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

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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

- 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

\[ SNR = \frac{P_{\text{sig}}}{P_{\text{noise}}} \]
Modulation and Demodulation

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

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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!
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

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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.

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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

Impulse Radios Seem “Simpler”

Sinusoidal Downconversion Radio

Subsampling Impulse Radio

Lower complexity, less power

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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: $\sim 10\text{MHz}$
  - 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
Wired Communication Systems

Data Stream → Encode Encrypt → Multiplex → Modulate → Line Driver → Copper Coax Twisted Pair Fiber

Data Stream → Decode Decrypt → De-Modulate → Receive Amp

Volts

© V–100’s of mV

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Data Stream

Modulate

Power Amplifier
mW – Watts

Volts

Cellular Voice (AMPS)
Digital Cellular (GSM/CDMA 2G/3G)
Short Range Data (WLAN, Bluetooth)

Demodulate

LNA

Filter

IF

A/D

Classic Super Heterodyne Receiver
Armstrong (1917)
Receiver Spectrum

- 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 interference.
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.
- 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:
\[
\frac{P_2}{P_1} = \left(\frac{x_1}{x_2}\right)^2
\]

\[d \approx \sqrt{15h} \text{ km}\]

- 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:

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**Source:** Pozar

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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:

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

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

- 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

- 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.

Measurements of 60 GHz channel response with directive antennas. [Courtesy of Chintan Thakkar]
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

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OFDM or Multicarrier Modulation

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

- 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 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:

\[
\nabla \times E = -\frac{\partial B}{\partial t}
\]

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

- For structures much smaller than the wavelength, the induced fields are reactive (capacitive, inductive) \( V_1 \propto j \omega M_{1n} I_n \)
- 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

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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

- $P_{RAD}$ 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

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

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

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

\[
H_\phi = \frac{jI_m e^{-j\beta R}}{2\pi R} F(\theta)
\]

\[
E_\theta = \eta_0 H_\phi = 120\pi H_\phi
\]

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

\[
R_r \approx 73.1\, \Omega
\]

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

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Results from Antenna Theory

- Define the effective area as the power intercepted by antenna for an incident plane wave of power density $S_{av}$

- By Electromagnetic Theory of Reciprocity:
  - Antenna receive pattern same as transmit pattern
  - Ratio of eff. area to antenna gain is a universal constant:
    $$\frac{A_{eff}}{D} = \frac{\lambda^2}{4\pi}$$

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Friis Propagation Equation

\[ P_r = D_1 \times \frac{P_t}{4\pi r^2} \times \frac{A_{e2}}{\lambda^2 D_2} \]

Gain of transmit antenna \[ A_{e1} \]

Effective capture area of receiver \[ A_{e2} \]

Power over surface area of sphere

\[ \frac{P_r}{P_t} = \frac{A_{e1} A_{e2}}{r^2 \lambda^2} \quad \leftrightarrow \quad \frac{P_r}{P_t} = \frac{D_1 D_2 \lambda^2}{(4\pi r)^2} \]

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Friis Implications

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

- 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 maximize 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

\[
f(\theta) = a_0 e^{j(N-1)k d \cos \theta} + a_1 e^{j(N-2)\psi} + \cdots + a_N
\]
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
\[
H = USV^T
\]
where $U$ and $V$ are orthogonal and $S$ is a diagonal matrix. Let’s pre-multiply the above equation by $U^T$
\[
U^T \vec{y} = S V^T \vec{x}
\]
\[
\vec{y}' = S \vec{x}'
\]
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 $S$
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.

$$P_L = \frac{2kT_0}{\lambda^2} \times \frac{\lambda^2}{4\pi} \times \frac{1}{2} \times 4\pi = kT_0$$
Maximum power transfer theorem:

\[ Z_{L,\text{opt}} = Z_s \]

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.

\[ \bar{v}_n^2 = 4kTR \quad [V^2/\text{Hz}] \]
\[ \bar{i}_n^2 = 4kTG \quad [A^2/\text{Hz}] \]
Noise Figure of a Two-Port

- Ratio of output available noise power to input available 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...

\[
F = \frac{v_{na}^2 + v_{ns}^2}{v_{ns}^2} = \frac{V_s^2 / v_{ns}^2}{G V_s^2 / G (v_{na}^2 + v_{ns}^2)} \frac{SNR_{input}}{SNR_{output}}
\]
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

- 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

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

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

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

\[
c \equiv \frac{CN_0}{S} = \frac{BN_0}{S} \log_2 \left( 1 + \frac{S}{N_0B} \right)
\]

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

- $C$ 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

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

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

$$P_{ant} = P_t - 1\text{ dB} - 100.4 \text{ dB} = -71.4 \text{ dBm}$$

$$SNR_{ant} = P_{ant} - 10 \log kTB = -71.4 \text{ dBm} + 94 \text{ dBm} = 22.6 \text{ dB}$$

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

$$C = 3.64B \quad \Rightarrow \quad R = 364 \text{ Mbps}$$
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 noisy (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 $-100 \text{ dBm}$ in the presence of an inband “jammer” or interference signal with power $-40 \text{ dBm}$.
- We would like to set the gain at $100 \text{ dB}$, 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 ($P_{-1\text{dB}}$), 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

In Band Signals

Out-of-Band Interference

Channel Selectivity

Band Selectivity

Power [dB]

Freq [Hz]
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

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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.
## Example: Cellular Phones

<table>
<thead>
<tr>
<th>Feature</th>
<th>GSM / GPRS EDGE</th>
<th>WCDMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defined by</td>
<td>ETSI</td>
<td>3GPP/ETSI</td>
</tr>
<tr>
<td>Access</td>
<td>FDM/TDMA</td>
<td>CDMA / Full Duplex</td>
</tr>
<tr>
<td>Modulation</td>
<td>0.3 GMSK (1bit/Symbol)</td>
<td>GPSK</td>
</tr>
<tr>
<td>Modulation Filter</td>
<td>0.3 Gaussian</td>
<td>Root Raised cosine a=0.22</td>
</tr>
<tr>
<td>Chan. Spacing</td>
<td>200(kHz)</td>
<td>5MHz</td>
</tr>
<tr>
<td>Symbol or Bit Rate</td>
<td>270.86bbs/sec</td>
<td>3.84 Mcps</td>
</tr>
<tr>
<td>RF Frequencies (MHz)</td>
<td>GSM900 880-915</td>
<td>Band(LILIII &amp; V)</td>
</tr>
<tr>
<td></td>
<td>DCS1800 1710-1755</td>
<td>I: 1920-1980(TX)</td>
</tr>
<tr>
<td></td>
<td>PCS1900 1850-1910</td>
<td>I: 2110-2170(RX)</td>
</tr>
<tr>
<td></td>
<td>(RX) 925-960</td>
<td>II: 1850-1910(TX)</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>II: 1930-1990(RX)</td>
</tr>
<tr>
<td>Approx. Range</td>
<td>~5km</td>
<td>III: 1710-1755(TX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>III: 1805-1880(RX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>V: 824-849(TX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>V: 889-894(RX)</td>
</tr>
<tr>
<td>Peak TX Power</td>
<td>33dBm (MS)</td>
<td>24dBm</td>
</tr>
<tr>
<td>Key Hardware &amp; Performance Challenges</td>
<td>(RX) Blocking @3MHz (RX)TX</td>
<td>TX-to-RX leakage @20MHz from carrier. Creates IP2, IP3 and NF issues.</td>
</tr>
<tr>
<td>EVM</td>
<td>5e (RMS), 20e(peak)</td>
<td>17.5%</td>
</tr>
<tr>
<td>Synt. Settling Time</td>
<td>180μsecs</td>
<td></td>
</tr>
<tr>
<td>Websites</td>
<td><a href="http://www.etsi.org">www.etsi.org</a></td>
<td><a href="http://www.3gpp.org">www.3gpp.org</a></td>
</tr>
</tbody>
</table>

- **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 achieves 270 Mb/s.

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

[www.wi-fi.org](http://www.wi-fi.org)  [www.ieee802.org/11](http://www.ieee802.org/11)
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)
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

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 \( \sim 10\log(500) - 41 \) 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

3-6 GHz is crowded?
Spectrum Reality

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

<table>
<thead>
<tr>
<th>#</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>10 WEP Lindow Lab [00146C]</td>
</tr>
<tr>
<td>3</td>
<td>25 WPA Wire(less) [00C049]</td>
</tr>
<tr>
<td>6</td>
<td>16 WEP Freezer [001495]</td>
</tr>
<tr>
<td>6</td>
<td>13 WEP kathyzhang [0016B6]</td>
</tr>
<tr>
<td>6</td>
<td>15 WPA Pachytesta [001451]</td>
</tr>
<tr>
<td>6</td>
<td>16 WEP 2WIRE250 [000D72]</td>
</tr>
<tr>
<td>6</td>
<td>14 WEP linksys [Links]</td>
</tr>
<tr>
<td>6</td>
<td>14 WEP 2WIRE326 [000D72]</td>
</tr>
<tr>
<td>6</td>
<td>27 WPA BENDOVER [Netgear]</td>
</tr>
<tr>
<td>6</td>
<td>15 WEP Portnoy [D-Link]</td>
</tr>
<tr>
<td>6</td>
<td>14 Jfresh [Links]</td>
</tr>
<tr>
<td>9</td>
<td>20 AirBears [0002A5]</td>
</tr>
<tr>
<td>9</td>
<td>21 KuriyanAir [Netgear]</td>
</tr>
<tr>
<td>11</td>
<td>18 calendar [Netgear]</td>
</tr>
<tr>
<td>11</td>
<td>24 AirBears [Orinoco]</td>
</tr>
<tr>
<td>11</td>
<td>0 psr.brk.barwn.net [T...</td>
</tr>
</tbody>
</table>

- university
- café signal
- apartments...
- university

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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....

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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 GHz 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

<table>
<thead>
<tr>
<th></th>
<th>UWB</th>
<th>60 GHz</th>
<th>CR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spectrum Access</strong></td>
<td>underlay</td>
<td>unlicensed</td>
<td>overlay</td>
</tr>
<tr>
<td><strong>Carrier</strong></td>
<td>[0-1],[3-10] GHz</td>
<td>[57-64] GHz</td>
<td>[0-1],[3-10] GHz</td>
</tr>
<tr>
<td><strong>Bandwidth</strong></td>
<td>&gt; 500 MHz</td>
<td>&gt; 1 GHz</td>
<td>&gt; 1 GHz</td>
</tr>
<tr>
<td><strong>Data Rates</strong></td>
<td>~ 100 Mb/s</td>
<td>~ 1 Gb/s</td>
<td>~ 10-1000 Mb/s</td>
</tr>
<tr>
<td><strong>Spectral Efficiency</strong></td>
<td>~0.2-1 b/s/Hz</td>
<td>~ 1 b/s/Hz</td>
<td>~ 0.1-10 b/s/Hz</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td>1-10 m</td>
<td>1-10 m</td>
<td>1m - 10 km</td>
</tr>
</tbody>
</table>

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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?

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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

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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)
Universal Mobility
Thirst for Bandwidth

1Gbps: The next wireless challenge!
CMOS Technology Trends

\[
f_t \approx \frac{g_m}{2\pi C_{gg}}
\]

\[
f_{\text{max}} \approx \frac{f_t}{2\sqrt{R_g(g_mC_{gd}/C_{gg}) + (R_g + r_{ch} + R_s)g_{ds}}}
\]

<table>
<thead>
<tr>
<th></th>
<th>130nm</th>
<th>90 nm</th>
<th>65nm</th>
<th>45nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>(F_t)</td>
<td>70 GHz</td>
<td>100 GHz</td>
<td>170 GHz</td>
<td>280 GHz</td>
</tr>
<tr>
<td>(F_{\text{max}})</td>
<td>135 GHz</td>
<td>200-300 GHz</td>
<td>340 GHz</td>
<td>560 GHz</td>
</tr>
<tr>
<td>(NF_{\text{min}} (60 \text{ GHz}))</td>
<td>4-5 dB</td>
<td>3-4 dB</td>
<td>3 dB</td>
<td>2.3 dB</td>
</tr>
<tr>
<td>Scaled (F_t)</td>
<td>70 GHz</td>
<td>101 GHz</td>
<td>140 GHz</td>
<td>202 GHz</td>
</tr>
</tbody>
</table>

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Measured

ITRS+projection
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
130nm Integrated Front-End

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

Reflections from the road surface as important radar image content

traffic scene

high resolution radar image range vs. azimuth
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 ... ?
Concealed Weapons Detection

Passive “Camera” contains many receivers

QinetiQ Passive Array

TeraView Ltd

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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

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