain of G (in dB), then we can refer the IM level to the input by writing $P_{IM,in}=P_{IM,out}-G$. Similarly, the input level of each tone is given by $P_{in}=P_{out}-G$.

$$P_{IIP3} = P_{in} + \frac{P_{in} - P_{IM,in}}{2} = \frac{3P_{in} - P_{IM,in}}{2} \qquad P_{in} = \frac{2P_{IIP3} + P_{IM,in}}{3}$$

❑The upper end of the SFDR is that value of P_{in} which makes $P_{IM,in}$ equal to the integrated noise of the receiver:

$$P_{in,max} = \frac{2P_{IIP3} + (-174\,\mathrm{dBm} + NF + 10\log B)}{3}$$

❑The SFDR is the difference between $P_{in,max}$ and the sensitivity:

$$SFDR = P_{in,max} - (-174\,\mathrm{dBm} + NF + 10\log B + SNR_{min})$$
$$= \frac{2(P_{IIP3} + 174\,\mathrm{dBm} - NF - 10\log B)}{3} - SNR_{min}$$

[B. Razavi, RF Microelectronics]

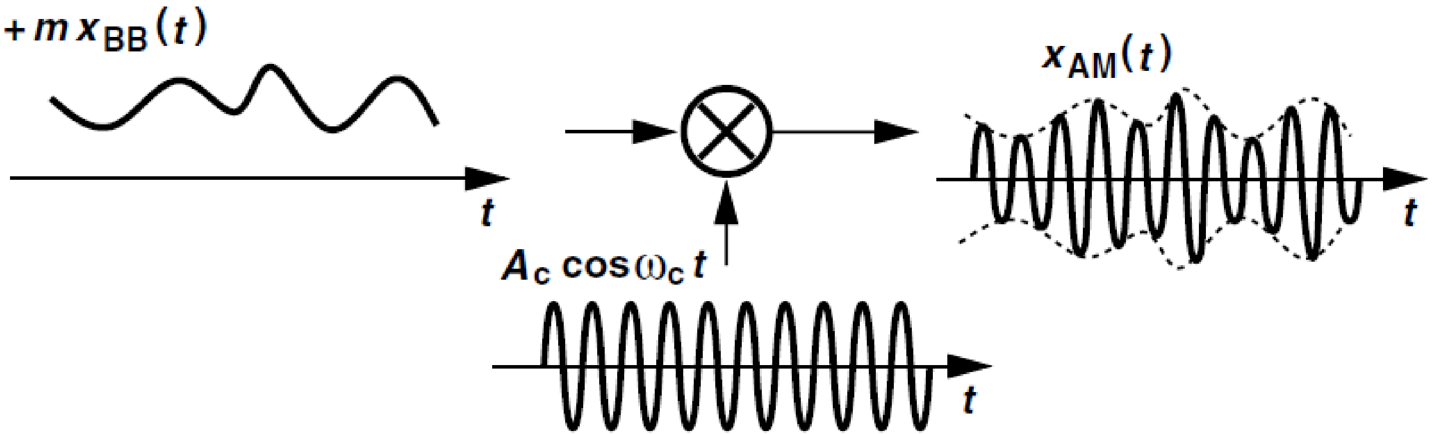
Modulation

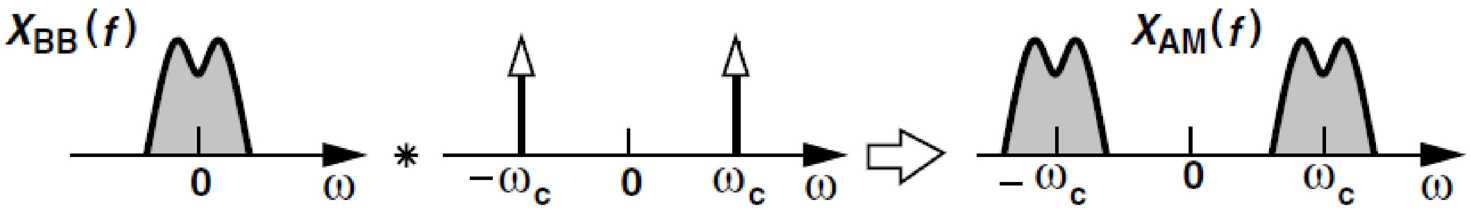
- **The information content (analog waveform or digital bits) are mapped onto the carrier wave using different modulation schemes**
  - **Classic analog techniques: Amplitude Modulation (AM), Frequency Modulation (FM), Phase Modulation (PM)**
  - **Simple digital modulation: On/Off Keying (OOK), Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), Phase Shift Keying (BPSK), Quadrature Amplitude Modulation (QAM)**
  - **Sophisticated digital modulation: Minimum Shift Keying (MSK), Pulse-Position Modulation (PPM), Orthogonal Frequency-Division Multiplexing (OFDM)**

[Ali Niknejad, EE142&EE242 of UC Berkeley]

Amplitude Modulation

❑For a baseband signal $x_{BB}(t)$, an amplitude-modulated (AM) waveform can be constructed as $x_{AM}(t) = A_c[1 + mx_{BB}(t)]\cos\omega_c t.$





[B. Razavi, RF Microelectronics]

Phase/Frequency Modulation

❑If the amplitude is constant and the excess phase is linearly proportional to the baseband signal, we say the carrier is phase-modulated:

$$x_{PM}(t) = A_c \cos[\omega_c t + m x_{BB}(t)]$$

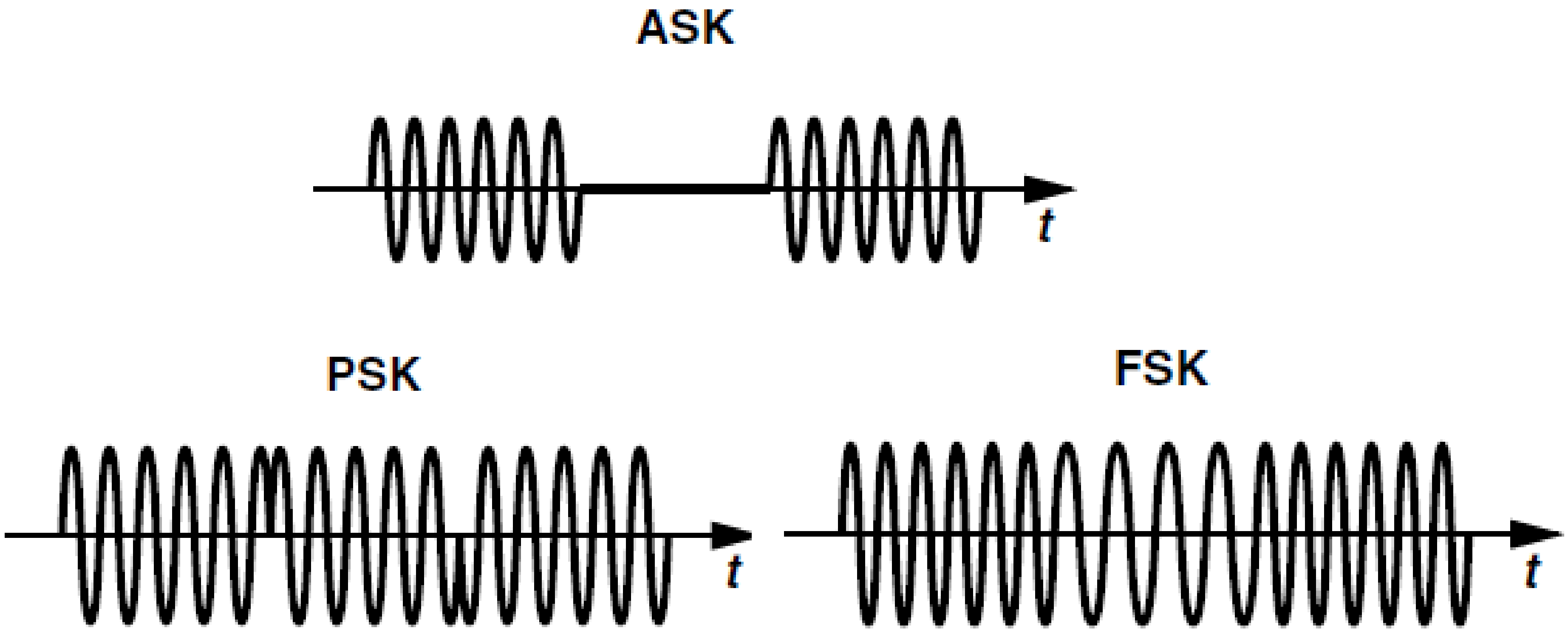
❑If the excess frequency, dθ/dt, is linearly proportional to the baseband signal, we say the carrier is frequency-modulated

$$x_{FM}(t) = A_c \cos[\omega_c t + m \int_{-\infty}^{t} x_{BB}(\tau) d\tau]$$

[B. Razavi, RF Microelectronics]

Digital Modulation

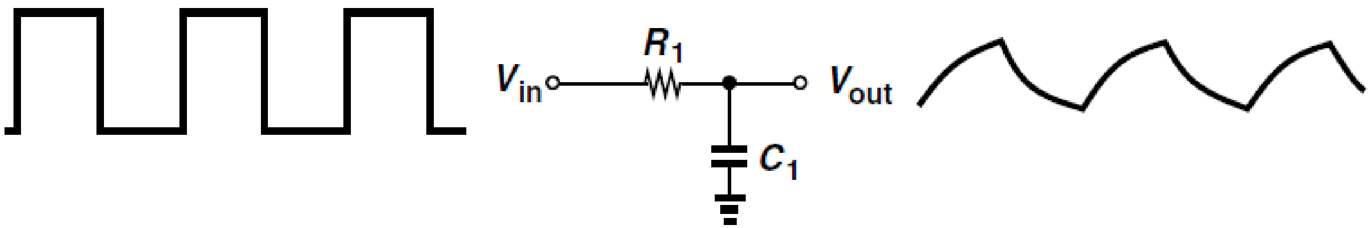
❑Carrying the information in digital form offers many advantages over communication in the analog domain:

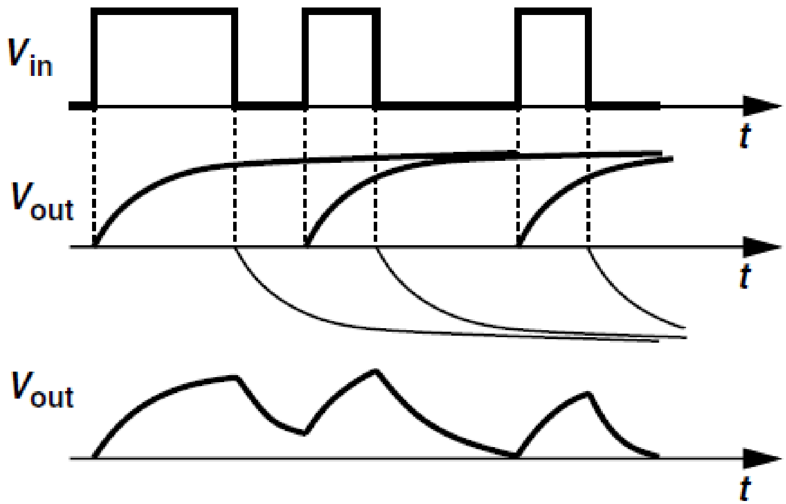


[B. Razavi, RF Microelectronics]

Intersymbol Interference (ISI)

❑A system can "distort" a signal if they do not provide sufficient bandwidth.



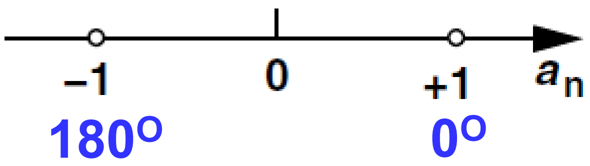


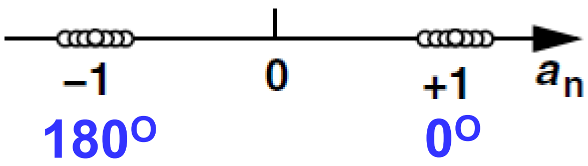
[B. Razavi, RF Microelectronics]

Signal Constellations

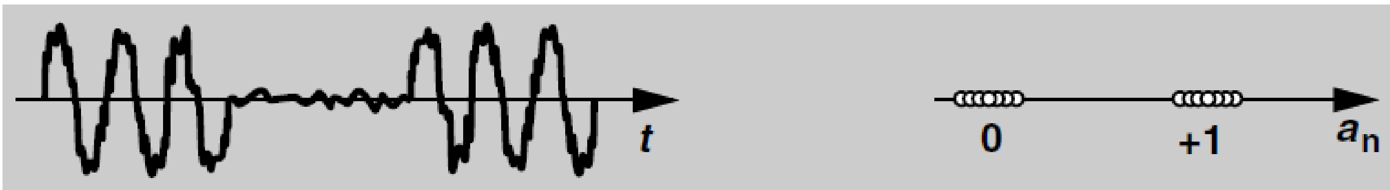
❑"Signal constellations" allow us to visualize modulation schemes and, more importantly, the effect of nonidealities on them.

$$x_{PSK}(t) = a_n \cos \omega_c t \qquad a_n = \pm 1$$





$$x_{ASK}(t) = a_n \cos \omega_c t \qquad a_n = 0,\ 1$$

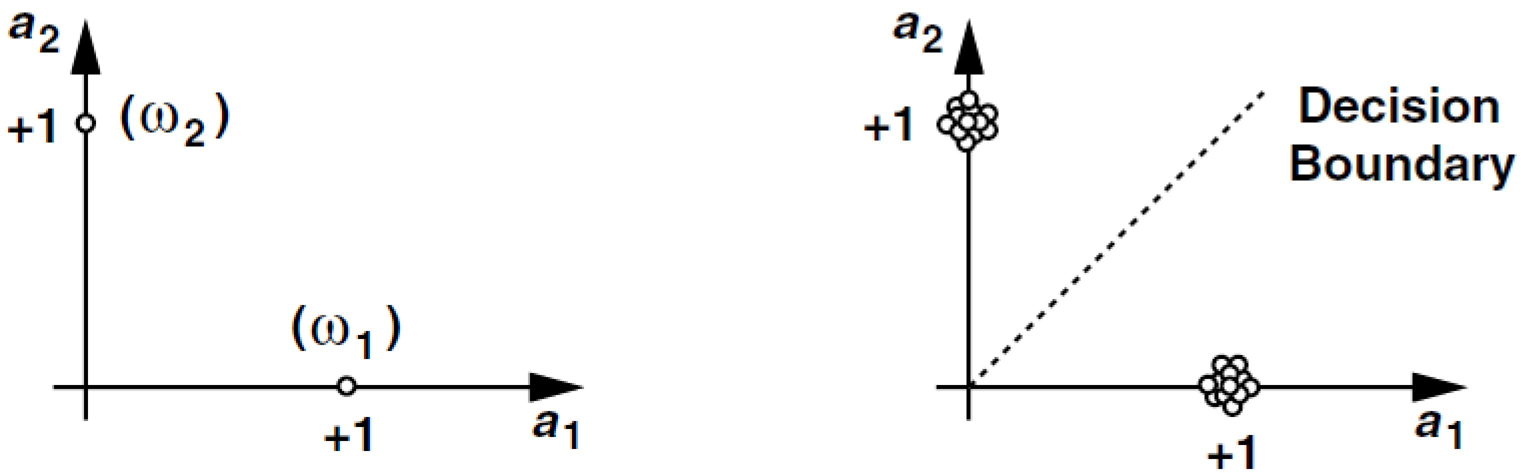


[B. Razavi, RF Microelectronics]

Signal Constellations

❑we consider an FSK signal, which can be expressed as

$$x_{FSK}(t) = a_1 \cos \omega_1 t + a_2 \cos \omega_2 t \qquad a_1 a_2 = 10 \text{ or } 01$$

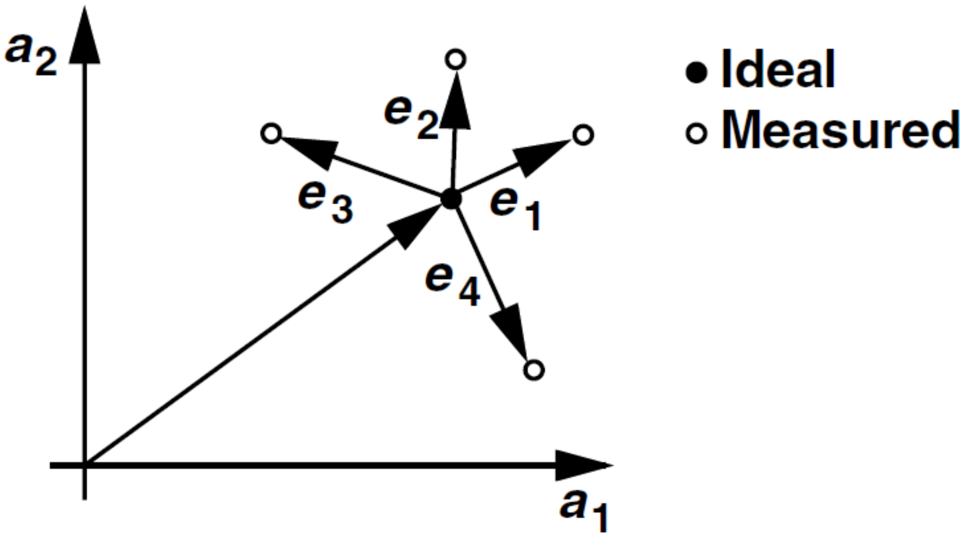


❑PSK signals are less susceptible to noise than are FSK signals because their constellation points are farther from each other. This type of insight makes constellations a useful tool in analyzing RF systems.

[B. Razavi, RF Microelectronics]

Error Vector Magnitude (EVM)

❑The EVM represents the deviation of the constellation points from their ideal positions



$$\mathrm{EVM} = \frac{1}{P_{avg}} \cdot \frac{1}{N} \sum_{j=1}^{N} e_j^2$$

❑Effects such as noise, nonlinearity, and ISI readily manifest themselves in EVM.

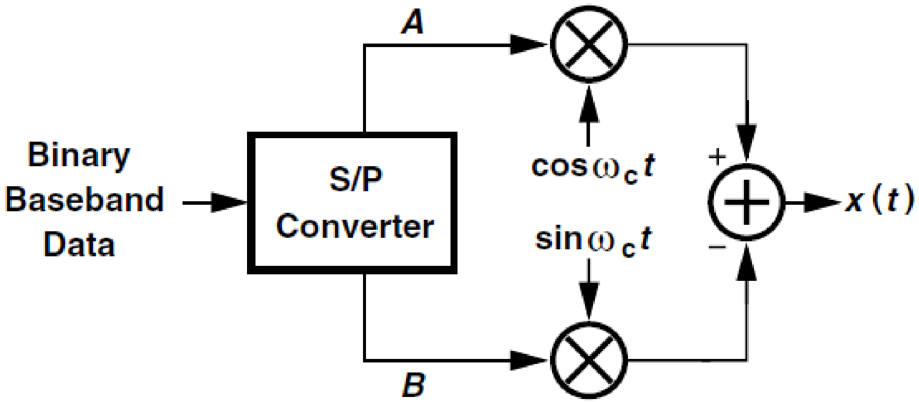
❑For transmitter design, EVM measurement is usually a MUST!

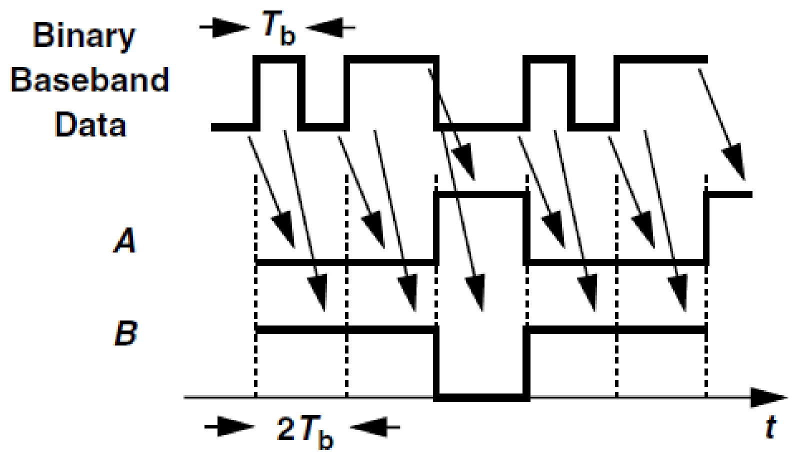
[B. Razavi, RF Microelectronics]

QPSK

- Binary PSK signals with square baseband pulses of width T_b seconds occupy a total bandwidth quite wider than $2/T_b$ hertz. In order to further reduce the bandwidth, “quadrature PSK” (QPSK) modulation can be performed.

$$x(t) = b_{2m} A_c \cos \omega_c t - b_{2m+1} A_c \sin \omega_c t$$



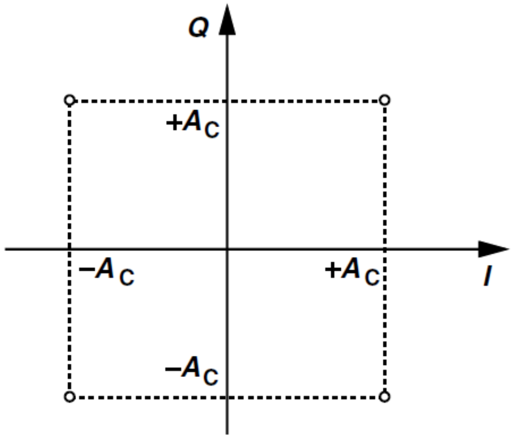


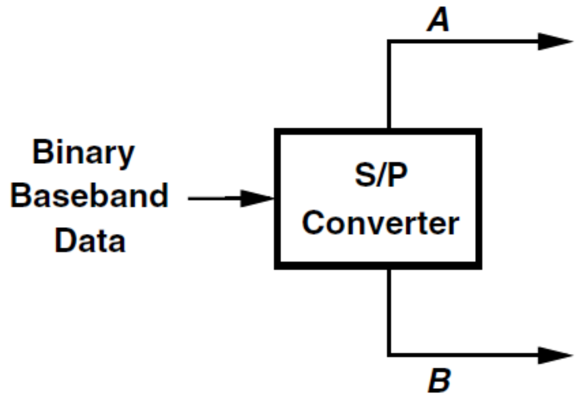
[B. Razavi, RF Microelectronics]

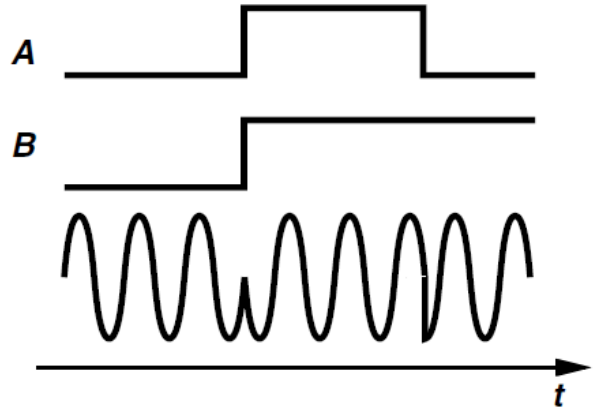
Offset-QPSK (OQPSK)

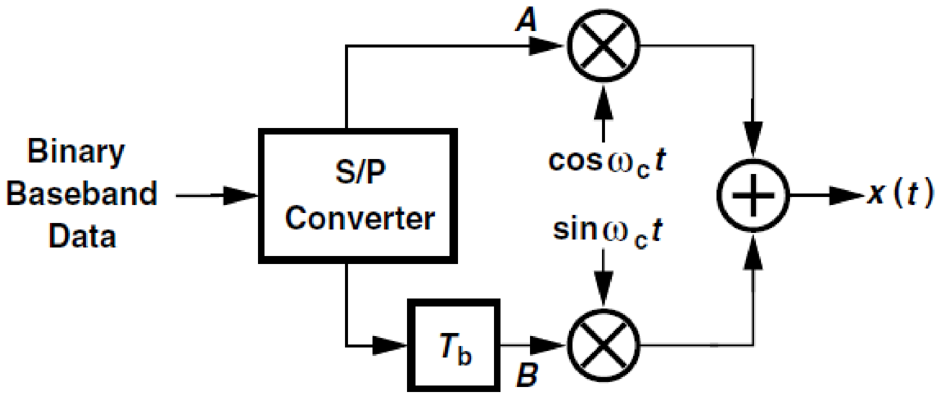
❑The QPSK constellation can be expressed by

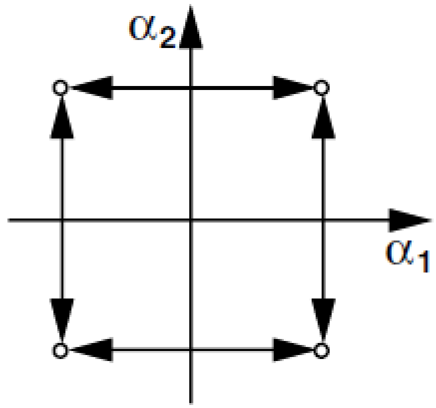
$$x(t) = \alpha_1 A_c \cos \omega_c t + \alpha_2 A_c \sin \omega_c t.$$







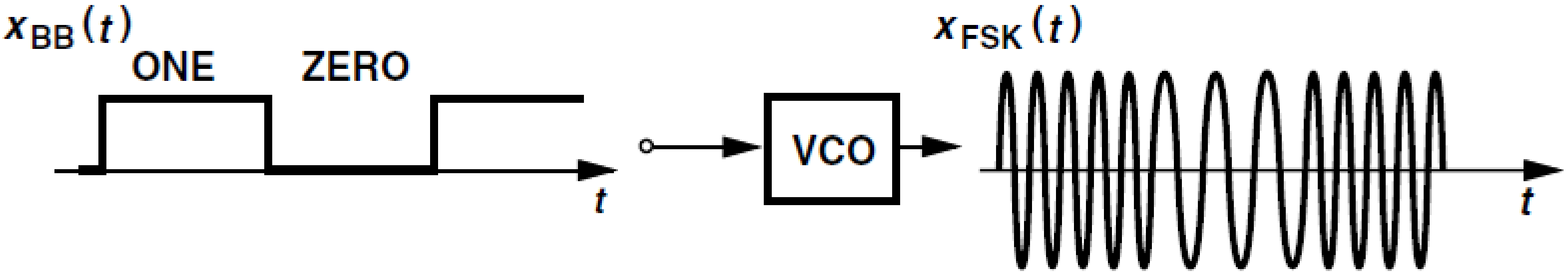


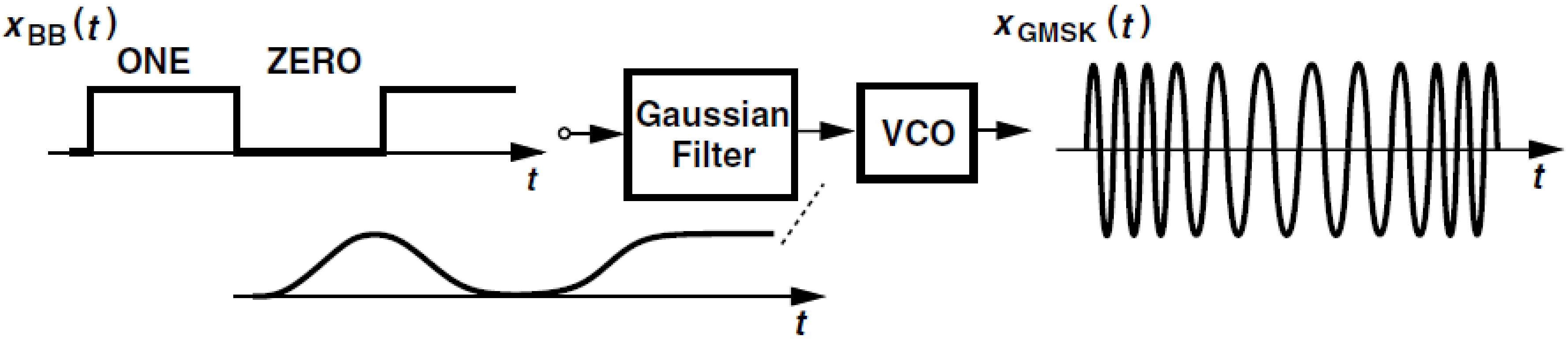


[B. Razavi, RF Microelectronics]

GMSK

❑To achieve a narrower spectrum, Gaussian filter is a common Method to shape the spectrum.





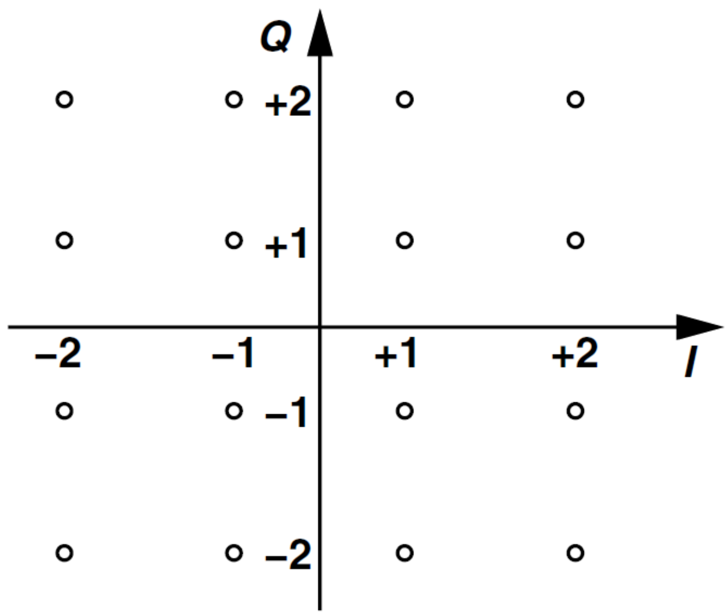
GMSK: Index=0.5 GFSK: Index=0.3

[B. Razavi, RF Microelectronics]

16QAM

❑Suppose we allow four possible amplitudes for the sine and cosine waveforms, e.g., ±1 and ±2, thus obtaining 16 possible output waveforms.

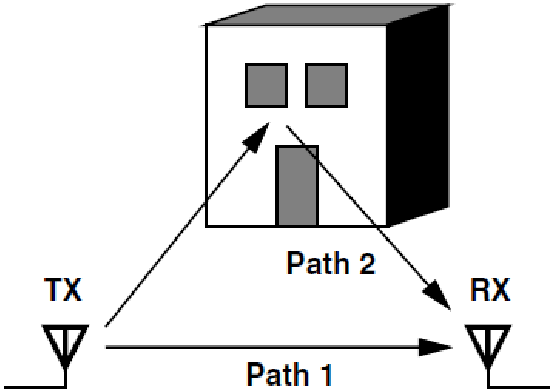
$$x_{16QAM}(t) = \alpha_1 A_c \cos\omega_c t - \alpha_2 A_c \sin\omega_c t \quad \alpha_1 = \pm 1, \pm 2,\ \alpha_2 = \pm 1, \pm 2$$

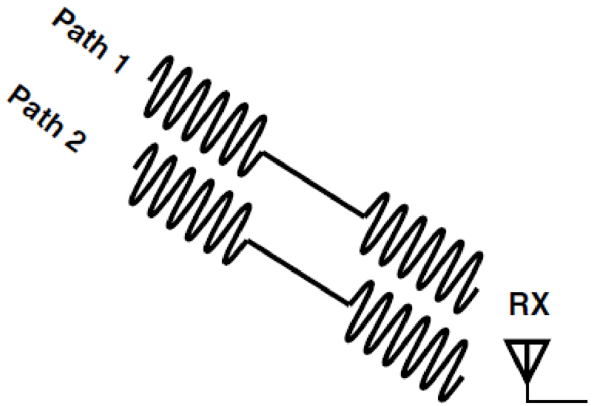


[B. Razavi, RF Microelectronics]

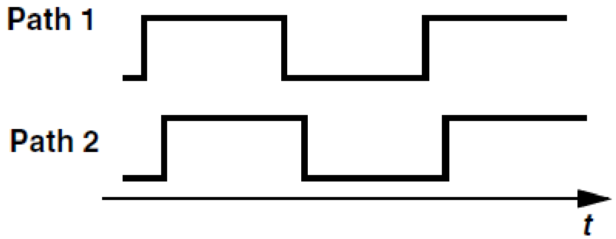
Multi-Path Propagation

❑The waves arrive at the RX with vastly different delays, leading to considerable intersymbol interference (ISI).





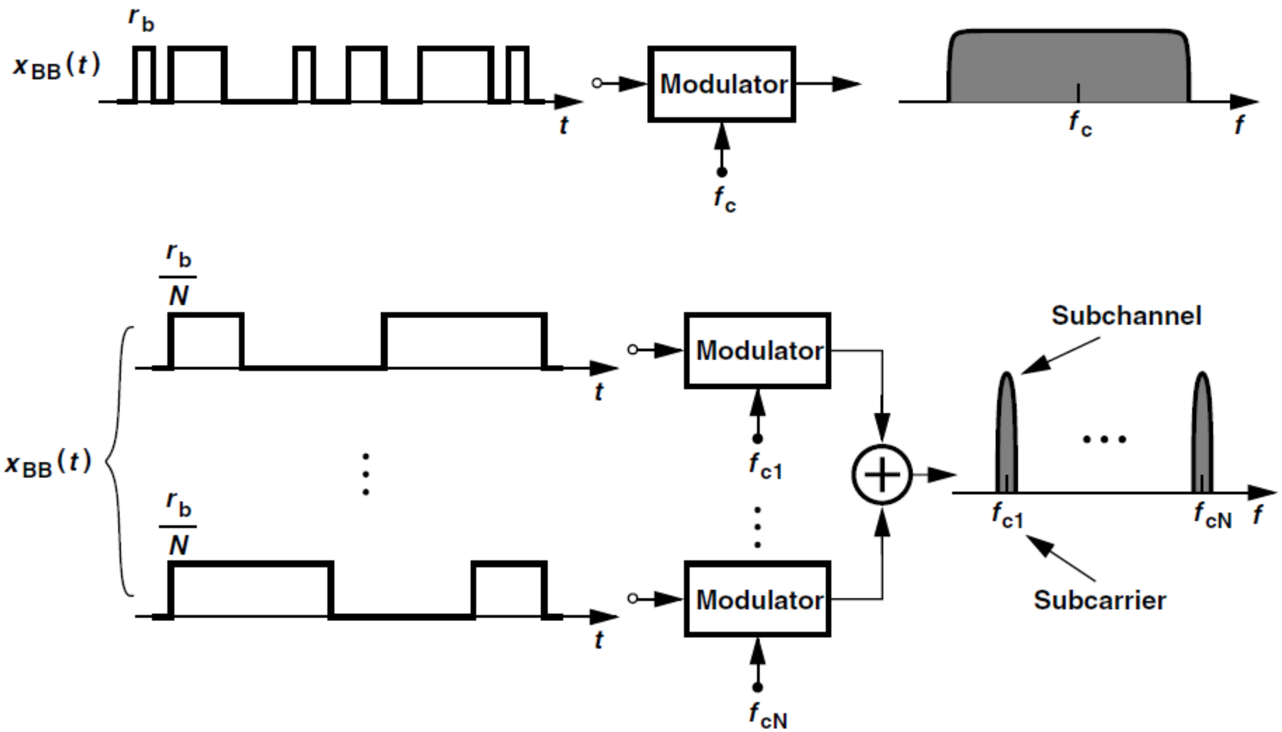
❑The communication inside office buildings and homes begins to suffer from multipath effects for data rates greater than 10 Mb/s.



[Ali Niknejad, EE142&EE242 of UC Berkeley]

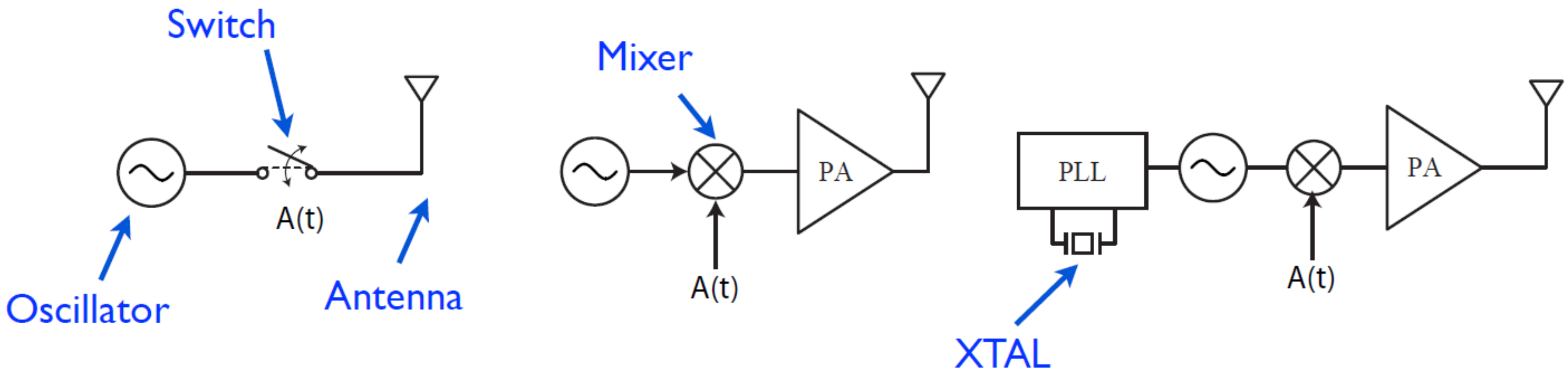
OFDM

❑In OFDM, the baseband data is first demultiplexed by a factor of N, producing N streams each having (symbol) rate of r_b/N, which are then impressed on N different carrier frequencies.



[B. Razavi, RF Microelectronics]

Simple AM Transmitters



❑Need an oscillator (carrier frequency) and a mechanism to vary amplitude of a sinusoidal signal (a multiplier works)

❑For digital OOK, this seems trivial (MOS switch for instance), but there are important issues (such as feedthrough, matching, loss).

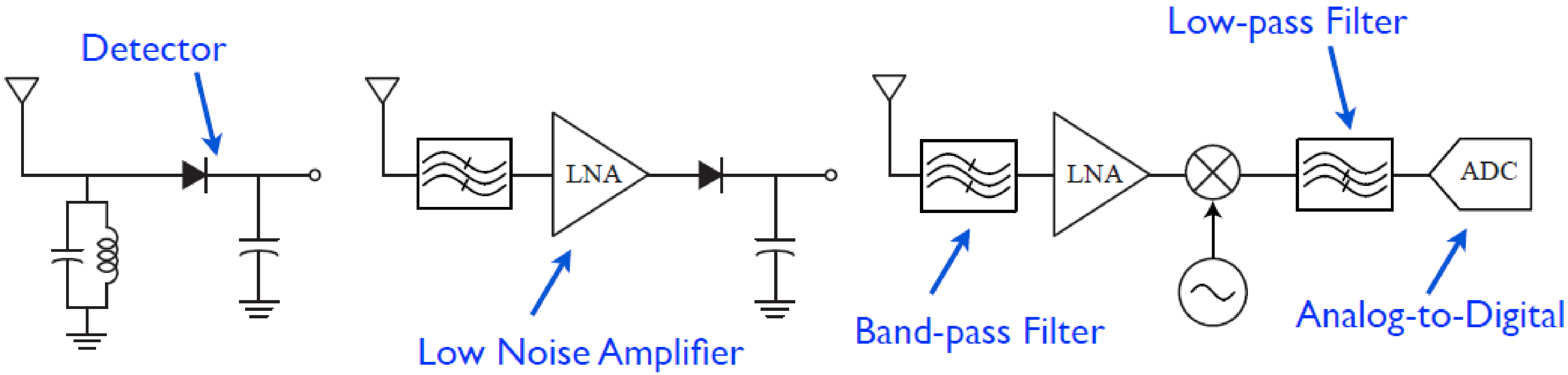
❑A multiplier, or "mixer", can also accomplish this task by multiplying the amplitude signal with a carrier signal.

❑For long range transmission, a Power Amplifier (PA) is needed to boost the signal power.

❑In order to provide a stable and precise frequency, a crystal (XTAL) resonator is used in a phased-locked loop.

[Ali Niknejad, EE142&EE242 of UC Berkeley]

Simple AM Receivers



❑A filter is used to “tune” the receiver to the desired band. An amplifier is usually needed since the signal is too weak to be detected.

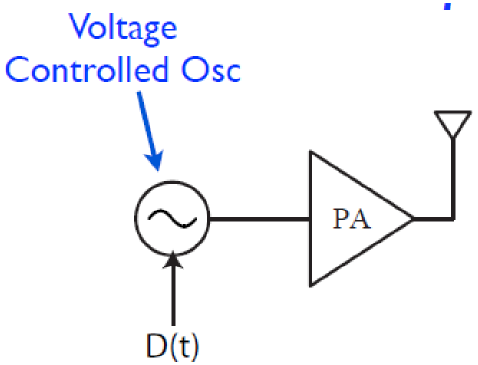
❑Detection occurs in analog or digital domain (an analog-to-digital “ADC” converter is needed).

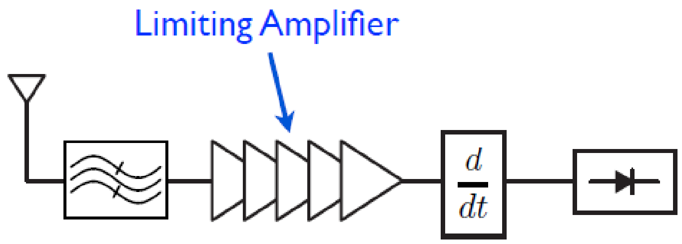
❑A mixer can be used to ``down-convert” the signal or to directly demodulate the signal:

$$A(t)\cos(\omega_0 t) \times \cos(\omega_0) = A(t)\cos^2(\omega_0 t) = A(t)\frac{1}{2}\left(1 + \cos(2\omega_0 t)\right)$$

[Ali Niknejad, EE142&EE242 of UC Berkeley]

Simple FM Transmitter/Receiver





$$\frac{d}{dt}\left(A_0 \cos(\omega_0 t + \phi(t))\right) = -A_0 \sin(\omega_0 t + \phi(t))\left(\omega_0 + \frac{d\phi}{dt}\right)$$

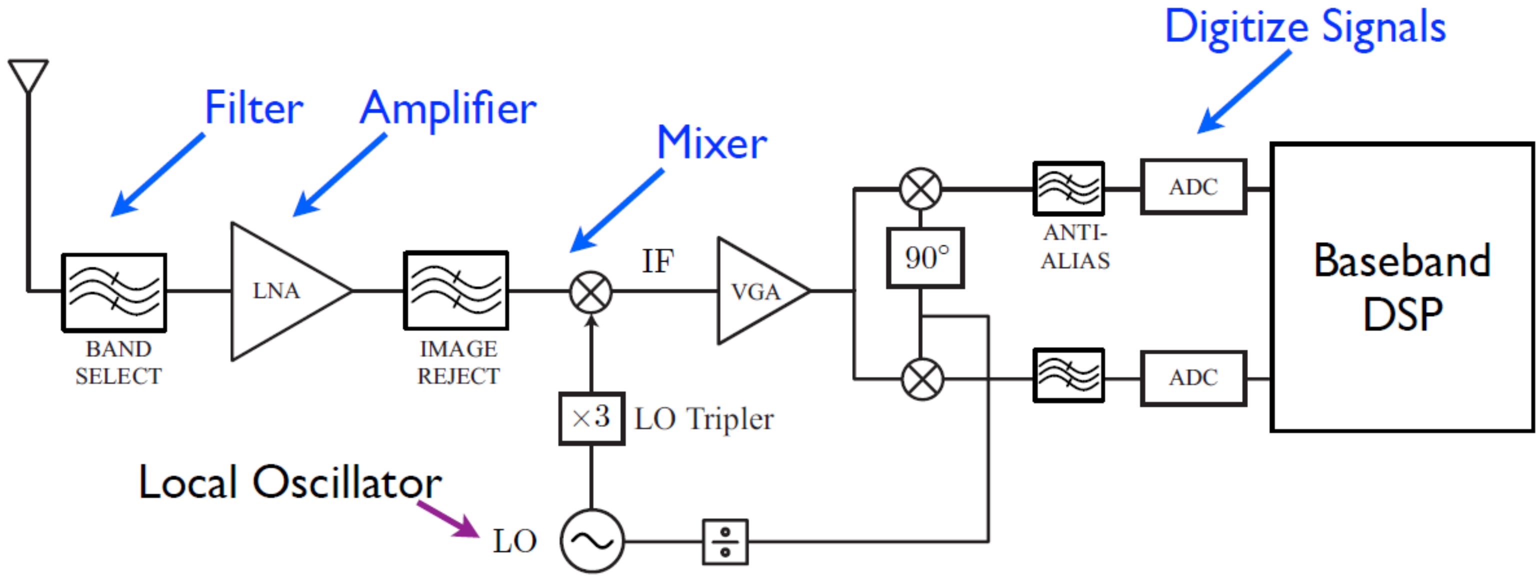
- **Tuning of an oscillator can perform the FSK task**

- **A differentiator converts "FM" into "AM". In a narrowband of frequencies, a circuit with a linear frequency response (the skirt of an LC tank) can be used to perform this task**

- **A Limiting Amplifier can be used to remove any residual AM before conversion**

[Ali Niknejad, EE142&EE242 of UC Berkeley]

A Modern Receiver

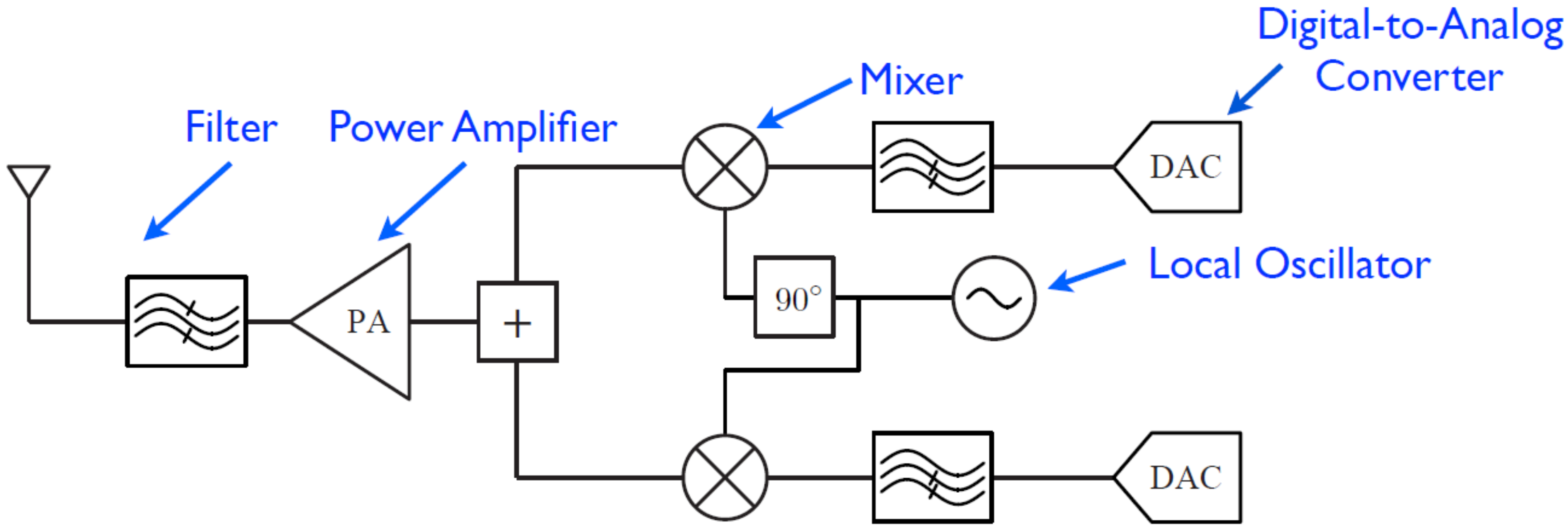


❑This is a generic super-heterodyne receiver. There are several important active and passive blocks in this system. Passive blocks include the antenna, switches, and filters. Active building blocks include:

- **LNA: Low noise amplifier**
- **LO: "Local" Oscillator**
- **VGA: Variable Gain Amplifier (or PGA for programmable gain amplifier)**
- **ADC: Analog to Digital Converter**
- **DSP: Digital Signal Processor**

[Ali Niknejad, EE142&EE242 of UC Berkeley]

A Superheterodyne Transmitter



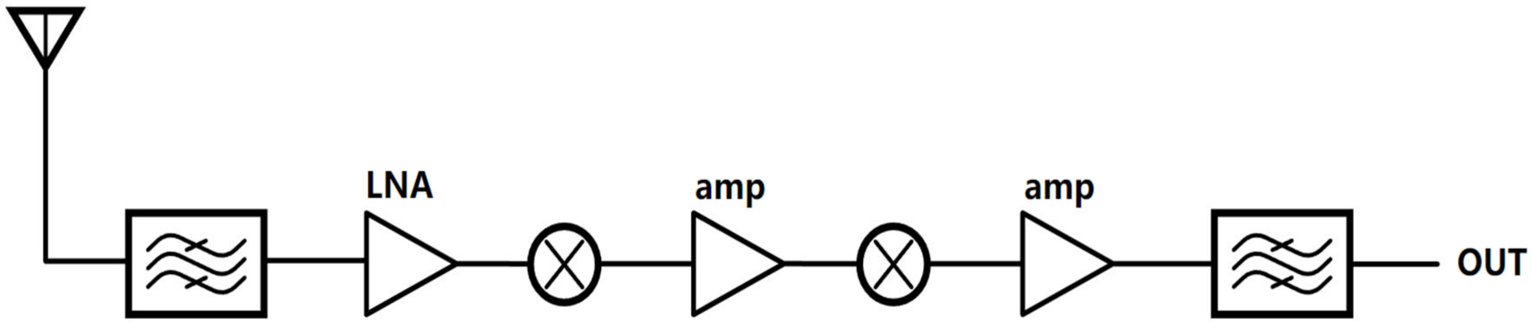
❑This is a generic heterodyne transmitter. In addition to passive antenna (often shared with receiver through a switch or duplexer) and filters, we have the following important active building blocks:

➢ DAC: Digital to Analog Converter
➢ Mixer: Up-conversion mixer
➢ VGA: To select desired output power (not shown)
➢ LO: Local Oscillator (Generated by a frequency synthesizer)
➢ PA: Power Amplifier

[Ali Niknejad, EE142&EE242 of UC Berkeley]

Project (30 Points)

Using ADS software to build a receiver link in the frequency of 2.4 GHz band, and the system block diagram is shown below:



Finish the calculation and simulation of the Power, Noise Figure, Gain, Output Power and Sensitivity

An electronic project report should be finished in English

(More details will be given on the website)

[Ali Niknejad, EE142&EE242 of UC Berkeley]