18-759 : Wireless Networks

Lecture 5: Even More Physical Layer

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http://www.cs.cmu.edu/~prs/wireless09/

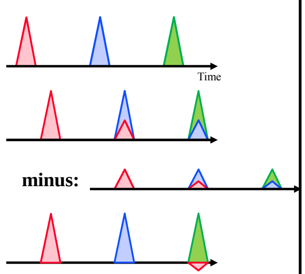
Outline

- 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

Typical Bad News Good News Story

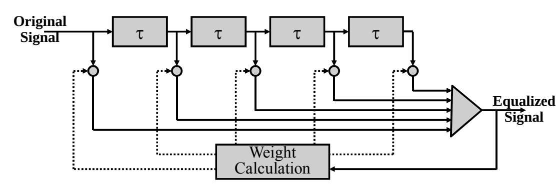
Inter-Symbol Interference

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

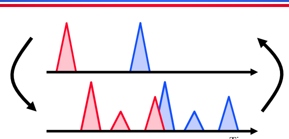


Dynamic Equalization

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



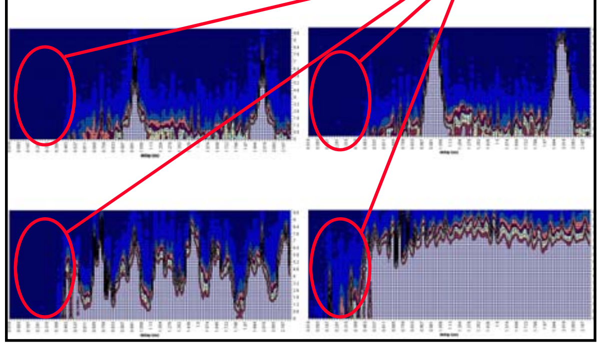
Equalization Discussion



- 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

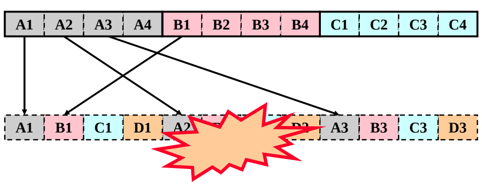
- Distribute signal over multiple "channels"
  - "Channels" experience independent fading
  - Reduces the error, i.e. only part of the signal is affected
- Time diversity: spread data out over time
  - Useful for bursty errors, e.g. slow fading
  - A specific form of channel coding
- Space diversity: 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 ½ 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

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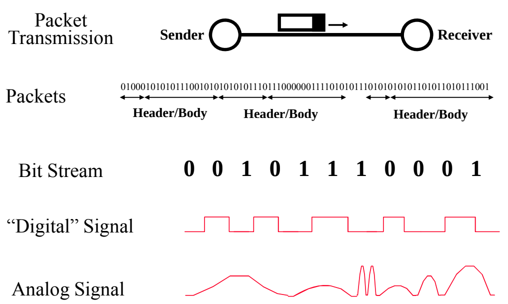
- Channel capacity
- Antennas and signal propagation
- Equalization and diversity
- Modulation and coding
  - » Coding and modulation
  - » Amplitude, frequency, phase
  - » Spread spectrum
  - » Code division multiple access
- Some newer technologies
- Spectrum access

From Signals to Packets

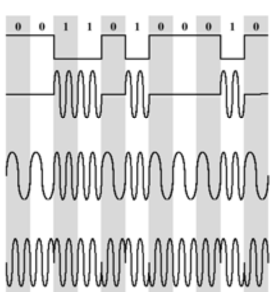


Factors Used to Compare Encoding Schemes

- 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

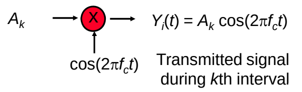
- One binary digit represented by presence of carrier, at constant amplitude
- Other binary digit represented by absence of carrier

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

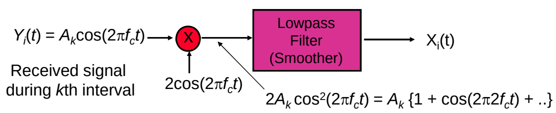
  – where the carrier signal is $A\cos(2\pi f_c t)$
- Inefficient because of sudden gain changes
  - » Only used when bandwidth is not a concern, e.g. on voice lines (< 1200 bps) or on digital fiber
- A can be a multi-bit symbol

Modulator & Demodulator

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



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



Binary Frequency-Shift Keying (BFSK)

- Two binary digits represented by two different frequencies near the carrier frequency

$$s(t) = \begin{cases} A\cos(2\pi f_1 t) & \text{binary } 1 \\ A\cos(2\pi f_2 t) & \text{binary } 0 \end{cases}$$

  - where f_1 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

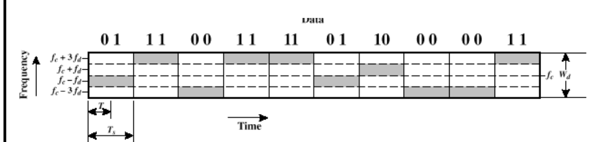
Multiple Frequency-Shift Keying (MFSK)

- More than two frequencies are used
- More bandwidth efficient but more susceptible to error

$$s_i(t) = A\cos 2\pi f_i t \quad 1 \le i \le M$$

  - $f_i = f_c + (2i - 1 - M) f_d$
  - f_c = the carrier frequency
  - 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 $T_s = LT$ seconds, where T is bit period

Multiple Frequency-Shift Keying (MFSK)



Phase-Shift Keying (PSK)

- Two-level PSK (BPSK)
  - Uses two phases to represent binary digits

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

$$= \begin{cases} A\cos(2\pi f_c t) & \text{binary } 1 \\ -A\cos(2\pi f_c t) & \text{binary } 0 \end{cases}$$

- 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

Phase-Shift Keying (PSK)

- Four-level PSK (QPSK)
  - Each element represents more than one bit

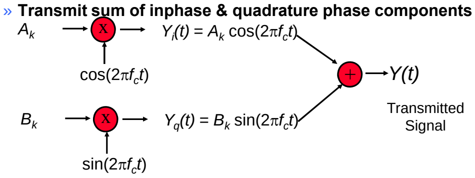
$$s(t) = \begin{cases} A\cos\left(2\pi f_c t + \frac{\pi}{4}\right) & 11 \\ A\cos\left(2\pi f_c t + \frac{3\pi}{4}\right) & 01 \\ A\cos\left(2\pi f_c t - \frac{3\pi}{4}\right) & 00 \\ A\cos\left(2\pi f_c t - \frac{\pi}{4}\right) & 10 \end{cases}$$

Some Examples

- **Gaussian Frequency Shift Keying.**
  - » "1" is a positive frequency shift from base
  - » "1" 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 pi/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

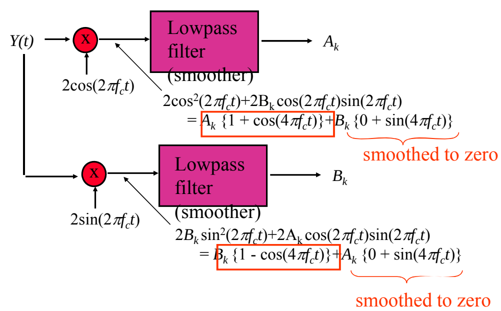
Quadrature Amplitude Modulation (QAM)

- **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



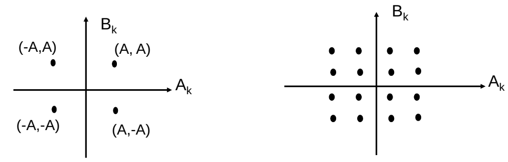
- $Y_i(t)$ and $Y_q(t)$ both occupy the bandpass channel
- QAM sends 2 pulses/Hz

QAM Demodulation



Signal Constellations

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



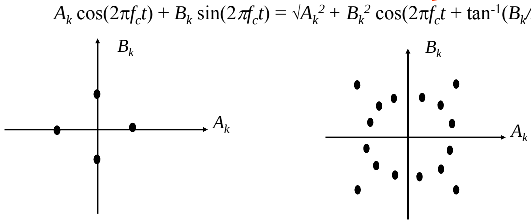
4 possible points per T sec.
2 bits / pulse

16 possible points per T sec.
4 bits / pulse

Other Signal Constellations

- **Point selected by amplitude & phase**

$$A_k\cos(2\pi f_c t) + B_k\sin(2\pi f_c t) = \sqrt{A_k^2 + B_k^2}\cos(2\pi f_c t + \tan^{-1}(B_k/A_k))$$

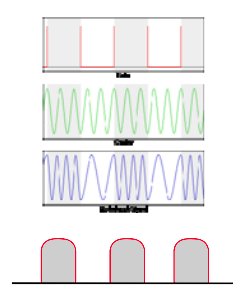


4 possible points per T sec.

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



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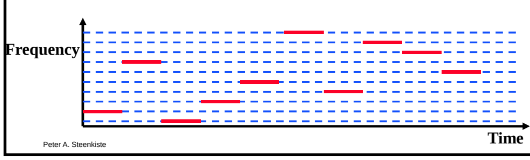
Spread Spectrum

- 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)

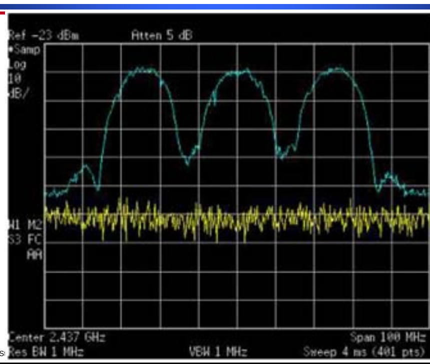
- Have the transmitter hop between a seemingly random sequence of frequencies
  - Each frequency has the bandwidth of the original signal
- Dwell time is the time spent using one frequency
- Spreading code determines the hopping sequence
  - Must be shared by sender and receiver (e.g. standardized)



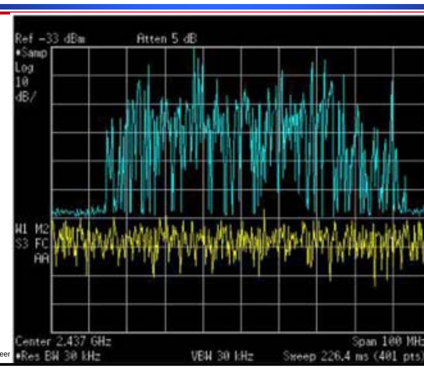
Example: Original 802.11 Standard (FH)

- 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
  - Mimimum deviation is 115 KHz
- Maximum data rate is 1 MHz