Outline

- RF introduction
- Modulation and multiplexing
- Channel capacity
- Antennas and signal propagation
- Equalization and diversity
  - Dynamic equalization
  - Diversity in space, frequency, and time
- Modulation and coding
- Some newer technologies
- Spectrum access

Inter-Symbol Interference

- Larger difference in path length can cause inter-symbol interference (ISI)
- Suppose the receiver can do some processing:
  - Add/subtracted scaled and delayed copies of the signal

Dynamic Equalization

- Goal is to deal with intersymbol interference
- Idea is to combine multiple delayed copies of the signal

Equalization Discussion

- Use multiple delayed copies of the received signal to try to reconstruct the original signal
- Weights are set dynamically
  - Typically based on some known “training” sequence
  - Effectively uses the multiple copies of the signal to reinforce each other
    - But only works for paths that differ in length by less than the depth of the pipeline

Does It Work?

0.45 microsec = 150 meter
Diversity Techniques

- Distribute signal over multiple “channels”
  - “Channels” experience independent fading
  - Reduces the error, i.e. only part of the signal is affected
- Time diversity: spread data out over time
  - Useful for bursty errors, e.g. slow fading
  - A specific form of channel coding
- Space diversity: use multiple nearby antennas and combine signals
  - Can be directional
- Frequency diversity: spread signal over multiple frequencies
  - For example, spread spectrum
  - Discussed later

Time Redundancy: Bit Stream Level

- Protects digital data by introducing redundancy in the transmitted data.
  - Error detection codes: can identify certain types of errors
  - Error correction codes: can fix certain types of errors
- Block codes provide Forward Error Correction (FEC) for blocks of data.
  - \((n, k)\) code: \(n\) bits are transmitted for \(k\) information bits
  - Simplest example: parity codes
  - Many different codes exist: Hamming, cyclic, Reed-Solomon, ...
- Convolutional codes provide protection for a continuous stream of bits.
  - Coding gain is \(n/k\)
  - Turbo codes: convolutional code with channel estimation

Time Diversity

- Spread blocks out over time.
- Can use FEC or other error recovery techniques to deal with burst errors.

Redundancy At Lower Levels

- We can also introduce redundancy at lower levels.
- Time diversity: expand bit stream into a richer digital signal that is then used to modulate the carrier signal
- Frequency diversity: spread the signal out over a broader frequency band
- Both are discussed at the end of the lecture

Space Diversity

- Use multiple antennas that pick up the signal in slightly different locations
- If antennas are sufficiently separated, chances are that the signals are mostly uncorrelated
- If one antenna experiences deep fading, chances are that the other antenna has a strong signal
  - Antennas should be separated by \(\frac{1}{2}\) wavelength or more
- Applies to both transmit and receive side
  - Channels are symmetric
- Can use more than two antennas!

Space Diversity Techniques

- On the receiving side:
  - Selection diversity: pick antenna with best SNR
  - Feedback/scanning: only switch if signals becomes weak
  - Maximal ratio combining: combine signals with a weight that is based on their SNR
  - Also: equal gain combining
- Transmitter can also use diversity, but needs help from receiver
  - Needs feedback on which antenna works best
- Diversity is very common in today’s 802.11 devices
  - Uses simple techniques, e.g. selection diversity
Typical Algorithm

- Assume 802.11 where successfully received packets are acknowledged.
- Receiver:
  - Uses the antenna with the strongest signal
  - Always use the same antenna to send the acknowledgement – gives feedback to the sender
- Sender:
  - Picks an antenna to transmit and learns about the channel quality based on the ACK
  - Needs to occasionally try the other antenna to explore the channel between all four channel pairs

Outline

- RF introduction
- Modulation and multiplexing
- Channel capacity
- Antennas and signal propagation
- Equalization and diversity
- Modulation and coding
  - Coding and modulation
  - Amplitude, frequency, phase
  - Spread spectrum
  - Code division multiple access
- Some newer technologies
- Spectrum access

From Signals to Packets

Packet Transmission

<table>
<thead>
<tr>
<th>Sender</th>
<th>Receiver</th>
</tr>
</thead>
</table>

Packets

<table>
<thead>
<tr>
<th>Header/Body</th>
<th>Header/Body</th>
<th>Header/Body</th>
</tr>
</thead>
</table>

Bit Stream

0 0 1 0 1 1 0 0 0 1

“Digital” Signal

Analog Signal

Factors Used to Compare Encoding Schemes

- Signal spectrum
  - With lack of high-frequency components, less bandwidth required
  - With no dc component, ac coupling via transformer possible
  - Transfer function of a channel is worse near band edges
- Clocking
  - Ease of determining beginning and end of each bit position
- Signal interference and noise immunity
  - Performance in the presence of noise
- Cost and complexity
  - The higher the signal rate to achieve a given data rate, the greater the cost

Basic Modulation Techniques

- Encode digital data in an analog signal
- Amplitude-shift keying (ASK)
  - Amplitude difference of carrier frequency
- Frequency-shift keying (FSK)
  - Frequency difference near carrier frequency
- Phase-shift keying (PSK)
  - Phase of carrier signal shifted

Amplitude-Shift Keying

- One binary digit represented by presence of carrier, at constant amplitude
- Other binary digit represented by absence of carrier

\[ x(t) = \begin{cases} 
A \cos(2\pi ft) & \text{binary 1} \\
0 & \text{binary 0}
\end{cases} \]

- Where the carrier signal is \( A \cos(2\pi ft) \)
- Inefficient because of sudden gain changes
  - Only used when bandwidth is not a concern, e.g. on voice lines (< 1200 bps) or on digital fiber
- A can be a multi-bit symbol
Modulator & Demodulator

Modulate \( \cos(2\pi f_c t) \) by multiplying by \( A_k \) for \( T \) seconds:

\[
Y(t) = A_k \cos(2\pi f_c t)
\]

Received signal during \( k \)th interval

Demodulate (recover \( A_k \)) by multiplying by \( 2\cos(2\pi f_c t) \) for \( T \) seconds and lowpass filtering (smoothing):

\[
2A_k \cos^2(2\pi f_c t) = A_k \{ 1 + \cos(2\pi 2f_c t) + \ldots \}
\]

Lowpass Filter (Smother)

Transmitted signal during \( k \)th interval

Received signal during \( k \)th interval

Binary Frequency-Shift Keying (BFSK)

- Two binary digits represented by two different frequencies near the carrier frequency
  \[
s(t) = \begin{cases} 
  A \cos(2\pi f_c t) & \text{binary 1} \\
  A \cos(2\pi f_2 t) & \text{binary 0}
\end{cases}
\]
  
  - where \( f_c \) and \( f_2 \) are offset from carrier frequency \( f_c \) by equal but opposite amounts

- Less susceptible to error than ASK

- Sometimes used for radio or on coax

- Demodulator looks for power around \( f_1 \) and \( f_2 \)

Multiple Frequency-Shift Keying (MFSK)

- More than two frequencies are used

- More bandwidth efficient but more susceptible to error

\[
s_i(t) = A \cos 2\pi f_i t \quad 1 \leq i \leq M
\]

- \( f_i = f_c + (2i-1 - M) f_d \)

- \( f_d \) = the difference frequency

- \( M \) = number of different signal elements = \( 2^L \)

- \( L \) = number of bits per signal element

- Each symbol represents \( L \) bits

  - Symbol length is \( T_s \cdot L \) seconds, where \( T_s \) is bit period

Phase-Shift Keying (PSK)

- Two-level PSK (BPSK)

  - Uses two phases to represent binary digits

  \[
s(t) = \begin{cases} 
  A \cos(2\pi f_c t) & \text{binary 1} \\
  A \cos(2\pi f_c t + \pi) & \text{binary 0}
\end{cases}
\]

- Differential PSK (DPSK)

  - Phase shift with reference to previous bit

    - Binary 0 = signal of same phase as previous signal burst
    - Binary 1 = signal of opposite phase to previous signal burst

Four-level PSK (QPSK)

- Each element represents more than one bit

\[
S(t) = \begin{cases} 
  A \cos \left( 2\pi f_c t + \frac{\pi}{4} \right) & 11 \\
  A \cos \left( 2\pi f_c t + \frac{3\pi}{4} \right) & 01 \\
  A \cos \left( 2\pi f_c t - \frac{3\pi}{4} \right) & 00 \\
  A \cos \left( 2\pi f_c t - \frac{\pi}{4} \right) & 10
\end{cases}
\]
Some Examples

- Gaussian Frequency Shift Keying.
  - “1” is a positive frequency shift from base
  - “0” is a negative frequency shift from base
  - Used in Bluetooth
- Differential quadrature phase shift keying.
  - Variant of “regular” frequency shift keying
  - Symbols are encoded as changes in phase
  - Requires decoding on π/4 phase shift
  - Used in 802.11b networks
- Quadrature Amplitude modulation.
  - Combines amplitude and phase modulation
  - Uses two amplitudes and 4 phases to represent the value of a 3 bit sequence

Quadrature Amplitude Modulation (QAM)

- QAM uses two-dimensional signaling
  - \( A_k \) modulates in-phase \( \cos(2\pi f_c t) \)
  - \( B_k \) modulates quadrature phase \( \sin(2\pi f_c t) \)
  - Transmit sum of inphase & quadrature phase components

\[
Y(t) = Y_i(t) + Y_q(t)
\]

\[
Y_i(t) = A_k \cos(2\pi f_c t)
\]

\[
Y_q(t) = B_k \sin(2\pi f_c t)
\]

\( Y_i(t) \) and \( Y_q(t) \) both occupy the bandpass channel
- QAM sends 2 pulses/Hz

QAM Demodulation

\[
Y(t) = 2\cos(2\pi f_c t) + 2\cos(2\pi f_c t) \sin(4\pi f_c t)
\]

\[
= 4 \cos(\theta) + 4 \sin(\theta)
\]

\[
= 4 \sqrt{A^2 + B^2} \sin(\tan^{-1}(B/A) + \pi f_c t)
\]

\[
= 4 \frac{\sqrt{A^2 + B^2}}{1 + \tan^2(\pi f_c T)} \sin(\pi f_c t)
\]

Signal Constellations

- Each pair \((A_k, B_k)\) defines a point in the plane
- Signal constellation set of signaling points

\[
(A_k, A_k) \quad (A_k, -A_k) \quad (-A_k, A_k) \quad (-A_k, -A_k)
\]

4 possible points per \( T \) sec.
2 bits / pulse

\[
(0, A) \quad (0, -A) \quad (A, 0) \quad (-A, 0)
\]

16 possible points per \( T \) sec.
4 bits / pulse

Other Signal Constellations

- Point selected by amplitude & phase
  \[
  A_k \cos(2\pi f_c t) + B_k \sin(2\pi f_c t) = \sqrt{A_k^2 + B_k^2} \cos(2\pi f_c t + \tan^{-1}(B_k/A_k))
  \]

4 possible points per \( T \) sec.
16 possible points per \( T \) sec.

Gaussian Frequency Shift Keying (GFSK)

- FSK can result in frequency deviations
- Uses more spectrum
- GFSK first passes the binary signal through Gaussian filter to smoothen it and then uses it to modulate the signal
- Used in Bluetooth
- Gaussian Minimum Shift Keying (GMSK) is a variant that keeps the frequency difference to a minimum
- Used in GSM
Outline

- RF introduction
- Modulation and multiplexing
- Channel capacity
- Antennas and signal propagation
- Equalization and diversity
- Modulation and coding
  - Coding and modulation
  - Amplitude, frequency, phase
  - Spread spectrum
  - Code division multiple access
- Some newer technologies
- Spectrum access

Spread Spectrum

- Spread transmission over a wider bandwidth
  - Don’t put all your eggs in one basket!
  - Remember discussion on “diversity”
- Good for military: jamming and interception becomes harder
- Also useful to minimize impact of a “bad” frequency in regular environments
- What can be gained from this apparent waste of spectrum?
  - Immunity from various kinds of noise and multipath distortion
  - Can be used for hiding and encrypting signals
  - Several users can independently use the same higher bandwidth with very little interference

Frequency Hopping Spread Spectrum (FHSS)

- Have the transmitter hop between a seemingly random sequence of frequencies
  - Each frequency has the bandwidth of the original signal
- Dwell time is the time spent using one frequency
- Spreading code determines the hopping sequence
  - Must be shared by sender and receiver (e.g., standardized)

Example: Original 802.11 Standard (FH)

- Used frequency hopping
- 96 channels of 1 MHz
  - Only 78 used in US; other countries used different numbers
  - Each channel carries only ~1% of the bandwidth
  - Uses 2 GFSK or 4 GFSK for modulation (1 or 2 Mbps)
- The dwell time must be < msec
  - Transmitter/receiver must be synchronized!
- Standard defined 26 orthogonal hop sequences
- Transmitter used a beacon on fixed frequency to inform the receiver of the hop sequence that will be used
- Can support multiple simultaneous transmissions – use different hop sequences

802.11 Spectrogram

Frequency Hopping Spectrogram
Example:
Bluetooth

- Uses frequency hopping spread spectrum in the 2.4 GHz ISM band
- Uses 79 frequencies with a spacing of 1 MHz
  - Other countries use different numbers of frequencies
- Frequency hopping rate is 1600 hops/s
- Signal uses GFSK
  - Minimum deviation is 115 KHz
- Maximum data rate is 1 MHz