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

- Multiply $\tilde{y}$ with the complex conjugate $\tilde{\mathbf{h}}$ of the channel vector $\mathbf{h}$
  » 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 $\tilde{\mathbf{h}}$ based on training data
The Details

- Complex conjugates: same real part but imaginary parts of opposite signs
  \[ \overline{h} \ast \overline{y} = \overline{h} \ast (\overline{h} \ast x + \overline{n}) \]
  Where \( h^* = [h_1^* \ h_2^*] = [a_1+b_1i \ a_2-b_2i] \)
- 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 \( Y \)

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
  - Minimum 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

| Original Signal | 1 | 1 | 0 | 0 | 0 | 0 |
| Spreading Code  | 0 | 0 | 1 | 1 | 0 | 1 |
| Transmitted Chips| 0 | 0 | 1 | 0 | 1 | 1 |
| Modulated Signal| 1 | 1 | 0 | 1 | 0 | 1 |

**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 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 is 1 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

- Transmit: P
- Receive: P

Packet Transmission

<table>
<thead>
<tr>
<th>Sender</th>
<th>Receiver</th>
</tr>
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<tbody>
<tr>
<td>0 0 1 0 1 1 0 0 1</td>
<td></td>
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Bit Stream

“Digital” Signal

Analog Signal

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
  \[ S_A(d) = d_1 c_1 + d_2 c_2 + d_3 c_3 + d_4 c_4 + d_5 c_5 + d_6 c_6 \]
  » For k=6, if d1=1, d2=0, d3=1, d4=0, d5=1, d6=0 (received pattern)
  » For k=6, if c1=1, c2=1, c3=1, c4=1, c5=1, c6=1 (coding sequence)
**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 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 for Direct Sequence Spread Spectrum**

These signals will look like noise to the receiver

**CDMA Example**

- **CDMA cellular standard.**
  - Used in the US, e.g. Sprint
  - Allocated 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