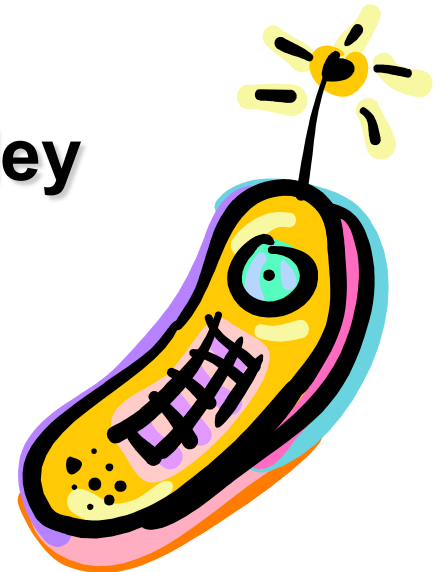# EECS 242: Introduction

Professor Ali M Niknejad

Advanced Communication Integrated Circuits

University of California, Berkeley

Course Syllabus

- Course Website: rfic.eecs.berkeley.edu/ee242
  - Updated lectures, homeworks, solutions, …
- Grading:
  - HW: 50%
  - Project: 50%
    - Project Proposal 5%, Midterm Report 10%, Final Report 35%
- Project: Design of critical communication circuit block meeting given specification. Final report due two weeks before final. Two interim reports are also graded to keep you on track. Students are encouraged to use material from research or industry but must demonstrate new work.
- Tools: SPICE, ADS/SpectreRF, Matlab/Mathematica

EECS 242 Topics

- Communication System Overview
- Transceiver Architectures
  - Choice of IF in receiver and transmitter
  - Polar TX architectures
  - Digitally intensive architectures
- Technology Evaluation (CMOS, BiCMOS/SiGe)
- Modeling
  - Review BSIM3/4, PSP, EKV
  - Passives (Inductors/Transformers)
- Linear Circuit/Noise Analysis Review
  - Design with Scattering Parameters
  - Noise circles, Gain circles, Power Circles

EECS 242 Topics (cont.)

- Distortion and Dynamic Range Limitations
  - Volterra Series, EVM and ACPR specifications
  - MOS non-linearity; MGTR and other techniques
  - SAWless architectures
- Power Amplifiers
  - Linear and Non-Linear Classes
  - Power combining (Transformers)
  - Stability
  - EVM and ACPR specs
- Mixers
  - Passive mixers, mixer IIP2/3
  - Time-Varying Noise Analysis ; Mixer noise simulation

EECS 242 Topics (cont.)

- Voltage Controlled Oscillators
  - Phase Noise and Jitter,
  - Quadrature VCOs,
  - Wide tuning range, Crystal/MEMS, MOS varactors
- Frequency Synthesizers
  - Fraq-N, Integer-N
  - Bandwidth; Spurs; Phase Noise
  - Dividers; Phase and Frequency Detection
- Wideband Circuit Building Blocks

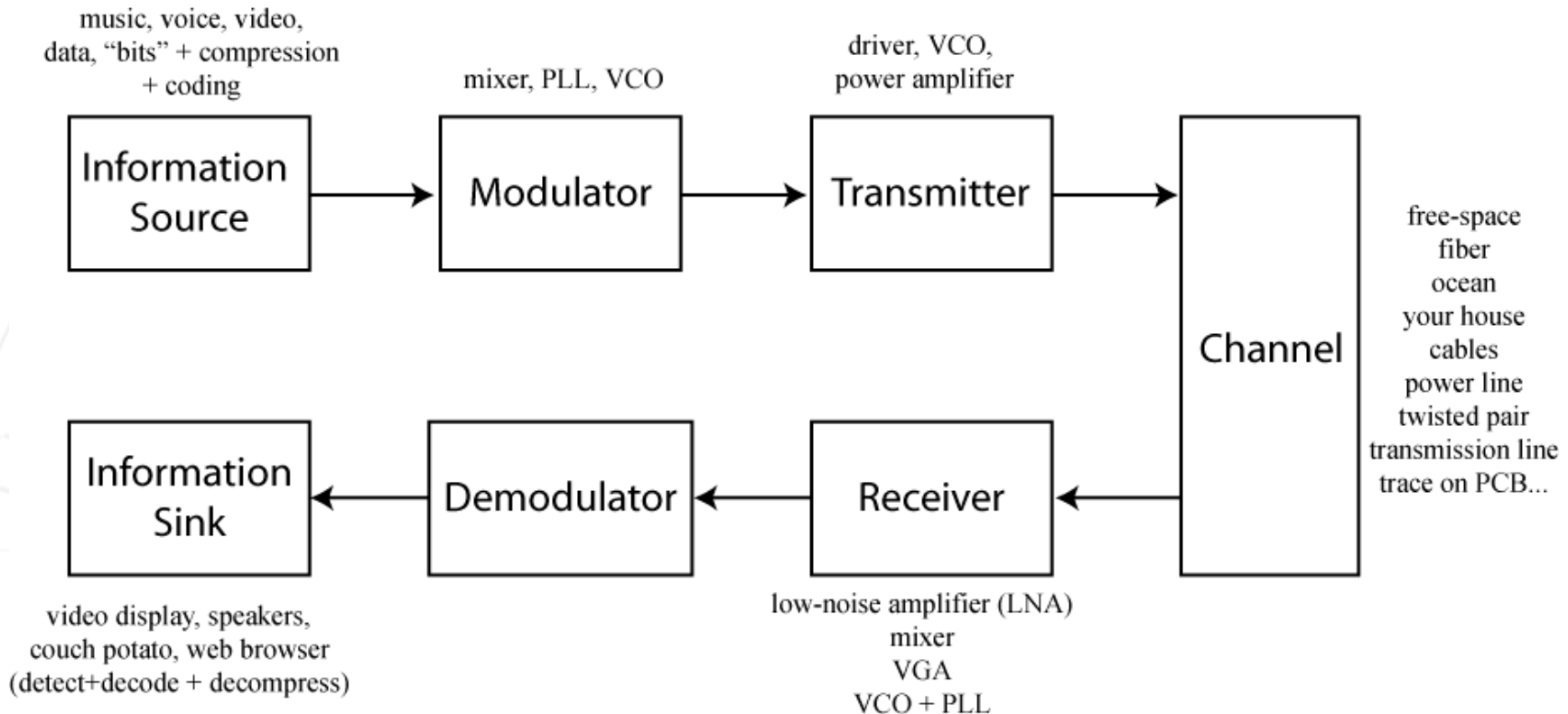# Introduction to Wired/Wireless

- Introduction to Communication System
  - Wired and Wireless Communication
  - Overview of Antennas and Signal Propagation
  - Channel Capacity, Noise, and Sensitivity
  - Multipath propagation

Model of Communication

Interference

P_t

Info *Source* → Medium → P_r → Info *Sink*

Noise

$$SNR = \frac{P_{sig}}{P_{noise}}$$
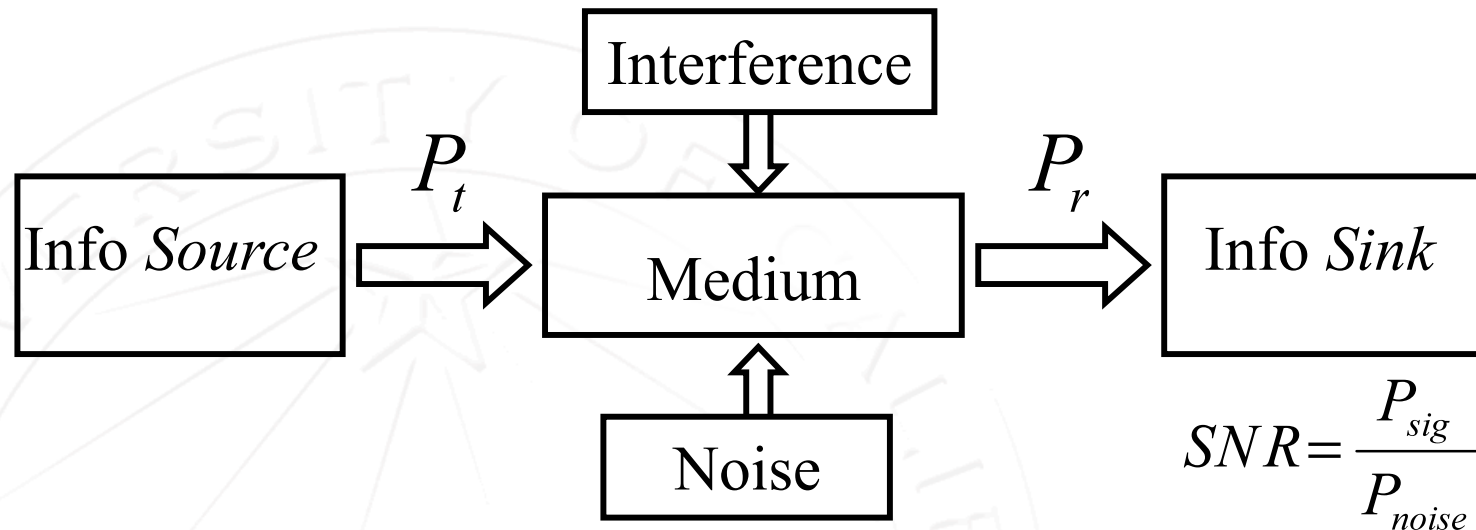
- Information *Source*: Analog or Digital
  - Voice: 4 kHz, 4 kbps (telephone)
  - Video: NTSC TV 6 MHz, 100 kbps – 1 Mbps Mpeg
  - Music: 20 kHz, 30 kbps – 128 kbps (MP3)
  - Internet Traffic: 1 kbps - 1.5 Mbps (dial-up, T1)
- *Medium*: Twisted-pair copper, coaxial cables, fiber, free-space (vacuum)
- *Noise*: Thermal noise from Atmosphere or Active/Passive Circuitry
- *Interference*: Mostly from human produced sources
  - Blockers, multi-path propagation, non-linearity and distortion

Modulation and Demodulation

music, voice, video,
data, "bits" + compression
+ coding

mixer, PLL, VCO

driver, VCO,
power amplifier

| Information Source | → | Modulator | → | Transmitter | → | Channel |

free-space
fiber
ocean
your house
cables
power line
twisted pair
transmission line
trace on PCB...

| Information Sink | ← | Demodulator | ← | Receiver | ← | Channel |

video display, speakers,
couch potato, web browser
(detect+decode + decompress)

low-noise amplifier (LNA)
mixer
VGA
VCO + PLL

- Signals must be modulated and demodulated onto an appropriate carrier
- Major role of circuitry is to frequency translate, amplify, and filter

Example: Telephone Comm

- Telephone communication occurs over "twisted pair" (TP) wiring, usually unshielded (UTP). Twisted pairs have better noise immunity when signals are transmitted differentially (and lower radiation).

- When cables are long (relative to the wavelength of the highest frequency), then they behave in a distributed manner (transmission line theory). This occurs because signals travel at the speed of light (about 300 meters in a microsecond in air). If we drive and terminate the cables in the characteristic impedance (100ohms for UTP), then the cables behave properly (like simple circuits) and only introduce a delay (and attenuation). Otherwise there are multiple reflections on the line at each interface between impedances.

- A signal at 10 MHz experiences about 30dB of attenuation when traveling 1000 ft / 305 m in UTP. This sets the limit to how far we can send signals before requiring gain. The attenuation increases sharply with frequency. Coaxial cables are much better, and fiber optic cables are orders of magnitude better!

Data Communication (LAN)

Dispersionless
Propagation

Phase Dispersion
Propagation
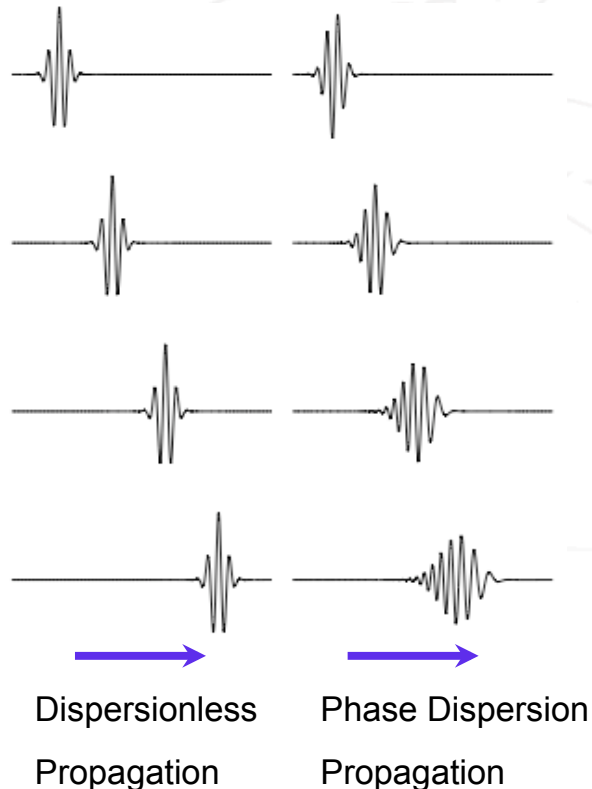
- Twisting the line decreases coupling but reduces the bandwidth (it's an artificial transmission line).
- When sending high speed data through a cable, we have to deal with several non-idealities:
  - Attenuation, Dispersion, Reflections → Inter Symbol Interference
- Attenuation is frequency dependent 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.

High-Speed Chip-to-Chip I/O
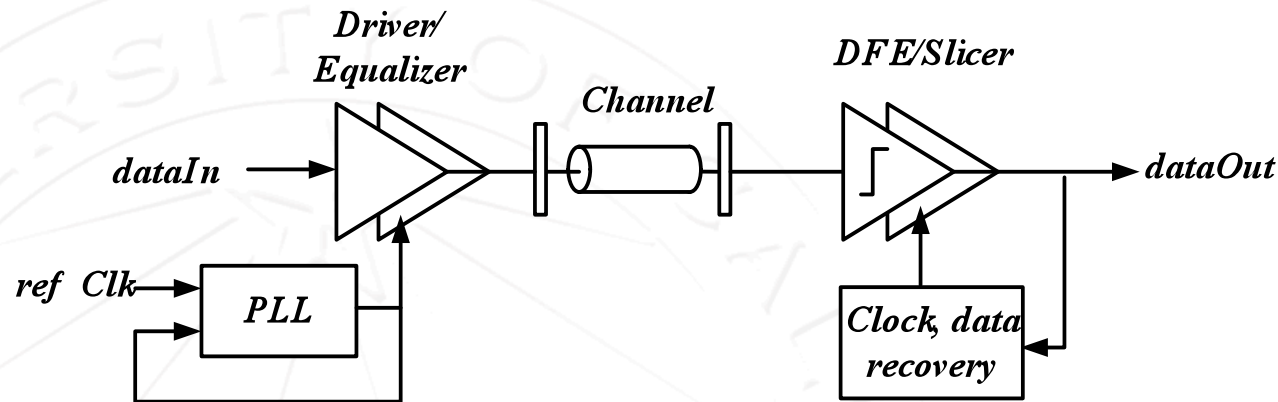
- Broadband mixed-signal processing
  - Simple modulation (2PAM), high bandwidth (5-10Gb/s)
  - Extremely energy-efficient: ~2pJ/bit [Palmer ISSCC 07]
- Link techniques
  - Low-complexity, high-speed analog signal path
  - Low-speed digital control/calibration

Slide courtesy of Prof. Elad Alon

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 $\sim \lambda$ (free space propagation wavelength).

- Since many users are sharing the same channel, we must contend with interference and come up with a good mechanism to share spectrum (FDMA, TDMA, CDMA).

- There are multiple paths from source to receiver, and some objects reflect the signal (ground) while others scatter the signal (trees). Also signals creep around obstacles (diffraction) and hence we have to deal with multi-path propagation.

- When source/receiver moves, we have a Dopper shift.

radiating fields

feed line
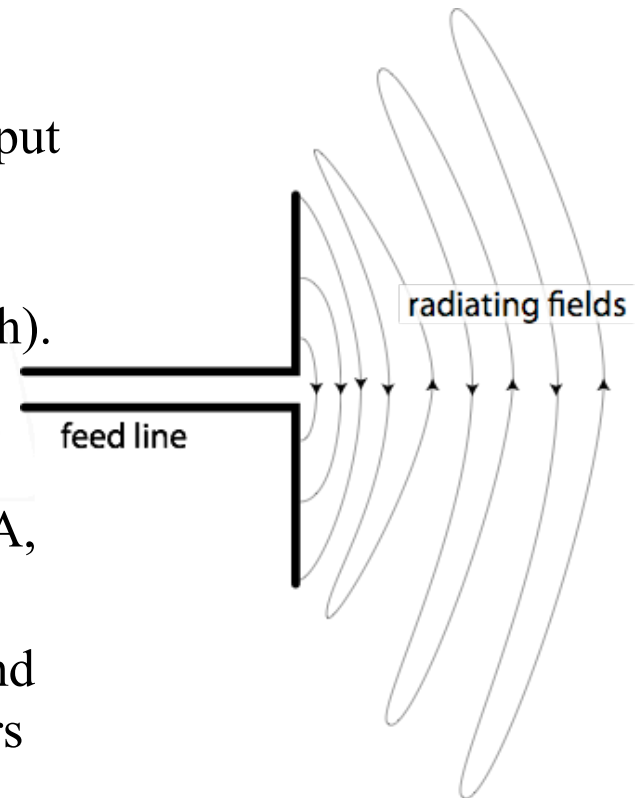
Narrowband vs. Broadband

- Carrier waveform (sinusoid versus pulse) and frequency/bandwidth

- Narrowband modulation uses a long duration carrier and amplitude/phase/frequency modulation (narrowband) to convey information. Bandwidth of signal is much lower than the carrier frequency.

- Narrowband has been favored since spectrum can be chopped up into channels and interference is easily managed.

- Ultrawideband uses short pulses or windowed carriers and thus occupies a very large bandwidth. Energy is spread across a wideband so transmit power has to be limited to avoid interference.

UWB vs. Narrowband Signaling
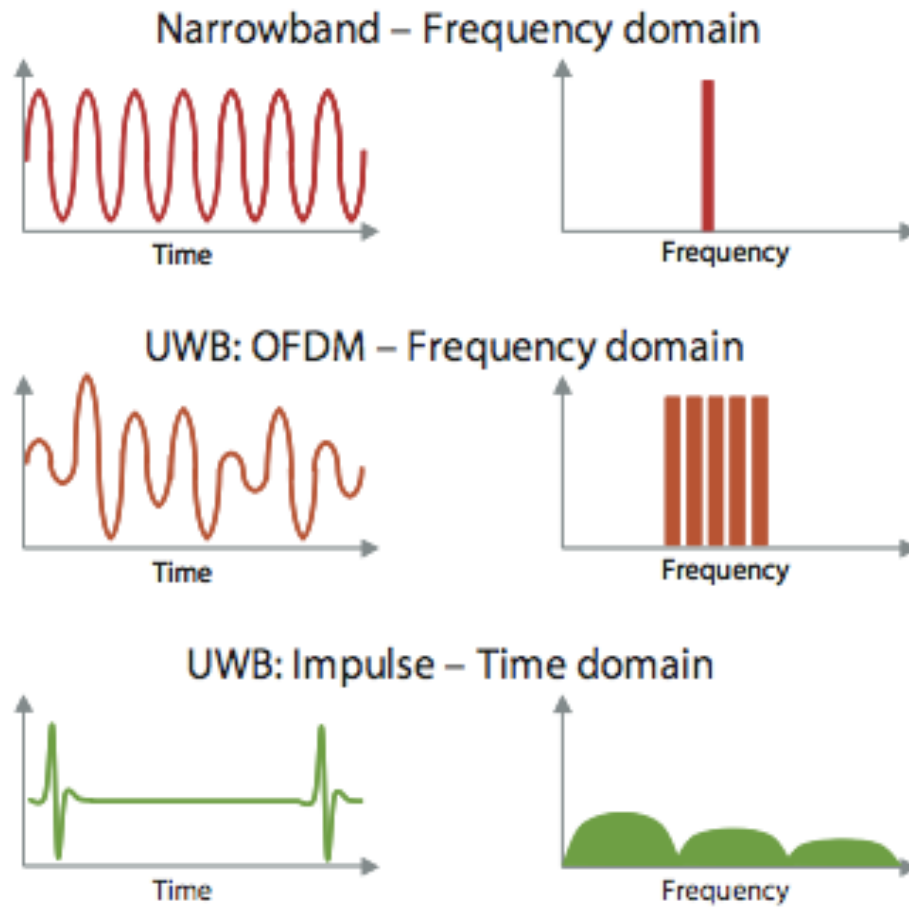
Narrowband – Frequency domain

UWB: OFDM – Frequency domain

UWB: Impulse – Time domain

Source: " A Baseband, Impulse Ultra-Wideband Transceiver Front-end for Low Power Applications," by Ian David O'Donnell, Technical Report No. UCB/EECS-2006-47

Impulse Radios Seem "Simpler"

Sinusoidal Downconversion Radio

Subsampling Impulse Radio
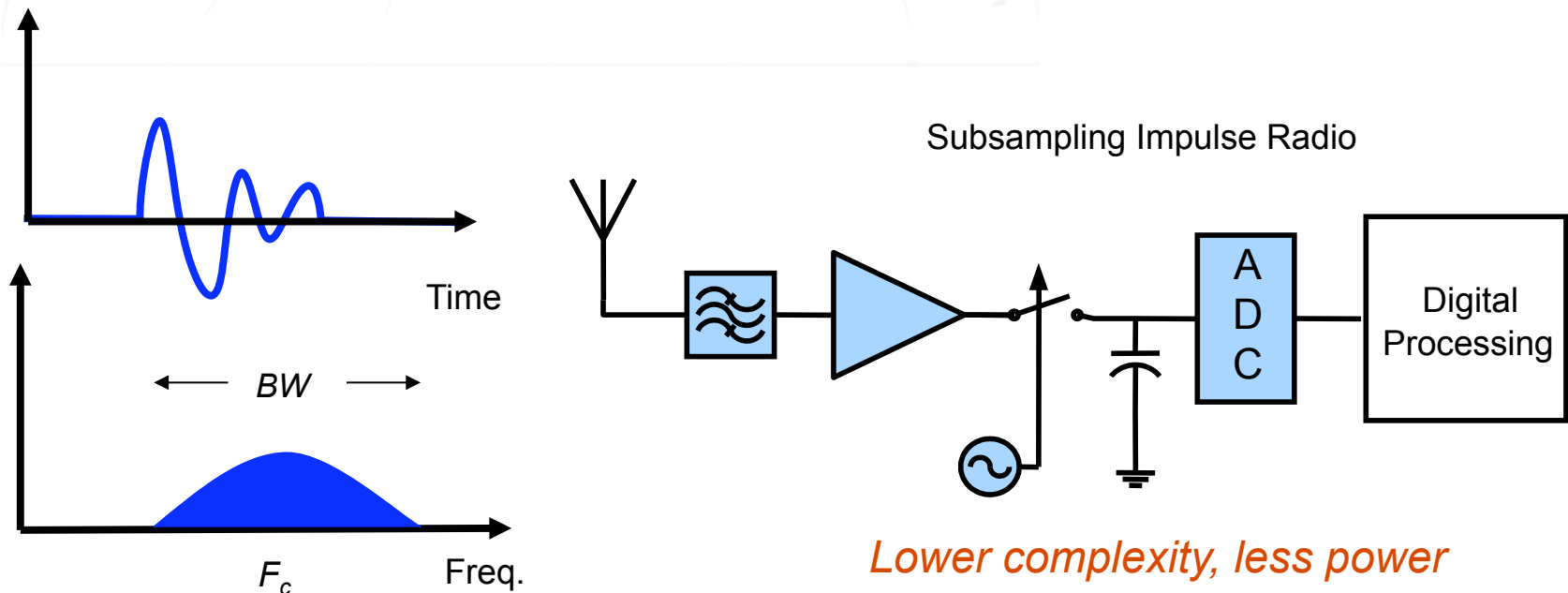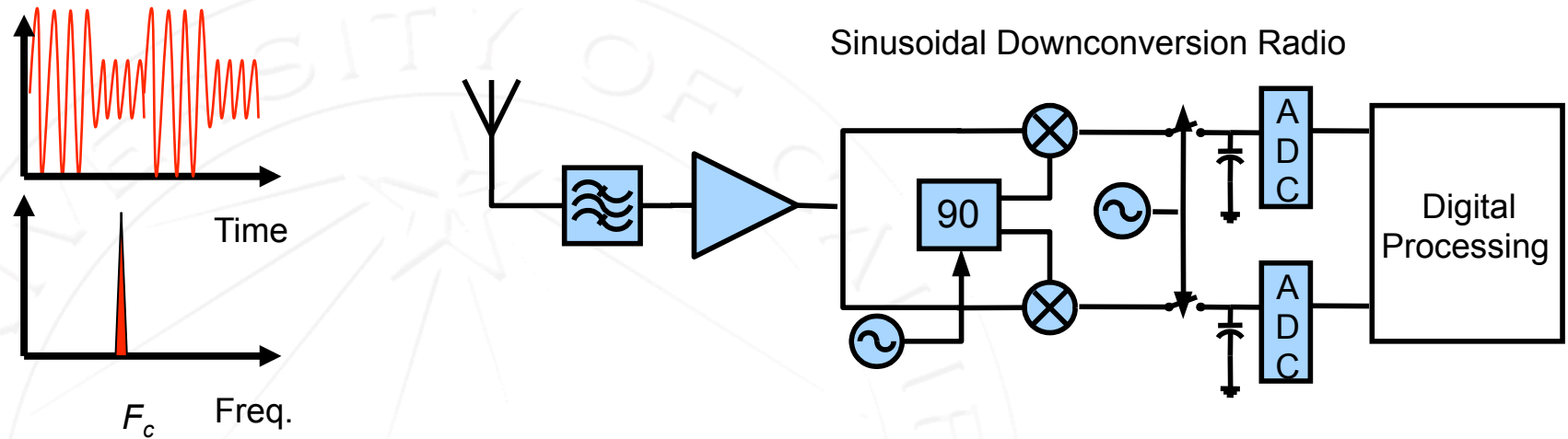
Lower complexity, less power

Choice of Carrier Frequency

- How is the RF carrier chosen? Government (FCC in the U.S.) since the spectrum is a shared resource. Other considerations include propagation characteristics and antenna size.

- Most information sources are baseband 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
    - Uncompressed video: ~ 10MHz
    - 802.11 b/g WLAN: 22MHz

- Some common carrier frequencies
    - 100 MHz, FM radio
    - 600 MHz, UHF television
    - 900 MHz, 1.8 GHz, cellular band
    - 2.4 GHz, 5.5 GHz WLAN
    - 3-10 GHz, proposed "ultra-wideband" (wireless USB)

FCC Allocation

Copyright © Prof. Ali M Niknejad

Wired Communication Systems

Wireless Communication System

Data Stream → Modulate → Power Amplifier mW – Watts → (antenna) Volts
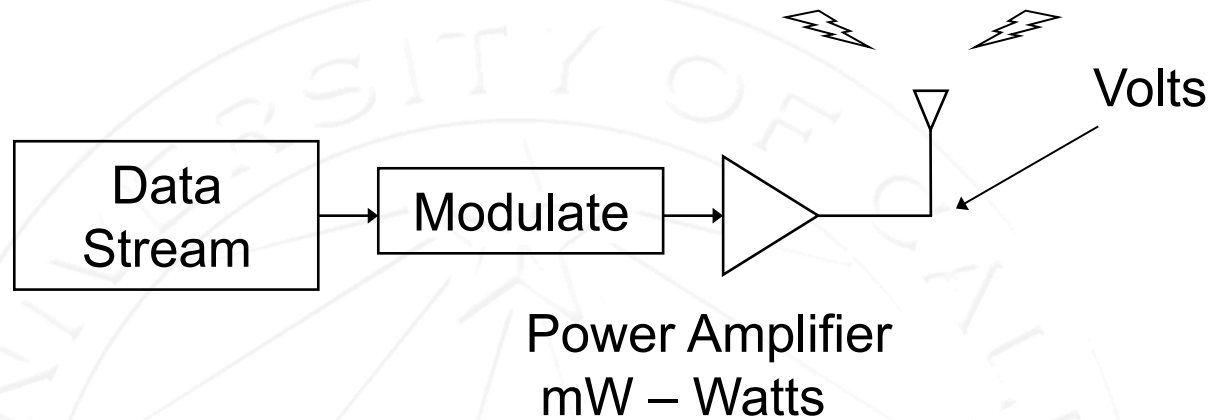
Cellular Voice (AMPS)
Digital Cellular (GSM/CDMA 2G/3G)
Short Range Data (WLAN, Bluetooth)

LNA   Demodulate

(antenna) → LNA → Demodulate (VCO) → Filter → IF → A/D

µV–100's of mV
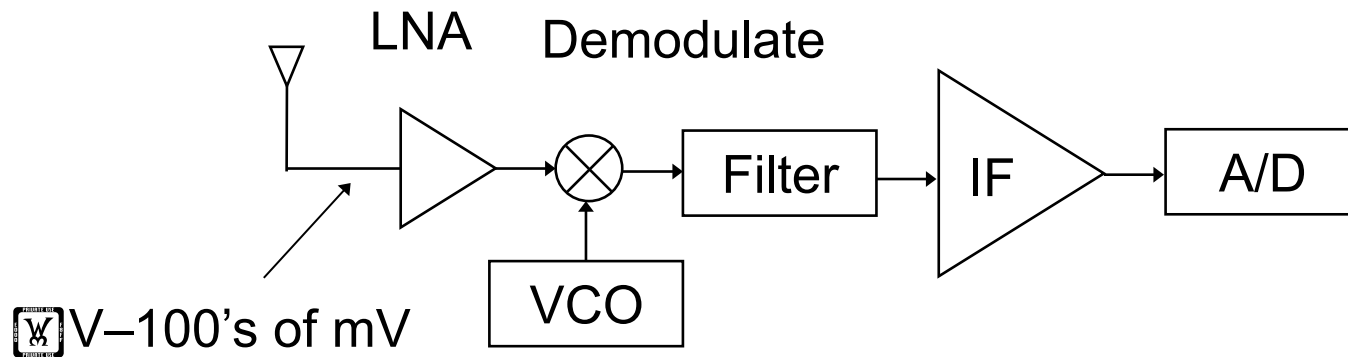
Classic Super Heterodyne Receiver
Armstrong (1917)

Receiver Spectrum

channel

interference

signal

noise
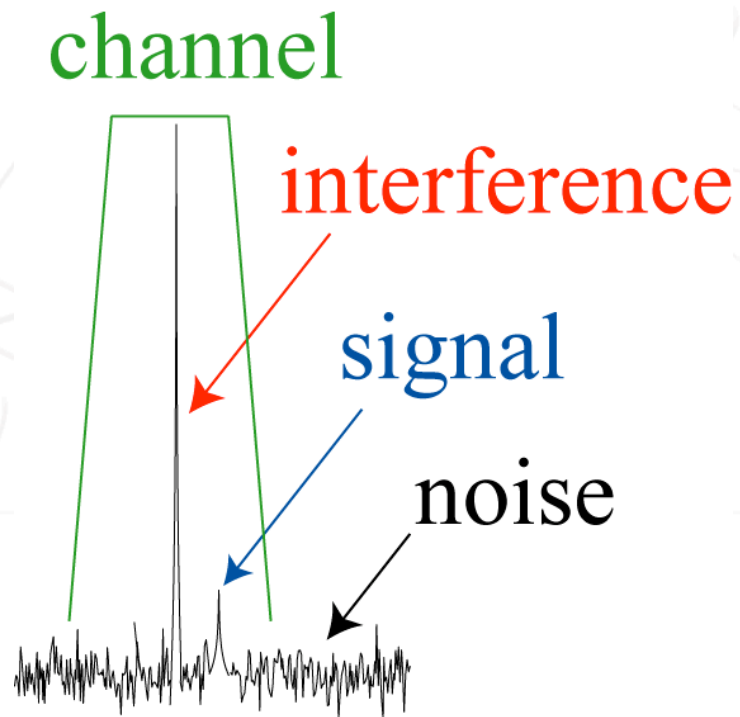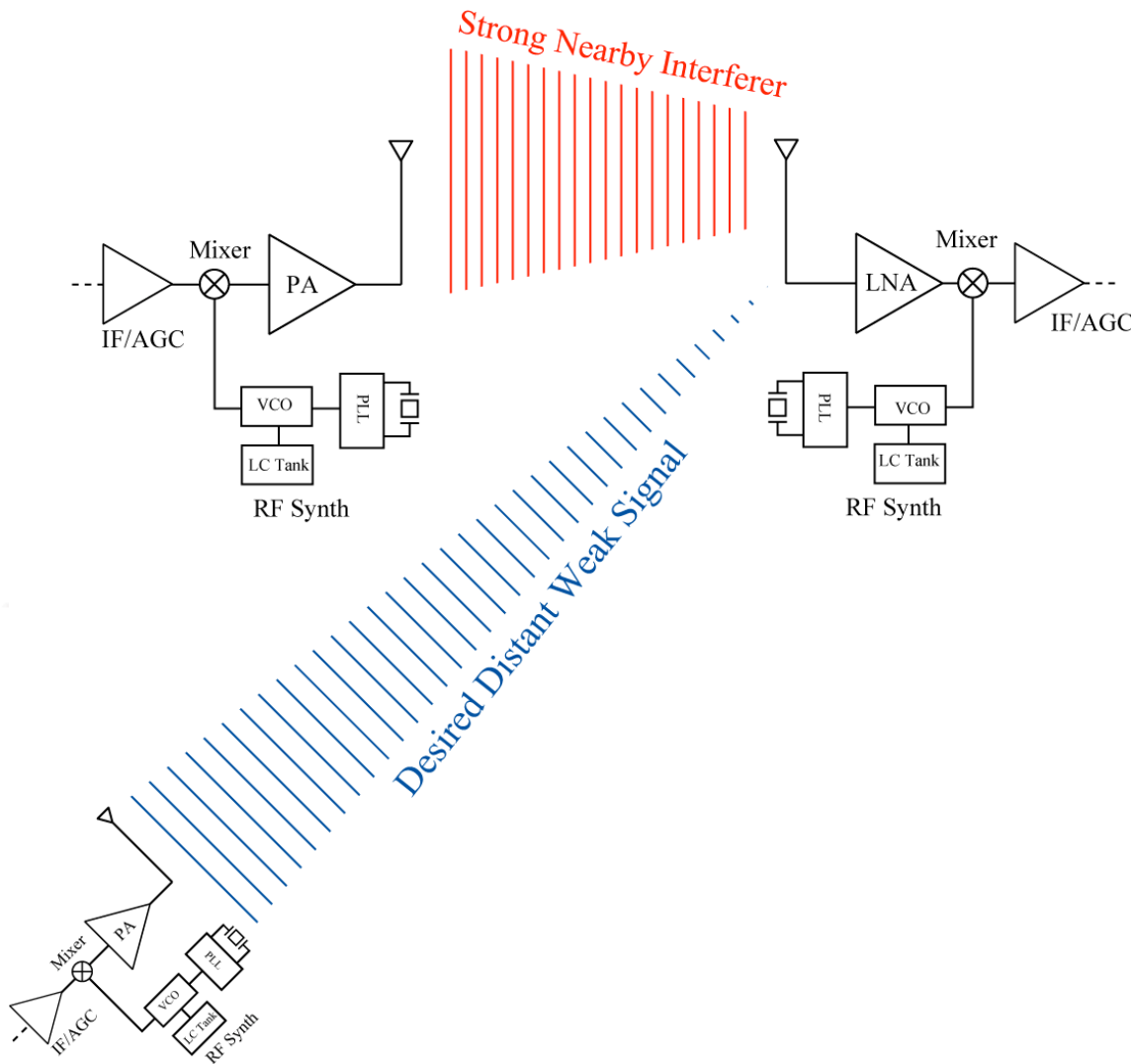
- Signal is often accompanied by interference, arising from other users of the same band (unfiltered) or users in other bands (filtered)

- Must be able to communicate in a worst case scenario of a very weak signal and a moderately large intererere

Loud Party Conversation

- Trying to receive a distant weak signal
- But also receive a nearby strong signal (jammer or blocker)
- Need low noise and high linearity to successfully converse…

Dynamic Range Summary

- 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.

Transmitter Spectrum
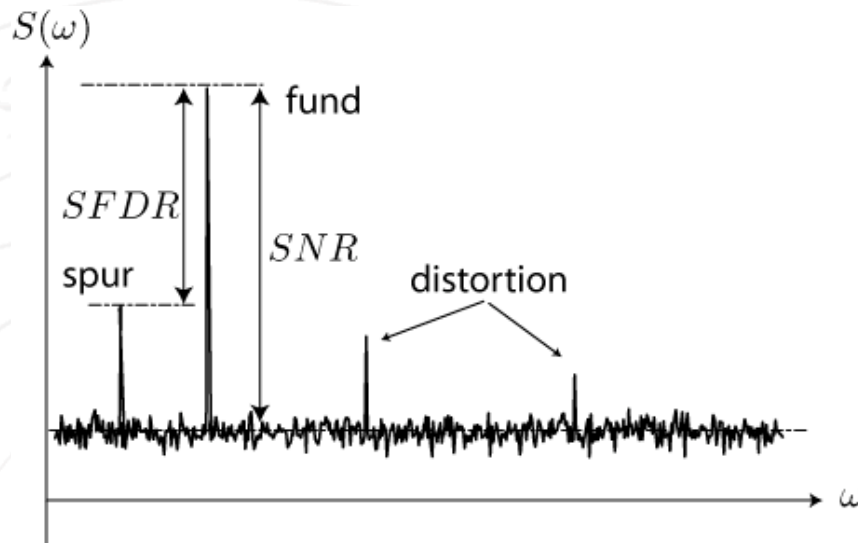
- The transmitter must amplify the modulated signal and deliver it to the antenna (or cable, fiber, etc) for transmission over the communication medium.
- Generating sufficient power in an efficient manner for transmission is a challenging task and requires a carefully designed power amplifier. Even the best RF power amplifiers do this with only about 60% efficiency.
- The transmitted spectrum is also corrupted by phase noise and distortion. Distortion products generated by the amplifier often set the spurious free dynamic range.

Medium for Info Transportation
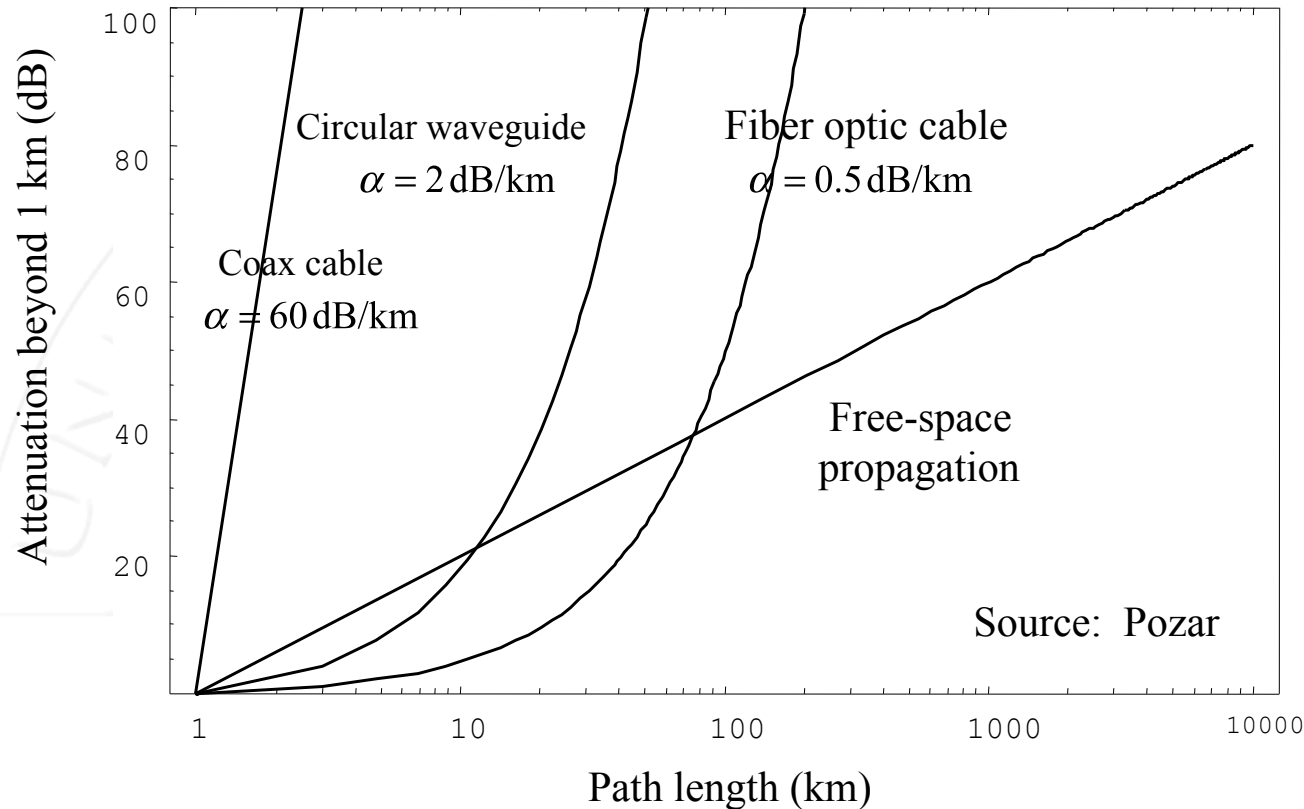
T- Line Attenuation:

$$\frac{P_2}{P_1} = e^{-\alpha(x_2 - x_1)}$$

Free-Space Propagation:
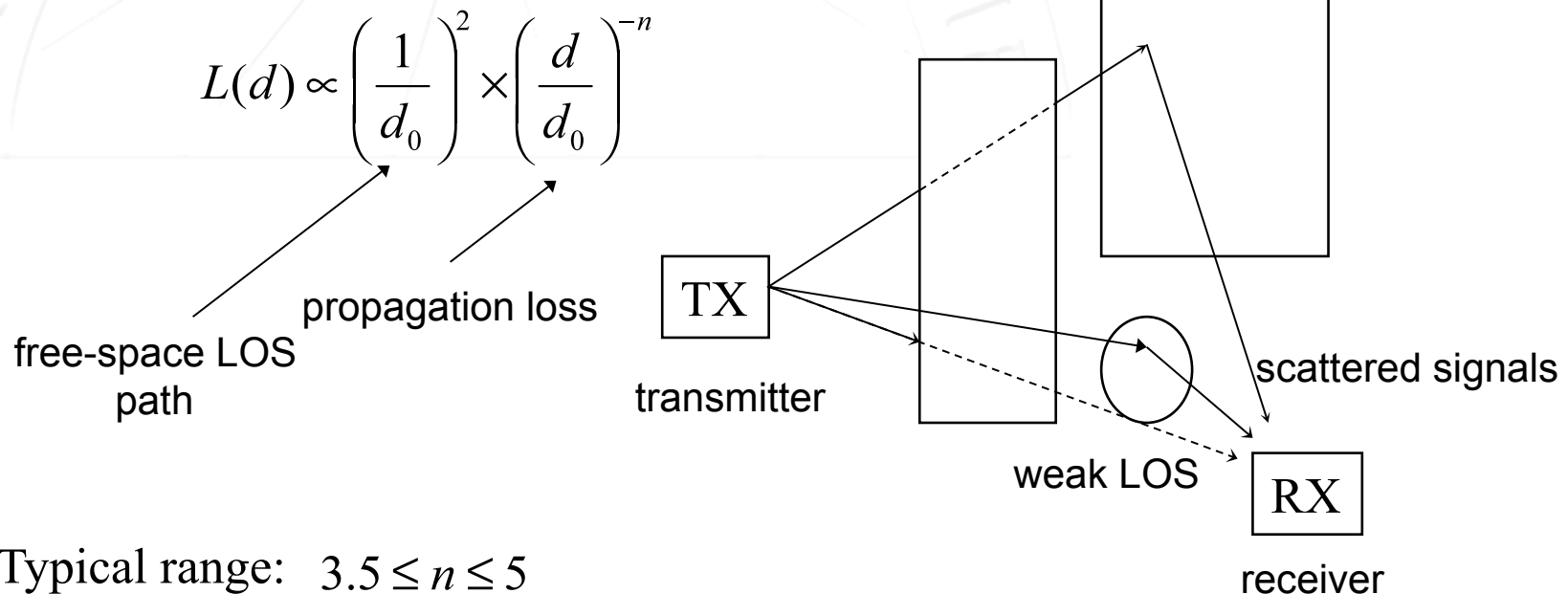
$$\frac{P_2}{P_1} = \left(\frac{x_1}{x_2}\right)^2$$

$$d \cong \sqrt{15h} \text{ km}$$

- **If we can tolerate an attenuation of 100 dB:**
  - Coax cable has range of a few km, waveguide has a range of about 100 km
  - Fiber has range of a few 100 km, Free-space has range of 100,000 km
- **Line-of-Sight (LOS) propagation limited by curvature of earth:**

Chart labels:
- Circular waveguide $\alpha = 2\,\text{dB/km}$
- Fiber optic cable $\alpha = 0.5\,\text{dB/km}$
- Coax cable $\alpha = 60\,\text{dB/km}$
- Free-space propagation
- Source: Pozar
- Attenuation beyond 1 km (dB)
- Path length (km)

Propagation in Mobile Environment

- Inverse Square Law assumes LOS propagation in free-space
- At high frequencies (> 10 GHz) the resonance in molecules attenuates signals
- In many situations the TX & RX don't "see" each other (NLOS)
- Multi-path propagation occurs through scattering off multiple objects
- Shadowing also occurs around obstructions
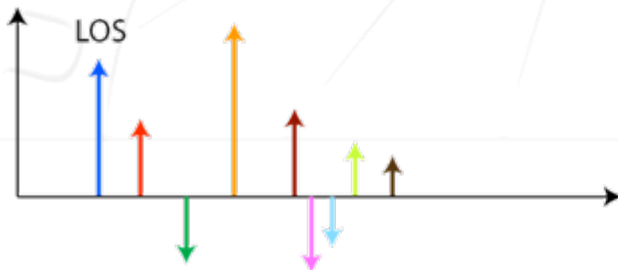- Empirical formula for path loss:

$$L(d) \propto \left(\frac{1}{d_0}\right)^2 \times \left(\frac{d}{d_0}\right)^{-n}$$

free-space LOS path

propagation loss

building

TX
transmitter

scattered signals

weak LOS

RX
receiver

- Typical range: $3.5 \leq n \leq 5$
- Envelope fading occurs when multi-path signals sum out of phase
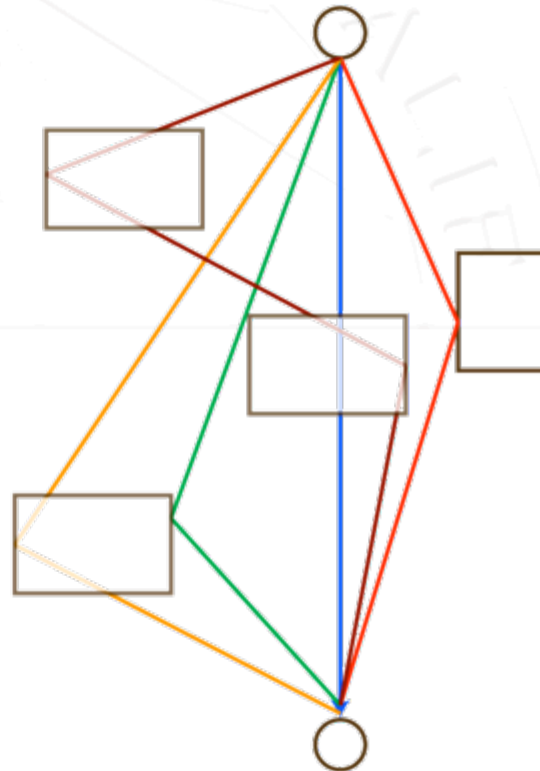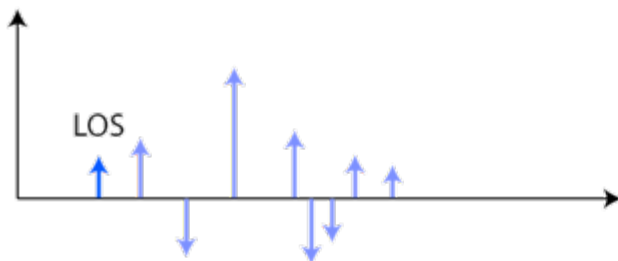
Multipath Impulse Response

No Multi-Path

LOS

With Multipath

LOS

Shadowed LOS Multipath

LOS

- Reflections, diffraction, and refraction for smooth objects
- Scattering for rough surfaces
- Depends on relative dielectric constants, angle and plane of incidence, etc.
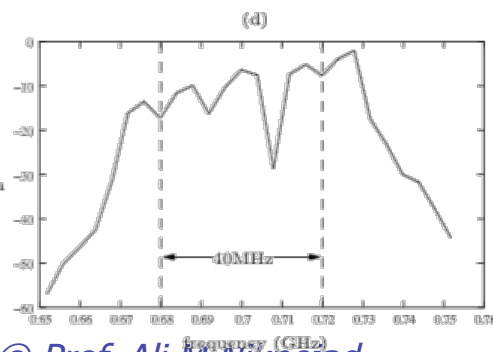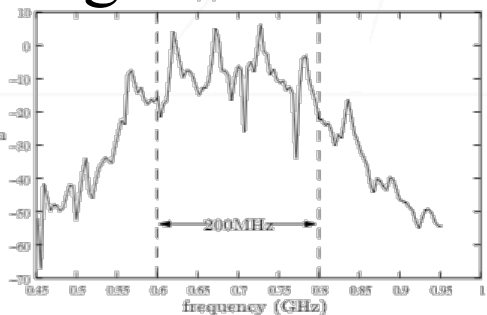
Multi-Path Fading

- In the frequency domain, the multi-path propagation can result in deep fades in the channel response.

- At particular frequencies, the direct path and alternative paths can be 180° out of phase, producing a null in the RX signal

- Consider that the signal phase changes as it propagates:

$$e^{k\delta x} = e^{2\pi \frac{\delta x}{\lambda}}$$

- If two paths differ in length by an odd multiple of a half-wavelength, destructive interference takes place.

- Since the wavelength is centimeters in the gigahertz regime, motion changes the multi-path fade (time-varying)

Coherence Time/Delay Spread

- The *coherence time*, T_c, is related to how fast the channel changes.

- The *delay spread*, T_d, is defined as the difference in propagation time between the longest and shortest path, counting only the paths with significant energy.

- Coherence BW: $W_c = 1/(2T_d)$

- Flat fading implies that the bandwidth of our signal is much smaller than the coherence bandwidth of the channel.

- Statistical models used to described channel when there is a lot of multipath.

60 GHz Point-to-Point Channel
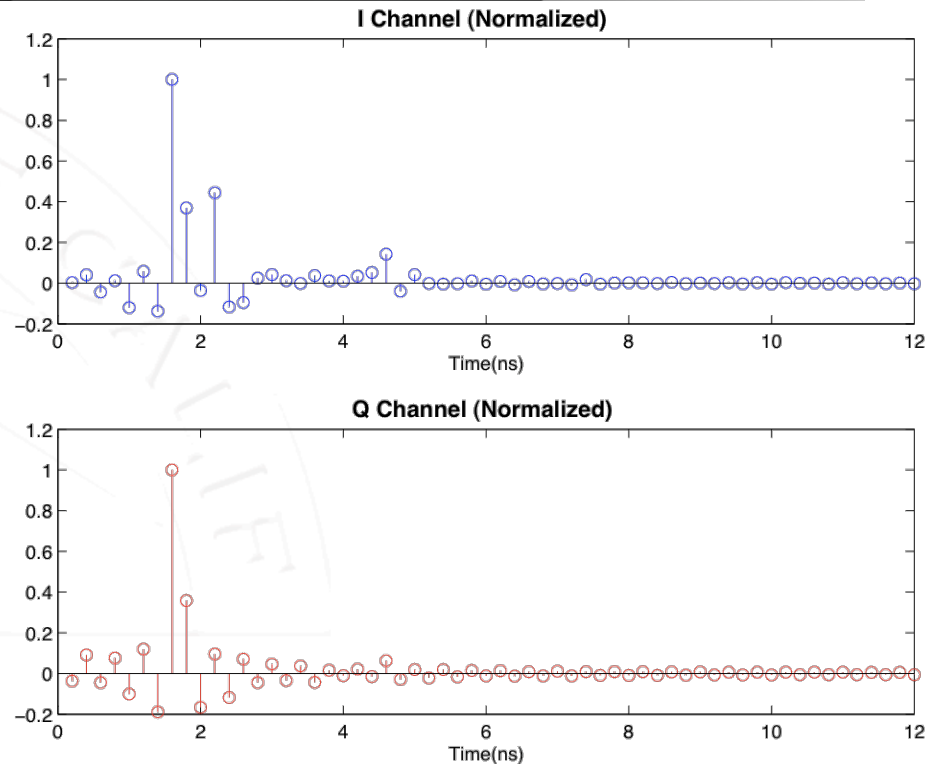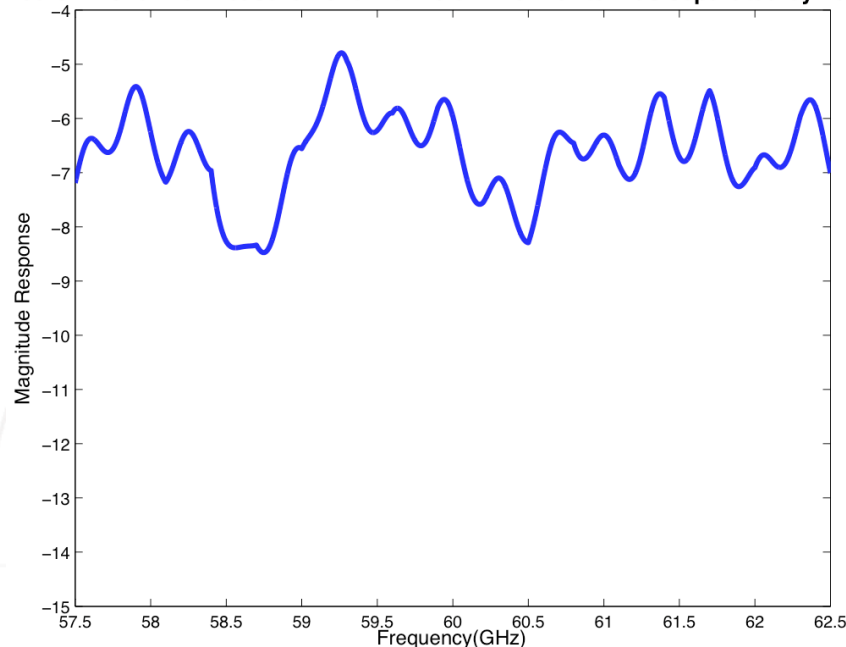
Measurements of 60 GHz channel response with dirctive antennas. [Courtesy of Chintan Thakkar]

- Impulse response shows that there are many "taps" required to capture all the energy of the signals due to multipath propagation.

- In the frequency domain, this results in frequency selective fading across the wideband channel.

Equalization

- A filter that compensates for the multipath effects of channel

- If we can "learn" the channel response with a test sequence, then we can program a filter to compensate for the channel.

- Decision Feedback Equalizer (DFE): Subtract out post-cursor ISI
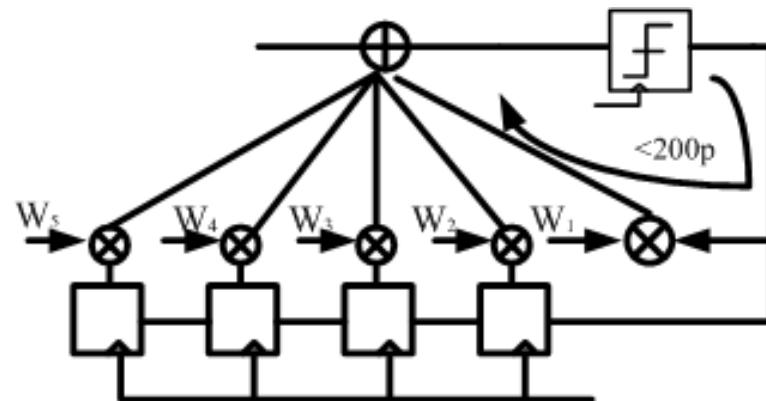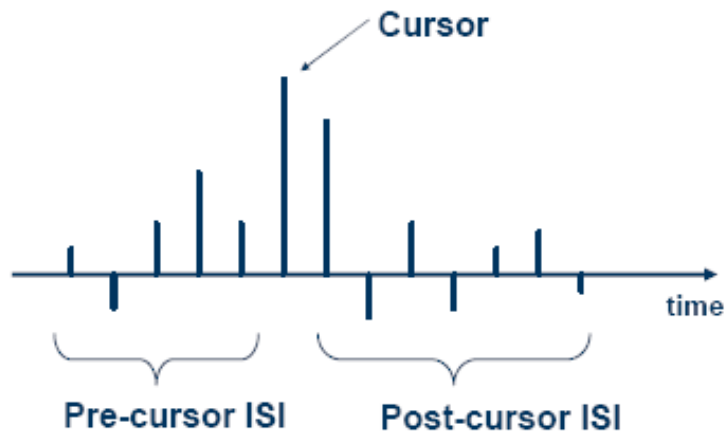
OFDM or Multicarrier Modulation
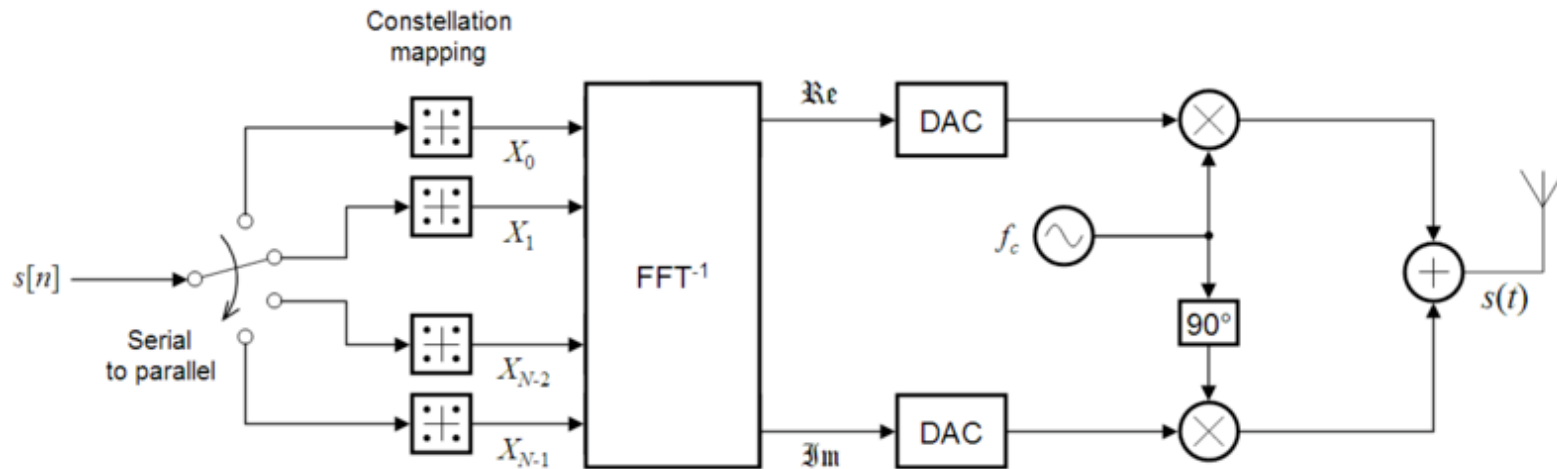
Source: Wikipedia (http://en.wikipedia.org/wiki/File:OFDM_transmitter_ideal.png)

- In a wideband wireless system there is frequency selective fading which makes the receiver design complicated (equalization). In wired communication high frequency dispersion and attenuation plays a similar role.

- A solution is to chop a wide bandwidth into sub-bands and use several closely spaced sub-carriers. Each sub-carrier is modulated with a slower data rate and is narrowband, and hence does not require equalization.

OFDM Receiver
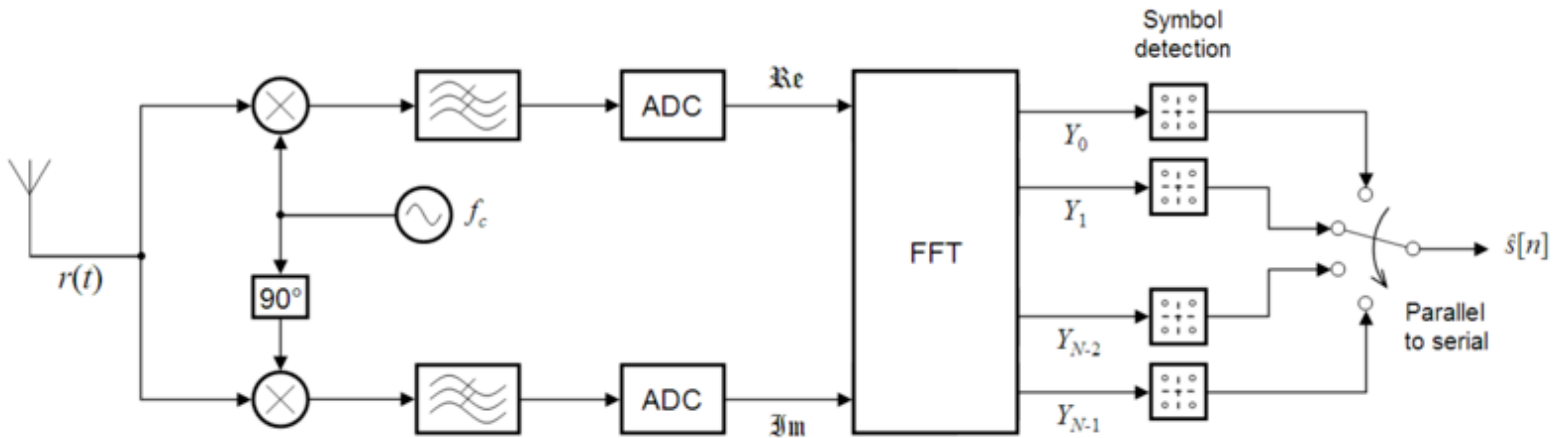
Source: Wikipedia (http://en.wikipedia.org/wiki/File:OFDM_receiver_ideal.png)

- This approach was popularized by 802.11a/g WLAN and ADSL.

- Receiver uses FFT to split the signal into sub-bands and each channel is demodulated separately. The FFT operation is expensive (compute).

- OFDM uses orthogonal sub-carriers to eliminate cross-talk between carriers and to eliminate the need for guard bands. For this accurate frequency synchronization is required.

- The spectrum of an OFDM signal has a high peak to average ratio, which requires a very linear (inefficient) PA.

Electromagnetic Propagation

- Electromagnetic radiation due to accelerating charge
- Static fields decay like $1/r^2$ while *dynamic* fields decay like $1/r$
- Fields propagate in vacuum at speed of light. A changing electric field acts as a current source for the magnetic field and vice versa:

$$\frac{\partial E}{\partial t} \quad \frac{\partial B}{\partial t} \quad \frac{\partial E}{\partial t} \quad \frac{\partial B}{\partial t}$$
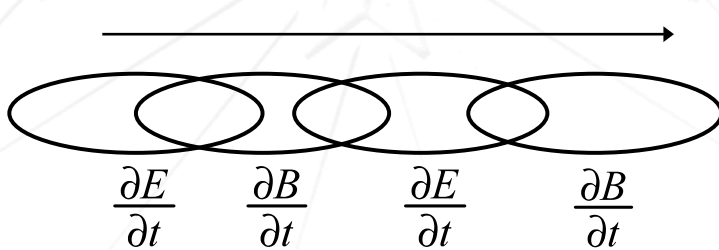
$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times B = \frac{1}{c^2}\frac{\partial E}{\partial t}$$

- For structures much smaller than the wavelength, the induced fields are reactive (capacitive, inductive) $\quad V_1 \propto j\omega M_{1n}I_n$
- For a structure on the order of a wavelength or more, the inherent delay causes real components in the induction

$$V_1 \propto j\omega M_{1n}I_n e^{-j\phi} = j\omega M_{1n}I_n\cos\phi + \omega M_{1n}I_n\sin\phi$$

- Real component represents radiated energy

Dipole Radiation

- Electromagnetic propagation occurs in a direction perpendicular to the plane of motion of the accelerating charge
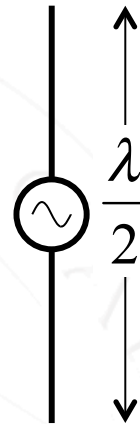

- Dipole does not radiate along z axis. The dipole has *directivity*.
- Antenna Directivity: The ability of an antenna to direct power in any given direction normalized to an isotropic radiator.
- Radiation Pattern: The relative far-zone field strength versus direction at a fixed distance.

Antenna Basic Parameters

$$P_{RAD} = \int F(\theta, \phi, r) r^2 d\Omega$$

$$D(\theta, \phi, r) = \frac{F(\theta, \phi, r)}{P_{RAD} / 4\pi r^2} = f(\theta, \phi)$$

$$G(\theta, \phi) = \frac{F(\theta, \phi)}{P_{INC} / 4\pi r^2}$$

$\dfrac{\lambda}{2}$

$$H_\phi = \frac{j I_m}{2\pi R} e^{-j\beta R} F(\theta)$$

$$E_\theta = \eta_0 H_\phi = 120\pi H_\phi$$

$$F(\theta) = \frac{\cos[(\pi/2)\cos\theta]}{\sin\theta}$$

$$R_r \approx 73.1\,\Omega$$

$$D \approx 1.64\,(2.15\,\text{dB})$$

- P_{RAD} is the average radiation power (integral over solid angle)
- D is the directivity, or the radiation pattern normalized to average power
- G is the gain, or the radiation pattern normalized to the incident power
- Radiation resistance R is the a fictitious resistor that dissipates power equal to power radiated. The resistor noise is due to incident radiation from the background and *not* from the resistance of the conductors in the antenna (an ideal antenna has zero resistance)
- The incident noise radiation on the antenna depends on the "background" temperature. If the antenna picks up energy from the sky and the earth, then an effective temp must be used

Results from Antenna Theory

source

matched load

$Z_L = Z_S^*$

$P_L = A_{eff} S_{av}$

plane-wave incident

time-average power density
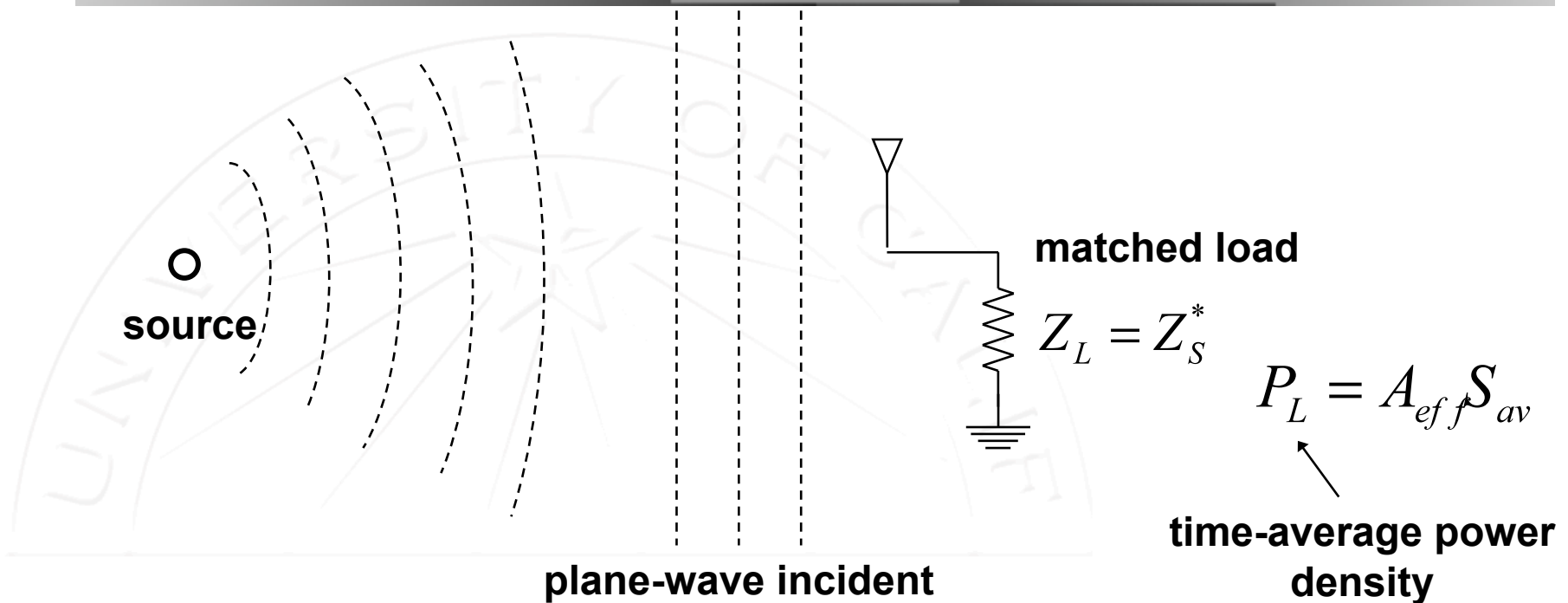
- Define the effective area as the power intercepted by antenna for an incident plane wave of power density *Sav*

- By Electromagnetic Theory of Reciprocity:
    - Antenna receive pattern same as transmit patter
    - Ratio of eff. area to antenna gain is a universal constant:

$$\frac{A_{eff}}{D} = \frac{\lambda^2}{4\pi}$$

Friis Propagation Equation

transmitter   **receiver**

$$P_r = D_1 \times \frac{P_t}{4\pi\, r^2} \times \underbrace{A_{e2}}_{\frac{\lambda^2}{4\pi} D_2}$$

Gain of transmit antenna   **Effective capture area of receiver**

Power over surface area of sphere

$$\frac{P_r}{P_t} = \frac{A_{e1} A_{e2}}{r^2 \lambda^2} \qquad \Longleftrightarrow \qquad \frac{P_r}{P_t} = \frac{D_1 D_2 \lambda^2}{(4\pi\, r)^2}$$

Friis Implications

$$\frac{P_r}{P_t} = \frac{D_1 D_2 \lambda^2}{(4\pi r)^2}$$

- For a fixed antenna gain (directivity), the attenuation drops quadratically with increasing frequency
- This makes sense since our capture area is proportional to the wavelength squared, which is decreasing
- But for a fixed area that we can dedicate to the antenna, the antenna gain increases with frequency. This can be realized as a dish antenna or an array

$$\frac{P_r}{P_t} = \frac{A_{e1} A_{e2}}{r^2 \lambda^2}$$

Advantages of Antenna Array
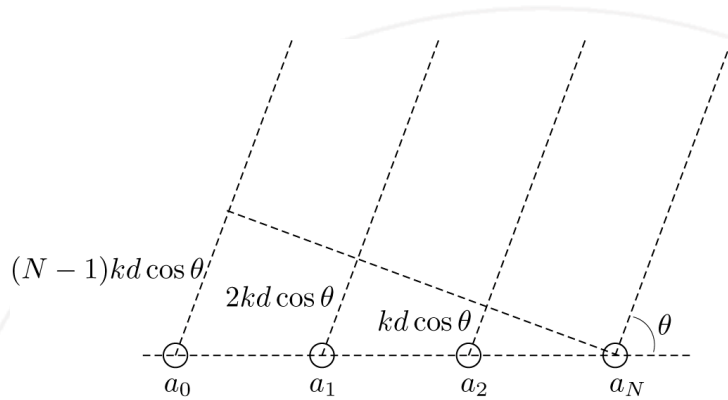
- Antenna array is dynamic and can point in any direction to maximized the received signal
- Enhanced receiver/transmitter antenna gain (reduced PA power, LNA gain)
- Improved diversity
- Reduced multi-path fading
- Null interfering signals
- Capacity enhancement through spatial coding
- Spatial power combining means
    - Less power per PA (~10 mW)
    - Simpler PA architecture
    - Automatic power control
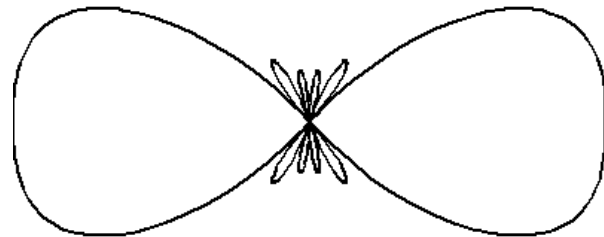
$$f(\theta) = a_0 e^{j(N-1)\overbrace{kd\cos\theta}^{\Psi}} + a_1 e^{j(N-2)\Psi} + \cdots + a_N$$

Spatial Capacity Improvement

- The antenna array transceiver can be represented as an $N \times 1$ MIMO system

$$\vec{y} = H\vec{x}$$

- If we factor the matrix H using the singular-value decomposition (SVD), we can rewrite this relationship in orthogonal coordinates

$$H = USV^T \qquad S = \begin{pmatrix} \sigma_1 & & \\ & \sigma_2 & \\ & & \ddots \end{pmatrix}$$

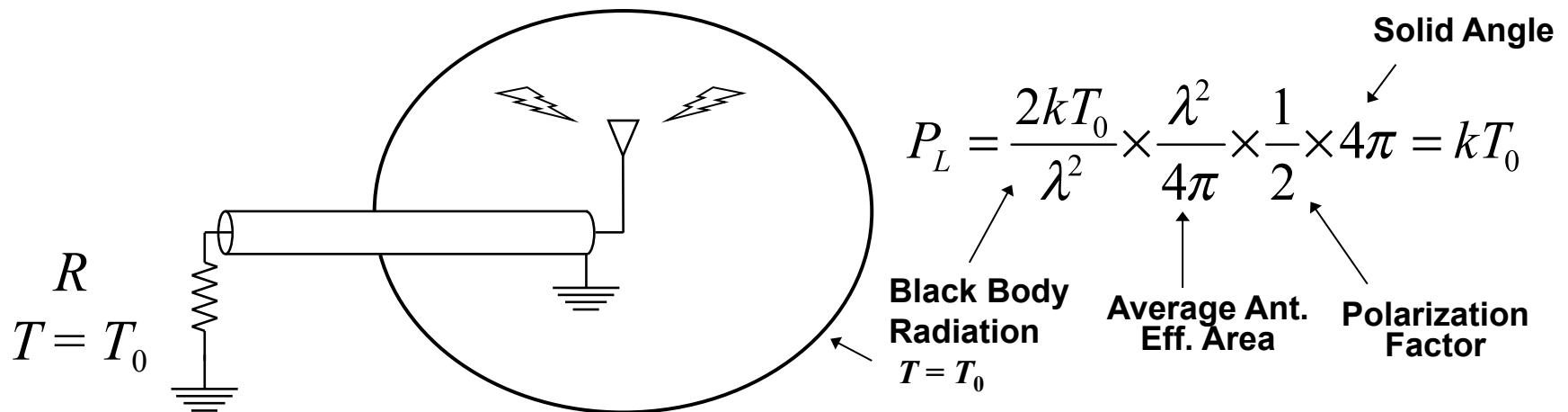where U and V are orthogonal and S is a diagonal matrix. Let's pre-multiply the above equation by U^T

$$\underbrace{U^T \vec{y}}_{y'} = S \underbrace{V^T \vec{x}}_{x'} \qquad \vec{y'} = S\vec{x'}$$

- The MIMO channel has been de-coupled into $N - N_s$ independent channels! N_s is the number of singular values of the matrix, corresponding to the non-zero values of S
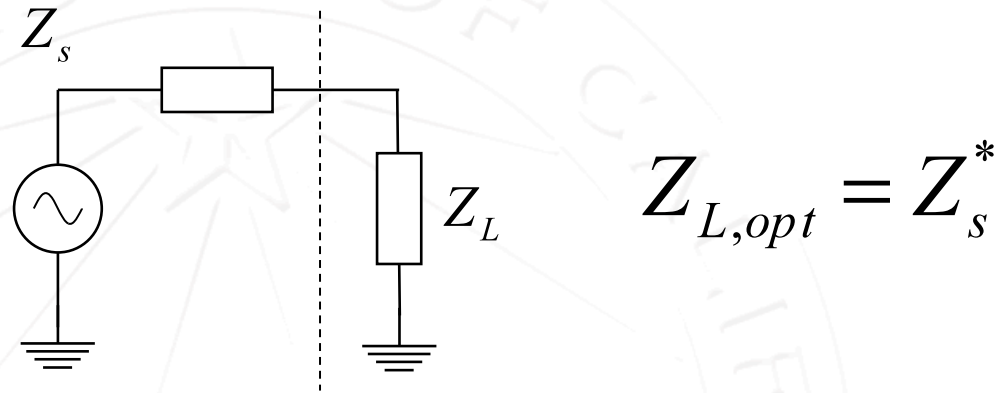
Noise in Communications

- The temperature T_0 of a system is proportional to the average kinetic energy. In a resistor the atoms are in constant thermal agitation and charge carriers (electrons) constantly collide with host atoms losing energy. Accelerating (decelerating) electrons radiate energy and act as a source of energy loss.
- Consider a resistor at thermal equilibrium with a "Black Body"
- Antenna picks up black body radiation and delivers power to a matched resistor. The resistor, though, remains at temperature T_0. The resistor, therefore, must also deliver an equal amount of energy to the antenna.
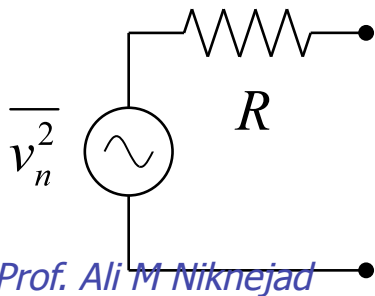
$$P_L = \frac{2kT_0}{\lambda^2} \times \frac{\lambda^2}{4\pi} \times \frac{1}{2} \times 4\pi = kT_0$$

Solid Angle

R

$T = T_0$

Black Body Radiation
$T = T_0$

Average Ant. Eff. Area

Polarization Factor

Equivalent Noise Voltage

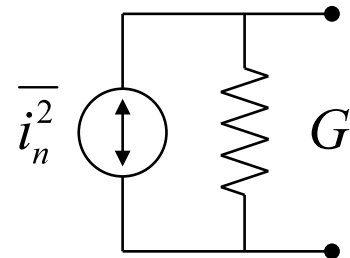- Maximum power transfer theorem:

$$Z_{L,opt} = Z_s^*$$

- A resistor at temperature T can deliver a maximum power of kT into a matched load
- Equivalent model has of noiseless resistor plus a voltage or current noise source

$$\overline{v_n^2} = 4kTR \ [\text{V}^2/\text{Hz}]$$

$$\overline{i_n^2} = 4kTG \ [\text{A}^2/\text{Hz}]$$

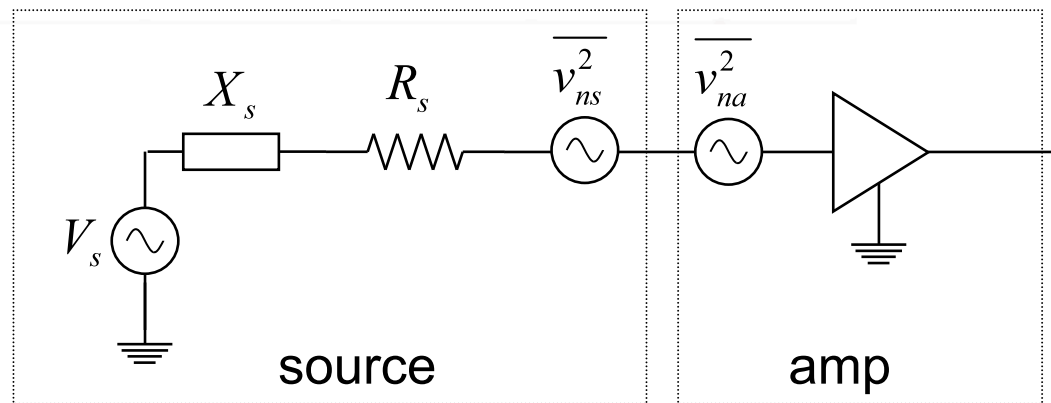# Noise Figure of a Two-Port

- Ratio of output available noise power to input avail noise power from a source at 290 °K

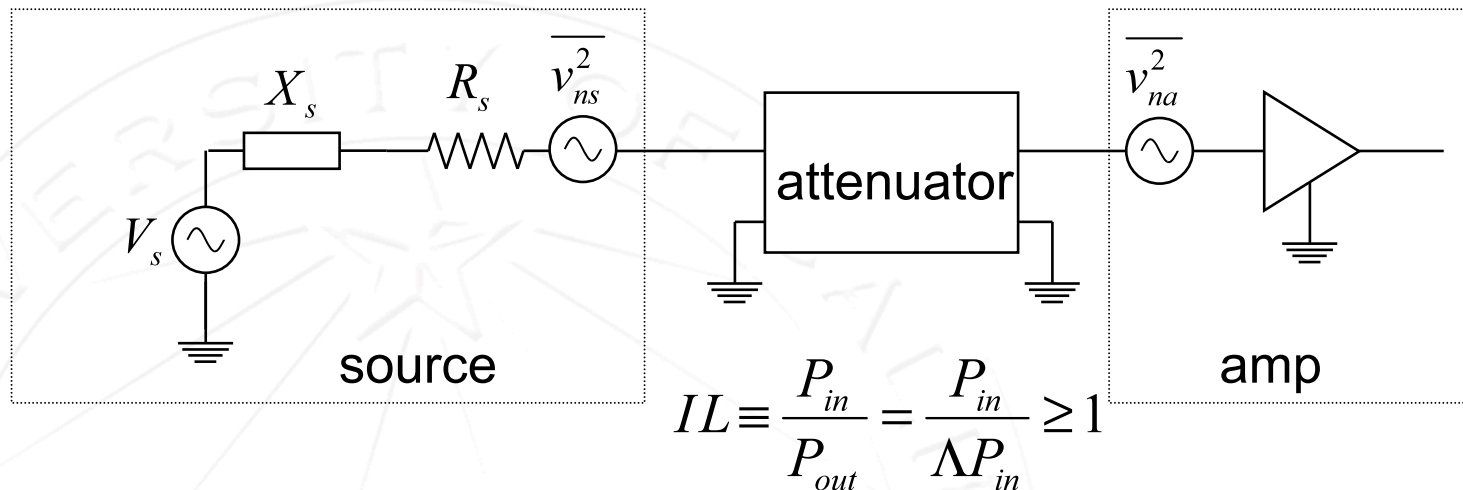$$F = \frac{\text{Noise Power Avail at Output}}{\text{Noise Power Avail From Source}}$$

$$= \frac{N_{amp} + N_{src}}{N_{src}} \geq 1$$

- If we reflect the noise power to the input of the amplifier…

source   amp

$$F = \frac{\overline{v_{na}^2} + \overline{v_{ns}^2}}{\overline{v_{ns}^2}} = \frac{V_s^2 / \overline{v_{ns}^2}}{GV_s^2 / G\left(\overline{v_{na}^2} + \overline{v_{ns}^2}\right)} = \frac{SNR_{input}}{SNR_{output}}$$

Noise Figure of an Attenuator

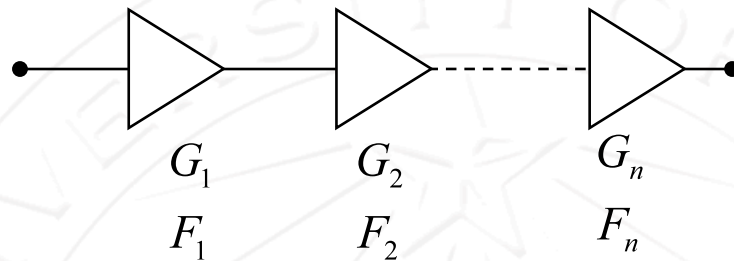$$IL \equiv \frac{P_{in}}{P_{out}} = \frac{P_{in}}{\Lambda P_{in}} \geq 1$$

- Assume attenuator is lossless and matched
- Available noise power at output remains unchanged (matched)
- Available noise power from source is attenuated

$$F = \frac{\overline{v_{ns}^2}}{\Lambda \overline{v_{ns}^2}} = \frac{1}{\Lambda} = IL$$

- Noise Figure degraded by insertion loss dB for dB

Noise Figure of Cascaded Blocks

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

- Classic result for a matched system (*EECS 142*)
- Noise Figure does not take into account gain
- A wire of zero length has *F=1* but it is not useful
- Another metric: Infinite Cascade Noise Figure

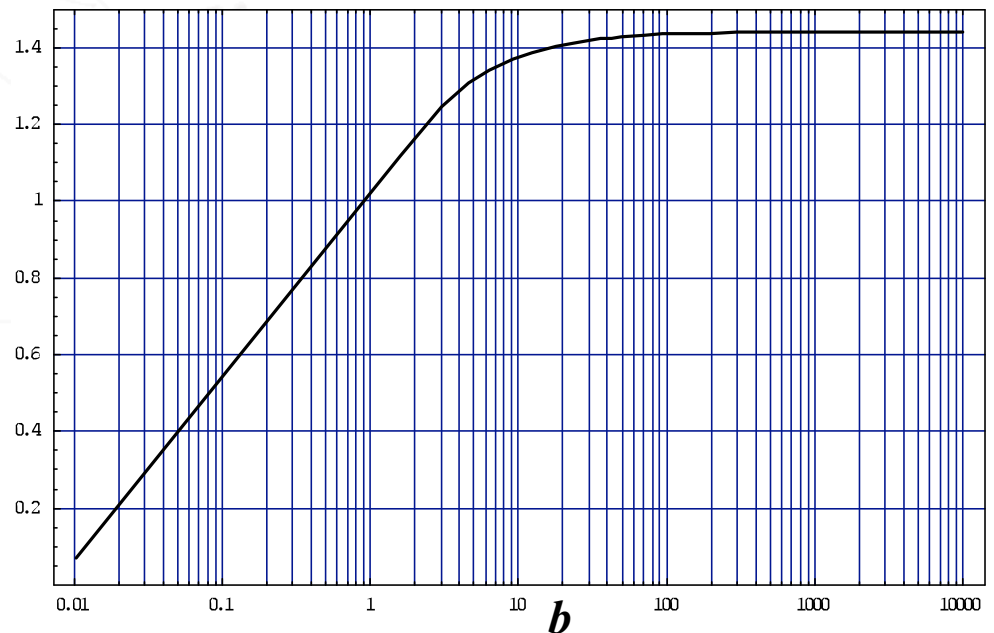$$F_\infty = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots = \frac{F - 1/G}{1 - 1/G}$$

Shannon's Capacity Theorem

- For a channel with bandwidth B and given amount of noise (AWG), what's the maximum channel capacity for error free transmission?
- Claude Shannon (1948) theoretical performance bound:

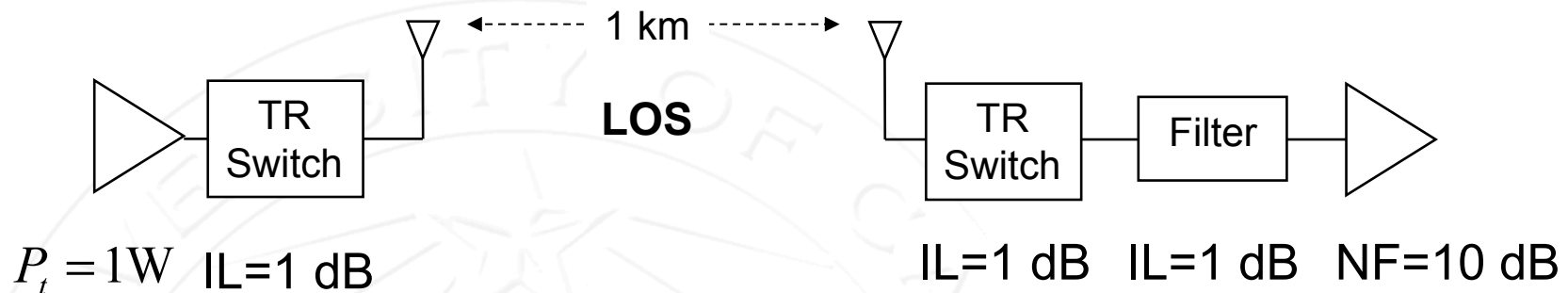$$C = B \log_2 \left(1 + \frac{S}{N} \right)$$

$$c \equiv \frac{CN_0}{S} = \frac{BN_0}{S} \log_2 \left(1 + \frac{S}{N_0 B} \right)$$

$$c = b \log_2 \left(1 + \frac{1}{b} \right)$$

- C is the capacity (bps), S and N are the signal and noise powers
- The natural BW of the system is defined as $b = S/N_0$
- Using more BW than b does not significantly improve capacity

Typical Link Budget

$$\frac{P_r}{P_t} = \frac{\lambda^2 D_1 D_2}{(4\pi r)^2} = -100.4\,\mathrm{dB}$$

■ What's the capacity of this system? Assume omni directional antennas and a center frequency of 2.5 GHz, B = 100 MHz

$$P_{ant} = P_t - 1\,\mathrm{dB} - 100.4\,\mathrm{dB} = -71.4\,\mathrm{dB}m$$

$$SNR_{ant} = P_{ant} - 10\log kTB = -71.4\,\mathrm{dB}m + 94\,\mathrm{dB}m = 22.6\,\mathrm{dB}$$

$$SNR_{IF} = SNR_{ant} - NF = 22.6\,\mathrm{dB} - 12 = 10.6\,\mathrm{dB}$$

$$C = 3.64B \qquad \Rightarrow \qquad R = 364\mathrm{Mbps}$$

Typical Receiver Architecture
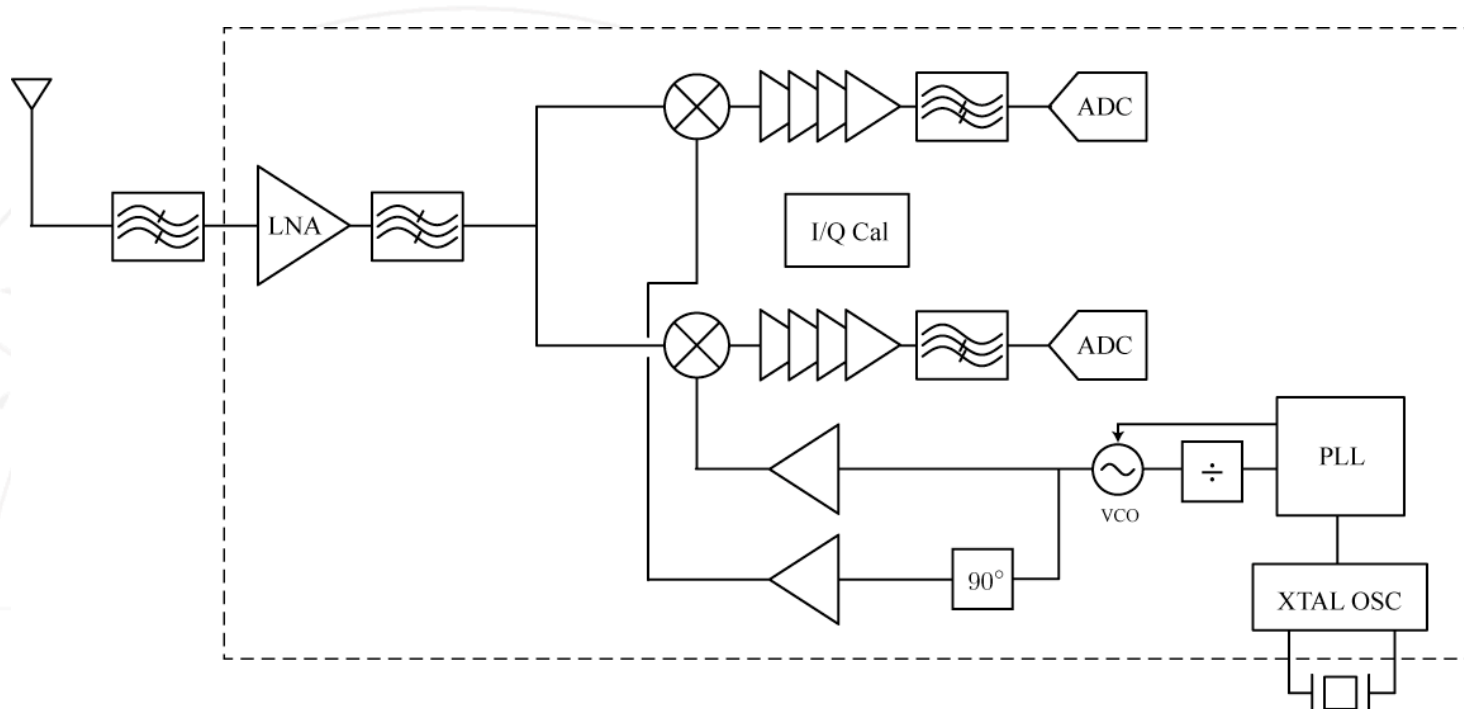
- Use low or zero-IF to eliminate need for high-Q high frequency tunable filter. Most receivers use off-chip front-end filters and crystal references.

- Most modern systems perform final demodulation in digital domain

Receiver Goal #1: Amplification

- A detector works well with a fairly strong signal. For instance, if the input referred noise is 10's mV, the input signal should be 10X or more larger.

- Since the received power can vary greatly in dynamic range from very weak levels (-110 dBm) to fairly strong signals (-20 dBm), the receiver should have *variable* gain in the range of 0 – 100 dB.

- Without variable gain, the dynamic range of a receiver is limited since the detector or ADC may have a limited range. For an ADC it's roughly 6 dB/bit.

- In gaining up the signal, we have to keep the noise and distortion small relative to the signal power to meet the required SNDR.

# Receiver Goal #2: Freq. Translation

- As the carrier frequency and the information signal are at very disparate frequencies (say 1 GHz versus 1 MHz), we require modulation and demodulation

- Also, we prefer to work at lower frequencies to save power. We would like to frequency translate our signal to "baseband" and perform filtering/gain rather than at RF. This means we should "mix" the signal as soon as possible.

- We shall see that mixers are prone to frequency translate many different frequencies to the same "IF", and so they are relatively noisey (NF ~ 10 dB). We must precede the mixers with a low noise amplifier (LNA) to overcome this noise.

Receiver Goals #3: Filtering

- Imagine trying to receive a signal at a power of -100 dBm in the presence of an inband "jammer" or interference signal with power -40 dBm.

- We would like to set the gain at 100 dB, but this would severely compress the receiver due to the jammer.

- We must therefore apply a sharp filter to remove the jamming signal before we apply all the gain.

- If these jammers (blockers/interferers) are not attenuated, they tend to reduce the gain of the signal (P_{-1dB}), increase the noise figure of the receiver (through mixing noise in other bands to the same IF, especially phase noise), and produce intermodulation products that fall in band and reduce the sensitivity of a receiver

Filtering in Receivers
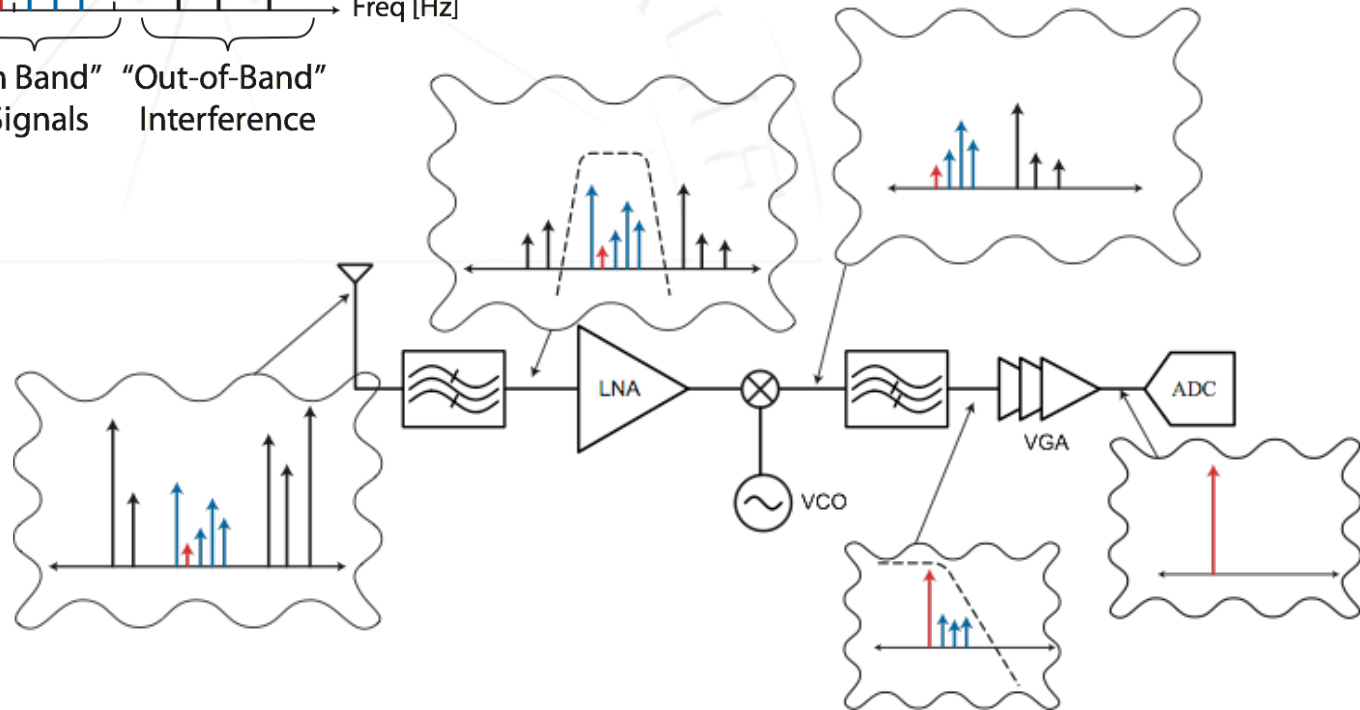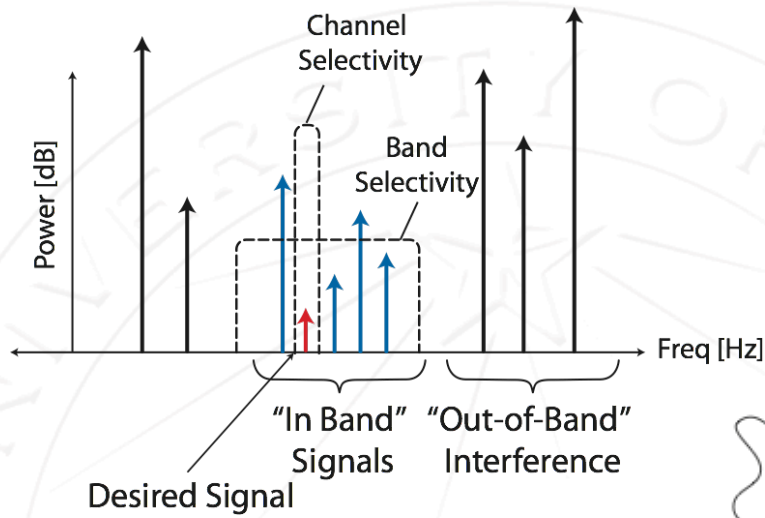
Transmitter Block Diagram
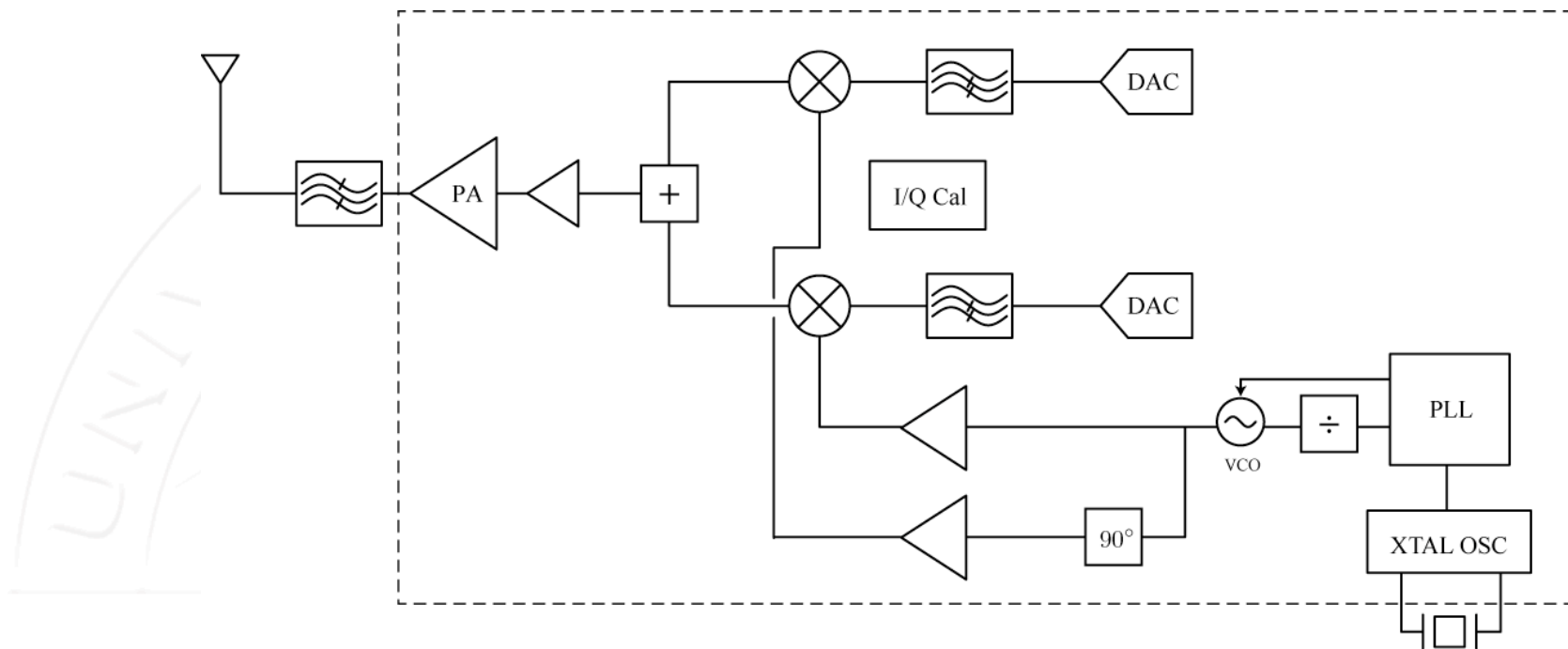
- DAC: Digital to Analog Converter

- Mixer: Up-conversion mixer (I/Q)

- VGA: To select desired output power

- Frequency Synthesizer: stable carrier frequency

- PA: Power Amplifier

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.

XTAL Ref   Phase/Frequency Detector   VCO
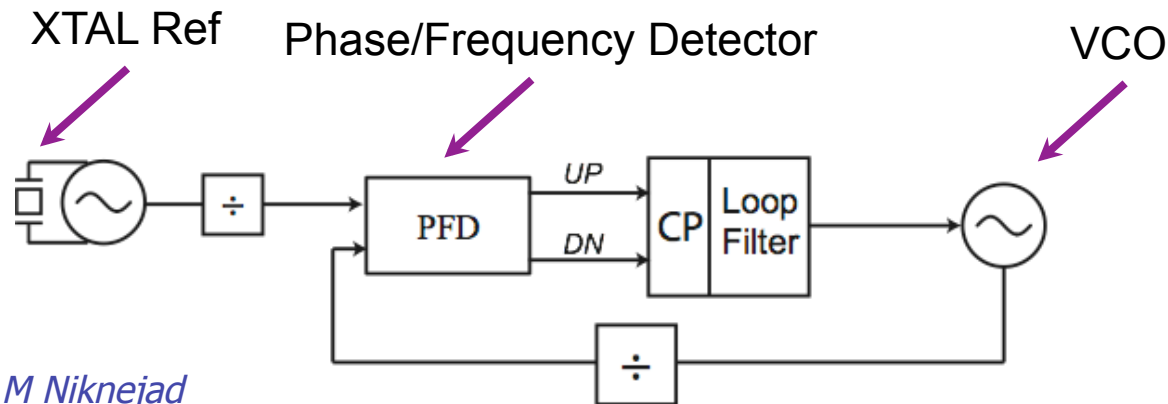
Example: Cellular Phones

Feature	GSM / GPRS EDGE	WCDMA
Defined by	ETSI	3GPP/ETSI
Access	FDM/TDMA	CDMA / Full Duplex
Modulation	0.3 GMSK (1bit/Symbol)	QPSK
Modulation Filter	0.3 Gaussian	Root Raised cosine a=0.22
Chan. Spacing	200(kHz)	5MHz
Symbol or Bit Rate	270.8bks/sec	3.84 Mcps
RF Frequencies (MHz)	GSM900 880-915 DCS1800 1710-1785 PCS1900 1850-1910 (RX) 925-960 180	Band(I,II,III, & V) I : 1920-1980(TX) I : 2110-2170(RX) II : 1850-1910(TX) II : 1930-1990(RX) III : 1710-1785(TX) III : 1805-1880(RX) V : 824-849(TX) V : 869-894(RX)
Approx. Range	~5km	~5km
Peak TX Power	33dBm (MS)	24dBm
Key Hardware & Performance Challenges	(RX) Blocking @ 3MHz (RX) (TX) TX noise in RX band @ 20MHz offset from carrier	TX-to-RX leakage @ 20MHz from carrier. Creates IP2, IP3 and NF issues.
EVM	5º (RMS), 20º(peak)	17.5%
Synt. Settling Time	180μsecs	
Websites	www.etsi.org www.3gpp.org	www.3gpp.org

- 1G: AMPS, NAMPS; FM/FDMA
- 2G: GSM/TDMA/FDMA
- 2.5G: GPRS, Edge
- 3G: W-CDMA, CDMA-2000
- 3.5G: HSDPA (High Speed Downlink Packet Access)
- 4G: LTE (Long Term Evolution)

Example: WLAN

- Spectrum is in the ISM bands (2.4 GHz, ~5 GHz) (unlicensed)

- Relatively high data rate compared to cellular but reduced range

- MIMO version is a draft standard but already shipping

- 802.11b/g only has 3 non-overlapping channels and a peak data rate of 11/54 Mb/s.

- 802.11n uses up to 4 spatial streams and acheives 270 Mb/s.

802.11(abg)	802.11n
IEEE	IEEE
CSMA-CA	CSMA-CA
DBPSK DQPSK OFDM BPSK	64 QAM on 108 OFDM
Gaussian or vendor specific	TBD
Depending on region and flavor. Chan. BWs include 10 MHz, 25 MHz, 30 MHz	20MHz or 40MHz (yet TBD)
11 Mchips/sec	Above 100Mbps
802.11b 2.4-2.48 GHz	802.11b 2.4-2.48 GHz
802.11a & g 4.9-5 GHz (Japan) 5.03-5.091 GHz (Japan) 5.15-5.35 GHz (UNII) 5.47-5.75 GHz 5.725-5.85 GHz (ISM, UNII)	802.11a & g 4.9-5 GHz (Japan) 5.03-5.091 GHz (Japan) 5.15-5.35 GHz (UNII) 5.47-5.75 GHz 5.725-5.85 GHz (ISM, UNII)
~100m	~300m
20dBm(bg) Country specific	TBD
Modulation of 64 QAM places high linearity demand on TX & RX, in addition to challenging synthesizer performance.	Cross channel interference.
5%(RMS)	TBD
www.wi-fi.org www.ieee802.org/11	www.wi-fi.org

Example: RFID

- Two main types: inductive (13.56 MHz) and RF (900 MHz)
- Tags are "passive" (no batteries) and use energy of field to power up circuitry
- Simple low power circuitry, extremely inexpensive (cents)
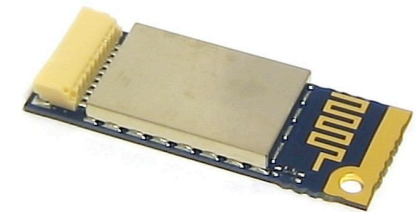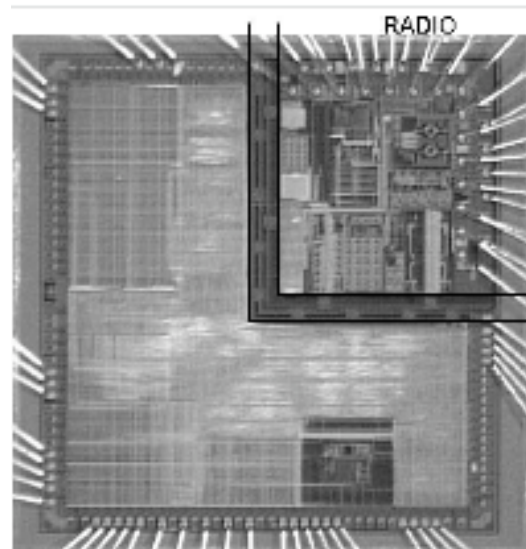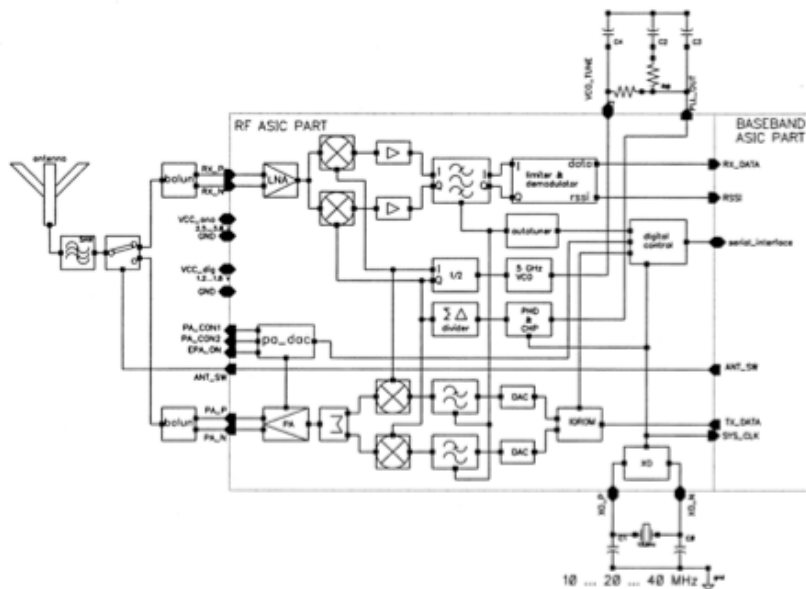

Electronic Toll

Alien Technology

Images from Wikipedia and alientechnology.com
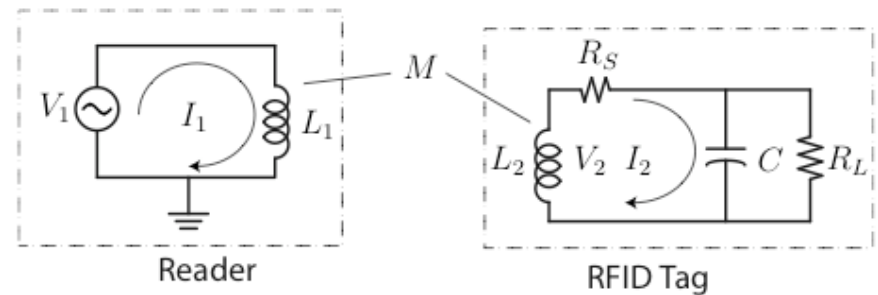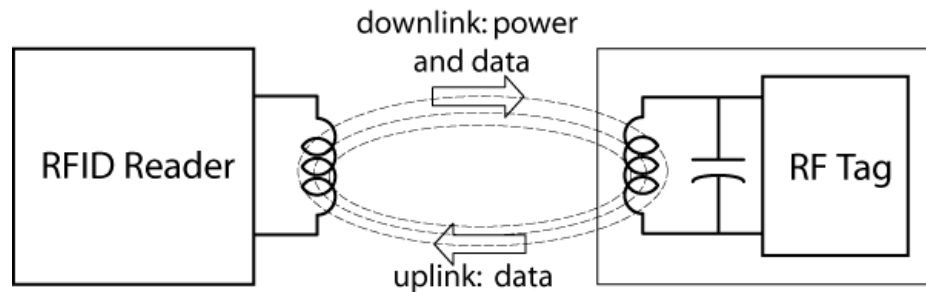
Example: Bluetooth

- Personal Area Network (PAN)
- Basic: 2.4 GHz ISM band, Frequency-Hopping Spread Spectrum (FHSS), Gaussian Phase Shift Keying (GFSK), 1 Mb/s. Typical power consumption ~ 50 mW → 50 nJ/bit
- Enhanced: Version 2.0 + EDR → 3 Mb/s
- Proposed WiMedia Alliance: 53 – 480 Mb/s

Source: Wikipedia

PTM van Zeijl, et al, Solid-State Circuits Conference, 2002. Digest of Technical

Example: Zigbee

- Based on the IEEE 802.15.4-2006 standard for wireless personal area networks (WPANs)

- ZigBee is a low-cost, low-power, wireless mesh networking standard

- ZigBee operates in the industrial, scientific and medical (ISM) radio bands; 868 MHz in Europe, 915 MHz in countries such as USA and Australia, and 2.4 GHz in most jurisdictions worldwide

- 5 MHz channels, BPSK and QPSK used, up to 250 kb/s, transmit power ~ 0 dBm (10 m)

- Issues: Energy per bit is significant. Typical radios consume 30 mW of power → 120 nJ/bit (low energy??)

Example: UWB

- Uses 3.1-10.6 GHz spectrum

- Transmit power must fall below -41. dBm/MHz (see mask)

- Must use at least 500 MHz of bandwidth or 20% (6 GHz → 1.2 GHz)

- Average power ~ 10*log(500) -41 dBm = -14 dBm

Two proposals:

Carrier free direct sequence ultra wideband technology (impulse radio)

MBOFDM, Multi-Band OFDM UWB. Transmit a 500 MHz wide OFDM signal. *Fast* (9ns) frequency hopping to mitigate interference.

Short range high speed communication link (480 Mb/s in a few meters). Ranging (radar) also possible.
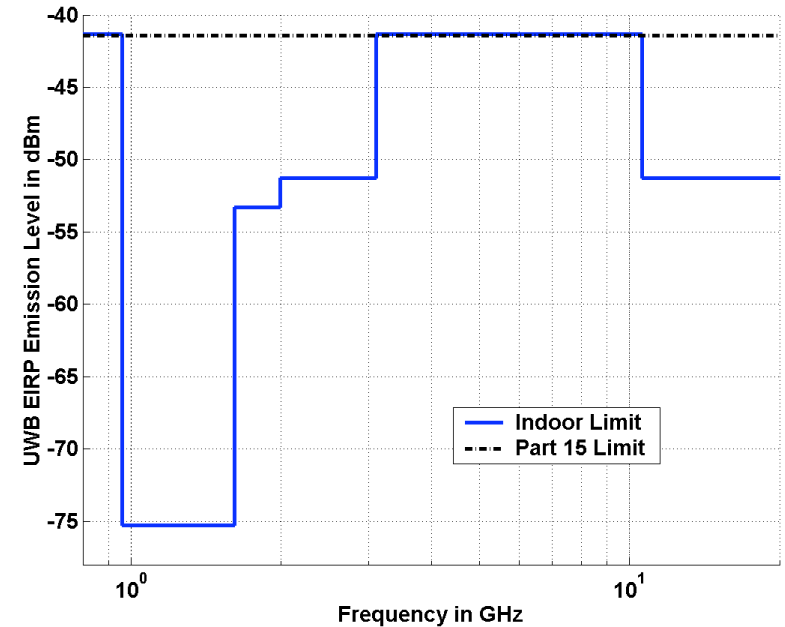
UWB Circuit Challenges

- Fast settling synthesizer (requires mixers and multiple VCOs)

- Wideband circuits (7 GHz), relatively low noise across a wideband. Wideband low dispersion antennas

- Low power baseband (FFT or equalization) – see figure
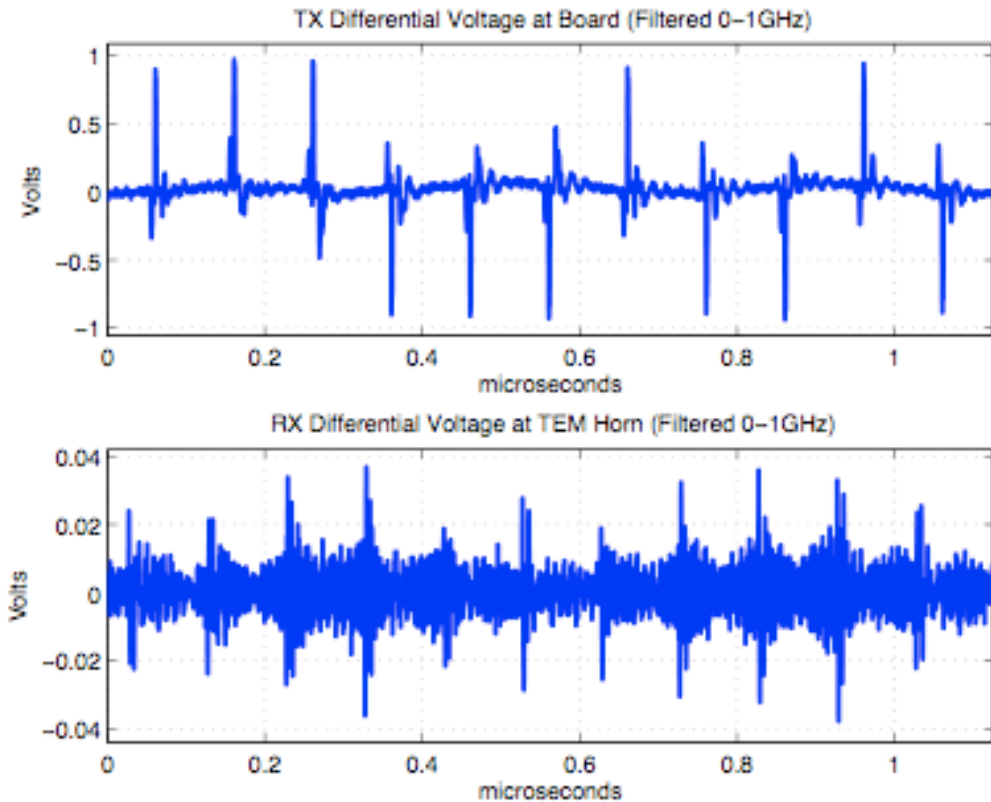
Source: " A Baseband, Impulse Ultra-Wideband Transceiver Front-end for Low Power Applications," by Ian David O'Donnell, Technical Report No. UCB/EECS-2006-47

3-6 GHz is crowded?
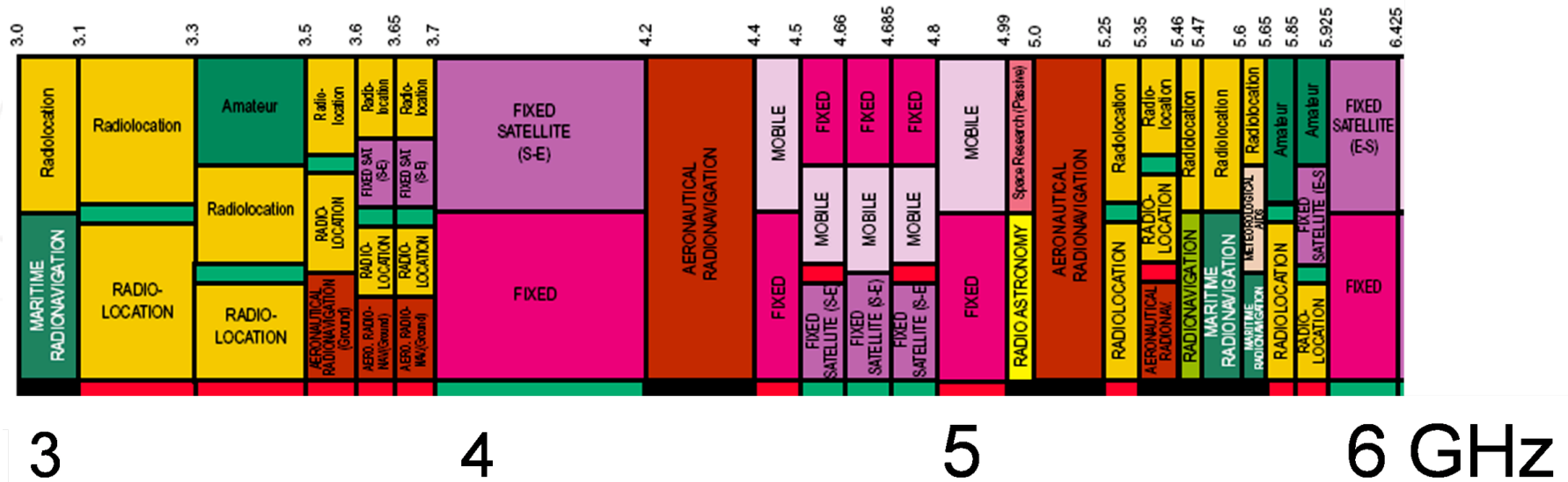
Spectrum Reality

- Measurements performed in downtown Berkeley (BWRC)
- 3-6 GHz poorly utilized
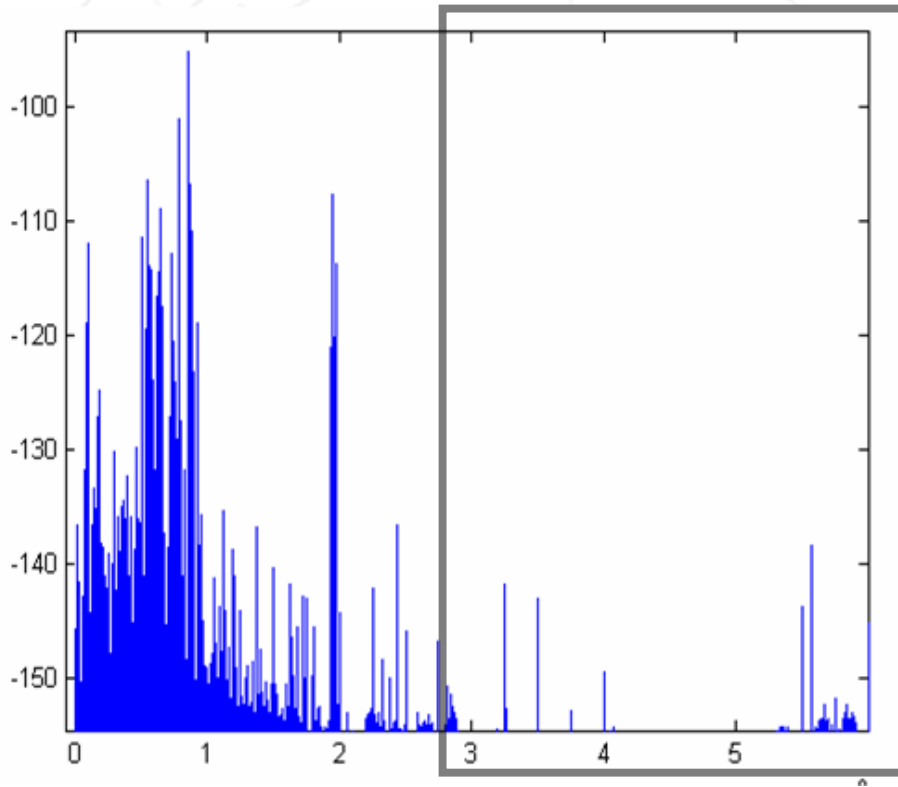
2.4 GHz Band

#	📶	🔒	Description
1	19		AirBears [00135F]
1	50		Yali's Cafe [Netopia]
3	10	WEP	Lindow Lab [00146C]
3	25	WPA	Wire(less) [00C049]
6	16	WEP	Freezer [001495]
6	13	WEP	kathyzhang [0016B6]
6	15	WPA	Pachytesta [001451]
6	16	WEP	2WIRE250 [000D72]
6	14		linksys [Linksys]
6	14	WEP	2WIRE326 [000D72]
6	27	WPA	BENDOVER [Netgear]
6	15	WEP	Portnoy [D-Link]
6	14		Jfresh [Linksys]
9	20		AirBears [0002A5]
9	21		KuriyanAir [Netgear]
11	18		calendar [Netgear]
11	24		AirBears [Orinoco]
11	0		psr.brk.barwn.net [T...

Netopia — Yali's Cafe — 11 Mbps — 1

university

café signal

apartments…

university

Cognitive Radio

- Assign primary users to spectrum

- Allow non-primary users to utilize spectrum if they can detect non usage

- If primary users needs spectrum, move to a new frequency band

Café Analogy…

Treat spectrum like a café….

Cafe Seating Policy

- If you arrive in an empty cafe, you take the first seat. Probably the best seat ...

- After the last table (next to kitchen or worse) is occupied, where do you go?

- Why not share a table? Which table do you share? The biggest and "prettiest" one ...

- But why not sit at those "reserved" tables?
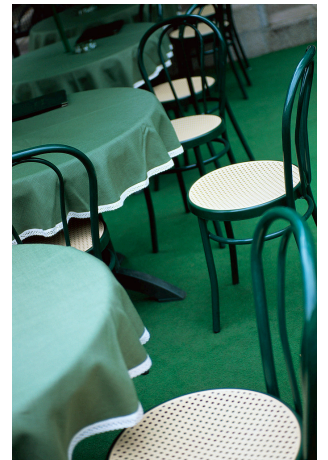
UWB (sit under table)

- Build a radio that utilizes existing spectrum without interference to "primary" users
- Transmit power below EMI mask of -41.3 dBm/MHz (bury yourself in noise)
- Utilize coding and large bandwidth to transmit information

Big Tables at 60 GHz
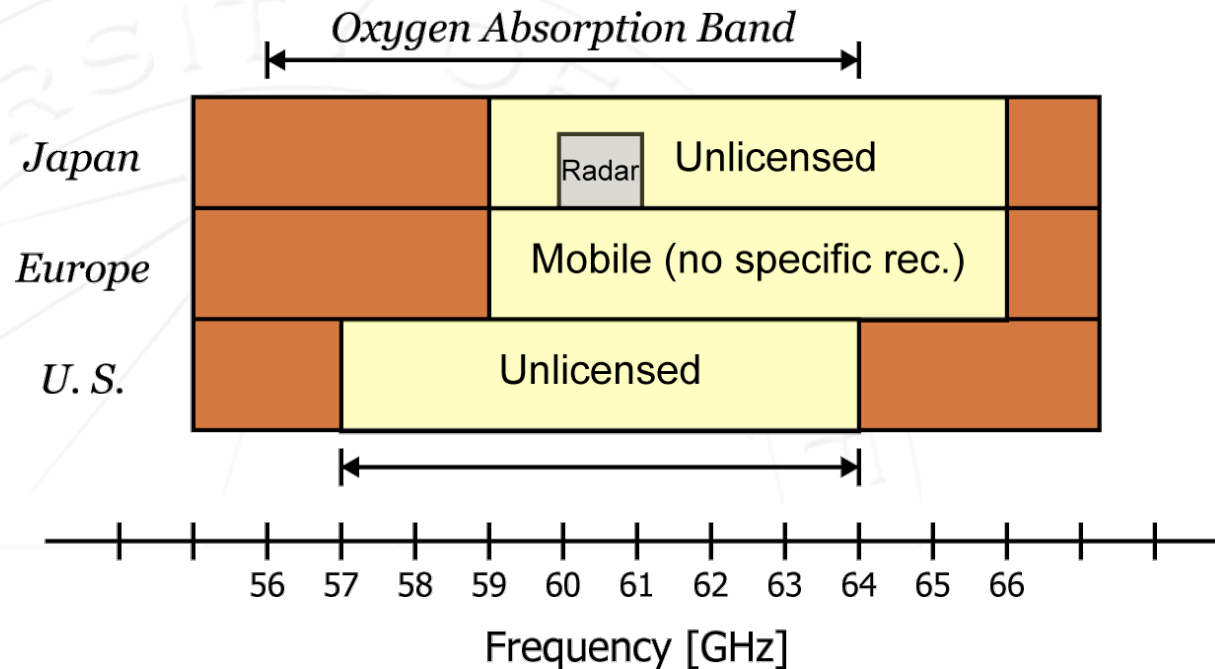
- But there's lots of bandwidth to be had! 7 GHz of unlicensed bandwidth in the U.S. and Japan
- Same amount of bandwidth is available in the 3-10 UWB band, TX power level is 10^4 times higher!

New Paradigms

- Underlay: Restrict transmit power and operate over ultra wide bandwidths (UWB)

- Far away: Operate in currently unused frequency bands (60 GHz)

- Overlay: Share spectrum with primary users

Comparison

	UWB	60 GHz	CR
Spectrum Access	underlay	unlicensed	overlay
Carrier	[0-1],[3-10] GHz	[57-64] GHz	[0-1],[3-10] GHz
Bandwidth	> 500 MHz	> 1 GHz	> 1 GHz
Data Rates	~ 100 Mb/s	~ 1 Gb/s	~ 10-1000 Mb/s
Spectral Efficiency	~0.2-1 b/s/Hz	~ 1 b/s/Hz	~ 0.1-10 b/s/Hz
Range	1-10 m	1-10 m	1m - 10 km

CR in Action
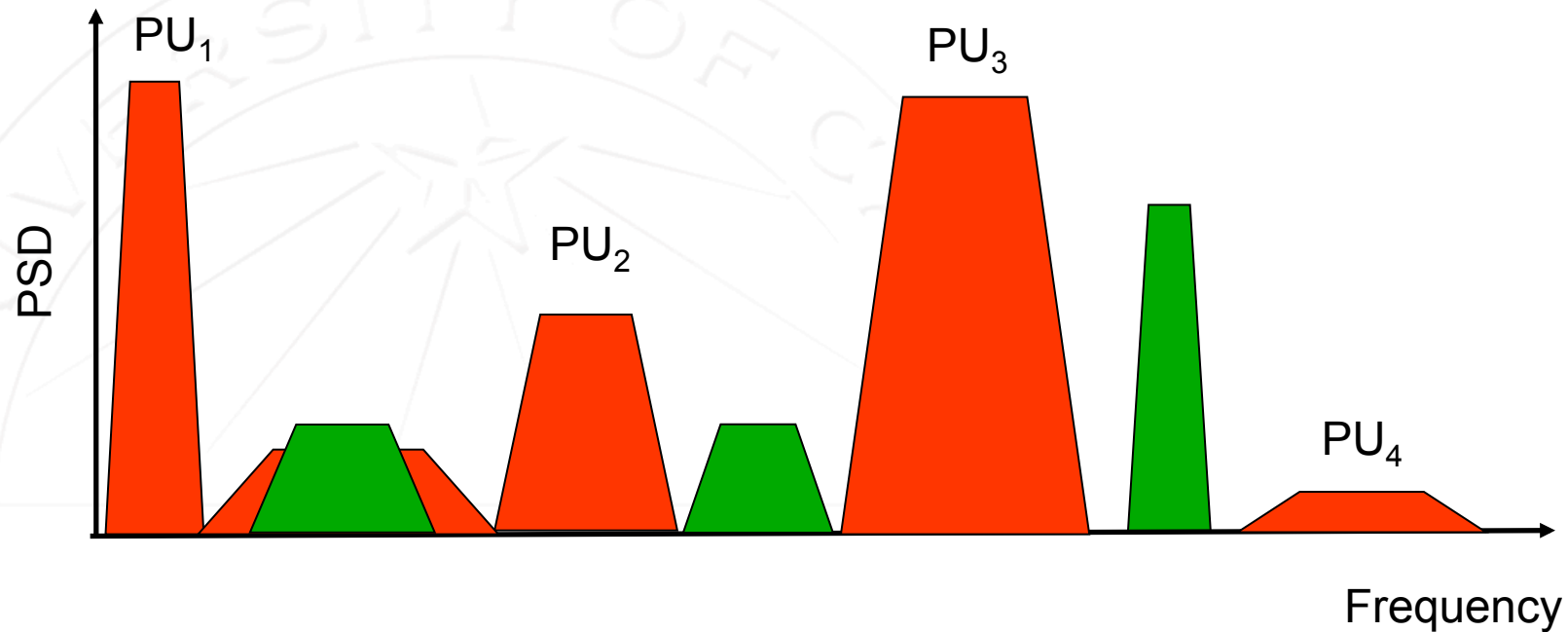
- sense the spectral environment over a wide bandwidth
- reliably detect presence/absence of primary users
- transmit in a primary user band only if unused
- adapt power levels and transmission bandwidths to avoid interference to any primary user

Can you hear me?
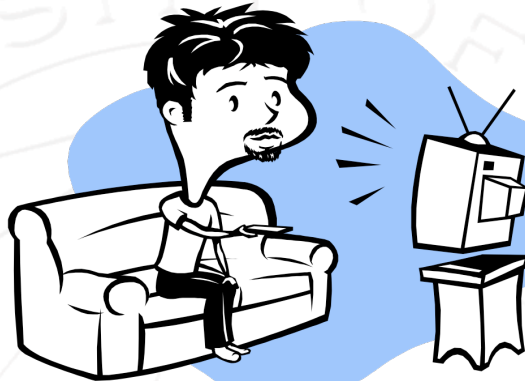
- If a CR cannot detect the presence of a primary user, that doesn't mean it's unused!
- Broadcast receiver is a classic example. The CR may be in a signal fade nearby and jam a TV station since it thinks no one is watching …

Wideband High DR Front-End
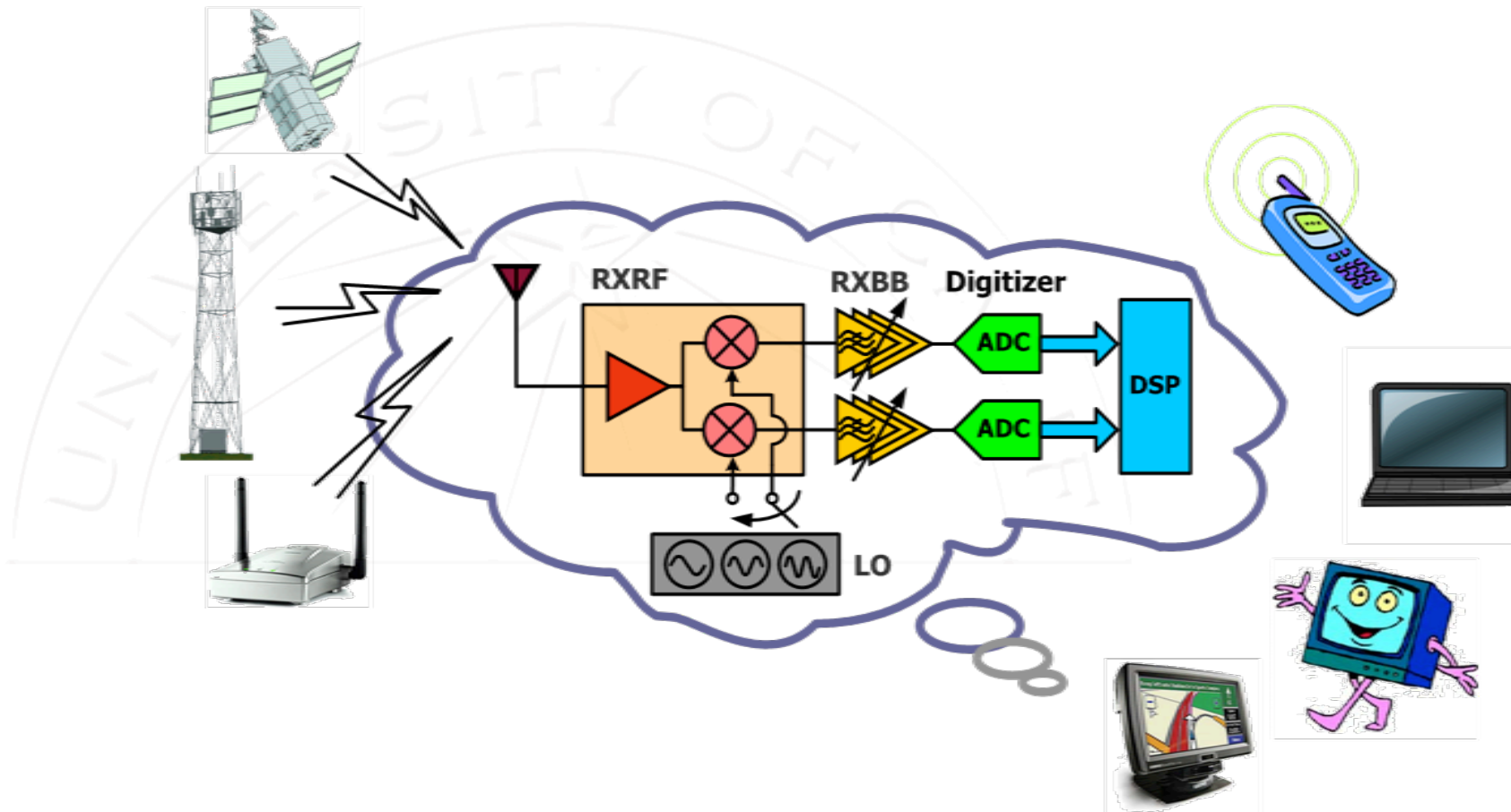
- Broadband, high dynamic range, reconfigurable front-end
- Can we design such a front-end using 45nm CMOS? 32nm? When is the party over?

Low Power Phased Array
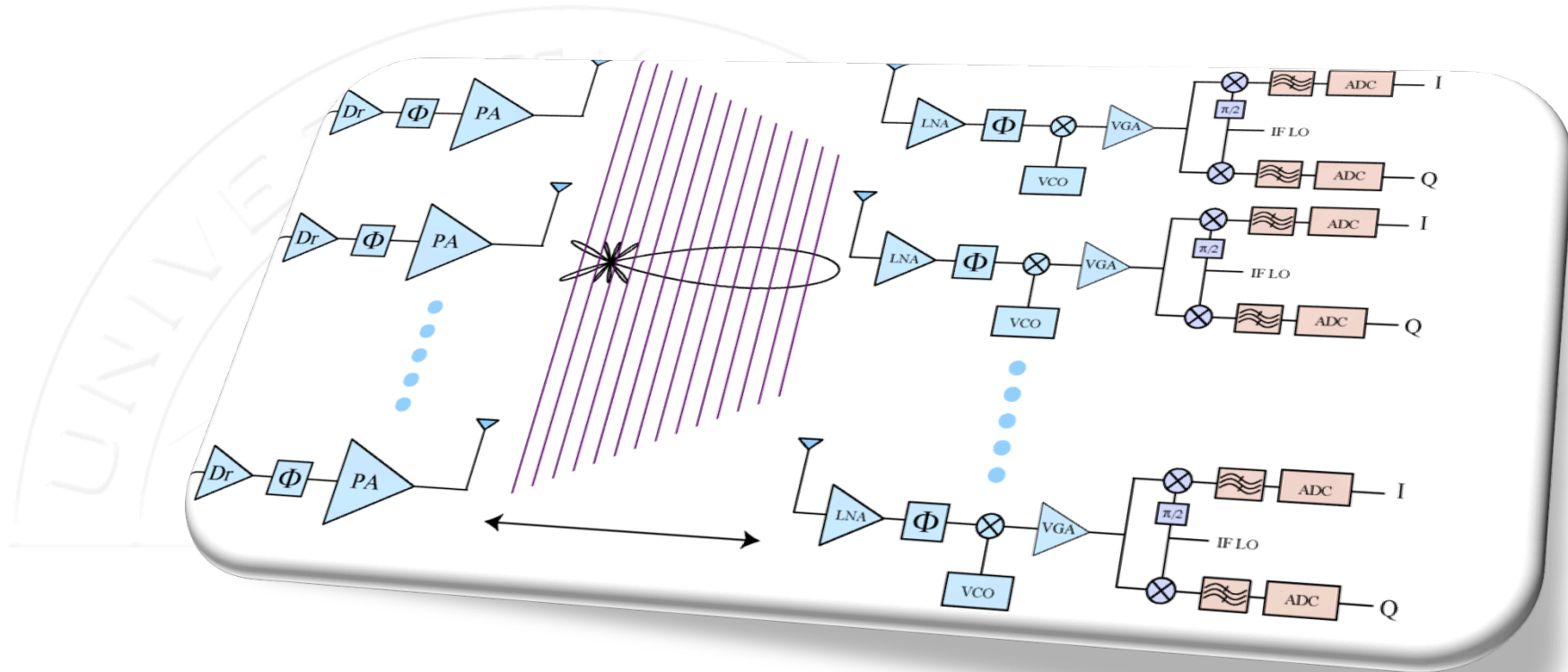
- A fully integrated low-cost Gb/s data communication using 60 GHz band.
- 10 Gb/s at 100mW per channel should be possible! (10pJ/bit) at 10's of meters

Jagadis Chandra Bose
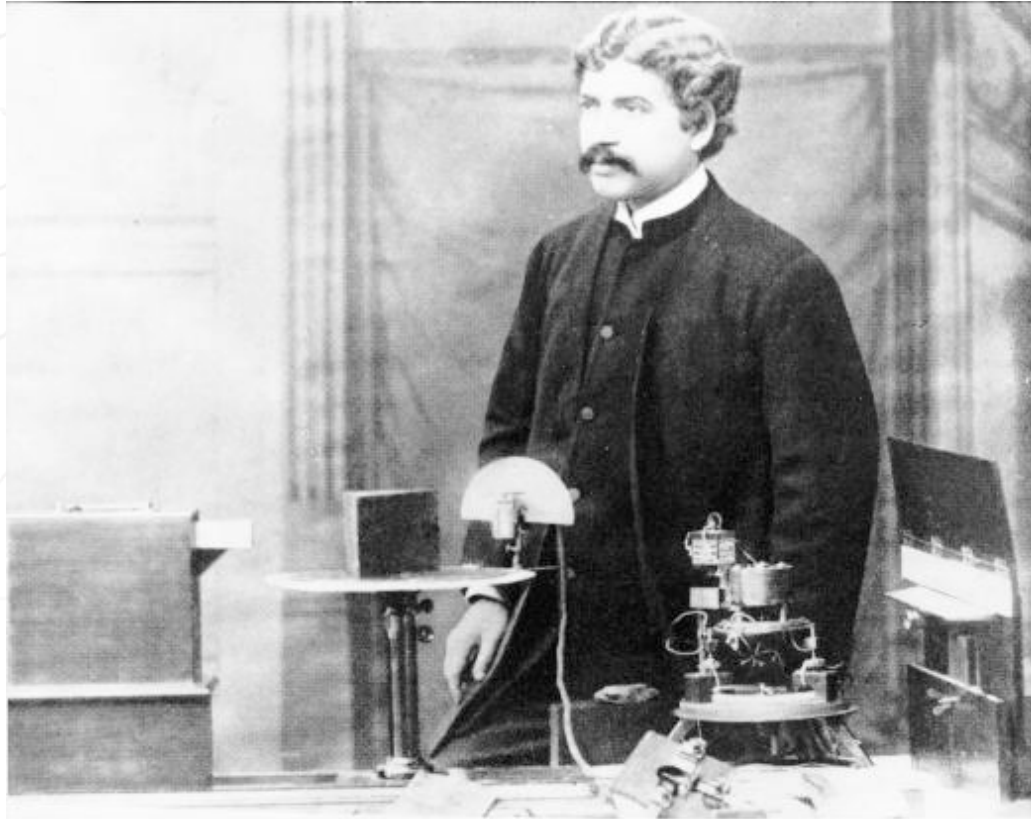
- "Just one hundred years ago, J.C. Bose described to the Royal Institution in London his research carried out in Calcutta at millimeter wavelengths. He used waveguides, horn antennas, dielectric lenses, various polarizers and even semiconductors at frequencies as high as 60 GHz…" (http://www.tuc.nrao.edu/~demerson/bose/bose.html)

The "Last Inch"

Point-to-Point Link
100m~1km
100Mbs~1Gbs

High speed wireless LAN

100 Mbs ~1Gbs

Last mile Broadband

802.15.3 mmWIG

Wireless home video and data link
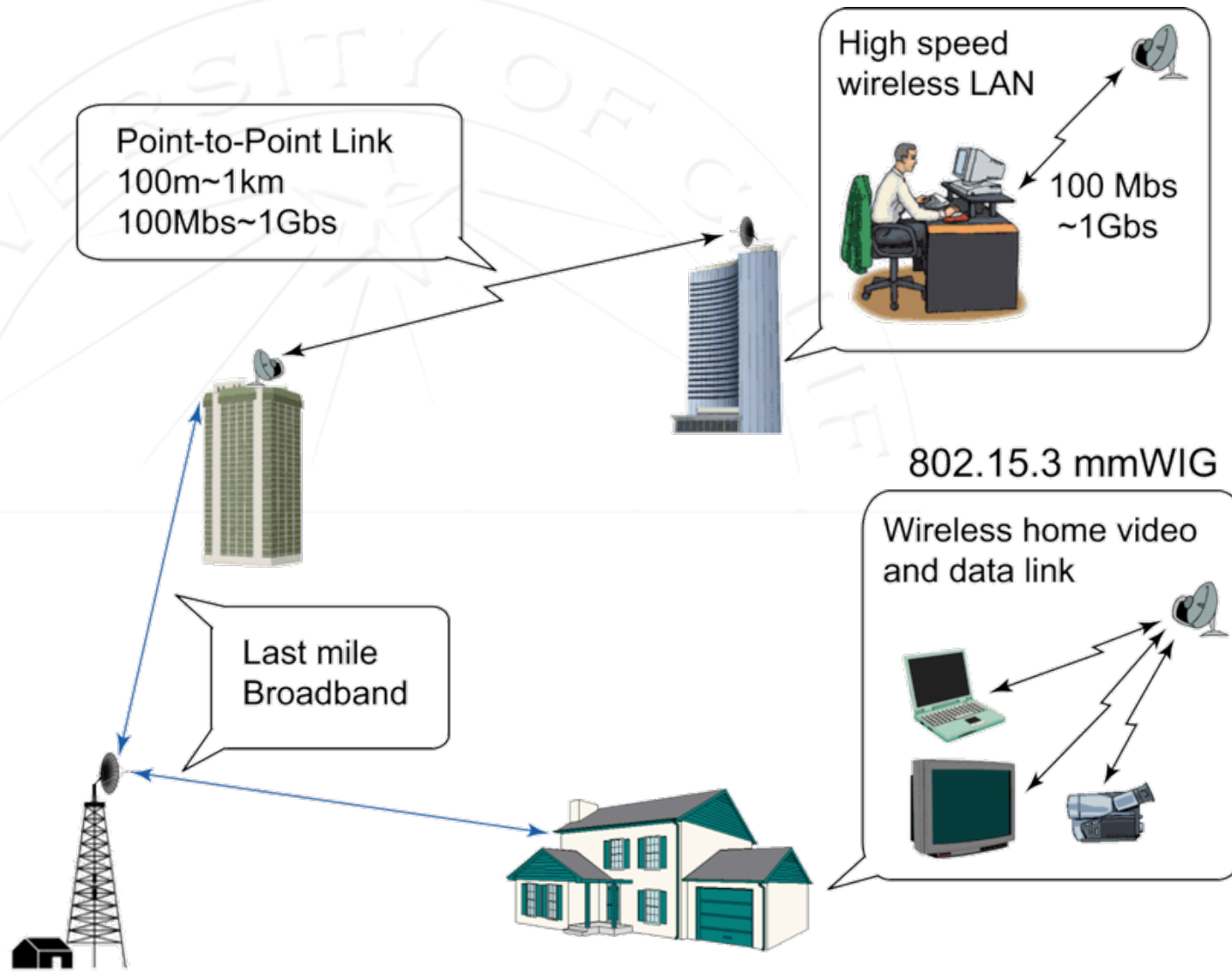
Universal Mobility

Thirst for Bandwidth
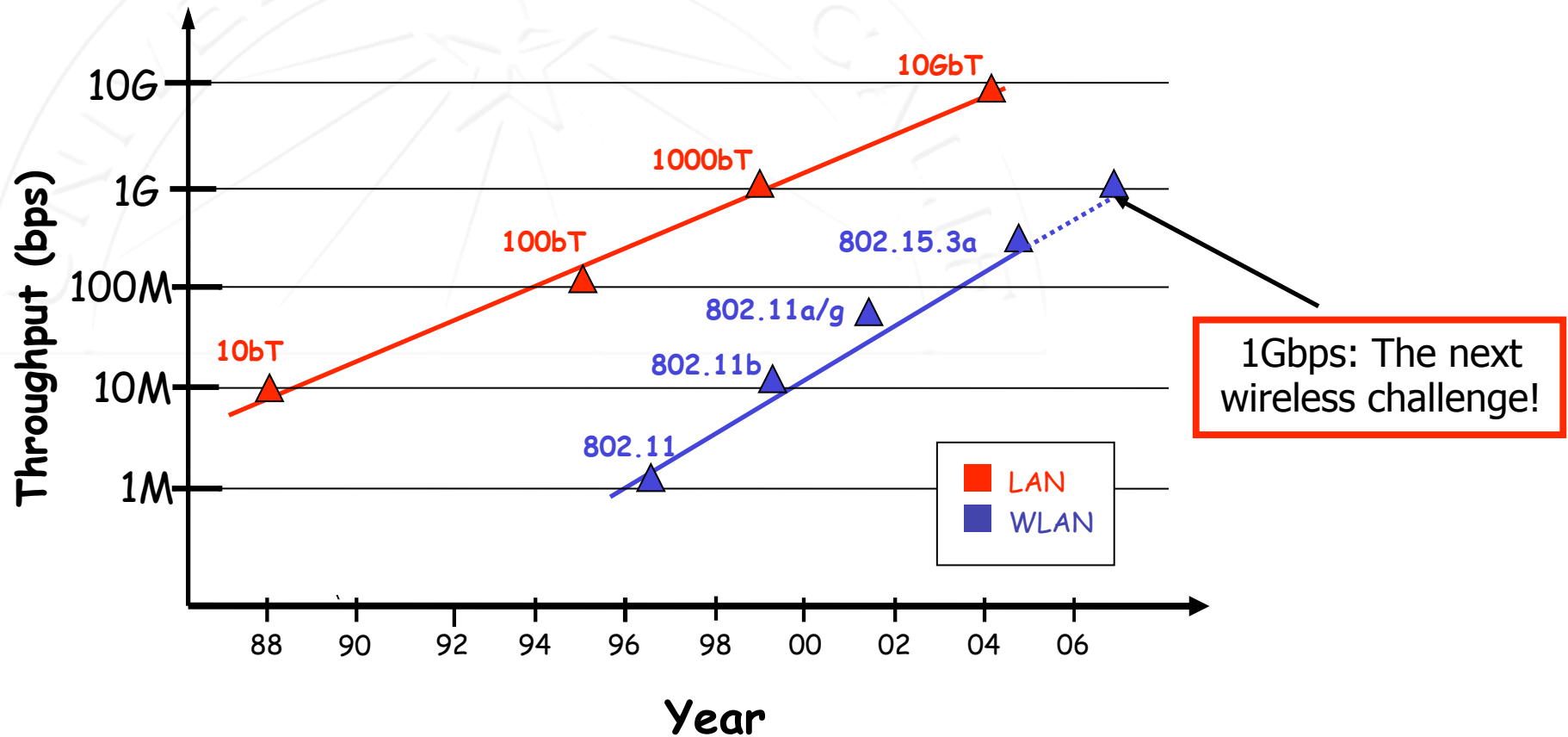
CMOS Technology Trends
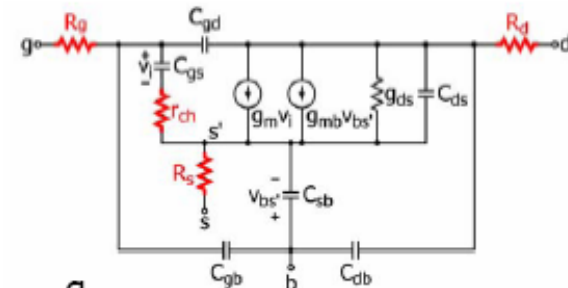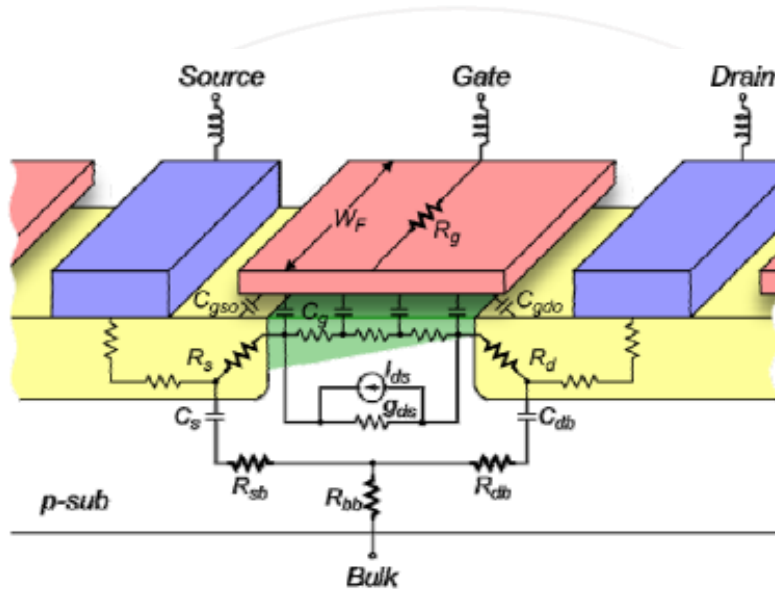
$$f_t \approx \frac{g_m}{2\pi C_{gg}}$$

$$f_{max} \approx \frac{f_t}{2\sqrt{R_g(g_m C_{gd}/C_{gg}) + (R_g + r_{ch} + R_s)g_{ds}}}$$

	130nm	90 nm	65nm	45nm
F_t	70 GHz	100 GHz	170 GHz	280 GHz
F_{max}	135 GHz	200-300 GHz	340 GHz	560 GHz
NF_{min} (60 GHz)	4-5 dB	3-4 dB	3 dB	2.3 dB
Scaled F_t	70 GHz	101 GHz	140 GHz	202 GHz

Measured   ITRS+projection

BWRC

Modeling Issues

- Transistors
  - Compact model not verified near fmax/ft
  - Table-based model lacks flexibility
  - Parasitics no longer negligible
  - Highly layout dependent

- Passives
  - Need accurate reactances
  - Loss not negligible
  - Scalable models desired

BWRC Measurement Setup

E5810A Gateway

HP-IB

LAN

IC-CAP 2002

Agilent 4284 LCR Meter

HP-IB
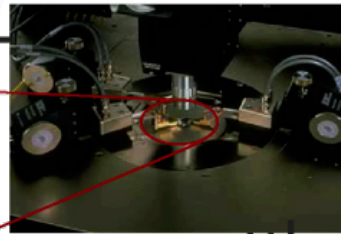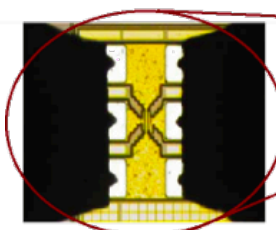
DUT/Probe Station

Cascade Microtech's
Summit 12000
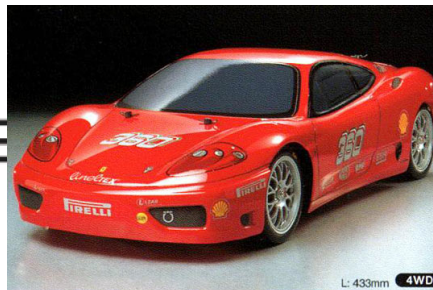
L: 433mm 4WD

A 65 GHz synthesizer and
a mm-Wave down-converter
extend measurement range of
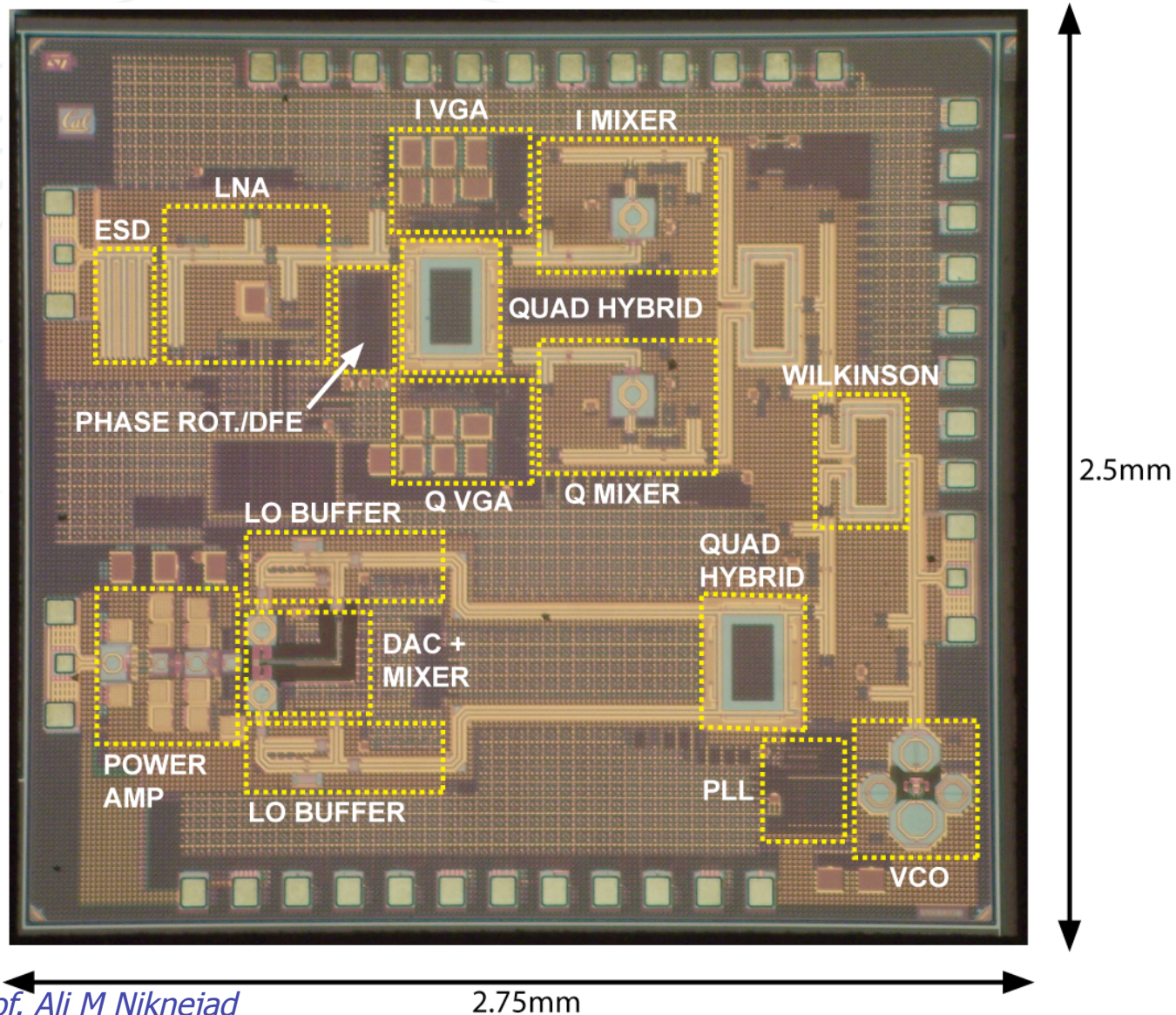HP 8970B and HP 8563E to 65 GHz

130nm Integrated Front-End
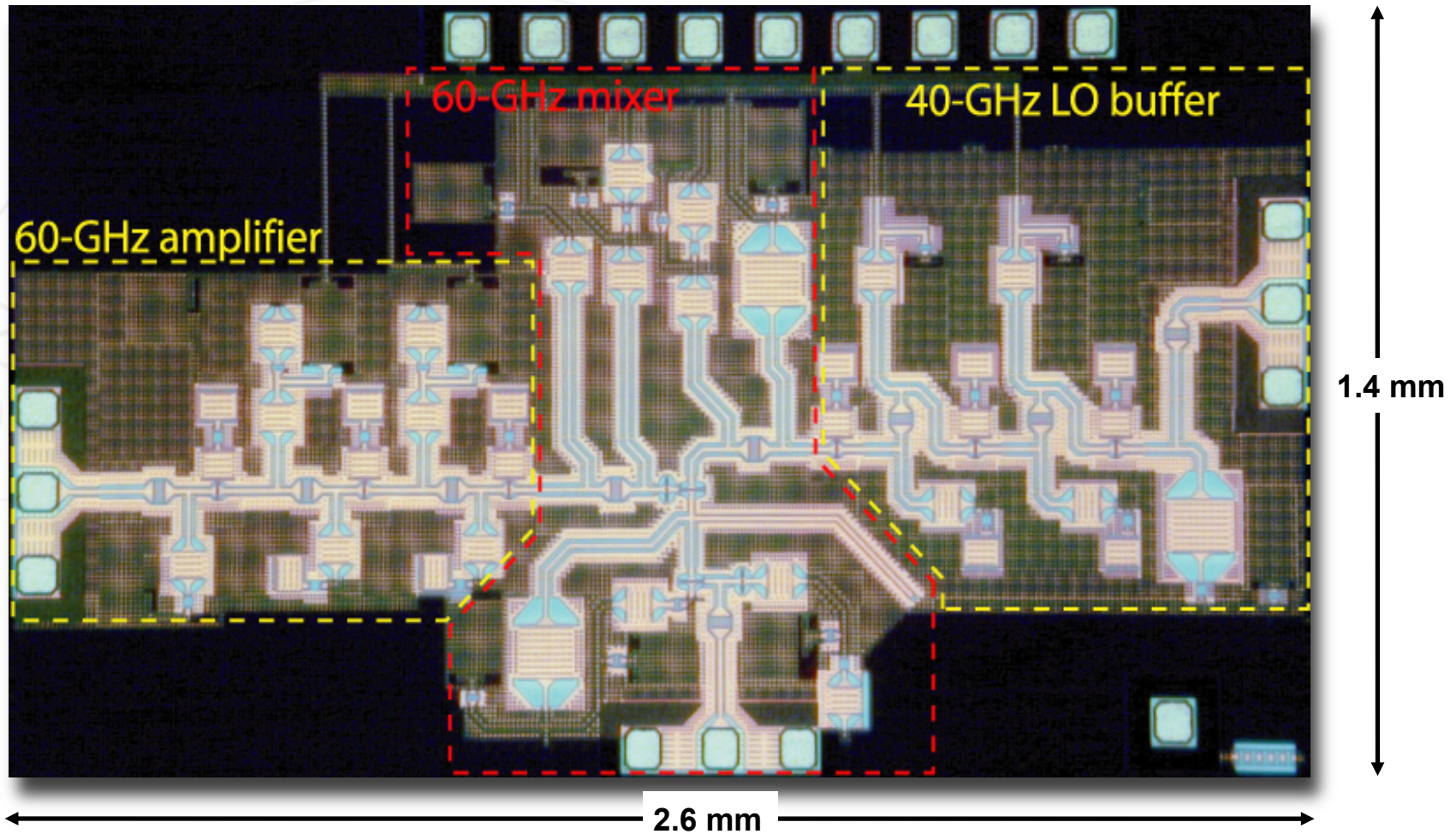
- 130 nm front-end: RF = 60 GHz, IF = 20 GHz
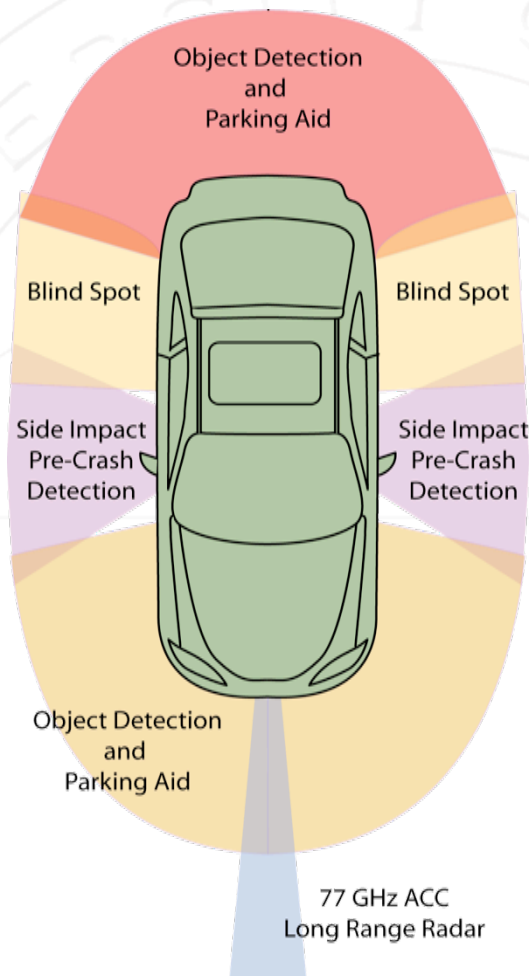- Measured conversion gain: 8 dB

Highly Integrated 60 GHz
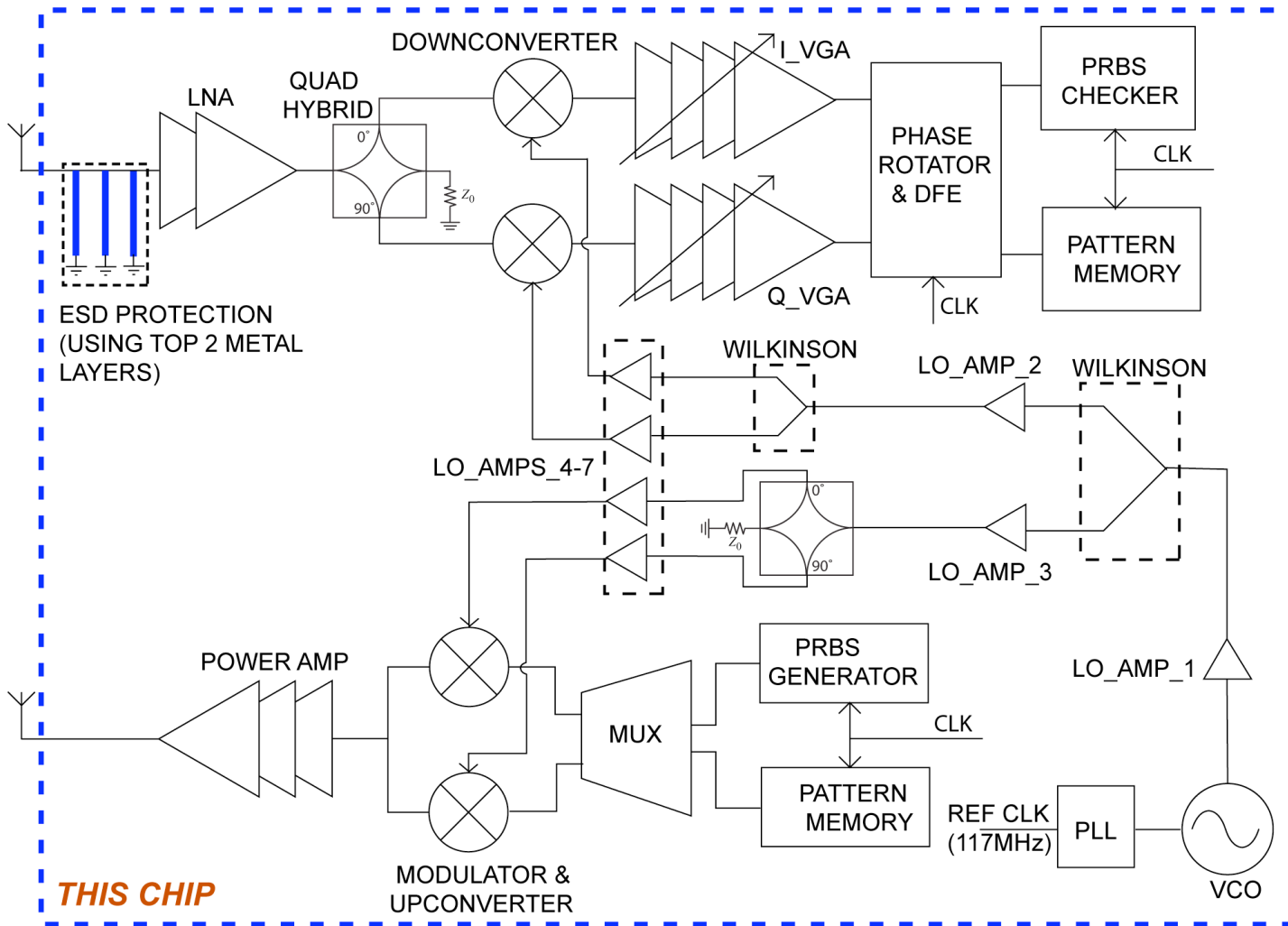
Berkeley 60 GHz Transceiver
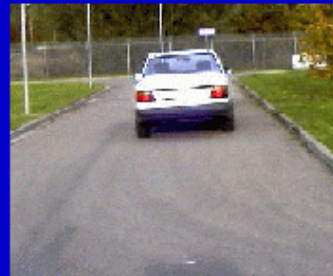
Automotive Radar

- Short range radar for parking assist, object detection
- Long range radars for automatic cruise control, low visibility (fog) object detection, impact warning
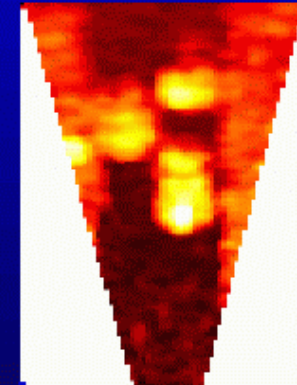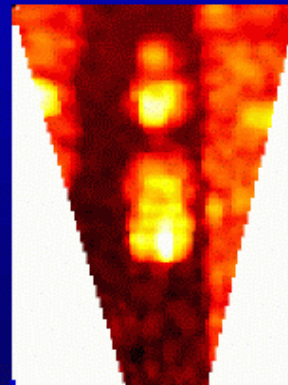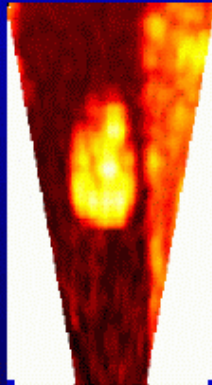- Long range vision: automatic driver

Radar Images

mm-Wave Imaging ... THz?

- Use of microwave scattering from objects to predict image

- A low-cost, noninvasive solution (meV versus keV)

- Active and Passive Microwave Imaging

- Ultrawideband imaging

- THz detection ... ?

freshly cut leaf

after 48 hours
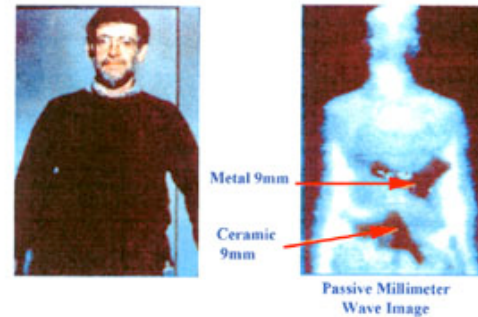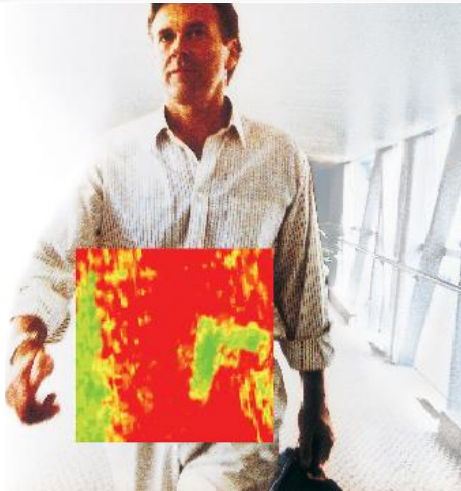
Water Concentration
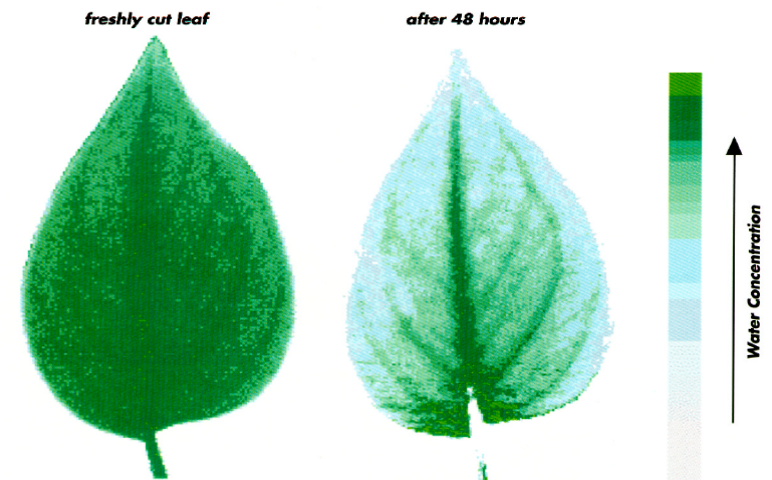
TeraView Ltd

Concealed Weapons Detection

Passive "Camera"
contains many receivers

QinetiQ Passive Array

TeraView Ltd

Distributed MIMO
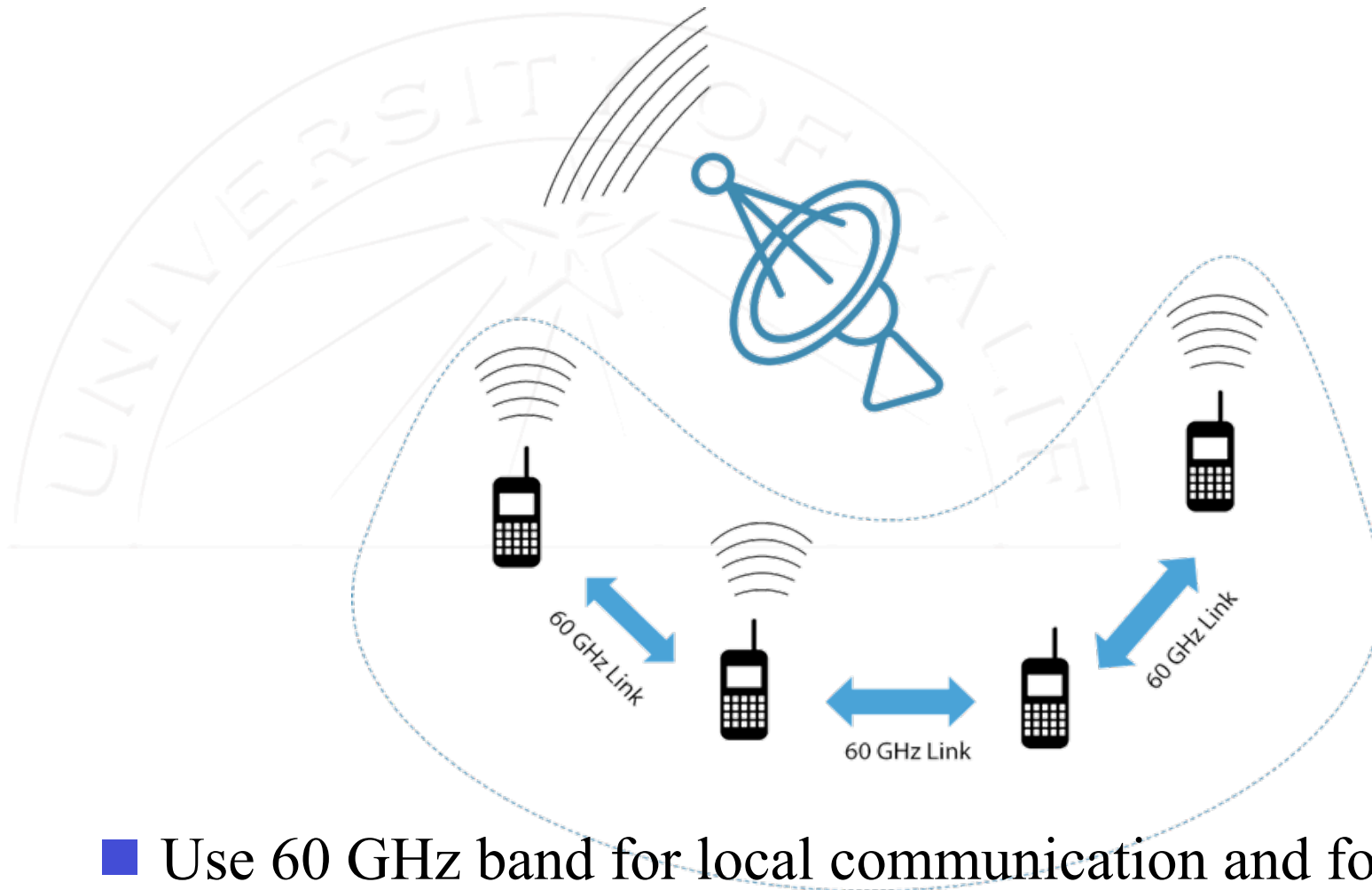
- Use 60 GHz band for local communication and form a MIMO at cellular bands using a cluster of radios.

Device Technology and Modeling

- Technology Evaluation
    - Comparison of active devices in various technologies: CMOS, BiCMOS, Bipolar, SiGe, GaAs, …

- Advanced MOSFET modeling
    - Short channel effects
    - BSIM3/4
    - EKV

- Passive Components
    - Inductors, capacitors, transformers, resistors…
    - MEMS resonators and switches

Small Signal Amplifiers

- Linear Two-Port Circuit Theory
  - Figures of merit
  - S-Parameters
  - Gain circles, stability circles
  - Matching Networks, Smith Chart

- Noise Analysis
  - Noise figure (review)
  - Noise circles on Smith Chart
  - Noise cancellation

Distortion and Non-Linearity

- Distortion and Dynamic Range Limitations
  - Low-frequency: Taylor series analysis (*review*)
  - High-frequency: Volterra series analysis
  - Harmonic, CM, IM, Compression, Blocking Performance
  - Distortion in wideband systems (Cable, CDMA, OFDM)
- High frequency distortion in BJT amplifiers
- Distortion in MOS amplifiers
  - MOS "sweet" spot, multi-gate biasing techniques

Power Amplifiers

- ## Power Amplifiers
  - Review of Classes A, B, C (*review*)
  - High-efficiency Classes E and F
- ## Power Combiners
  - Wilkinson, Transformers, "DAT"
- ## High efficiency power amplifiers
  - Doherty, Liu Transformer Combiner
- ## Transmitter Architectures
- ## Linearization

Mixers

- ## Mixers and Noise
  - Review of operation (*EECS 142*)
  - Time-varying systems and noise
  - Non-linear noise analysis and SpectreRF (PSS)
  - Sampling and sub-sampling

- ## Receiver Architectures
  - Complex modulation
  - Image rejection
  - Super-heterodyne, zero-IF, low-IF
  - "Digital" radios, low power radios

Oscillators & Frequency Synthesis

- Voltage Controlled Oscillators
  - Feedback Theory and Circuit Implementation (*review*)
  - Passive Devices and Resonant Tanks (*review*)
  - Crystal & MEMS Oscillators
  - Quadrature oscillators
  - Phase noise analysis; jitter
  - MOS varactor, DCO, capacitor banks
- Frequency Synthesizers
  - Review of PLL operation
  - High-speed frequency dividers
  - Integer-*N* and Fractional-*N* Architectures

Wideband Building Blocks

- Variable Gain Amplifiers
  - CMOS and bipolar realizations
  - Diff pair and Gilbert cell blocks
  - High-frequency distortion

- Wideband Building Block Circuits
  - Exp, Log, Multipliers, Square, Square Root
  - Absolute Value, Peak-Detectors, Limiters
  - High-speed I-to-V and V-to-I Circuits