18-759 : Wireless Networks

Lecture 6: Final Physical Layer

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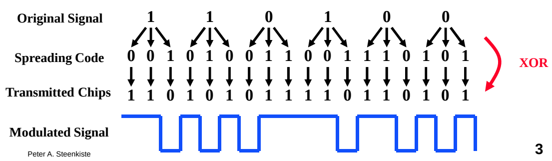
http://www.cs.cmu.edu/~prs/wireless09/

Outline

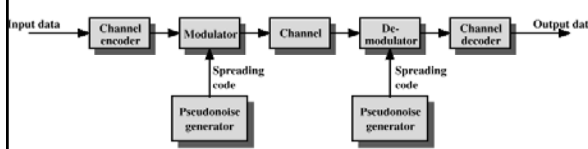
- RF introduction
- Modulation and multiplexing
- Channel capacity
- Antennas and signal propagation
- Equalization and diversity
- Modulation and coding
  - » Coding and modulation
  - » Amplitude, frequency, phase
  - » Spread spectrum
  - » Code division multiple access
- Some newer technologies
-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

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

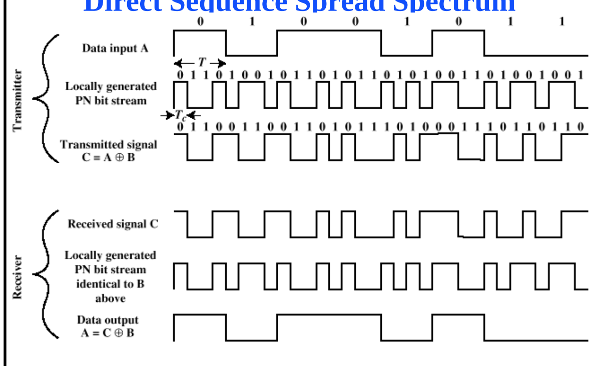
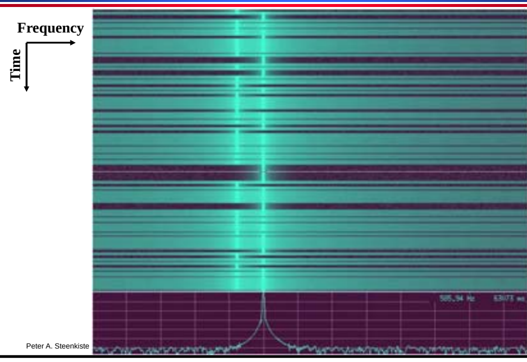


Figure 7.6 Example of Direct Sequence Spread Spectrum

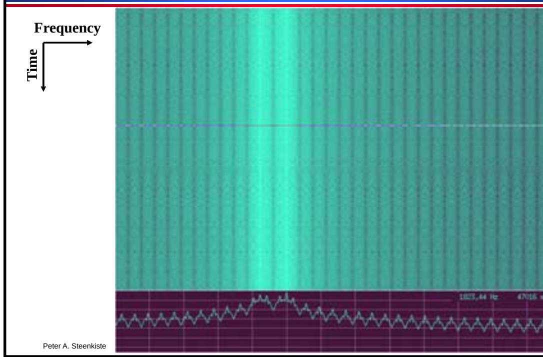
Properties

- 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 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

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 DQPSK modulation.
  - » I.e. 4 values for each chip
- Maximum rate is 11 Mbps
  - » Symbol rate at 1.375 MSymbols/sec, at 8 bpS = 11 Mbps
- 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
  - » There are exceptions
- 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
  - » 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

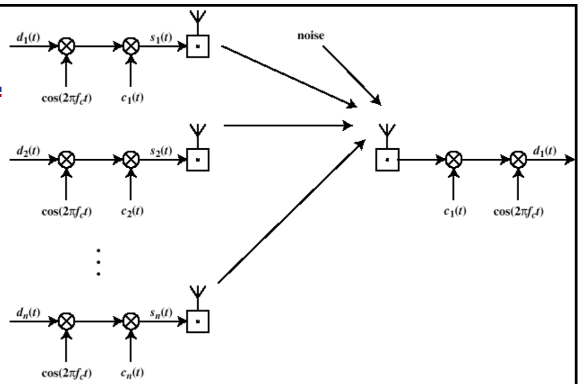
- Basic Principles of CDMA
  - *D* = rate of data signal
  - Break each bit into *k chips* - user-specific fixed pattern
  - Chip data rate of new channel = *kD*
- If *k*=6 and code is a sequence of 1s and -1s
  - For a ‘1’ bit, A sends code as chip pattern
    - <c1, c2, c3, c4, c5, c6>
  - For a ‘0’ 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



Categories of Spreading Sequences

- Spreading Sequence Categories
  - Pseudo-noise (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

Outline

- RF introduction
- Modulation and multiplexing
- Channel capacity
- Antennas and signal propagation
- Equalization and diversity
- Modulation and coding
- Some newer technologies
  - » OFDM
  - » UWB
  - » MIMO
- Spectrum access

How Do We Increase Rates?

- Two challenges related to multipath:
- As rates increase, symbol times shrink and the effects of inter-symbol interference becomes more pronounced
  - » See earlier examples
- Frequency selective fading starts to have a bigger impact because there is less redundancy in the signal
- So we need an encoding that has longer symbol times and allows us to fight frequency selective interference

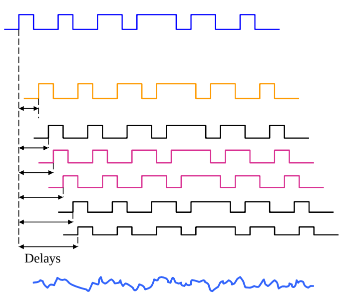
Inter-Symbol-Interference

Transmitted signal:

Received Signals:

Line-of-sight:

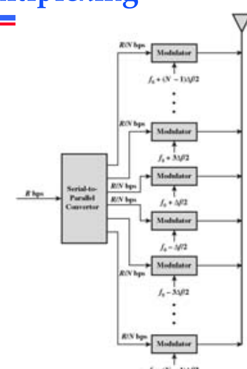
Reflected:



The symbols add up on the channel
→ Distortion!

OFDM - Orthogonal Frequency Division Multiplexing

- Distribute bits over N subcarriers that use different frequencies in the band B
  - » Multi-carrier modulation
  - » Each signal uses ~B/N bandwidth
- Since each subcarrier only encodes 1/N of the bit stream, each symbol takes N times longer in time
- But how can we can we efficiently pack many subcarriers in a band?



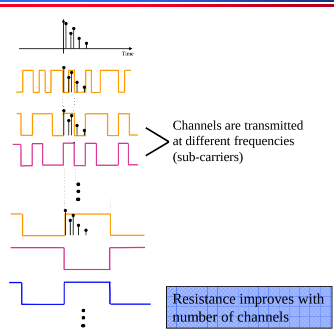
Distributing Bits over Subcarriers

Channel impulse response

Single Channel

2 Channels

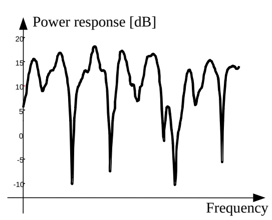
8 Channels



Channels are transmitted at different frequencies (sub-carriers)

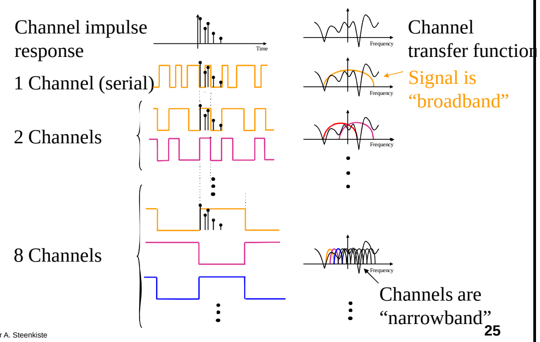
Resistance improves with number of channels

Frequency-Selective Radio Channel



- Interference of reflected (and LOS) radio waves results in frequency dependent fading
- Impact is reduced for narrow channels

Benefits of Narrow Band Channels

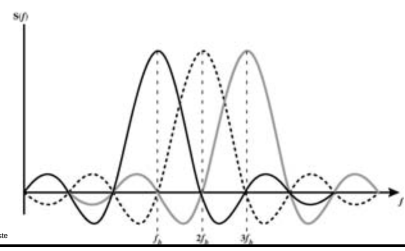


Fighting ISI

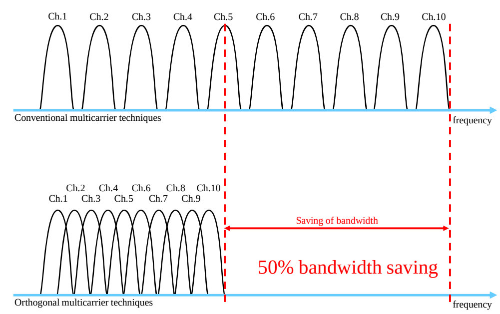
- Frequency selective fading will only affects some subcarriers
  - » May be able to simply amplify affected subcarriers
    - – No need for complex dynamic equalizer
  - » Use redundancy to deal with data loss on bad subcarriers
- Further reduce ISI effects by sending a "cyclic prefix" before every burst of symbols
  - » Can be used to absorb delayed copies of real symbols, without affecting the symbols in the next burst
  - » Prefix is a copy of the tail of the symbol burst to maintain a smooth symbol
  - » E.g. a cyclic prefix of 64 symbols and data bursts of 256 symbols using QPSK modulation
- Increase throughput by increasing subcarriers
  - » Does not affect the symbol time!

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



Densely Packing OFDM Channels



Example: 802.11a

- Uses OFDM with up to 48 subcarriers
- Subcarrier spacing is 0.3125 MHz
- Subcarriers are modulated using BPSK, QPSK, 16-QAM, and 64-QAM
- Uses a convolutional code at a rate of ½, 2/3, or ¾ to provide forward error correction
- Results in data rates of 6, 9, 12, 18, 24, 36, 48, and 54 MBps
- Cyclic prefix is 25% of a symbol burst (16 versus 64)
- OFDM is also used for higher 802.11g rates

Ultra WideBand

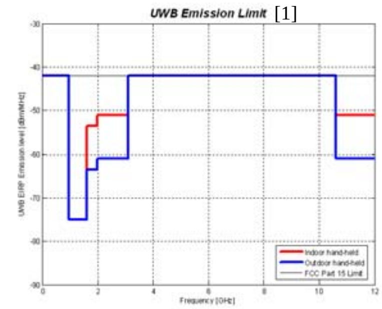
$$C = B \log_2 (1 + \mathrm{SNR})$$

- Can achieve high throughputs with low SNR by using a high B
- Motivation is the 802.15.3a (high rate PAN) standards effort
  - » Targets high speed, short distance communication
- But where do I find this much spectrum?
- Use a transmit power that is low enough to so it will not affect other users
  - » Can be used in most licensed frequency bands (with FCC permission, of course)

FCC UWB Rules

- UWB technically defined as:
  - » Width of signal > 500 MHz, or $B_f = 2\frac{f_H - f_L}{f_H + f_L} > 0.2$
- Approved for 3.1 GHz to 10.6 GHz
- Power limit is -41.3 dBm/MHz
  - » Note that the limit is not on the total signal but across the part of the spectrum that is used
- Results in a frequency mask that must be satisfied
- Certain narrow bands must be filtered out
  - » E.g. certain radio astronomy bands
  - » Depends on the country

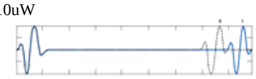
FCC Regulations



Basic Impulse Information Modulation

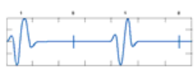
Pulse length ~ 200ps; Energy concentrated in 2-6GHz band;
Voltage swing ~100mV; Power ~ 10uW

- Pulse Position Modulation (PPM)



- Pulse Amplitude Modulation (PAM)

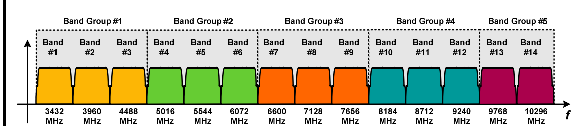
- On-Off Keying (OOK)



- Bi-Phase Modulation (BPSK)

Multi-band OFDM

- Central Idea #1:
  - » Divide the spectrum into bands that are 528 MHz wide.



- Advantages:
  - » Transmitter and receiver process smaller bandwidth signals.
  - » Instantaneous processing BW = 528 MHz.

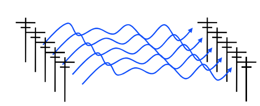
So why is UWB so interesting?

- 7.5 Ghz of "free spectrum" in the U.S.
  - » FCC recently legalized UWB for commercial use
  - » Spectrum allocation overlays existing users, but its allowed power level is very low to minimize interference
- Very high data rates possible
  - » 500 Mbps can be achieved at distances of 10 feet under current regulations
- Simple CMOS transmitters at very low power
  - » Suitable for battery-operated devices
  - » Low power is CMOS friendly
  - » "Moore's Law Radio" --Data rate scales with the shorter pulse widths made possible with ever faster CMOS circuits
- Low cost
  - » Nearly "all digital" radio ?
  - » Integration of more components on a chip (antennas?)

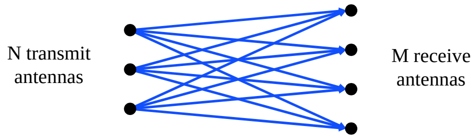
How Do We Increase Throughput in Wireless?

- Wired world: pull more wires!

- Wireless world: use more antennas?



MIMO
Multiple In Multiple Out



- N x M subchannels
- Fading on channels is supposed to be largely independent
- Combines ideas from spatial and time diversity
- Very effective if there is no direct line of sight
  - » Subchannels become more independent

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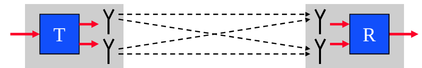
MIMO
How Does it Work?

- Coordinate the processing at the transmitter and receiver to overcome channel impairments
  - » Maximize throughput or minimize interference
  - » Can be viewed as generalization of earlier techniques



I x T x C x R = O

- Optimize T and R to achieve desired effect
  - » But: each arrow in the channel represents multiple paths!
- Very effective if there is no direct line of sight
  - » Subchannels become more independent

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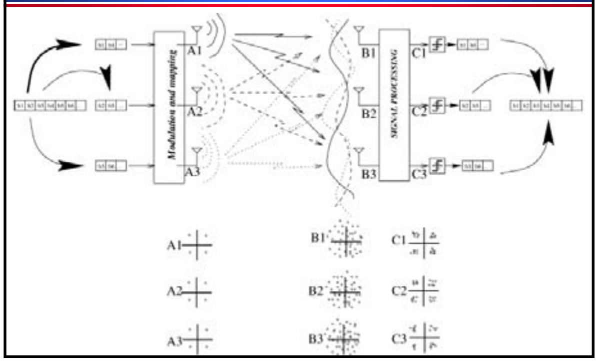
An Example of
Space Coding



A Math View

- Transmitted Code Vector:

$$\mathbf{c}_l = [\ c_1(l),\ c_2(l),\ \cdots,\ c_N(l)\ ]^T$$

- Channel Matrix:

$$\mathbf{H} = \begin{bmatrix} \alpha_{11} & \alpha_{12} & \cdots & \alpha_{1N} \\ \alpha_{21} & \alpha_{22} & \cdots & \alpha_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_{M1} & \alpha_{M2} & \cdots & \alpha_{MN} \end{bmatrix}$$

- Received Signal Vector:

$$\mathbf{r}(l) = \mathbf{H} \cdot \mathbf{c}_l + \mathbf{n}(l)$$

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MIMO Discussion

- MIMO is often combined with OFDM
  - » Fight the effects of multi-path as well
- For example used in 802.11n in the 2.4 GHz band
- Uses two of the non-overlapping “WiFi channels”
  - » Raises lots of compatibility issues
  - » Potential throughputs of 100 of Mbps

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General Frequency Ranges

- Microwave frequency range
  - » 1 GHz to 40 GHz and higher
  - » Directional beams possible
  - » Suitable for point-to-point transmission
  - » Used for satellite communications
- Radio frequency range
  - » 30 MHz to 1 GHz
  - » Suitable for omnidirectional applications
- Infrared frequency range
  - » Roughly, 3×10^{11} to 2×10^{14} Hz
  - » Useful in local point-to-point multipoint applications within confined areas

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Wireless Communication Looks Pretty Easy?

- 300 GHz is huge amount of spectrum!
  - » Spectrum can also be reused in space
- Not quite that easy:
  - » Most of it is hard or expensive to use!
  - » Noise and interference limits efficiency
  - » Most of the spectrum is allocated by FCC
- FCC controls who can use the spectrum and how it can be used.
  - » Need a license for most of the spectrum
  - » Limits on power, placement of transmitters, coding, ..
  - » Need rules to optimize benefit: guarantee emergency services, simplify communication, return on capital investment, …

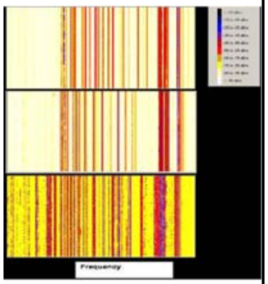
Spectrum Allocation

See:
http://www.ntia.doc.gov/osmhome/allochrt.html

- Most bands are allocated.
- Industrial, Scientific, and Medical (ISM) bands are "unlicensed".
  - » But still subject to various constraints on the operator, e.g. 1 W output
  - » 433-868 MHz (Europe)
  - » 902-928 MHz (US)
  - » 2.4000-2.4835 GHz
  - » Unlicensed National Information Infrastructure (UNII) band is 5.725-5.875 GHz

Spectrum Use is Limited

- Most of the spectrum is mostly unused most of the time
  - » E.g. 17% of spectrum used below 2 GHz in Manhattan during republican convention
  - » Only a few frequencies see heavy use regularly, e.g. unlicensed, cellular
- Efforts to make spectrum use more dynamic and efficient
  - » Opportunistic users, secondary markets, etc.



Snapshot of utilization of 700 MHz slice of spectrum below 1 GHz