18-452/18-750
Wireless Networks and Applications
Lecture 6: Physical Layer
Spread Spectrum and OFDM

Peter Steenkiste

Carnegie Mellon University

Spring Semester 2024

http://www.cs.cmu.edu/~prs/wirelessS24/

Announcements

- **Both waiting lists have cleared!**
  - » 24 + 4 students with a max capacity of 30
- **Please complete the two short surveys on gradescope**
  - » Status of monitor mode: we need to know how many students still have problems
  - » Survey on your wireless interests
- **Setting up your laptop for P1**
  - » Please use piazza group for questions (not private mode) if you have problems
  - » We need to know asap how many students have problems so we know how to best move forward

Outline

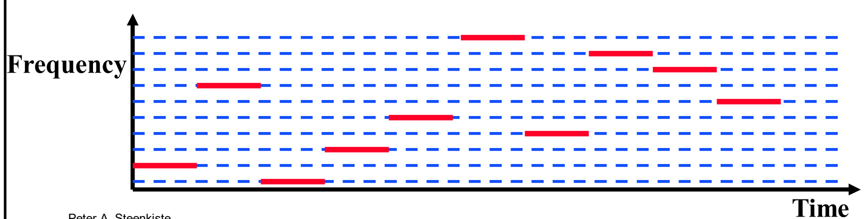
- RF introduction
- Modulation and multiplexing
- Channel capacity
- Antennas and signal propagation
- Modulation
- Diversity and coding
  - » Space, time and frequency diversity
  - » Spread spectrum
- OFDM and MIMO

Spread Spectrum

- Example of "redundancy in frequency"
- Spread transmission (much) wider spectrum band than needed for the intended bit rate
- Reduce impact of a "bad" frequencies
  - » Also in military: jamming and interception becomes harder
- The price is that you use more spectrum
- What can be gained from this apparent waste of spectrum?
  1. Provides a safety buffer to the receiver to overcome impact of bad channel properties
  2. Several users can independently use the same higher bandwidth with very little interference
     - Key idea: traffic of other users looks like noise

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 on one frequency
- Spreading code determines the hopping sequence
  - » Must be shared by sender and receiver (i.e., standardized)
  - » Using different spreading codes minimizes interference



Peter A. Steenkiste 5

5

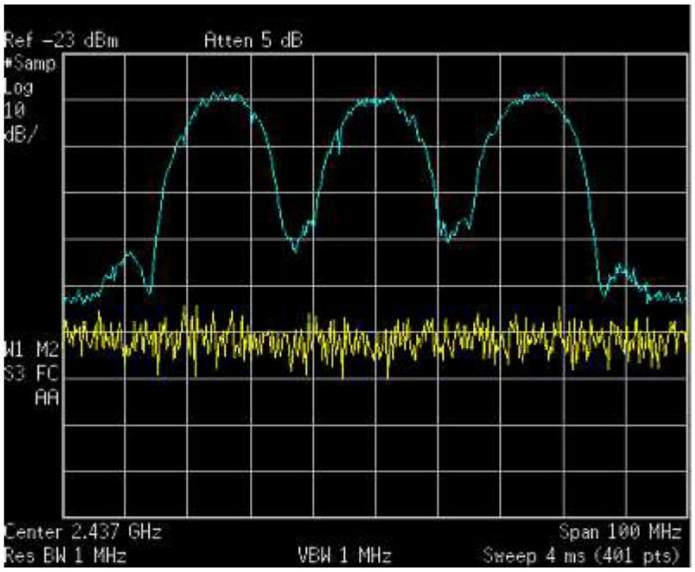
Example: Bluetooth

- 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 Mbps
- Also used in the original WiFi standard

Peter A. Steenkiste 6

6

802.11b Spectrogram

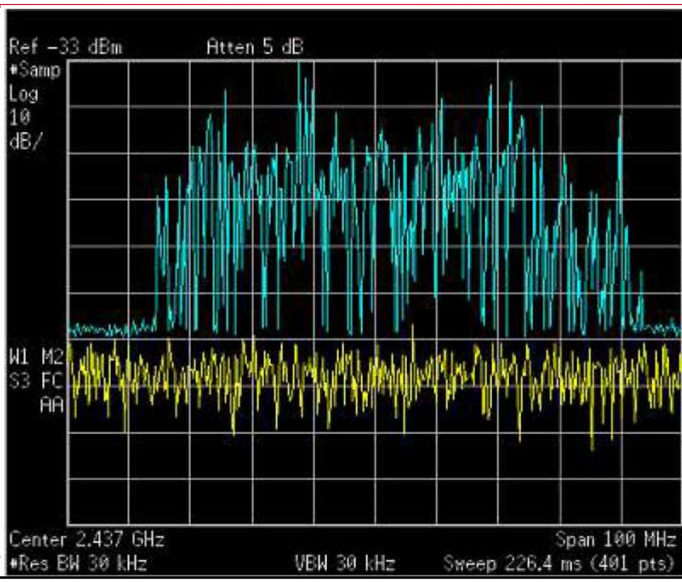


Peter A. St

7

7

Frequency Hopping Spectrogram



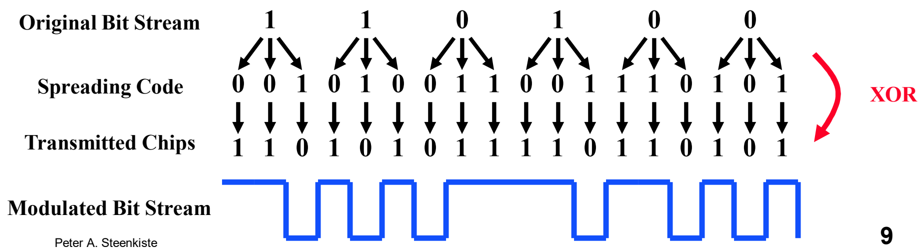
Peter A. Steer

8

8

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

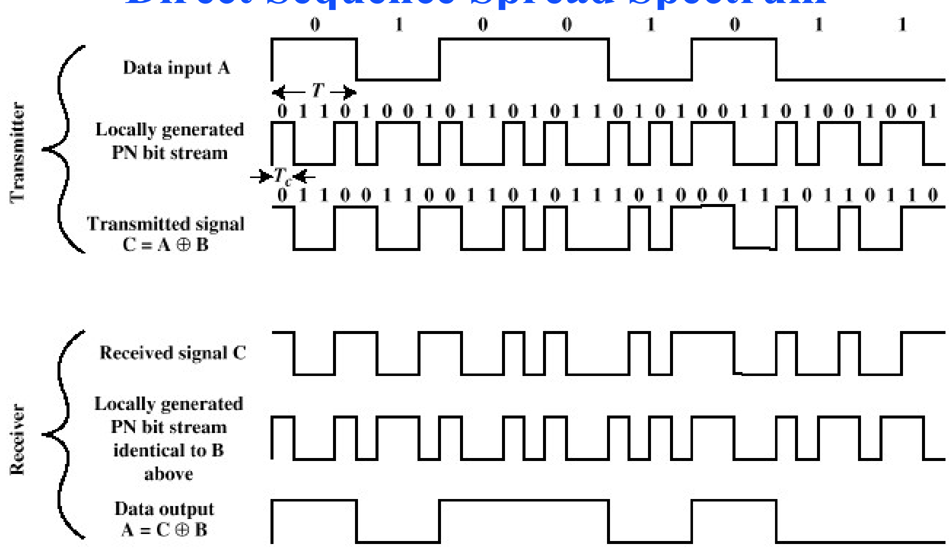


Peter A. Steenkiste

9

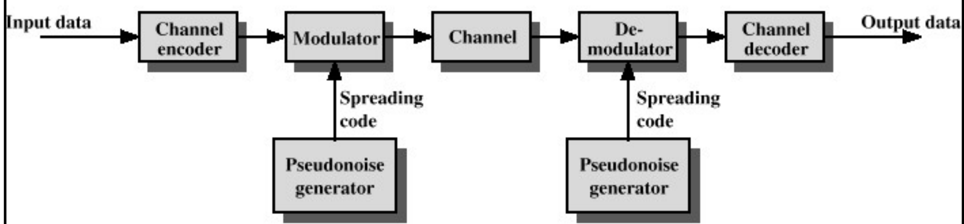
9

Direct Sequence Spread Spectrum



10

Spread Spectrum

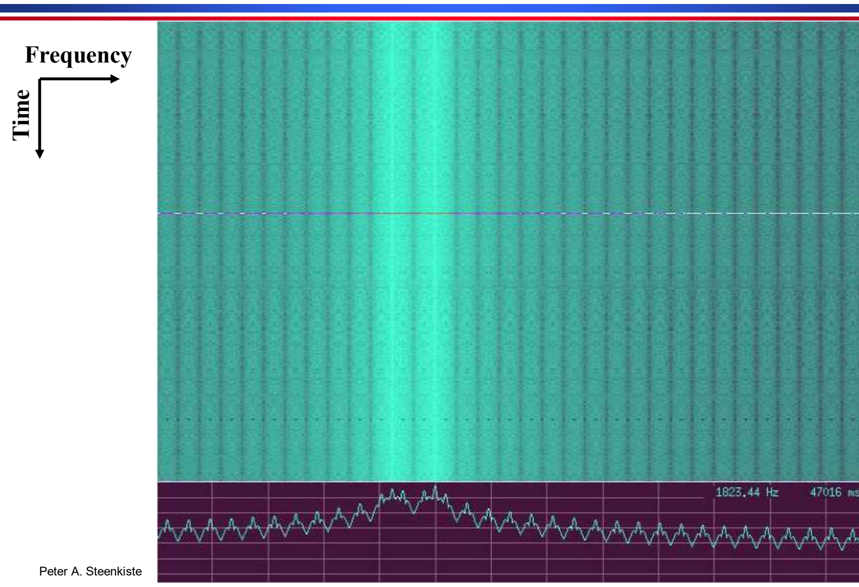


Peter A. Steenkiste

11

11

Spectrogram: DSSS-encoded Signal



Peter A. Steenkiste

2

12

DSSS 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 very resilient.
  - » Effective against noise and multi-path
  - » DSSS signal 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)
  - » E.g., Code Division Multiple Access - next

Peter A. Steenkiste 13

13

Code Division Multiple Access

- Users use a spectrum band at the same time, but they use different codes to spread their data over the frequency band
  - » Spread spectrum with users use different orthogonal spreading sequences, i.e. they have minimal overlap
  - » Base station manages spreading codes
  - » Alternative to sharing spectrum by serializing packet transmissions, e.g., WiFi standards
- The signal of other users will appear as noise
  - » But the transmissions are very robust because of the use of spread spectrum
- Offers an easy way to share spectrum
  - » Adding users will increase the noise for each user
  - » This will reduce their throughput – spectrum sharing!

Peter A. Steenkiste 14

14

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

Peter A. Steenkiste

15

15

CDMA Example

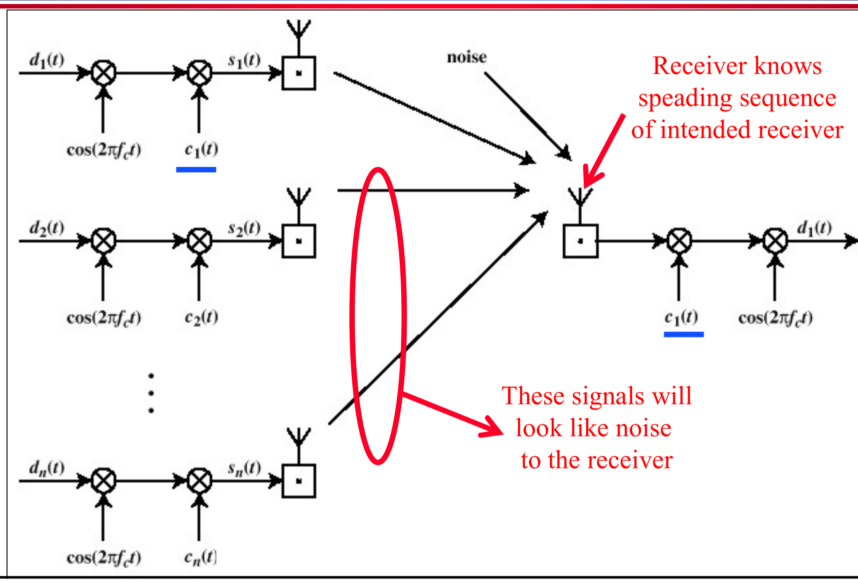
- User A code = <1, –1, –1, 1, –1, 1>
  - » To send a 1 bit = <1, –1, –1, 1, –1, 1>
  - » To send a 0 bit = <–1, 1, 1, –1, 1, –1>
- User B code = <1, 1, –1, – 1, 1, 1>
  - » To send a 1 bit = <1, 1, –1, –1, 1, 1>
- Receiver receiving with A’s code
  - » (A’s code) x (received chip pattern)
    - – User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

Peter A. Steenkiste

16

16

CDMA for Direct Sequence Spread Spectrum



17

Example: Original 802.11 Standard (DSSS)

- The DS PHY uses a 1 Msymbol/s rate with an 11-to-1 spreading ratio
  - » 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

Peter A. Steenkiste 18

18

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 lower throughput for each user, e.g. more information lost due to errors
  - » How graceful the degradation is depends on how orthogonal the codes are (standardized)
- Problem: 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. nodes closer to the basestation use a lower transmission power than remote nodes

Peter A. Steenkiste 19

19

CDMA Example

- CDMA cellular standard
  - » 3G standards
  - » 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

Peter A. Steenkiste 20

20

Summary

- Spread spectrum achieves robustness by spreading out the signal over a wide channel
  - » Sending different data blocks on different frequencies vs
  - » 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

Peter A. Steenkiste

21

21

Outline

- RF introduction
- Modulation and multiplexing
- Channel capacity
- Antennas and signal propagation
- Modulation
- Diversity and coding
- OFDM and MIMO

Peter A. Steenkiste

22

22

How Do We Increase Rates?

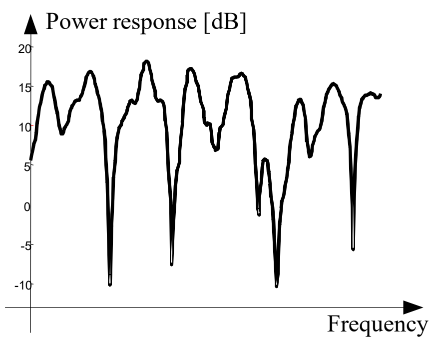
- Two challenges related to multipath:
- Frequency selective fading has a bigger impact at *high data rates*
  - » There is less redundance in the transmitted
- It also has bigger impact on *wide-band channels*
  - » An easy way to increase bit rate!
- As rates increase, *symbol times shrink* and the effects of inter-symbol interference becomes more pronounced
  - » There is a limit on how much we can shrink symbol times
- We need an encoding/modulation solution that has long symbol times and limits the impact of frequency selective fading

Peter A. Steenkiste

23

23

Frequency-Selective Radio Channel



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

Peter A. Steenkiste

24

24

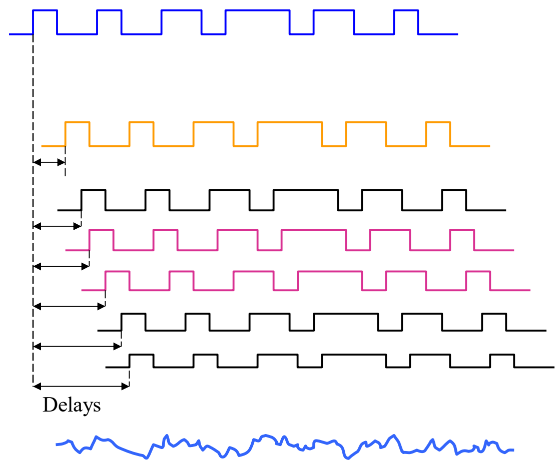
Inter-Symbol-Interference

Transmitted signal:

Received Signals:

Line-of-sight:

Reflected:



The symbols add up on the channel
→ Distortion!

Peter A. Steenkiste

25

25

Distributing Bits over Subcarriers

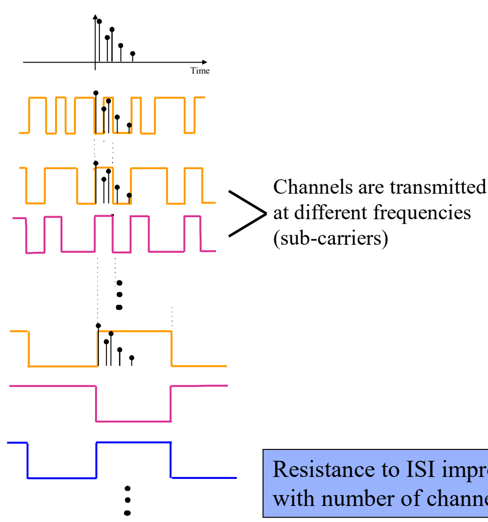
Channel impulse response

Single Carrier

2 Carriers

8 Carriers

⋮



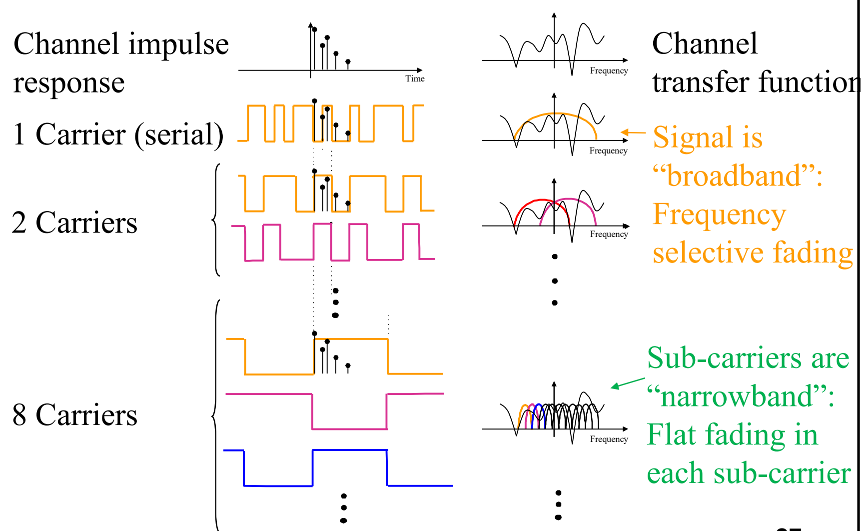
Resistance to ISI improves with number of channels

Peter A. Steenkiste

26

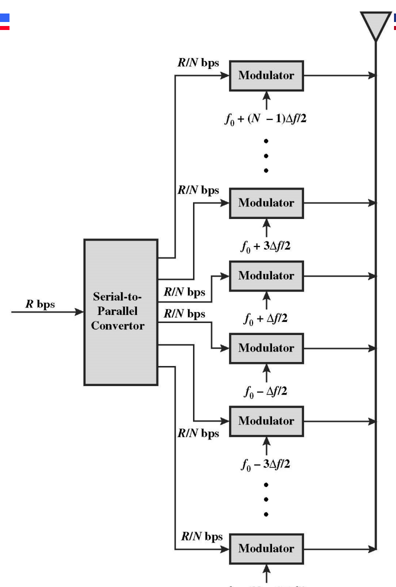
26

Benefits of Narrow Band Channels

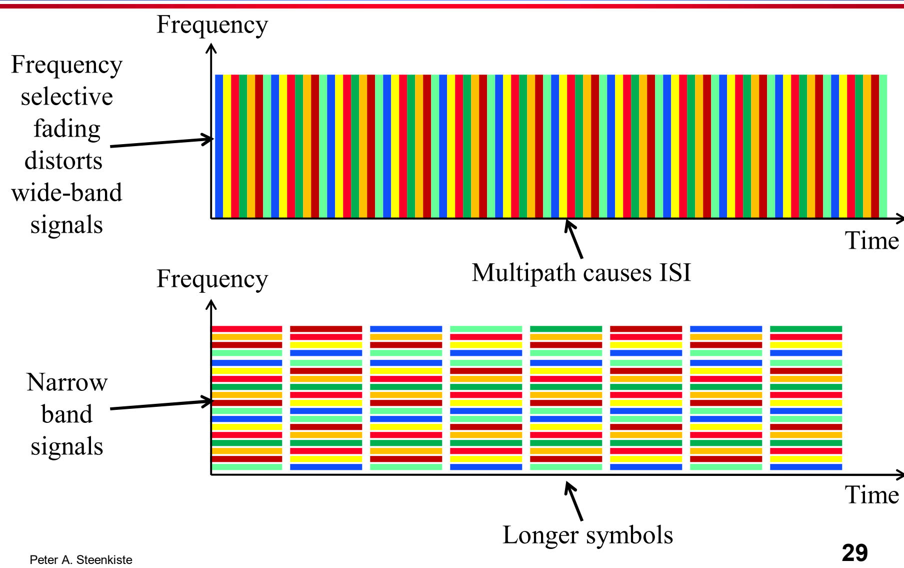


OFDM - Orthogonal Frequency Division Multiplexing

- 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
- Since signals are narrower, fighting frequency selective fading is easier



OFDM Transmission



Peter A. Steenkiste

29

29

Fighting ISI

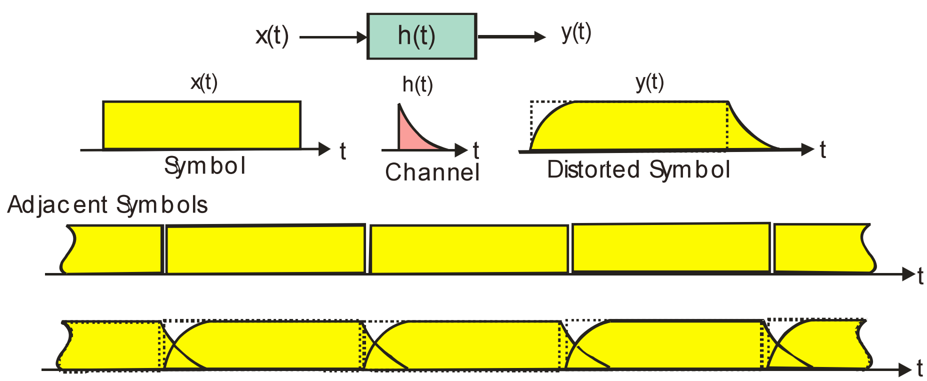
- **Frequency selective fading will only affects some subcarriers**
  - » **May be able to simply amplify affected subcarriers**
  - » **No need for complex dynamic equalizer**
    - – **Become less effective with shorter symbols**
- **Further reduce ISI effects by sending a "cyclic prefix" before every 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**

Peter A. Steenkiste

30

30

Adjacent Symbol Interference (ASI)
Symbol Smearing Due to Channel

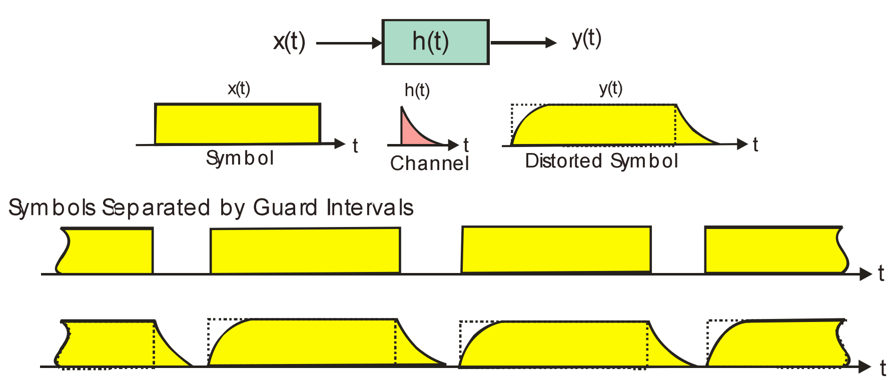


Peter A. Steenkiste

Slide Prof Harris, SDSU **31**

31

Reduce Impact of
Inter-Symbol Interference



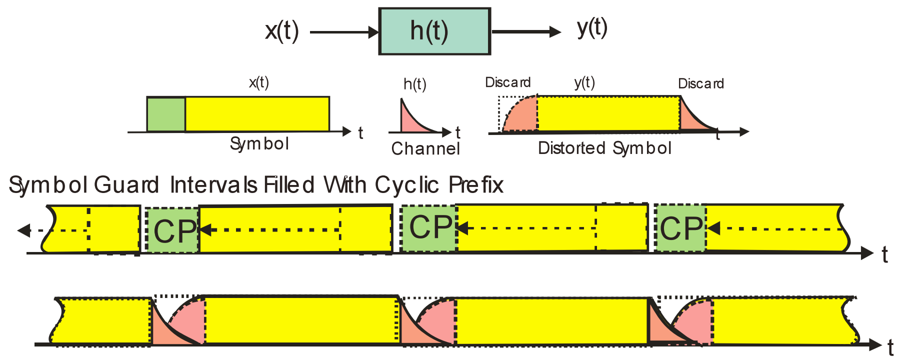
- **Separate symbols in time to avoid that they overlap at receiver**
- **The drawback is the sharp changes in signal strength will increase how much spectrum is used**
  - » **Can result in Adjacent Channel Interference**

Peter A. Steenkiste

Slide Prof Harris, SDSU **32**

32

Insert Cyclic Prefix to Suppress Adjacent Channel Interference (ACI)

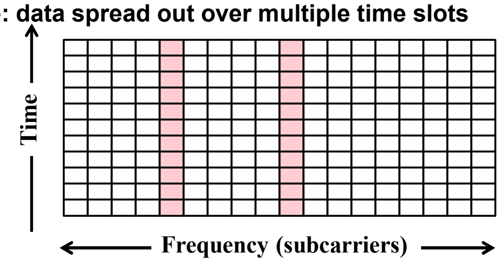


- "Fill the gap" with a copy of part of the symbol
  - Has the same characteristics of the symbols leading to a smooth transition
- Receiver ignores the signal in the gap

Slide Prof Harris, SDSU

Use of Redundancy in OFDM

- OFDM uses error coding as described earlier
  - Degree of error coding depends on channel conditions
- OFDM offers frequency and diversity
  - Frequency: data is spread out over multiple subcarriers
  - Time: data spread out over multiple time slots



- Combining OFDM with MIMO adds space diversity (discussed later in course)

Implementing OFDM

- This is great, but OFDM looks very complicated!
- How many radios do I need? 48?
- How do I get 48 (or more) subcarriers packed very densely?
- Do I need guard bands between the subcarriers, and if so, how wide?
  - » Looks like a lot of wasted spectrum

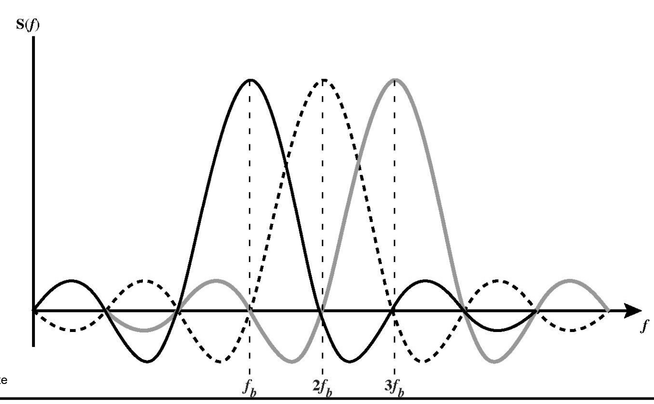
Peter A. Steenkiste

35

35

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

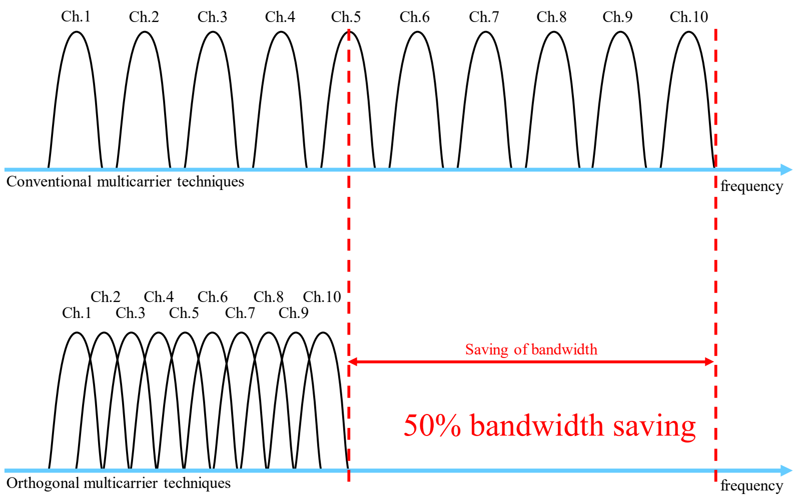


Peter A. Steenkiste

36

36

Densely Packing OFDM Channels

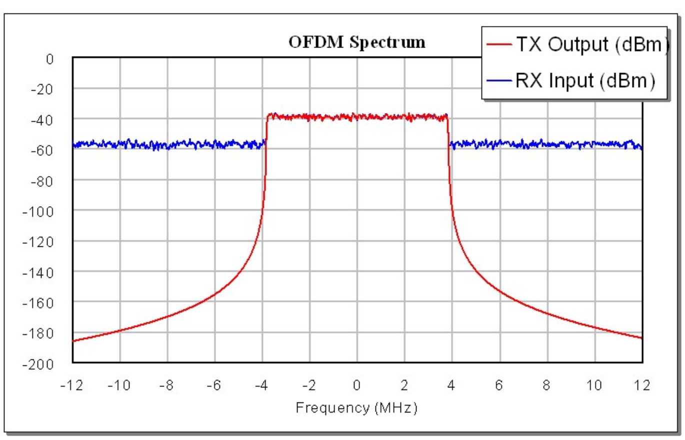


Peter A. Steenkiste

37

37

OFDM Spectrum Use



Peter A. Steenkiste

38

38

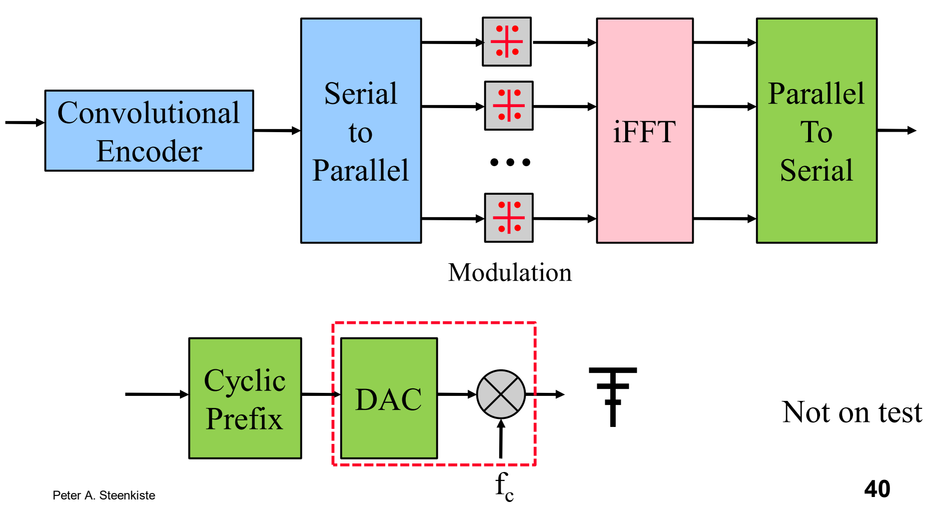
Implementing OFDM

- Naïve approach: modulate individual subcarriers and move them to the right frequency
  - » Not practical: the subcarriers are packed very densely and their spacing must be very precise
  - » Also complicated: lots of signals to deal with!
- How it works: radio modulates the subcarriers and combines them in the digital domain and then converts the signal to the analog domain
  - » The details do not matter for this course
- Practical implication: symbol time is inverse proportional to the subcarrier spacing
  - » 802.11a/n/ac: symbol time 3.2 μsec; spacing 312.5 KHz
  - » 802.11ax: symbol time 12.8 μ sec; 78.125 KHz

Peter A. Steenkiste 39

39

OFDM Transmitter Digital!



Not on test

Peter A. Steenkiste 40

40

OFDM in WiFi

- OFDM is used in all "post b" WiFi standard
- Example: 802.11a
- 20 MHz band, with a signal of 16.6 MHz
- 52 subcarriers: 48 for data, 4 pilots
- Modulations: BPSK, QPSK, 16-QAM, 64-QAM
- 3.2 microsec symbol duration, including a 0.8 microsec guard interval
  - » "Only" 52 orthogonal subcarrier
- Modulation and coding scheme determines the bit rates
  - » Next slide

Modulation and Coding Schemes (MCS) for 802.11a

Symbol rate is 12 Msymbols/sec

MCS index	RATE bits	Modulation type	Coding rate	Data rate (Mbit/s)
13	1101	BPSK	1/2	6
16	1111	BPSK	3/4	9
5	0101	QPSK	1/2	12
7	0111	QPSK	3/4	18
9	1001	16-QAM	1/2	24
11	1011	16-QAM	3/4	36
1	0001	64-QAM	2/3	48
3	0011	64-QAM	3/4	54

Example: 802.11ax

Modulation and coding schemes

MCS index[i]	Modulation type	Coding rate	Data rate (Mbit/s)[i]							
			20 MHz channels		40 MHz channels		80 MHz channels		160 MHz channels	
			1600 ns GI[ii]	800 ns GI	1600 ns GI	800 ns GI	1600 ns GI	800 ns GI	1600 ns GI	800 ns GI
0	BPSK	1/2	8	8.6	16	17.2	34	36.0	68	72
1	QPSK	1/2	16	17.2	33	34.4	68	72.1	136	144
2	QPSK	3/4	24	25.8	49	51.6	102	108.1	204	216
3	16-QAM	1/2	33	34.4	65	68.8	136	144.1	272	282
4	16-QAM	3/4	49	51.6	98	103.2	204	216.2	408	432
5	64-QAM	2/3	65	68.8	130	137.6	272	288.2	544	576
6	64-QAM	3/4	73	77.4	146	154.9	306	324.4	613	649
7	64-QAM	5/6	81	86.0	163	172.1	340	360.3	681	721
8	256-QAM	3/4	98	103.2	195	206.5	408	432.4	817	865
9	256-QAM	5/6	108	114.7	217	229.4	453	480.4	907	961
10	1024-QAM	3/4	122	129.0	244	258.1	510	540.4	1021	1081
11	1024-QAM	5/6	135	143.4	271	286.8	567	600.5	1134	1201

[1] **MCS**: Modulation Coding Scheme

Source https://en.wikipedia.org/wiki/Wi-Fi_6

Discussion

- OFDM is very effective in fighting frequency selective fading and ISI
- Finally a free lunch?
- No – you introduce some overhead
  - Frequency: you need space between the sub carriers
  - Time: You need to insert prefixes between symbols
- You also add complexity
  - More complex radio (but compute cycles are cheap)
  - The OFDM signal is fairly flat in the frequency domain, so it is very variable in the time domain
    - High peak-to-average Power ratio (PAPR)
    - Can be a problem for simple, mobile devices

Summary

- OFDM fights frequency selective fading and inter-symbol interface to increase rates
  - Both become more significant at higher rates
  - It modules a large number of narrow-band signals (subcarriers) instead of a single wide channel
  - Cyclic prefixes are used to separate symbols
- It uses time and frequency diversity, combined with coding (FEC) to reduce the effect of fading
  - Can "pick" the right bit rate for the observed channel conditions by adjusting both the modulation and coding parameters