Integrated Circuits for Communication

EECS 142/242A
Course Overview
Spring 2025

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# *Course Logistics*

- Instructor: Ali Niknejad (niknejad@berkeley.edu)

- Graduate Student Instructors:
  - Hesham Beshary (discussion)
  - Kunmo Kim (lab)
  - Yahia Ibrahim (lab)

- Course websites:
  - bCourses – HW posting and submission, video links
  - Ed– for students to learn from each other, monitored by instructors on a daily (not hourly) basis

- No office hours in the first week

Textbook

- There is no required textbook for the course. Course notes and a working PDF textbook for the course are in development and a git repo will be shared with students (feedback and corrections welcome!). The following references may also be useful:

  - *Electromagnetics for High-Speed Analog and Digital Communication Circuits*, Ali Niknejad, Cambridge University Press, 2007.

  - *RF Microelectronics*, 2nd Edition, Behzad Razavi. Pearson Education, Inc., 2012. This is a very complete reference and is a great resource for the course.
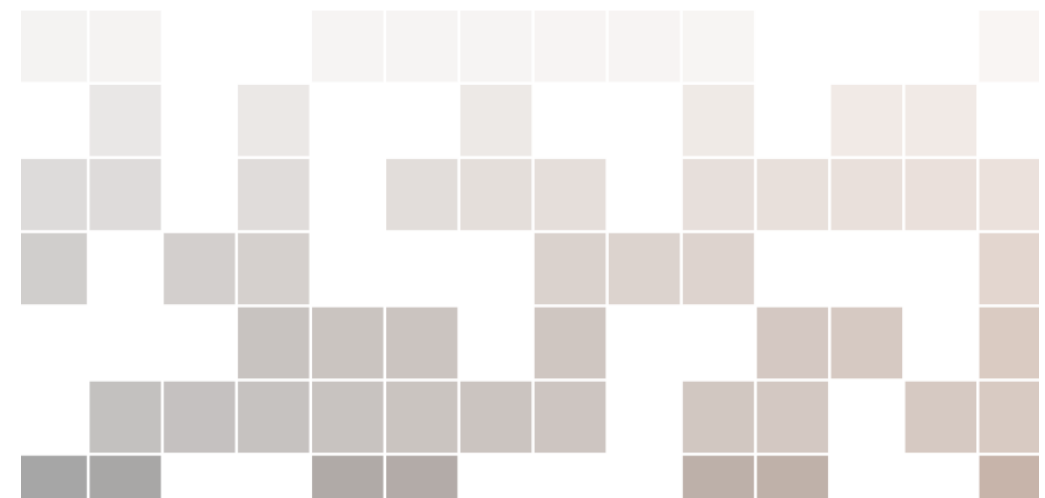
RF Book In Development

- Direct mirror of course notes

- Work in development, use at your own risk !

- Look on bCourses for latest copy. I'll try to update it on a weekly basis.

- Please do not share or post on a public site since I plan to publish it in the near future.
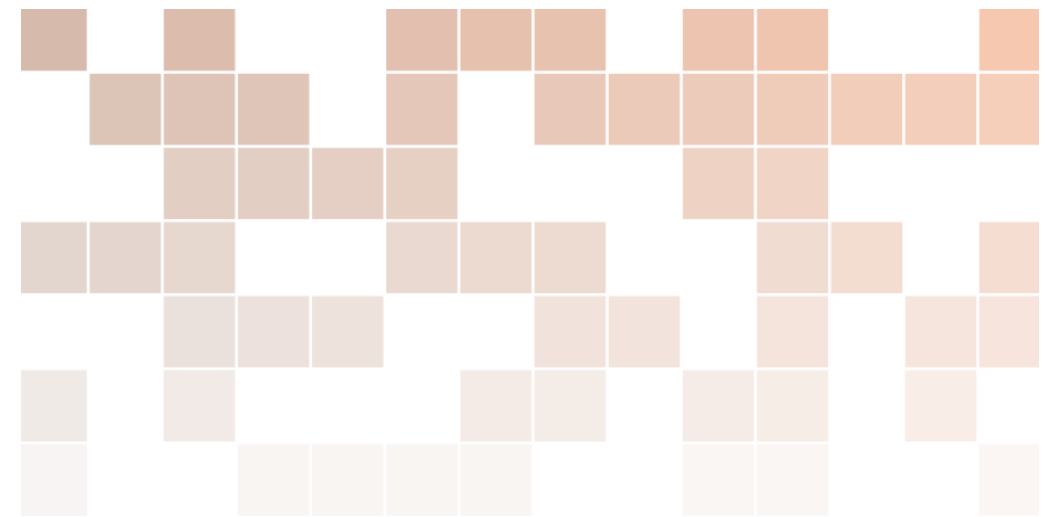
Communication Circuits

RF, Microwaves, mm-Waves, THz, and Beyond

Ali M. Niknejad

Prerequisites

- Students directly from 105 to boost interest in radio frequency circuit techniques
  - 105 students will definitely have a few extra challenges since they will not be familiar with all topics. Such topics and problems will be marked as optional and only assigned to 242A student.

- 140: Very helpful background, especially differential amplifiers, feedback, and stability.

- 120: More familiarity with signals and systems but everything you need is covered in 16AB, 105

- (Frequency Domain and Transfer Functions, Bode)

Course Logistics

- Grading policy:

	142	242A
HW	25%	25%
Midterm	25%	25%
Lab	25%	25%
Final	25%	25%

- Exams: No clobbering

- Graduate and undergraduates on a different scale

- Late homeworks get 50% of credit if turned in before solutions are posted. 25% after solutions posted. These are applied on top of the grade.

Homeworks

- Weekly (mostly) homework assignments

- Extra problems for 242A students

- Easier warmup problems for everyone to get familiar with material followed by more challenging problems

- Main tool – Keysight Pathwaves Advanced Design System (ADS), Cadence SpectreRF

- First HW / labs – Overview of tools, equipment, safety

- Discussion section on ADS tutorial

- Submission - bCourses

Labs

- All students are required to complete several hands-on laboratory assignments:
  - Do pre-lab and background reading before attending lab
  - Pre-lab invovles doing some calculations and simulations

- Labs are designed to reinforce abstract concepts from class with real world examples

- You will design and build your own filters, amplifiers, mixers, and oscillators using SMT (surface mount tech) components on a PCB

- The first few labs will take much longer … don't despair!

Course Modules

- 1: Introduction & Review

- 2: Transmission Lines & Smith Chart

- 3: Amplifier Design

- 4: Distortion

- 5: Noise

- 6: Mixers

- 7: Oscillators & Frequency Synthesis

- 8: Power Amplifiers and Transmitters
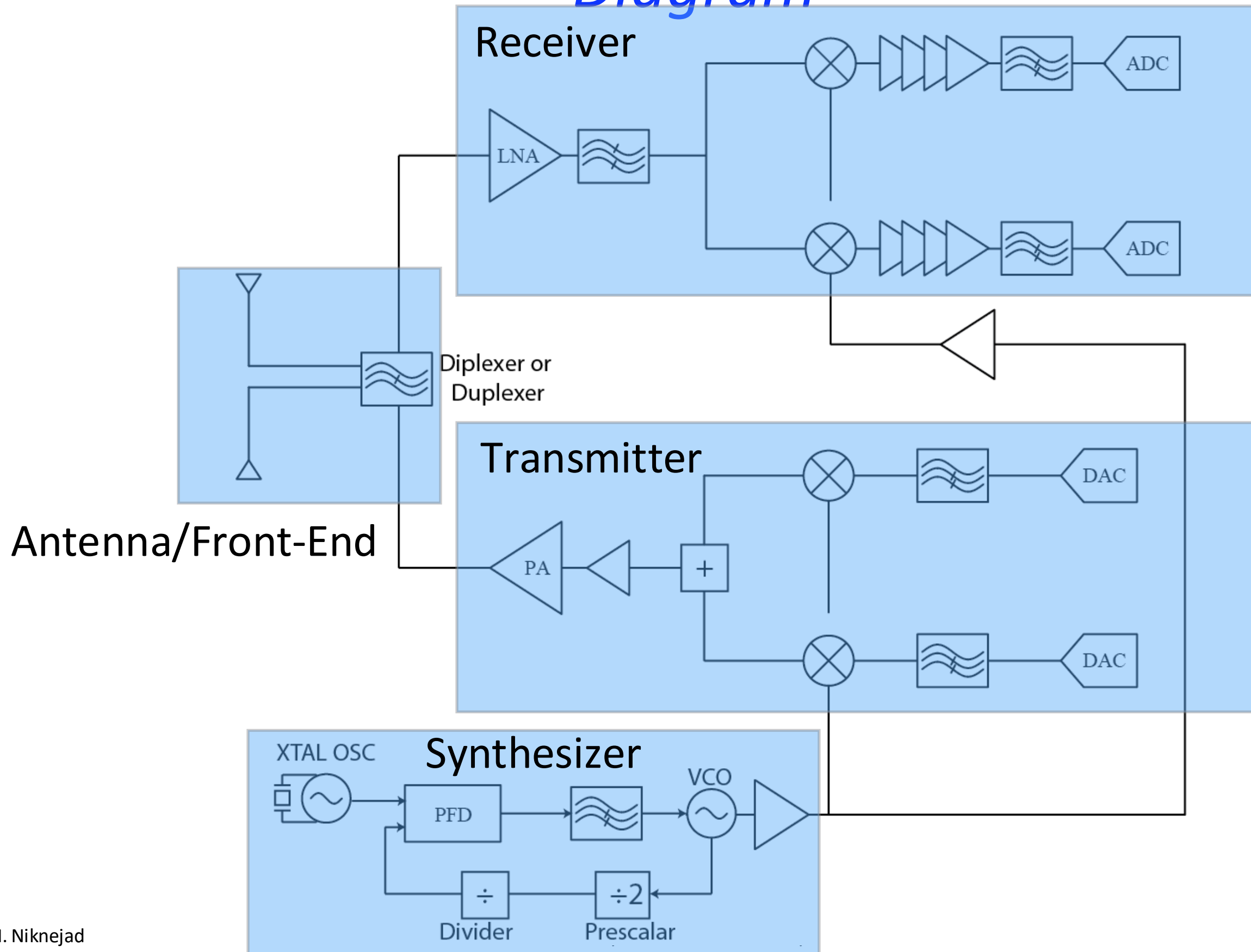
Course Prerequisites

- Basic knowledge of devices (FETs, BJT), I-V relations, C-V relations

- [review] Small signal models and key parameters (gain, bandwidth, relation to fT) **[fT not covered in 105]**

- Linear analog circuits (single and multi-stage amplifiers, differential amplifiers, feedback) **[differential not covered in 105]**

- Linear systems (impulse response function, frequency domain, Fourier series and ~~transforms, Laplace transforms~~)

- Optional: Probability and stochastic processes (noise and noise transfer functions).

Applications

- RF transceivers for wireless communication

  - WiFi, Bluetooth, 3G/4G/5G, satellite communication, etc.

- High speed data communication

  - High speed links, clock and data recovery, equalization of channel

  - Optical communication front-ends

- Radar and Sensors

  - Autonomous driving, automatic cruise control

- Precision Instrumentation

- Medical Imaging

  - MRI receivers

- Radio Astronomy

  - Much of what we "see" is redshifted into the THz, mm-wave and RF spectrum (evidence of the big bang)

Module 1: Radio Transceiver Block Diagram

Receiver

ADC

ADC

LNA

Diplexer or Duplexer

Transmitter

PA

+

DAC

DAC

Antenna/Front-End

Synthesizer

XTAL OSC

PFD

VCO

÷ Divider

÷2 Prescalar

Module 2: Transmission Lines and Smith Chart

- Topics include the interface of high frequency blocks using transmission lines, interconnect, and filters.

- Transmission lines in both the time and frequency domain.

- Design of LC and transmission line circuits for impedance matching.

- The Smith Chart as a visualization aid.
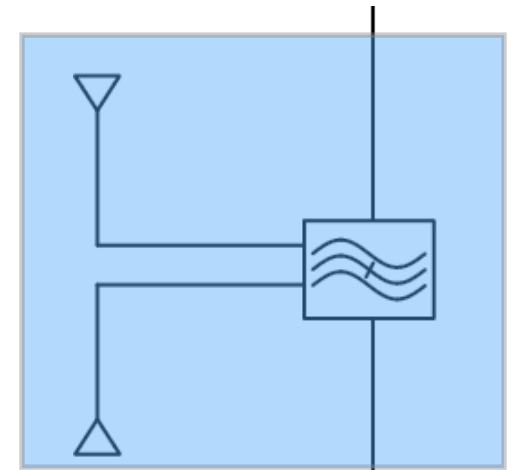
Antenna/Front-End

Module 3A: Wideband and High-Frequency Amplifiers

- Review of frequency response

  - Gain bandwidth product

  - Feedback amplifiers

- Applications:

  - Fiber optic front-end, Instrumentation, IF gain stages, UWB

- Tuned amplifiers and matching networks

  - Review of RLC networks and resonance, Tuned amplifiers, Matching networks, Capacitive and inductor transformers, Magnetic transformers

- Optimal amplifier design (maximum gain, stability, matching, *noise, linearity*)

- Technology: CMOS, BJT, SiGe HBT (MESFET, JFET)

Module 3B: (Power) Amplifier Design

- Output power capability

- Power gain, efficiency

- Different classes of operation

- "Linear" Amplifiers: Class A, B, C

- Switching mode amplifiers: Class D
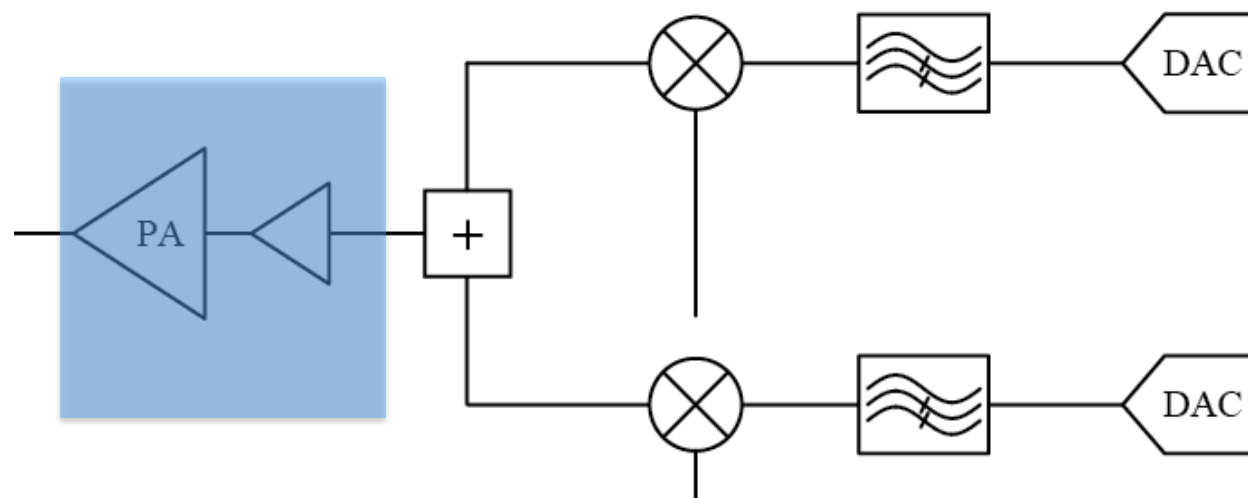
Module 4: Distortion in Circuits

- The transmitter spectrum is corrupted by distortion generated by active devices
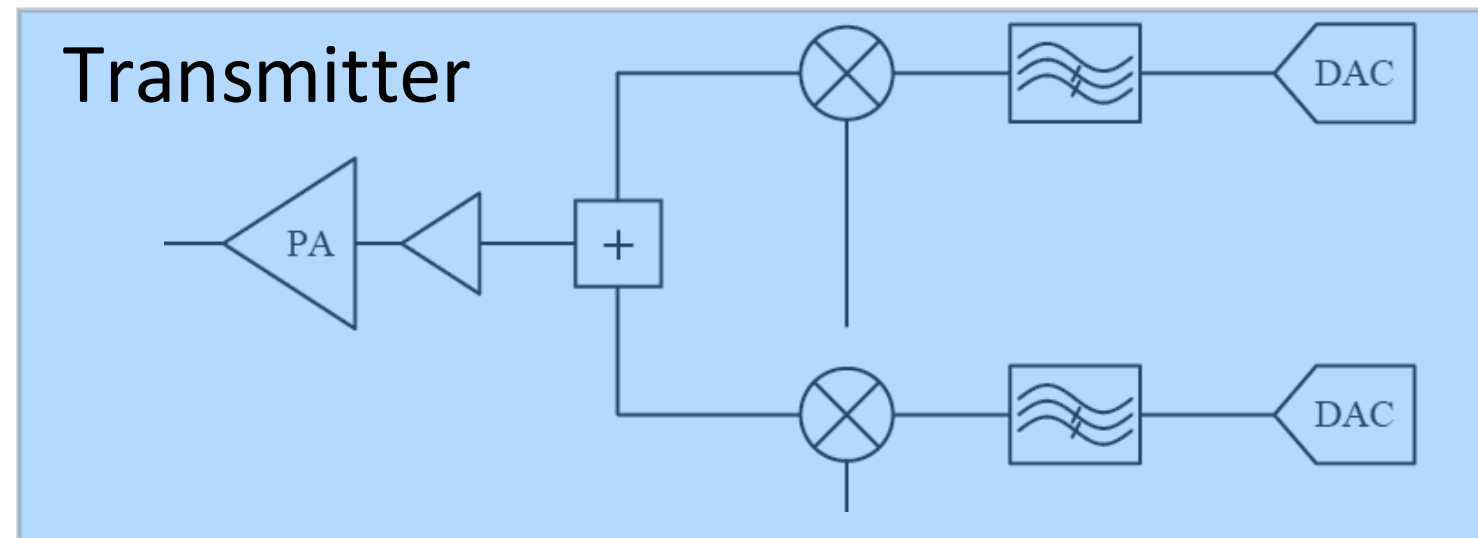
- Source of distortion in electronic circuits

- Device characteristics and large signal models

- Distortion reduction techniques

- Measurement of distortion (harmonic, inter-modulation, cross-modulation)

- Effect of feedback on distortion

- System distortion specifications

Module 5: Noise in Electronic Systems

- The performance of a receiver is fundamentally limited by the level of noise added to the signal

- Source of noise

- System Noise calculations

  - Input/output referred noise

  - Noise figure of an amplifier

  - Low noise amplifier design (LNA)

  - Noise figure of a cascade of amplifiers (or blocks)

  - Link budgets

- Applications:

  - LNA for receiver

  - Instrumentation

  - IF amplifiers

Receiver
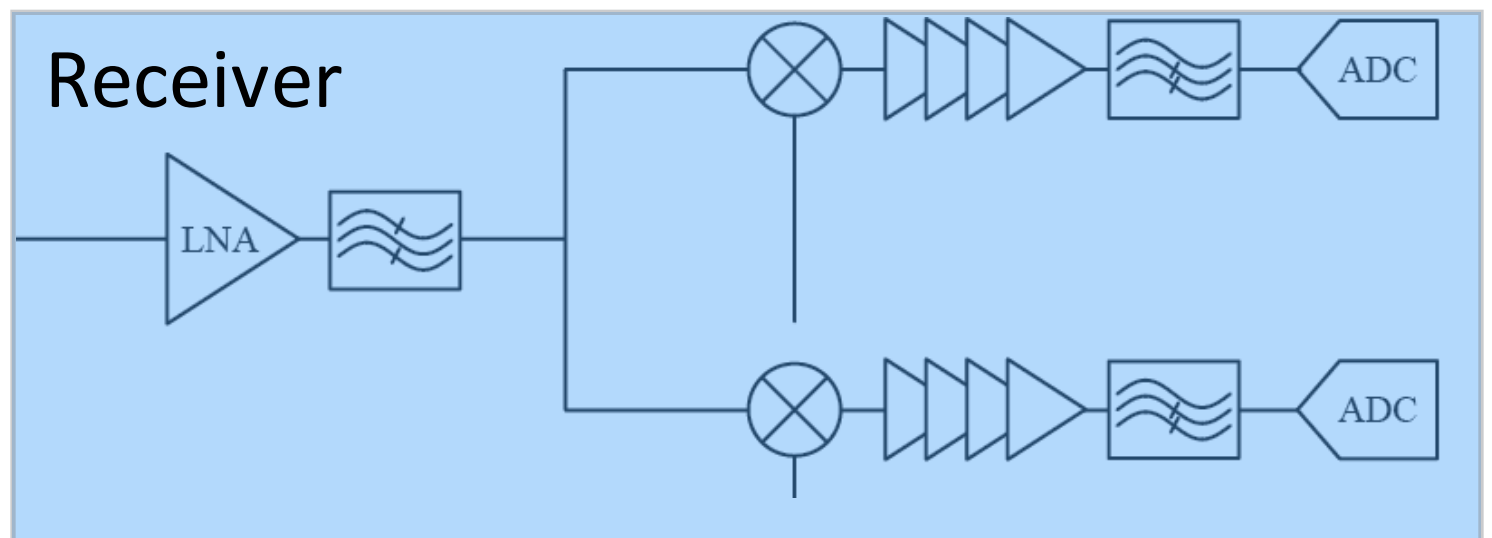
Module 6: Mixers and Commutating Circuits

- Frequency translation/conversion in LTV circuits

- Voltage-switching mixers

- Current commutating mixers

- Balanced mixers

- Conversion gain, terminal impedances

- System specifications and transceiver architectures

- Mixers are used to up-convert (Tx) and down-concern (Rx) and modulate the signal to/from the antenna.
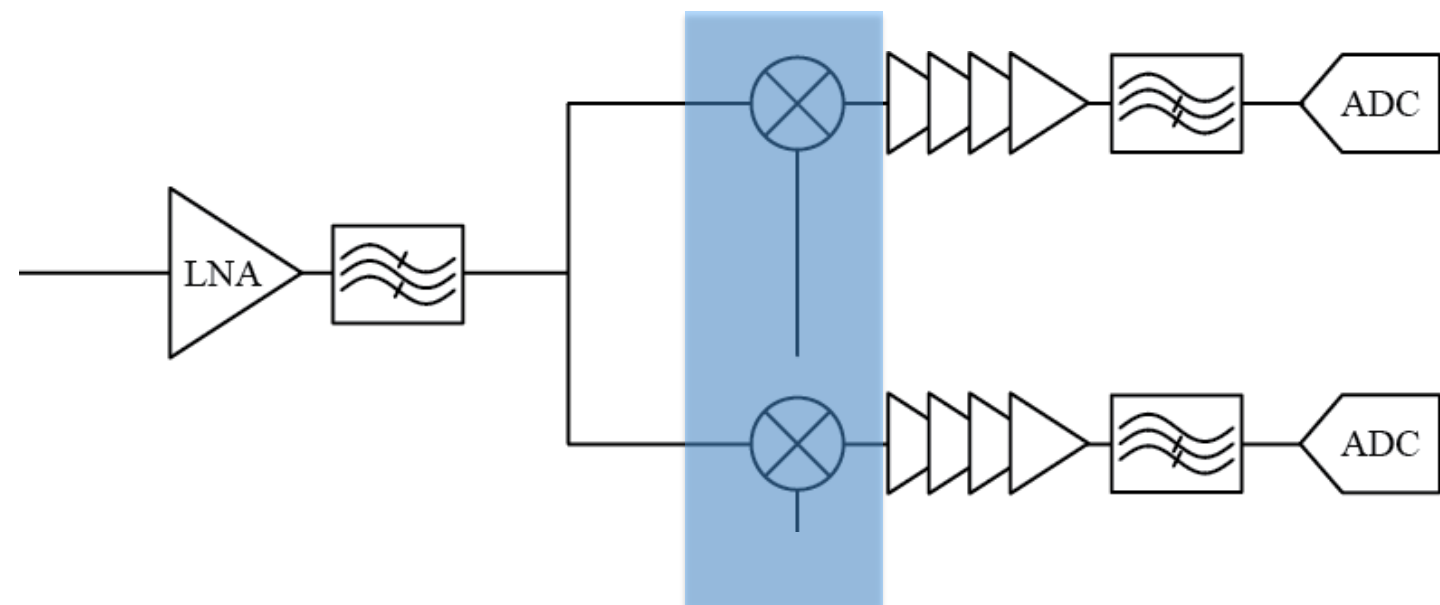
Module 7A: Autonomous Circuits: Oscillators

- Start-Up and Steady-State Analysis

- Amplitude and frequency stability

- Concept of negative resistance

- Oscillator topologies (Colpitts, Hartley, Clapp, Cross-coupled,...)

- Waveform distortion

- Ring and relaxation oscillators

- Voltage Controlled Oscillators (VCOs)

- Introduction to Frequency Synthesis (PLLs)
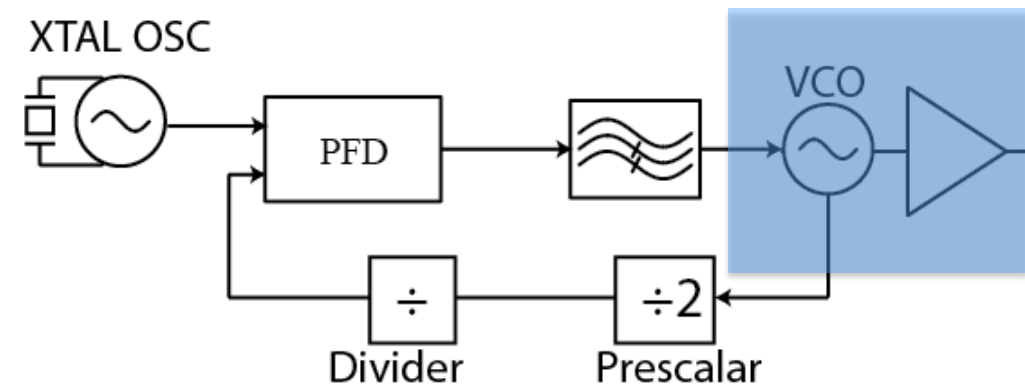
Module 7B: Frequency Synthesis

- Since carrier frequencies are used for RF modulation, a transmitter and receiver need to synthesize a precise and stable reference frequency. Since the reference frequency changes based on which "channel" is employed, the synthesizer must be tunable. Think of the tuning "knob" on an radio receiver.

- The reference signal is generated by a voltage-controlled oscillator (VCO) and "locked" to a much more stable reference signal, usually provided by a precision quartz crystal resonator (XTAL).

- A phase-locked loop (PLL) synthesizer is a feedback system employed to provide the locking and tuning.
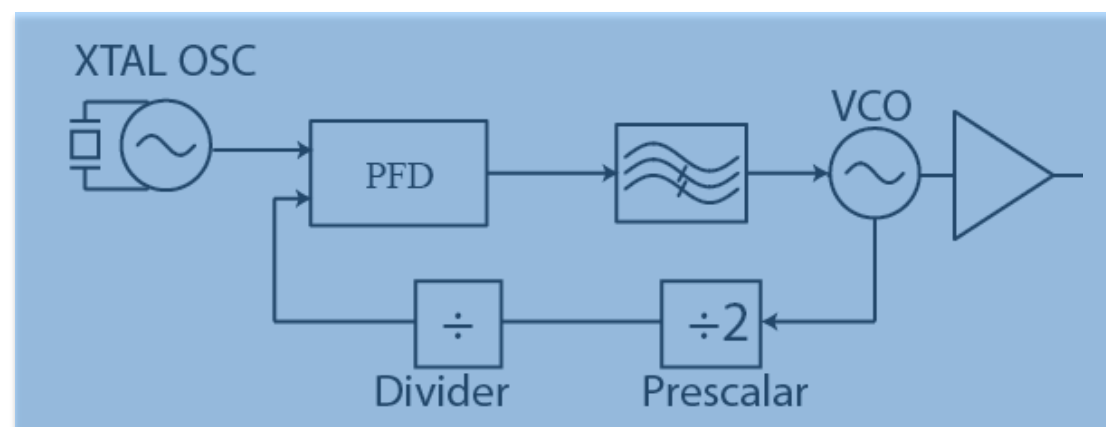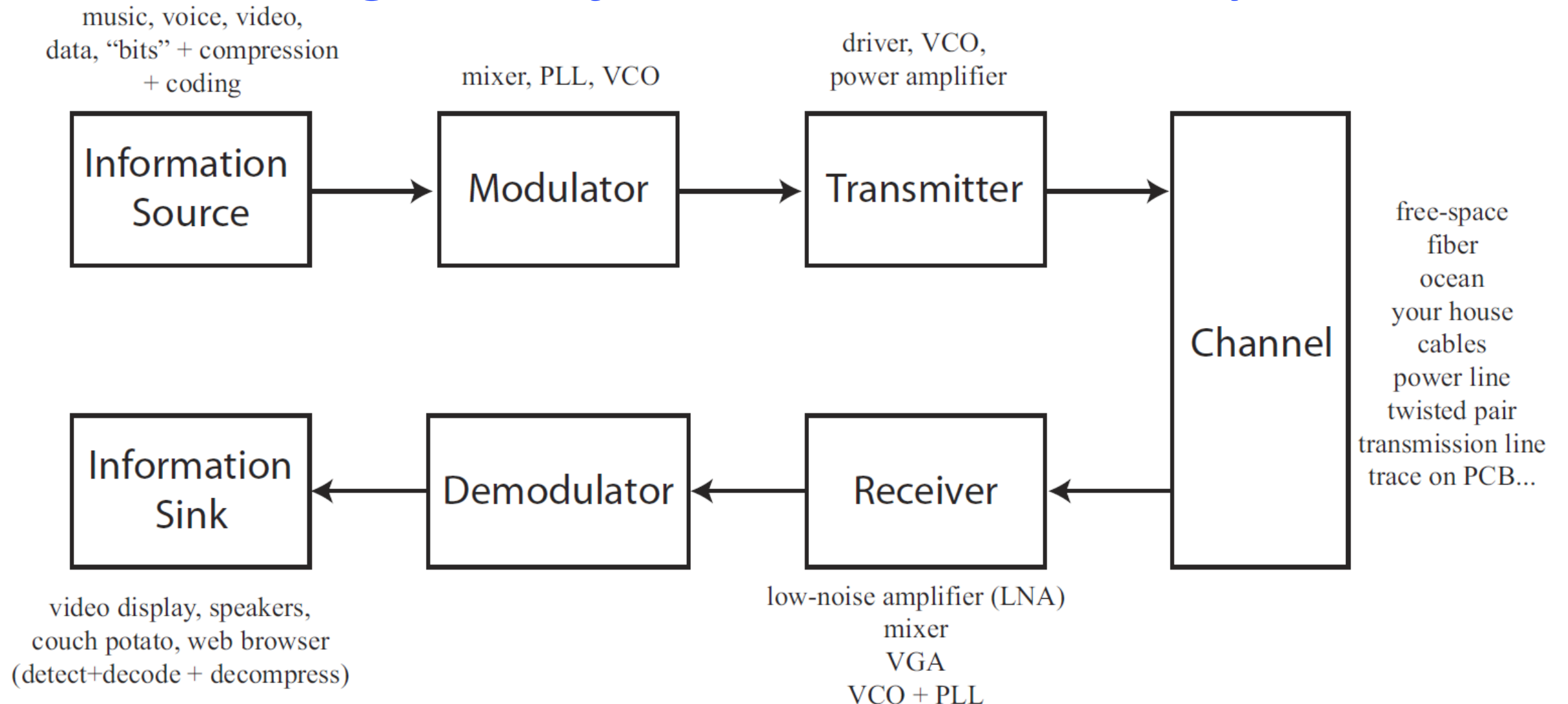
Overview of Communication Systems

# Block Diagram of Communication System

- A typical communication system can be partitioned into a transmitter, a channel, and a receiver.

- In this course we will study the circuits that interface from the channel to the receiver/transmitter. These circuits are at the "front-end'" of the transceiver and operate at high frequency.

Source Data

- Most information sources are baseband (BB) in nature, where we arbitrarily define the bandwidth BW as the highest frequency of interest. This usually means that beyond the BW the integrated energy is negligible compared to the energy in the bandwidth.

- The bandwidth of some common signals:

  - High fidelity audio: 20 kHz

  - Telephone: 5 kHz

  - Uncompressed analog video: $\sim$ 10 MHz

  - 802.11 b/g WLAN: 22 MHz   802.11 n/a/ax 20/40/80/160 MHz

  - HD Video (HDMI 1.3+) ~ 340 MHz

- The source is often compressed to conserve bandwidth. Lossless compression (LZW like Zip files) or lossy (like MP3, JPEG, or MPEG video) can be used depending on the application.

Data Communication (LAN)

Dispersionless
Propagation

Phase Dispersion
Propagation
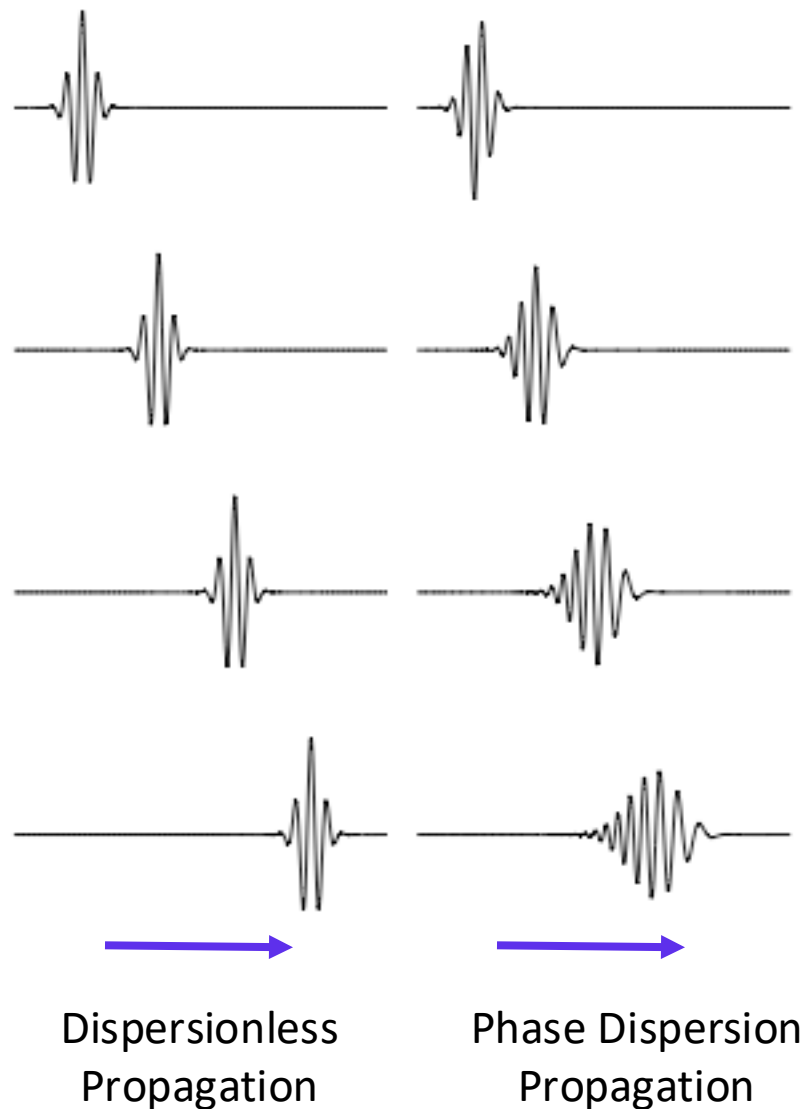
- When sending high speed data through a cable, we have to deal with several non-idealities:

  - Attenuation, Dispersion, Reflections → Inter Symbol Interference

- Attenuation is frequency dependent and causes dispersion, especially at higher frequencies. The phase response of the line is also not perfectly linear (constant group delay), and this causes more dispersion.

- Equalization is used at the source and receiver to compensate for the non-ideality of the line. But the "channel" has to be characterized first.

Wireless Propagation

- Wireless links use antennas to convert wave energy on a transmission line to free-space propagating waveform (377 ohms in free-space).

- Think of an antenna as a transducer with a given input impedance, efficiency, gain/directivity. The more gain, the more directive the antenna. Efficient antennas are ~ λ (free space propagation wavelength).
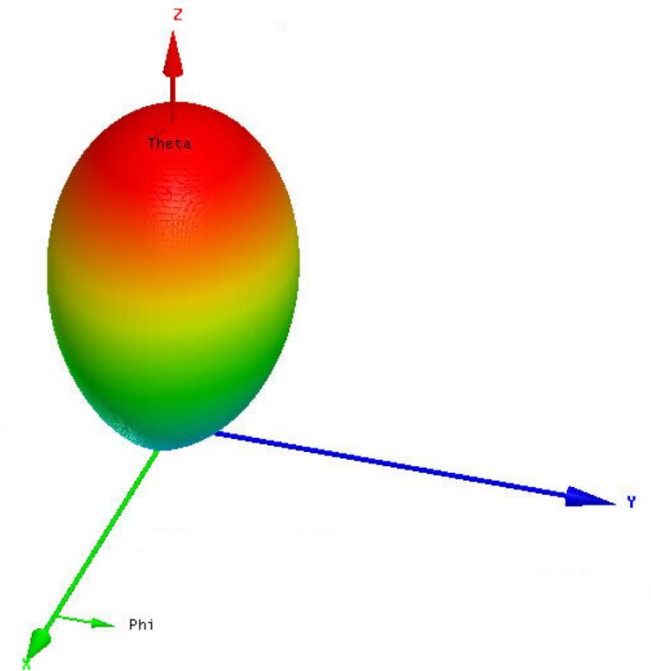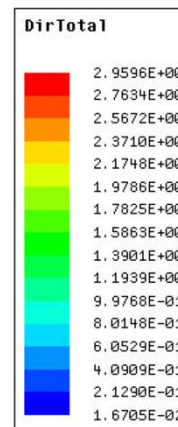
radiating fields

feed line

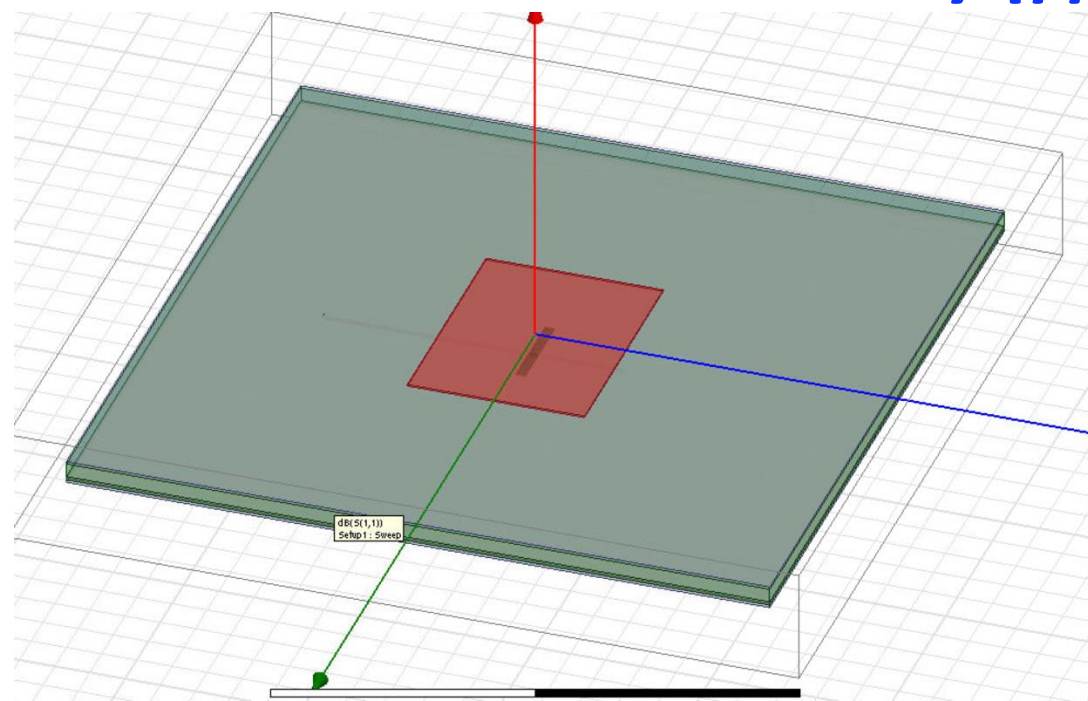G_{TX} G_{RX}

P_{TX} P_{RX}

R
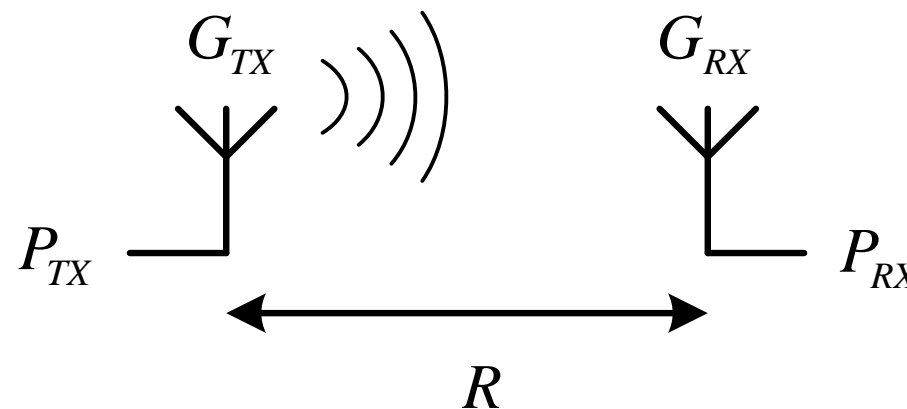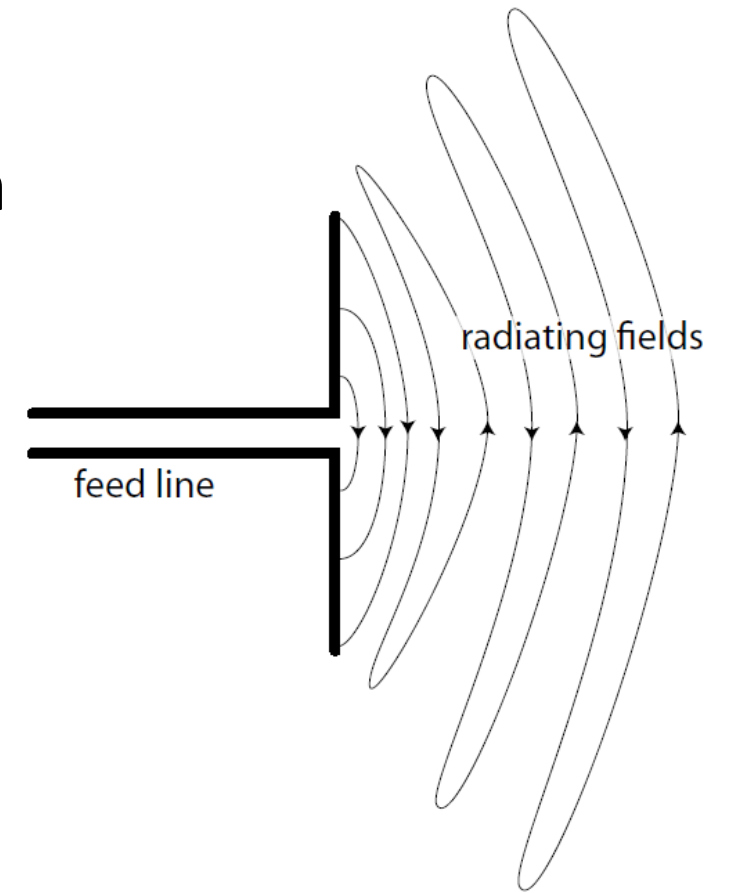
Friis transmission equation

$$P_{RX} = G_{TX} \frac{P_{TX}}{4\pi R^2} A_{eff,RX} = P_{TX} G_{TX} \left(\frac{\lambda}{4\pi R} \right)^2 G_{RX}$$

A – antenna aperture
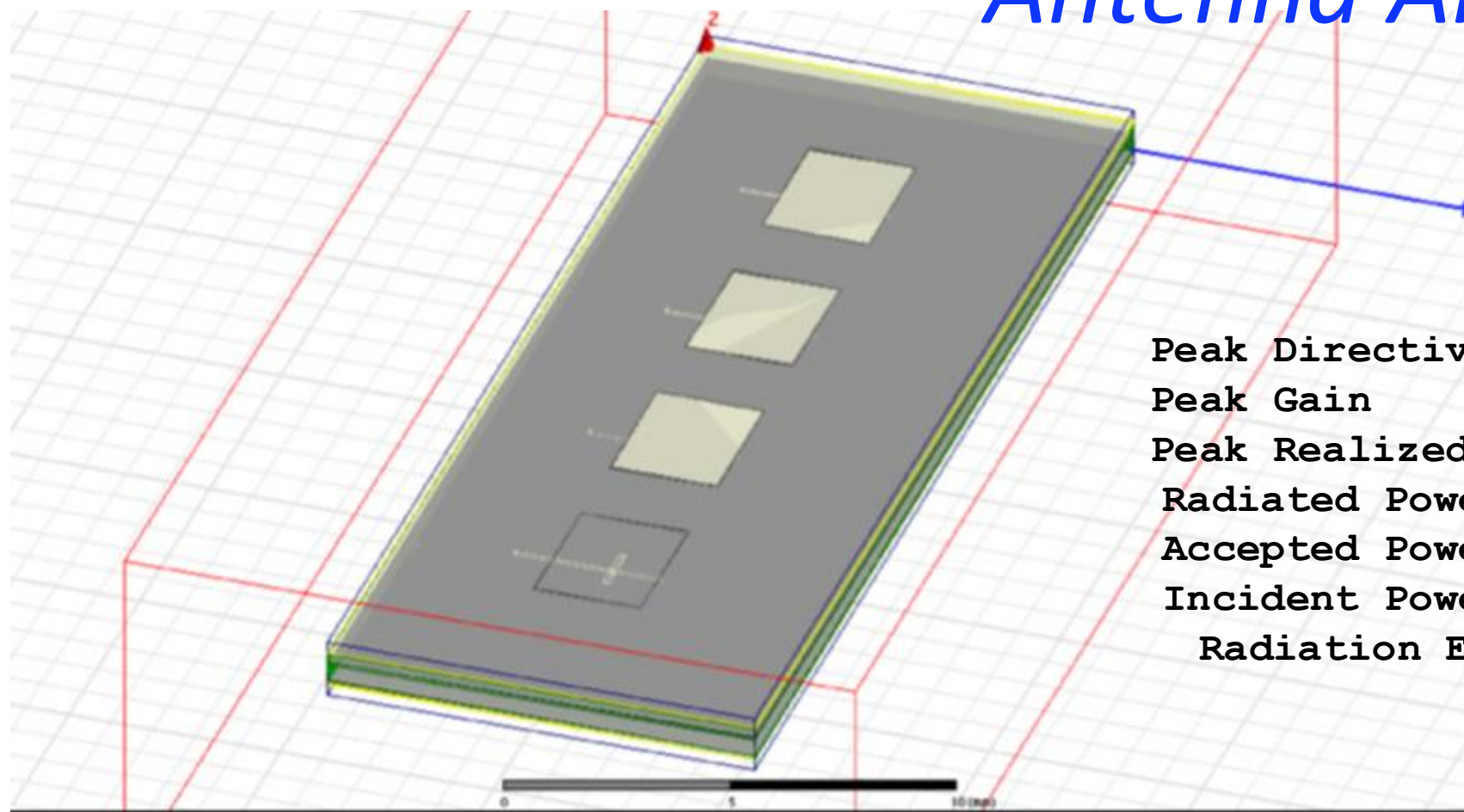G – antenna gain
η – radiation efficiency

$$G = \frac{4\pi A_{eff}}{\lambda^2} = \frac{4\pi \eta A_{phys}}{\lambda^2}$$

Antenna Gain

- Patch antenna is a resonator that radiates broadside

- It can be implemented on a planar surface, such as a PCB

- Note that it cannot radiate into PCB (due to ground plane), so it radiates up and has "gain" (more radiation up than omnidirectional antenna)

Antenna Array

Peak Directivity	16.1 dBi
Peak Gain	15.0 dBi
Peak Realized Gain	14.5 dBi
Radiated Power	35.9 mW
Accepted Power	38.7 mW
Incident Power	40.0 mW
Radiation Efficiency	93%

- An array of antennas have more gain since they power combine in space preferentially when the radiation is in phase.   If all driven with same power, they will radiate broadside in phase.

- Note even if we split input power by 4, there's net gain !

Radiation Patter (Fan)

- The radiation pattern of an individual element is "squeezed" in the direction of the array to provide more directional gain.

- By adjusting the phase of each element, we can move the solid angle of peak radiation
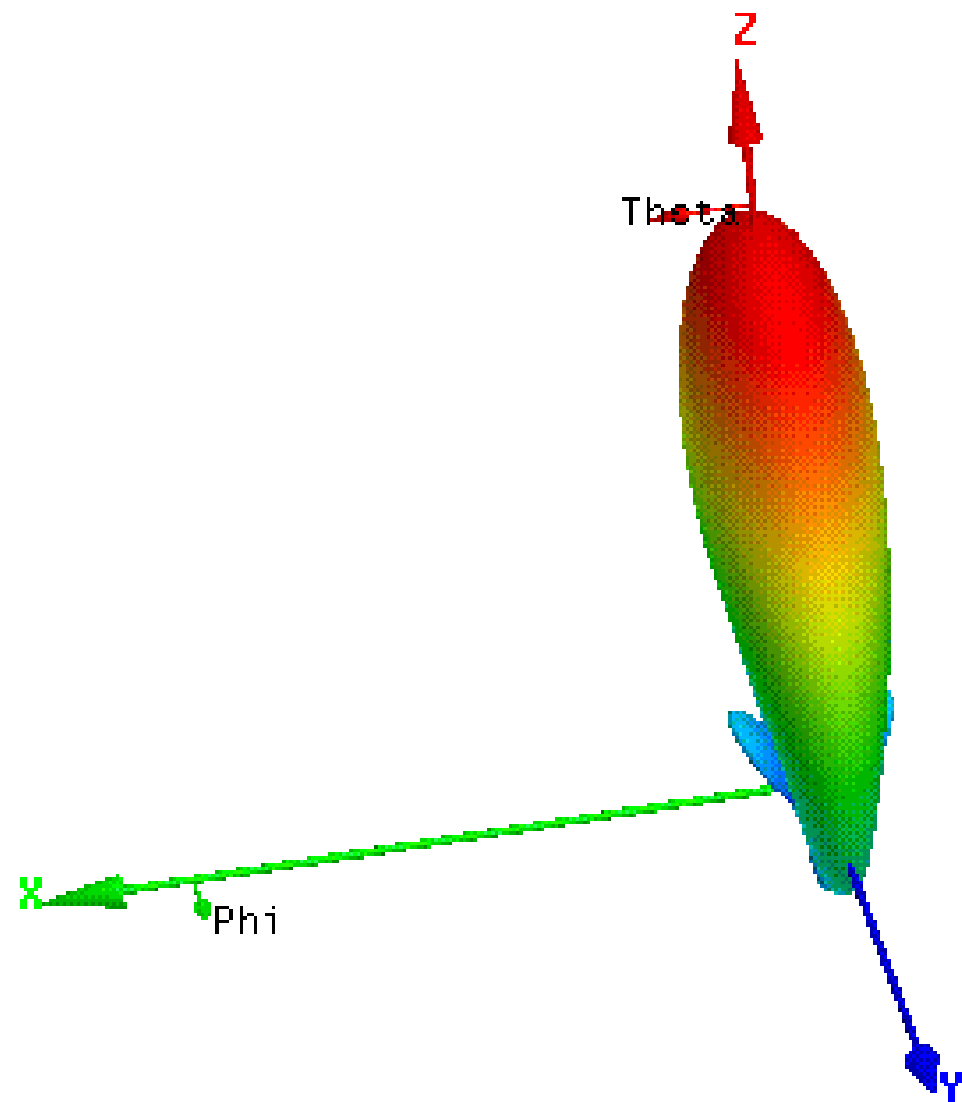
Spectrum Regulation

- Since efficient transmission and signal propagation requires an antenna with physical dimension of $\sim\lambda$ (wavelength), higher frequencies are favorable for portable applications. For instance, at 3GHz, the free-space wavelength is 10cm ($\lambda = c/f$)

  - Reason: Physically small antennas have small radiation resistance, which translates into low efficiency (since the physical resistance can be smaller or comparable to the radiation resistance)

- In the U.S., the FCC regulates spectrum usage [AM band ~ 1000 kHz, FM band ~ 100 MHz, UHF ~ 500 MHz, Cell phones 800 MHz - 1.9 GHz, WiFi 2.4 GHz (ISM band)]. Emerging bands: TV bands, 3-10 GHz UWB, 60 GHz.

  - Several new bands for 5G mm-wave radios include 24 GHz, 28 GHz, 39 GHz, and other bands (lots more spectrum)

- Typically each band is further divided into several channels so that spectrum can be shared. Channel spacing is set by the signal bandwidth.

- While spectrum was traditionally highly regulated and licensed, in the past two decades we have witnessed an explosion in wireless communication (cordless phones, Bluetooth, WiFi) using unlicensed bands (such as the ISM -- Industrial, Scientific, and Medical -- in the 900 MHz and 2.4/5 GHz)

Don't throw out the Baby with the bathwater!
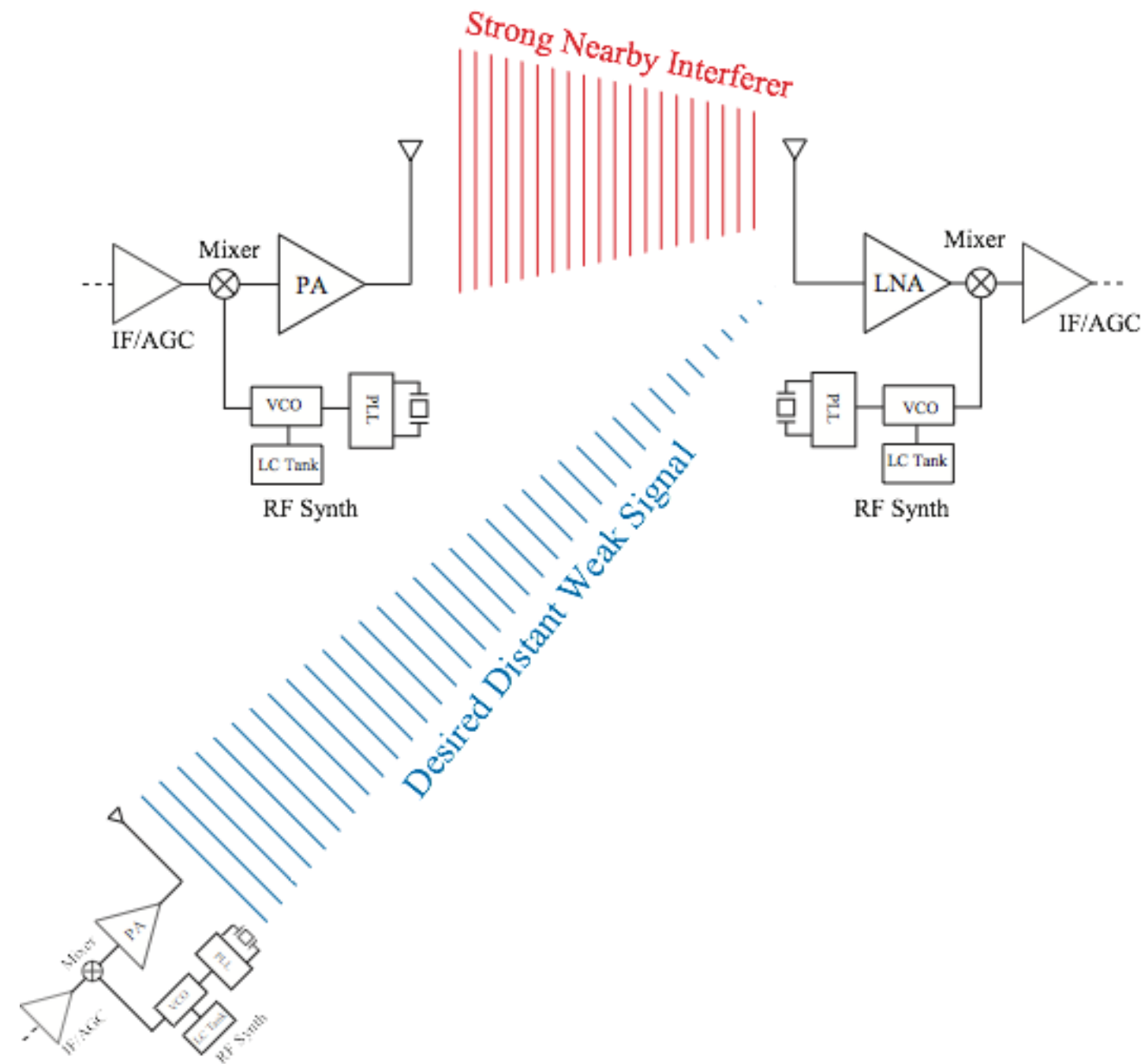
- Near/Far Problem: Nearby jammer makes it difficult to listen to a far away desired signal.

Interference

- In order to detect a signal in the presence of noise, the signal must meet a certain SNR (signal-noise-ratio) requirement. Typically this is ~10dB for many simple modulation schemes. For an analog signal, the ear/eyes can also tolerate a certain amount of noise (try it!).

- Note that the desired signal is often much weaker than other signals. In addition to out of band interfering signals, which can be easily filtered out, we also must contend with strong in-band interferers. These nearby signals are often other channels in the spectrum, or other users of the spectrum.

- The dynamic range of a wireless signal is VERY large, on the order of 80 dB. The signal strength varies a great deal as the user moves closer or further from a base-station (access point).

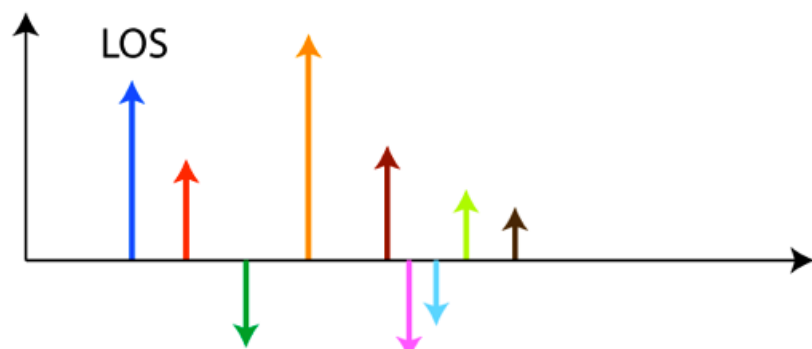- Due to multi-path propagation and shadowing, the signal strength varies in a time varying fashion.
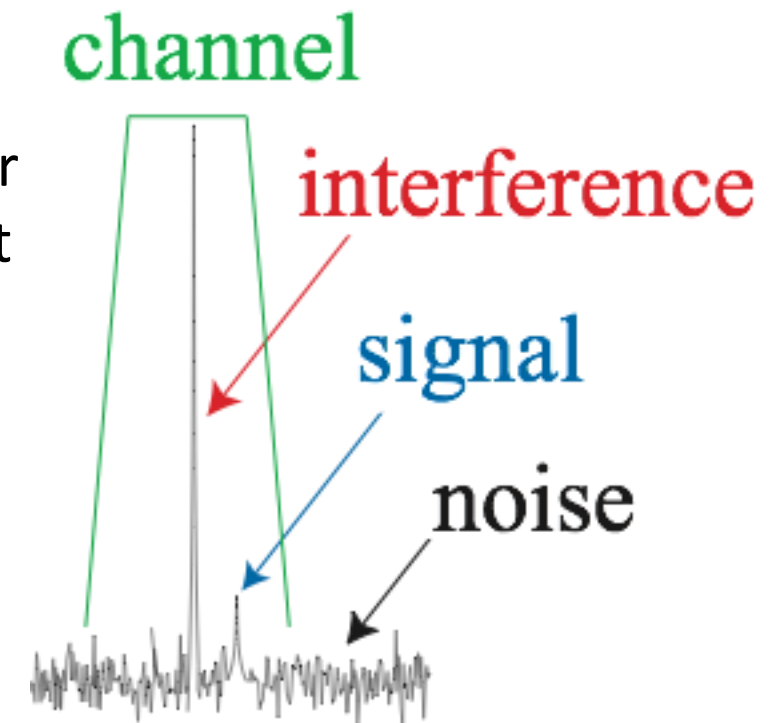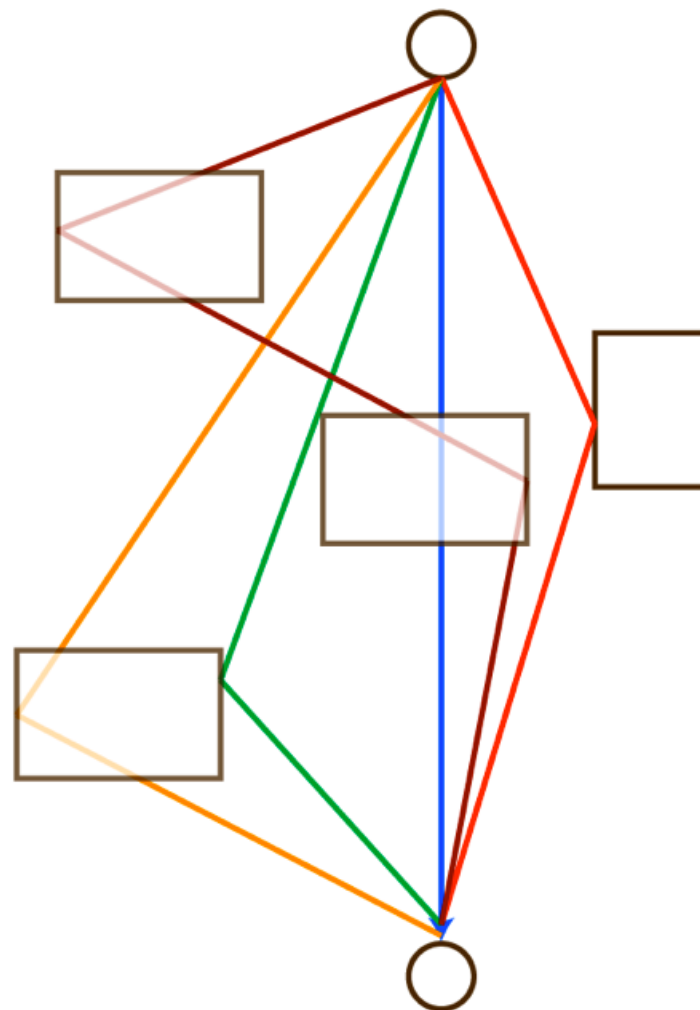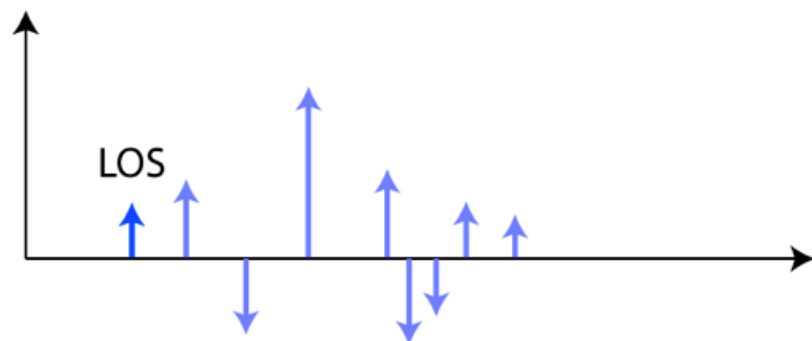
Multi-Path Propagation


No Multi-Path

With Multipath

Shadowed LOS Multipath

- In addition to contending with interfering signals and noise, wireless propagation is marred by multi-path propagation and fading

- There are multiple paths from source to destination (LOS and NLOS)

- The delay spread is a measure of the amount of time we must wait after the first RX signal to process most of the energy of the signal
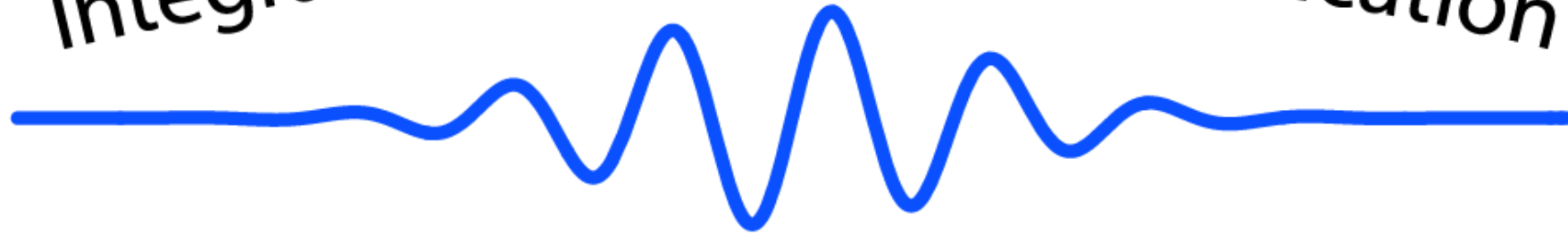
Transceiver Overview

Simple AM Transmitters (TX)
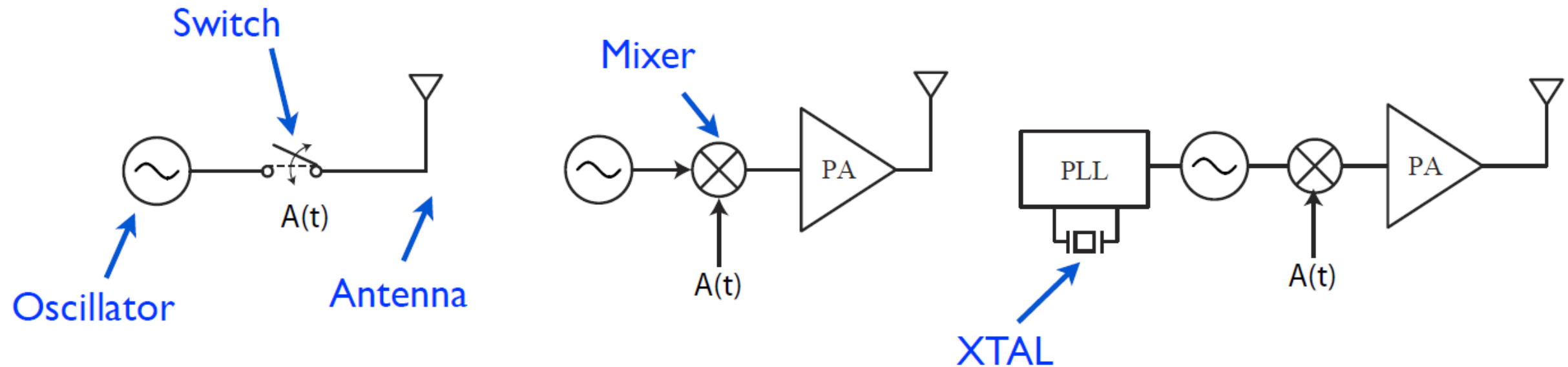
- Need an oscillator (carrier frequency) and a mechanism to vary amplitude of a sinusoidal signal (a multiplier works).

- 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.

Simple AM Receivers (RX)
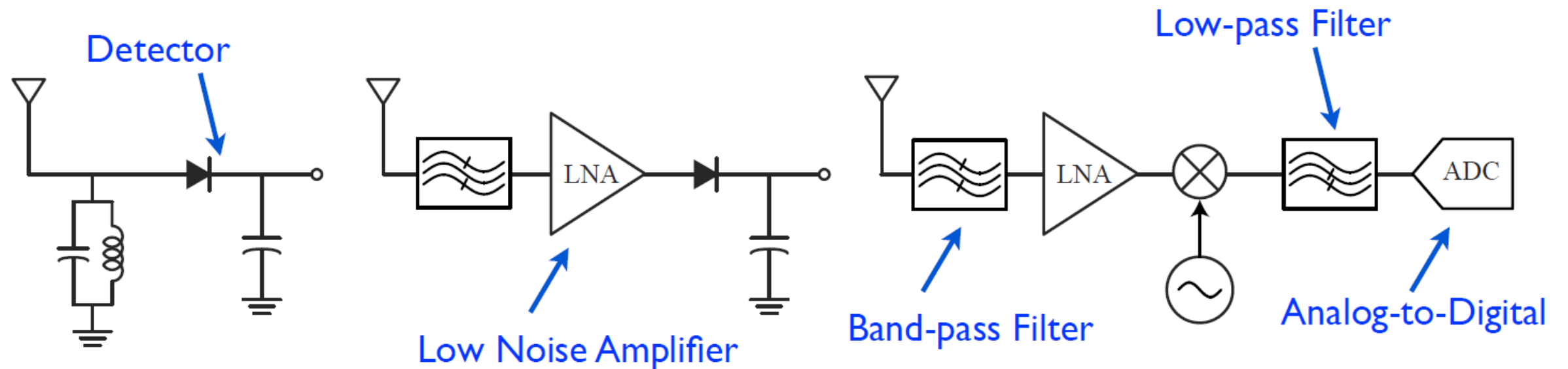
- A filter is used to "tune" the receiver to the desired band. An amplifier is usually needed since the signal is too weak to be detected.

- 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:

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

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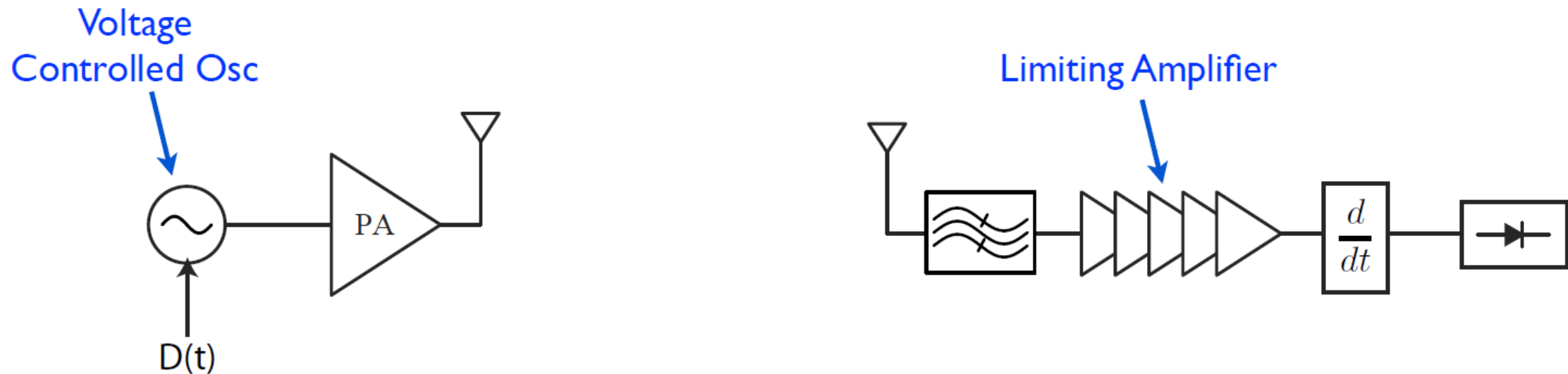
$$\frac{d}{dt}\left(A_0 \cos(\omega_0 t + \phi(t))\right) = -A_0 \sin(\omega_0 t + \phi(t))\left(\omega_0 + \frac{d\phi}{dt}\right)$$

- A voltage controlled oscillator (VCO) is an oscillator that uses a varactor (variable capacitor) to adjust the oscillation frequency. A ring oscillator can also perform this task (vary delay per stage by adjusting the current or voltage in the inverter stages)

- 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.

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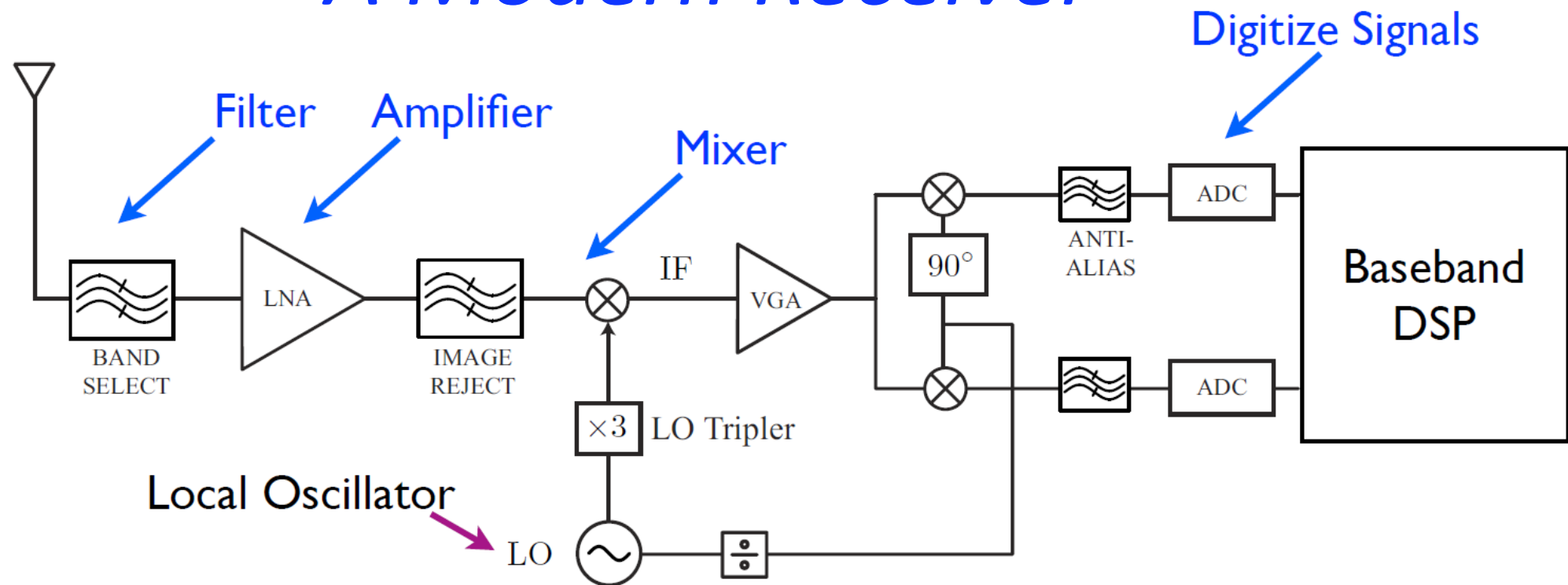
- This is a generic super-heterodyne receiver. There are several important *active* and *passive* blocks in this system. Passive blocks include the antenna, switches, and filters. Active building blocks include:

  - 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

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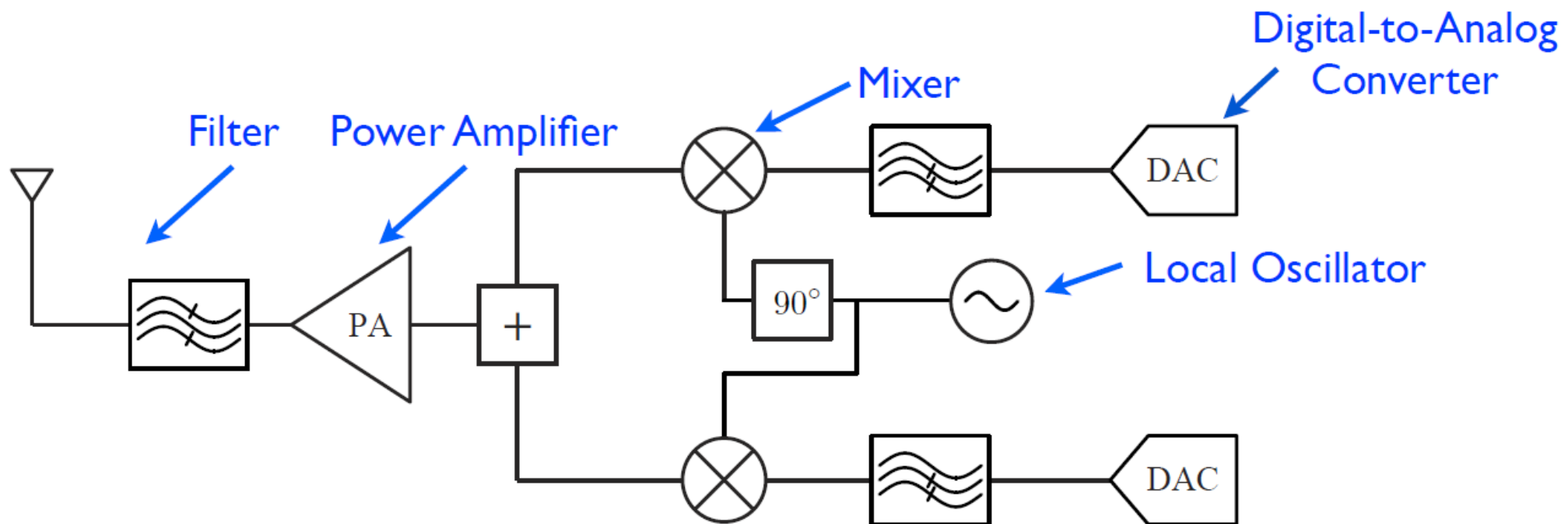
- This is a generic heterodyne transmitter. In addition to passive antenna (often shared with receiver through a switch or duplexer) and filters, we have the following important active building blocks:

  - 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

Received Signal Strength

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

- 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 –70dBm. This corresponds to a power of P = 1E-7 mW = 1E-10 W=100pW. The voltage on the antenna can be approximated by

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

- where, $Z_0 = 50\,\Omega$ is the antenna impedance.

Receiver Selectivity: Filtering

- A cell phone can work with very smaller signals. For instance for P = -100 dBm, or P = 1E-13 W, we have

$$V = \sqrt{100 \cdot 10^{-13}} = \sqrt{10} \times 10^{-6} \sim 3\,\mu\text{V}$$

- This is indeed a tiny signal. We need a voltage gain of about 100dBV to bring this signal into the range for baseband processing.

- Now imagine an interference signal of strength -40dBm, 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.

Filtering in Receivers

Transmitter Spectrum
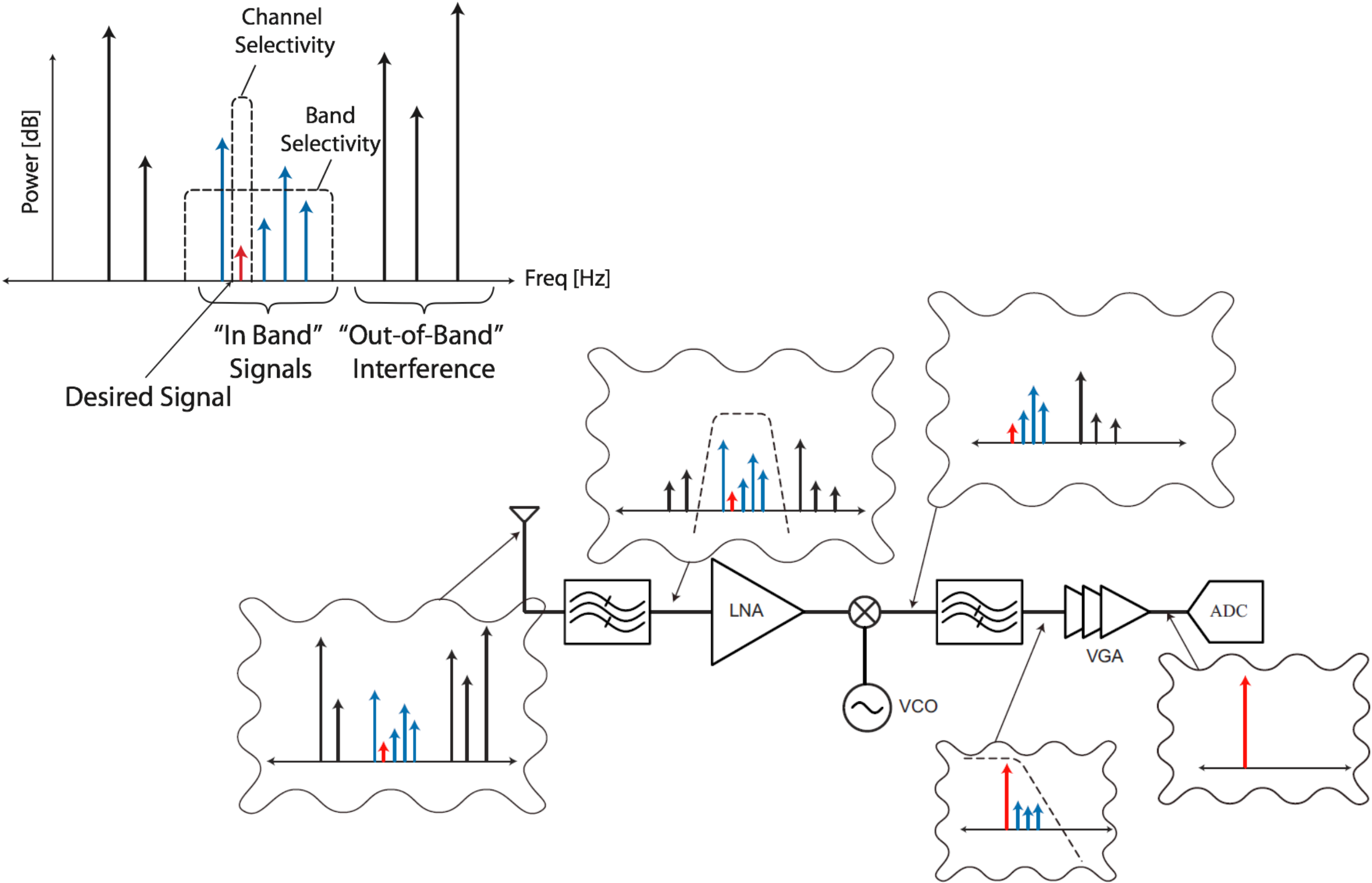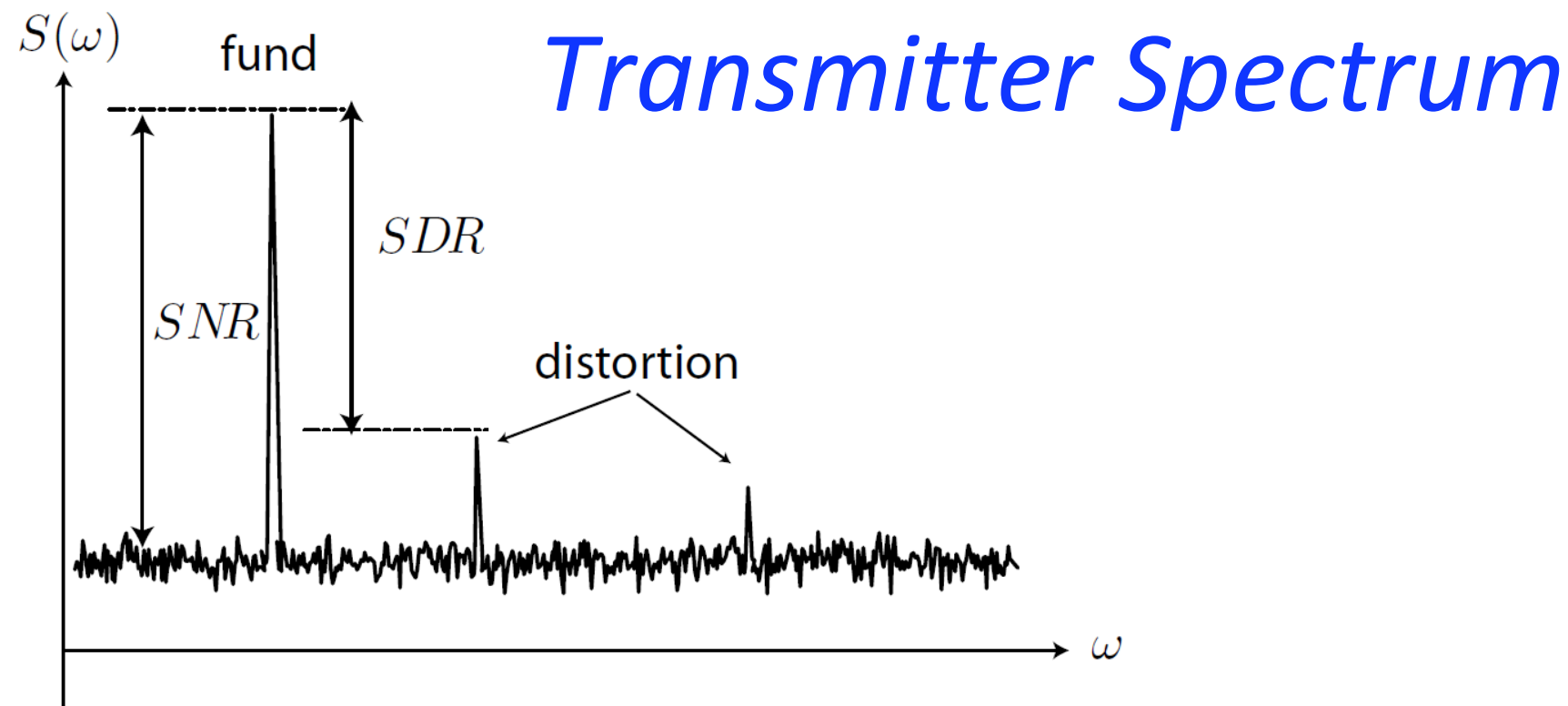
- The transmitter must amplify the modulated signal and deliver it to the antenna (or cable, fiber, etc) for transmission over the communication medium.

- Generating sufficient power in an efficient manner for transmission is a challenging task and requires a carefully designed power amplifier. Even the best RF power amplifiers do this with only about 60% efficiency at RF frequencies.

- The transmitted spectrum is also corrupted by *phase noise* and *distortion*. Distortion products corrupt the spectrum for other users and must be filtered out.