15-496 : A Hand-on Introduction to Wireless Networks
Lecture 4: Physical Layer

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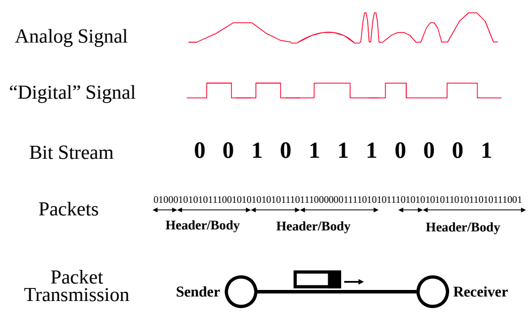
Spring Semester 2008
http://www.cs.cmu.edu/~prs/wireless08/

Outline

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

From Signals to Packets

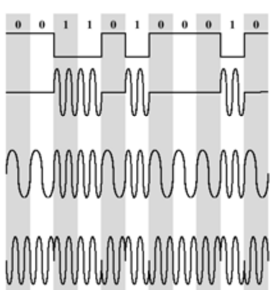


Factors Used to Compare Encoding Schemes

- 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

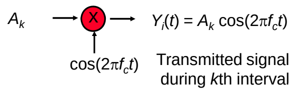
- One binary digit represented by presence of carrier, at constant amplitude
- Other binary digit represented by absence of carrier

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

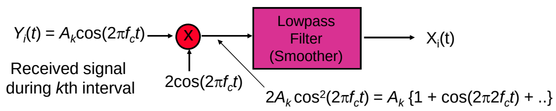
  – where the carrier signal is $A\cos(2\pi f_c t)$
- Inefficient because of sudden gain changes
  - » Only used when bandwidth is not a concern, e.g. on voice lines (< 1200 bps) or on digital fiber

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**

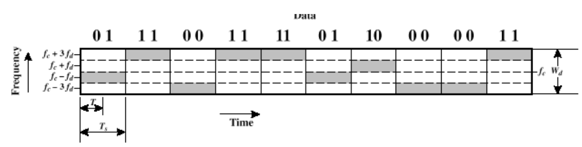
Multiple Frequency-Shift Keying (MFSK)

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

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

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

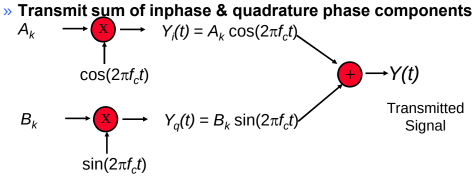
$$s(t) = \begin{cases} A\cos\left(2\pi f_c t + \frac{\pi}{4}\right) & 11 \\ A\cos\left(2\pi f_c t + \frac{3\pi}{4}\right) & 01 \\ A\cos\left(2\pi f_c t - \frac{3\pi}{4}\right) & 00 \\ A\cos\left(2\pi f_c t - \frac{\pi}{4}\right) & 10 \end{cases}$$

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.**
  - » **Four different phases representing a pair of bits**
  - » **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)

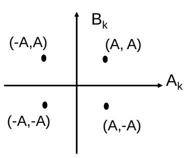
- **QAM uses two-dimensional signaling**
  - » **A_k modulates in-phase $\cos(2\pi f_c t)$**
  - » **B_k modulates quadrature phase $\sin(2\pi f_c t)$**
  - » **Transmit sum of inphase & quadrature phase components**



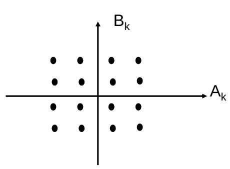
- $Y_i(t)$ and $Y_q(t)$ both occupy the bandpass channel
- QAM sends 2 pulses/Hz

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

Outline

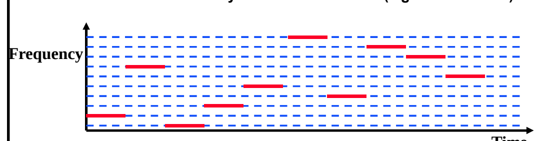
- **RF introduction**
- **Modulation**
- **Antennas and signal propagation**
- **Equalization and diversity**
- **Channel coding**
  - » **Amplitude, frequency, phase**
  - » **Spread spectrum**
  - » **Code division multiple access**

Spread Spectrum

- **Spread transmission over a wider bandwidth**
  - » **Don't put all your eggs in one basket!**
- **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)

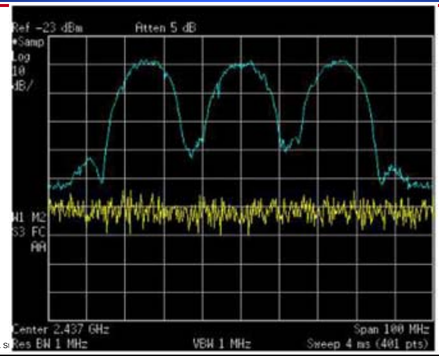
- **Have the transmitter hop between a seemingly random sequence of frequencies**
  - » **Each frequency has the bandwidth of the original signal**
- **Dwell time is the time spent using one frequency**
- **Spreading code determines the hopping sequence**
  - » **Must be shared by sender and receiver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



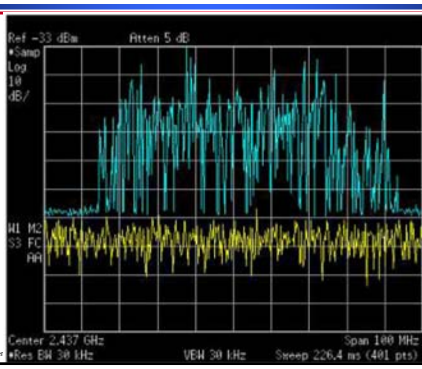
Example: Original 802.11 Standard

- Used frequency hopping
- 96 channels of 1 MHz (only 78 used in US).
  - » Each channel carries only ~1% of the bandwidth
- The dwell time is 390 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

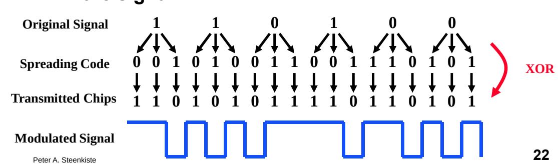


Frequency Hopping Spectrogram

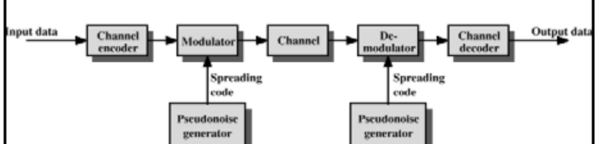


Direct Sequence Spread Spectrum (DSSS)

- Each bit in original signal is represented by multiple bits (chips) in the transmitted signal
- Spreading code spreads signal across a wider frequency band
  - » Spread is in direct proportion to number of bits used
  - » E.g. exclusive-OR of the bits with the spreading code
- The resulting bit stream is used to modulate the signal



Spread Spectrum



Direct Sequence Spread Spectrum

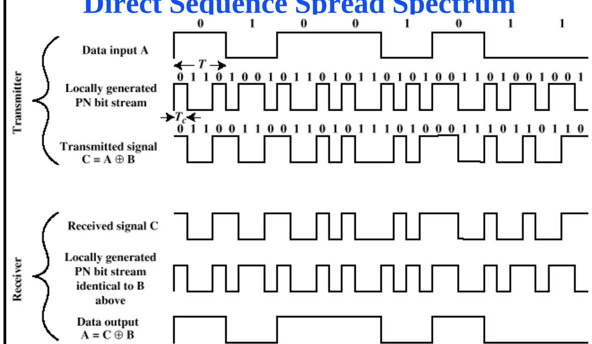
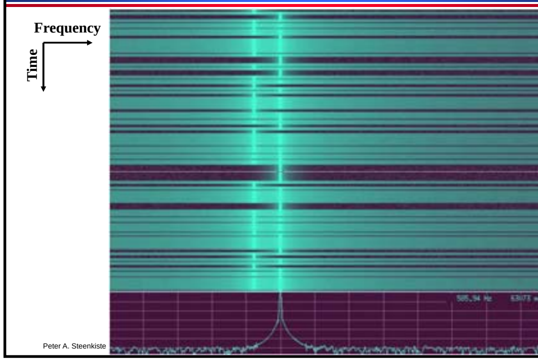


Figure 7.6 Example of Direct Sequence Spread Spectrum

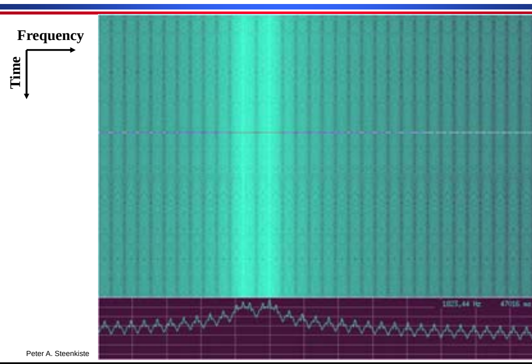
Properties

- Since each bit is sent as multiple chips, you need more bps bandwidth to send the signal.
  - » Number of chips per bit is called the spreading ratio
  - » This is the spreading part of spread spectrum
- Given the Nyquist and Shannon results, you need more spectral bandwidth to do this.
  - » Spreading the signal over the spectrum
- Advantage is that is transmission is more resilient.
  - » DSSS signal will look like noise in a narrow band
  - » Can lose some chips in a word and recover easily
- Multiple users can share bandwidth (easily).
  - » Follows directly from Shannon (capacity is there)
  - » Use a different chipping sequence

Spectrogram: Original FSK Signal



Spectrogram: DSSS-encoded Signal



Example: Original 802.11

- The DS PHY used an 11-to-1 spreading ratio and a Barker chipping sequence.
  - » Barker sequence has low autocorrelation properties – why?
- Receiver decodes by counting the number of “1” bits in each word
  - » 6 “1” bits correspond to a 0 data bit
- Chips were transmitted using B-PSK modulation.
  - » Data rate was 1 Mbps (i.e. 11 Mchips/sec)
  - » Extended to 2 Mbps by using a Q-PSK modulation
    - – Requires the detection of a ¼ phase shift

Example: Current 802.11b

- (Maximum) data rate is 11 Mbs.
- Uses Complementary Code Keying (CCK).
  - » Complementary means that the code has good auto-correlation properties
    - – Want nice properties to ease recovery in the presence of noise, multipath interference, ..
  - » Each word is mapped onto an 8 bit chip sequence
  - » Symbol rate at 1.375 MSymbols/sec, at 8 bpS = 11 Mbps
- The CKK chip stream is transmitted using Q-PSK modulation.
  - » I.e. 4 values
- What about lower rates?

Discussion

- Spread spectrum is very widely used
- Effective against noise and multipath
  - » Signal looks like noise to other nodes
  - » Multiple transmitters can use the same frequency range
- FCC requires the use of spread spectrum in ISM band
  - » If signal is above a certain power level
- Is also used in higher speed 802.11 versions.
  - » No surprise!

Code Division Multiple Access

- Users share spectrum and time, but use different codes to spread their data over frequencies
  - » DSSS where users use different spreading sequences
  - » Use spreading sequences that are orthogonal, i.e. they have minimal overlap
- The idea is that users will only rarely overlap and the inherent robustness of DSSS will allow users to recover if there is a conflict
  - » Overlap = use the same the frequency at the same time
  - » The signal of other users will appear as noise

CDMA Principle

- Basic Principles of CDMA
  - » *D* = rate of data signal
  - » Break each bit into *k chips* - user-specific fixed pattern
  - » Chip data rate of new channel = *kD*
- If *k*=6 and code is a sequence of 1s and -1s
  - » For a '1' bit, A sends code as chip pattern
    - – <c1, c2, c3, c4, c5, c6>
  - » For a '0' bit, A sends complement of code
    - – <-c1, -c2, -c3, -c4, -c5, -c6>
- Receiver knows sender's code and performs electronic decode function

$$S_u(d) = d1\times c1 + d2\times c2 + d3\times c3 + d4\times c4 + d5\times c5 + d6\times c6$$

  - – <d1, d2, d3, d4, d5, d6> = received chip pattern
  - – <c1, c2, c3, c4, c5, c6> = sender's code

CDMA Example

- User A code = <1, –1, –1, 1, –1, 1>
  - » To send a 1 bit = <1, –1, –1, 1, –1, 1>
  - » To send a 0 bit = <–1, 1, 1, –1, 1, –1>
- User B code = <1, 1, –1, – 1, 1, 1>
  - » To send a 1 bit = <1, 1, –1, –1, 1, 1>
- Receiver receiving with A's code
  - » (A's code) x (received chip pattern)
    - – User A '1' bit: 6 -> 1
    - – User A '0' bit: -6 -> 0
    - – User B '1' bit: 0 -> unwanted signal ignored

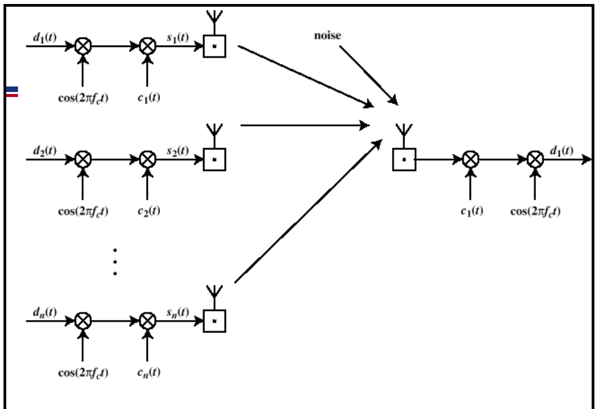


Figure 7.11 CDMA in a DSSS Environment

Categories of Spreading Sequences

- Spreading Sequence Categories
  - » PN sequences
  - » Orthogonal codes
- For FHSS systems
  - » PN sequences most common
- For DSSS systems not employing CDMA
  - » PN sequences most common
- For DSSS CDMA systems
  - » PN sequences
  - » Orthogonal codes

CDMA Discussion

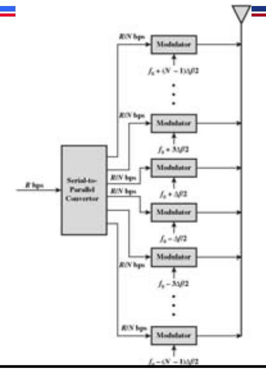
- CDMA does not assign a fixed bandwidth to each user but a user's bandwidth depends on the load.
  - » More users results more "noise" and less throughput for each user, e.g. more information lost due to errors
  - » How graceful the degradation is depends on how orthogonal the codes are
  - » TDMA and FDMA have a fixed channel capacity
- Weaker signals may be lost in the clutter.
  - » This will systematically put the same node pairs at a disadvantage – not acceptable
  - » The solution is to add power control, i.e. nearby nodes use a lower transmission power than remote nodes

CDMA Example

- CDMA cellular standard.
  - » Used in the US, e.g. Sprint
- Allocates 1.228 MHz for base station to mobile communication.
  - » Shared by 64 "code channels"
  - » Used for voice (55), paging service (8), and control (1)
- Provides a lot error coding to recover from errors.
  - » Voice data is 8550 bps
  - » Coding and FEC increase this to 19.2 kbps
  - » Then spread out over 1.228 MHz using DSSS; uses QPSK

OFDM - Orthogonal Frequency Division Multiplexing

- Distribute bits over N subcarriers are different frequencies
  - » Each bit takes N times as much time to send
- Several advantages:
  - » With FEC, resistant to frequency selective fading
  - » Reduces sensitivity to intersymbol interference (ISI) since bit times are longer
- Used e.g. in 802.11a



Subcarriers are "Orthogonal"

- Peaks of spectral density of each carrier coincide with the zeros of the other carriers
  - » Carriers can be packed very densely with minimal interference
  - » Requires very good control over frequencies