18-452/18-750
Wireless Networks and Applications
Lecture 6: Physical Layer
Diversity and Coding

Peter Steenkiste
Carnegie Mellon University

Spring Semester 2017
http://www.cs.cmu.edu/~prs/wirelessS17/

Outline

- RF introduction
- Modulation and multiplexing
- Channel capacity
- Antennas and signal propagation
- Modulation
- Diversity and coding
  - » Space, time and frequency diversity
- OFDM

Typical
Bad News
Good News
Story

Diversity Techniques

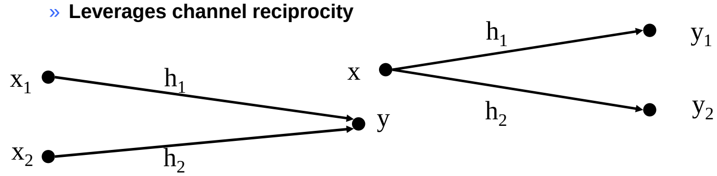
- The quality of the channel depends on time, space, and frequency
- Space diversity: use multiple nearby antennas and combine signals
  - » Both at the sender and the receiver
- Time diversity: spread data out over time
  - » Useful for burst errors, i.e., errors are clustered in time
- Frequency diversity: spread signal over multiple frequencies
  - » For example, spread spectrum
- Distribute data over multiple “channels”
  - » “Channels” experience different frequency selective fading, so only part of the data is affected

Space Diversity

- Use multiple antennas that pick up/transmit the signal in slightly different locations
- If antennas are sufficiently separated, instantaneous channel conditions are independent
  - » Antennas should be separated by ½ wavelength or more
- If one antenna experiences deep fading, the other antenna has a strong signal
- Represents a wide class of techniques
  - » Use on transmit and receive side - channels are symmetric
  - » Level of sophistication of the algorithms used
  - » Can use more than two antennas!

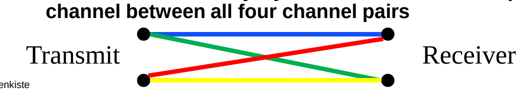
Selection Diversity

- **Receiver diversity: receiver picks the antenna with the best SNR**
  - Very easy
- **Transmit diversity: sender picks the antenna that offers the best channel to the receiver**
  - Transmitter can learn the channel conditions based on signals sent by the receiver
  - Leverages channel reciprocity



Simple Algorithm in (older) 802.11

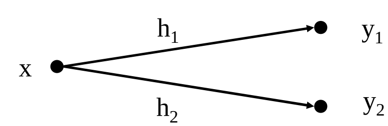
- **Combine transmit + receive selection diversity**
  - Assume packets are acknowledged – why?
- **How to explore all channels to find the best one … or at least the best transmit antenna**
- **Receiver:**
  - Uses the antenna with the strongest signal
  - Always use the same antenna to send the acknowledgement – 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



Receiver Diversity
Can we Do Better?

- **But why not use both signals?**
  - 2 Signals contain more information than 1
  - What can go wrong?
- **Simply adding the two signals has drawbacks:**
  - Signals may be out of phase, e.g. kind of like multi-path; can reduce the signal strength!
  - We want to make sure we do not amplify the noise
- **Maximal ratio combining: combine signals with a weight that is based on their SNR**
  - Weight will favor the strongest signal (highest SNR)
  - Also: equal gain combining as a quick and dirty alternative

Receiver Diversity Optimization



$$\vec{y} = \vec{h} * x + \vec{n}$$

$$\vec{h} = \begin{bmatrix} h_1 \\ h_2 \end{bmatrix}$$

- **Multiply $\vec{y}$ with the complex conjugate $\vec{h}^*$ of the channel vector $\vec{h}$**
  - Aligns the phases of the two signals so they amplify each other
  - Scales the signals with their magnitude so the effect of noise is not amplified
- **Can learn $\vec{h}$ based on training data**

The Details

- Complex conjugates: same real part but imaginary parts of opposite signs

$$\vec{h}^* * \vec{y} = \vec{h}^* * (\vec{h} * x + \vec{n})$$

$$\text{Where } h^* = [h_1^* \;\; h_2^*] = [\, a_1+b_1 i \;\; a_2-b_2 i]$$

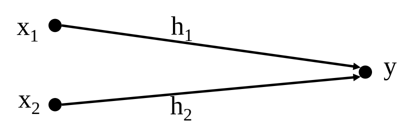
- Result:

  signal x is scaled by $a_1^2 + b_1^2 + a_2^2 + b_2^2$

  noise becomes: $h_1^* * n_1 + h_2^* * n_2$

Transmit Diversity

- Same as receive diversity but the transmitter has multiple antennas
- Maximum ratio combining: sender "precodes" the signal
  - » Pre-align the phases at receiver and distribute power over the transmit antennas (total power fixed)
- How does transmitter learn channel?
  - » Channel reciprocity: learn from packets received Y



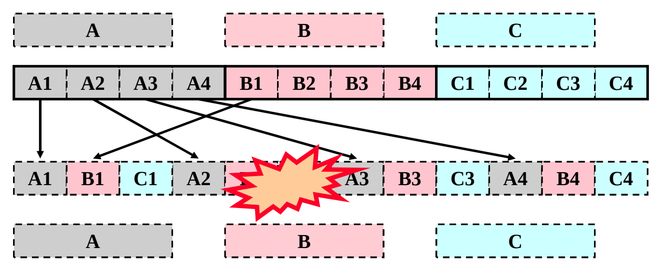
$$y = \vec{h} * \vec{x} + n$$

Adding Redundancy

- 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

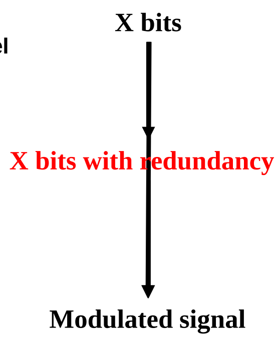
Combine Redundancy with Time Diversity

- Fading can cause burst errors: a relatively long sequence of bits is corrupted
- Spread blocks of bytes out over time so redundancy can help recover from the burst
  - » Example: only need 3 out of 4 to recover the data



Bits, Symbols, and Chips

- Redundancy and time diversity can be added easily at the application layer
- Can we do it lower in the stack?
  - » Need to adapt quickly to the channel
- So far: use bits to directly modulate the signal
- Idea: add a coding layer – provides a level of indirection
- Can add redundancy and adjust level of redundancy quickly based on channel conditions



Discussion

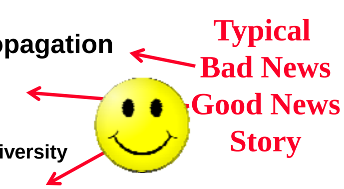
- Error coding increases robustness at the expense of having to send more bits
  - » Technically this means that you need more spectrum
- But: since you can tolerate some errors, you may be able to increase the bit rate through more aggressive modulation
- Coding and modulation combined offer a lot of flexibility to optimize transmission
- Next steps:
  - » Apply a similar idea to frequency diversity
  - » Combine coding with frequency and time diversity in OFDM

Summary

- Space diversity really helps in overcoming fading
  - » Very widely deployed
  - » Will build on this when we discuss MIMO
- Coding is also an effective way to improve throughput
  - » Widely used in all modern standards
  - » Coding, combined with modulation, can be adapt quickly to channel conditions

Outline

- RF introduction
- Modulation and multiplexing
- Channel capacity
- Antennas and signal propagation
- Modulation
- Diversity and coding
  - » Space, time and frequency diversity
- OFDM

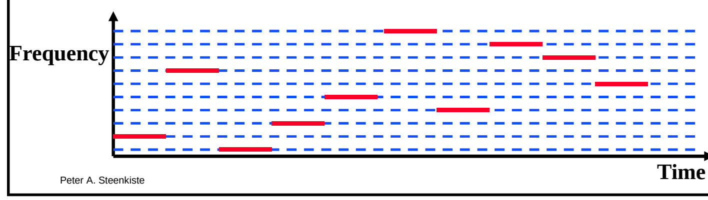


Spread Spectrum

- 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
- But what is the cost?
- 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)

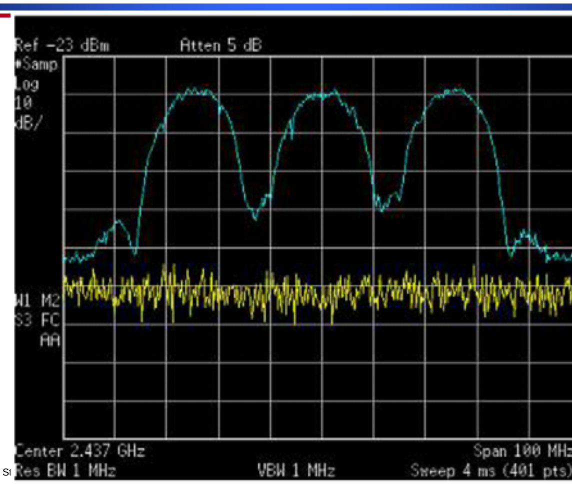
- Have the transmitter hop between a seemingly random sequence of frequencies
  - » Each frequency has the bandwidth of the original signal
- Dwell time is the time spent using one frequency
- Spreading code determines the hopping sequence
  - » Must be shared by sender and receiver (e.g. standardized)



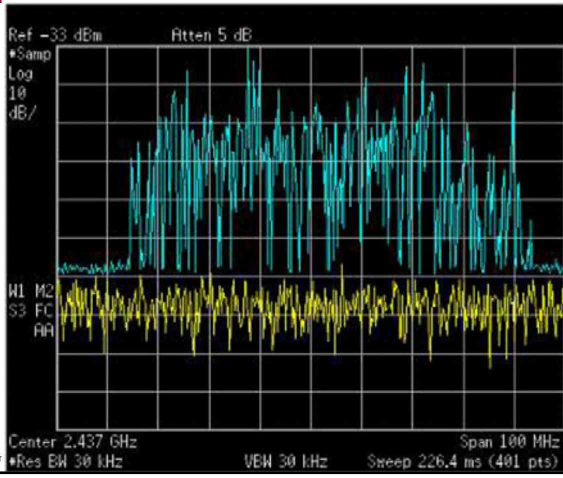
Example: Original 802.11 Standard (FH)

- 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 was configurable
  - » FCC set an upper bound of 400 msec
  - » Transmitter/receiver must be synchronized
- Standard defined 26 orthogonal hop sequences
- Transmitter used a beacon on fixed frequency to inform the receiver of its hop sequence
- Can support multiple simultaneous transmissions – use different hop sequences
  - » E.g. up to 10 co-located APs with their clients

802.11 Spectrogram



Frequency Hopping Spectrogram

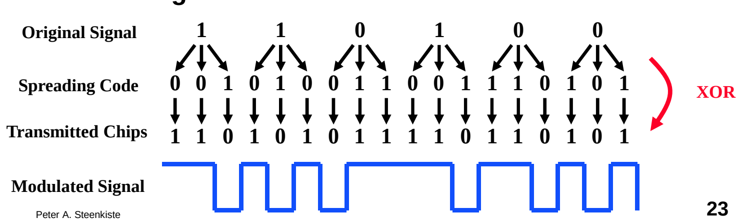


Example: Bluetooth

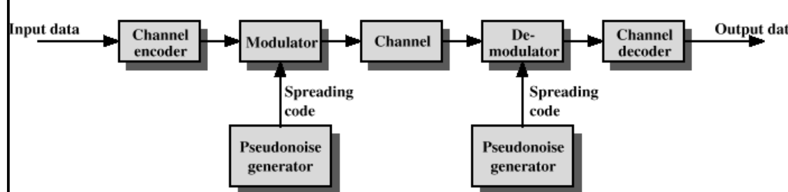
- Uses frequency hopping spread spectrum in the 2.4 GHz ISM band
- Uses 79 frequencies with a spacing of 1 MHz
  - » Other countries use different numbers of frequencies
- Frequency hopping rate is 1600 hops/s
- Signal uses GFSK
  - » Mimimum deviation is 115 KHz
- Maximum data rate is 1 MHz

Direct Sequence Spread Spectrum (DSSS)

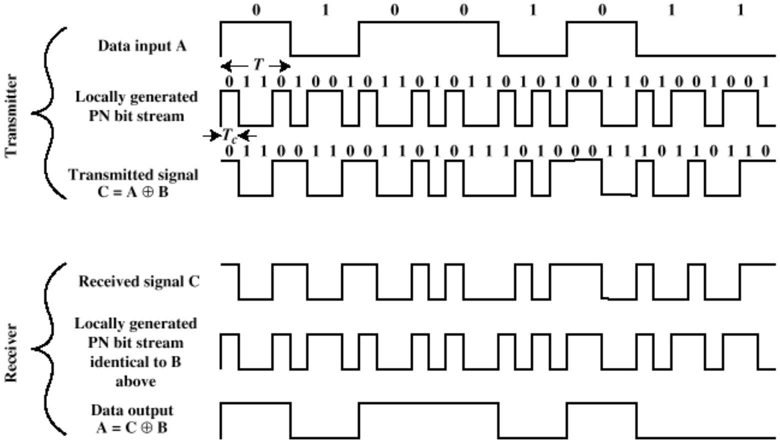
- Each bit in original signal is represented by multiple bits (chips) in the transmitted signal
- Spreading code spreads signal across a wider frequency band
  - » Spread is in direct proportion to number of bits used
  - » E.g. exclusive-OR of the bits with the spreading code
- The resulting bit stream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



Spread Spectrum



Direct Sequence Spread Spectrum



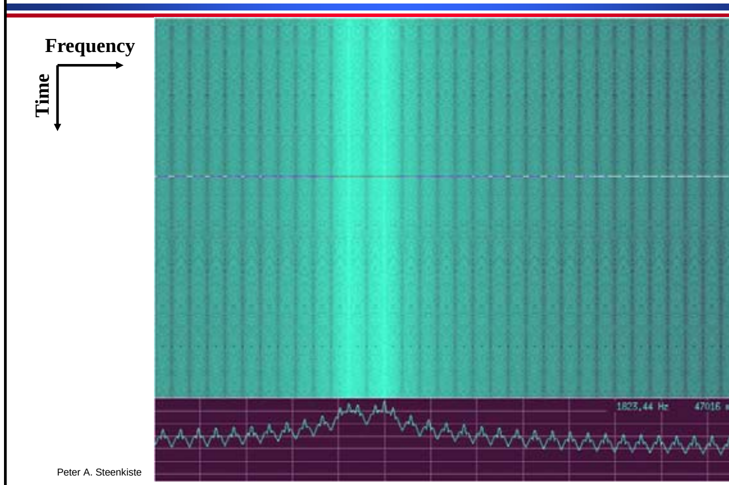
Properties

- 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
- 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.
  - Effective against noise and multi-path
  - 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)
  - Next topic

Example: Original 802.11 Standard (DSSS)

- The DS PHY uses a 1 Msymbol/s rate with an 11-to-1 spreading ratio and a Barker chipping sequence
  - Barker sequence has low autocorrelation properties – why?
  - Uses about 22 MHz
- 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 DBPSK modulation
  - Resulting data rate is1 Mbps (i.e. 11 Mchips/sec)
  - Extended to 2 Mbps by using a DQPSK modulation
    - Requires the detection of a ¼ phase shift

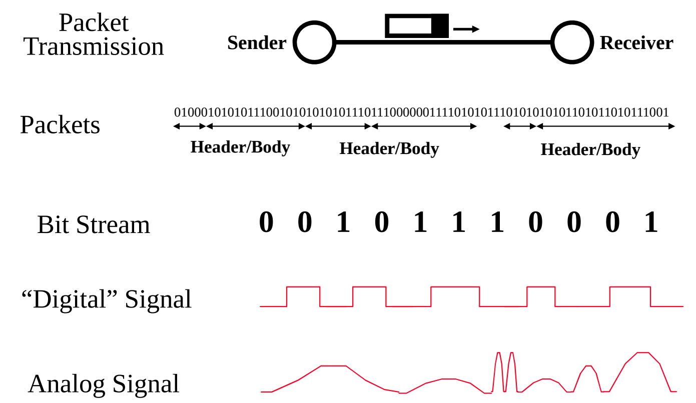
Spectrogram: DSSS-encoded Signal



Outline

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

From Signals to Packets



Code Division Multiple Access

- Users share spectrum, i.e., use it at the same time, but they use different codes to spread their data over the frequency
  - » DSSS where users use different spreading sequences
  - » Use spreading sequences that are orthogonal, i.e. they have minimal overlap
  - » Frequency hopping with different hop sequences
- 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

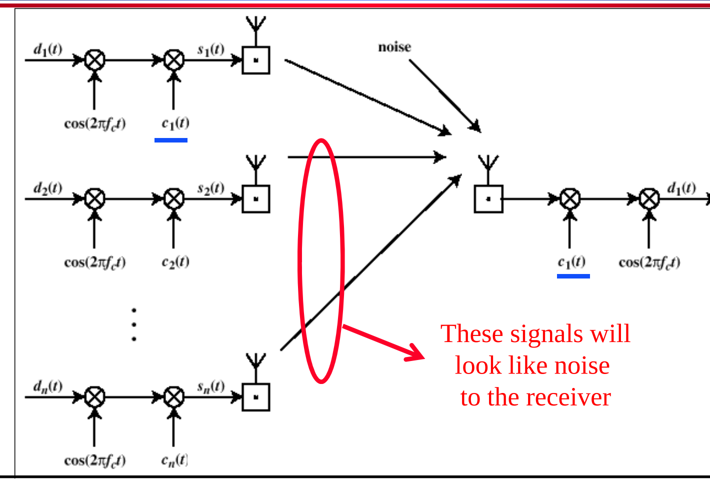
$$S_u(d) = d1 \times c1 + d2 \times c2 + d3 \times c3 + d4 \times c4 + d5 \times c5 + d6 \times c6$$

  - – <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

CDMA for Direct Sequence Spread Spectrum



CDMA Discussion

- CDMA does not assign a fixed bandwidth but a user's bandwidth depends on the traffic load
  - » More users results in 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

Summary

- **Spread spectrum achieves robustness by spreading out the signal over a wide channel**
  - » **Sending different data blocks on different frequencies, or**
  - » **Spreading all data across the entire channel**
- **CDMA builds on the same concept by allowing multiple senders to simultaneously use the same channel**
  - » **Sender and receive must coordinate so receiver can decode the data**