18-452/18-750
Wireless Networks and Applications
Lecture 7: Physical Layer
OFDM

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http://www.cs.cmu.edu/~prs/wirelessS17/

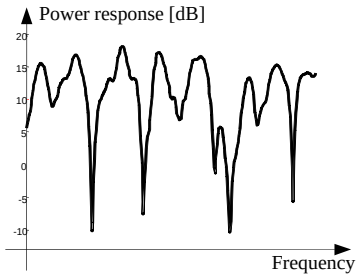
Outline

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

How Do We Increase Rates?

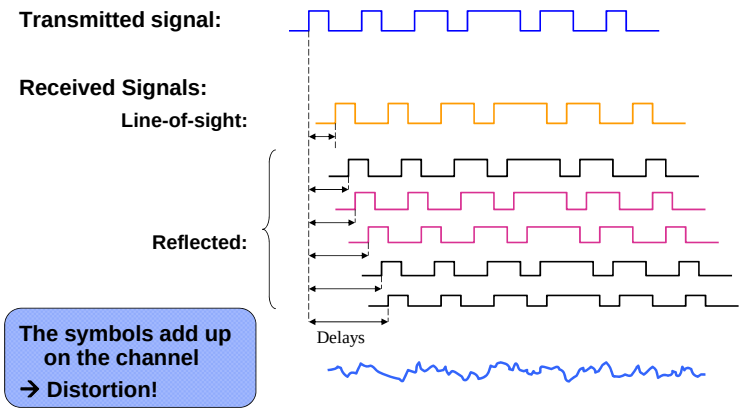
- Two challenges related to multipath:
- Frequency selective fading starts to have a bigger impact because there is less redundancy in the signal
- As rates increase, symbol times shrink and the effects of inter-symbol interference becomes more pronounced
  - » See earlier examples
- We would like an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

Frequency-Selective Radio Channel

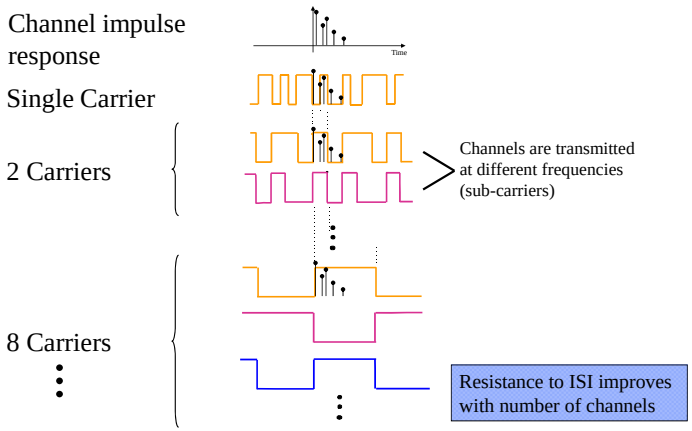


- Interference of reflected and LOS radio waves results in frequency dependent fading
- Impact is reduced for narrow channels

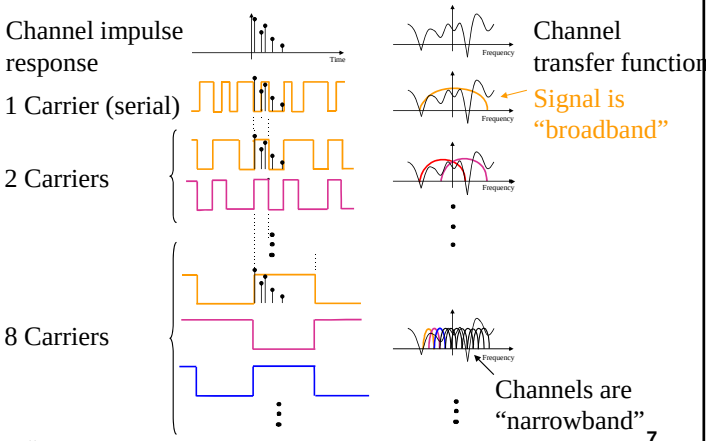
Inter-Symbol-Interference



Distributing Bits over Subcarriers

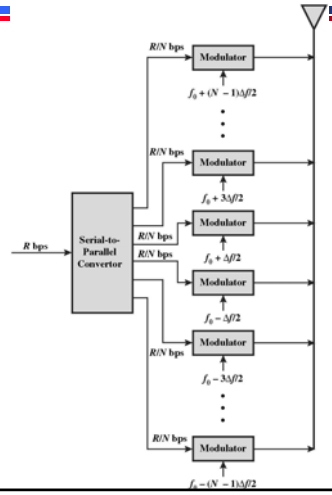


Benefits of Narrow Band Channels

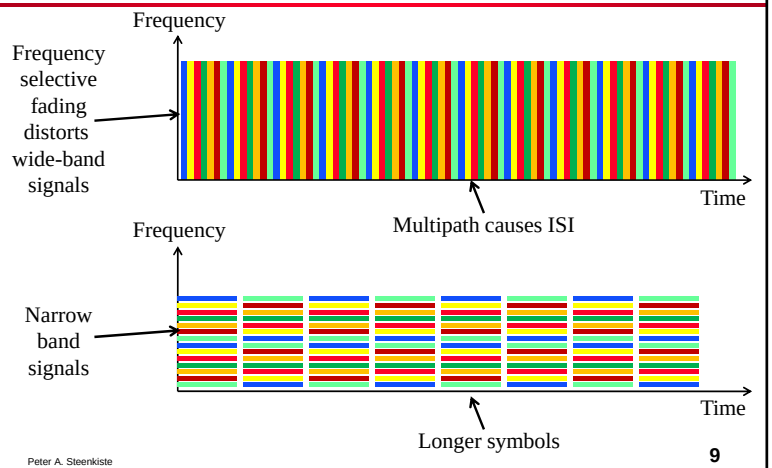


OFDM - Orthogonal Frequency Division Multiplexing

- **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**



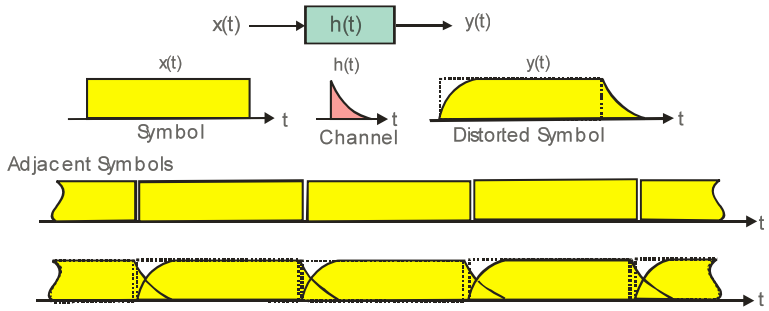
OFDM Transmission



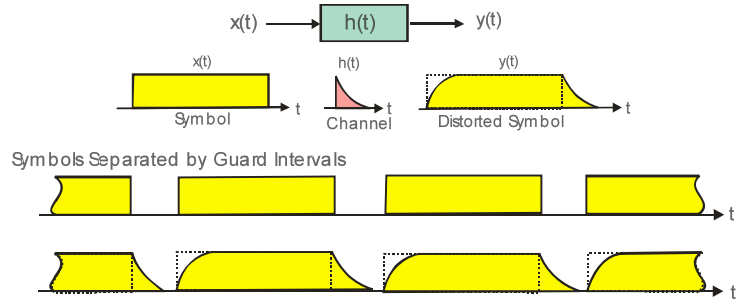
Fighting ISI

- **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**

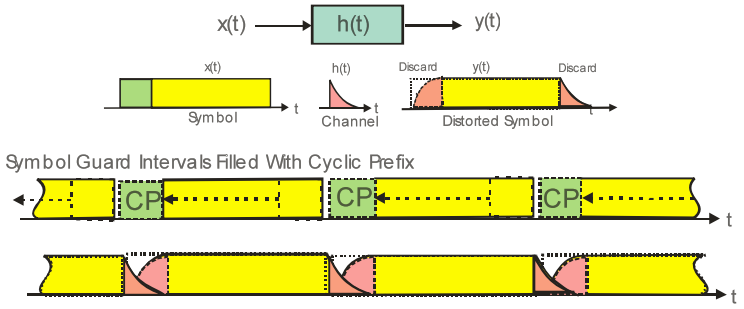
Adjacent Symbol Interference (ASI) Symbol Smearing Due to Channel



Guard Interval Inserted Between Adjacent Symbols to Suppress ASI

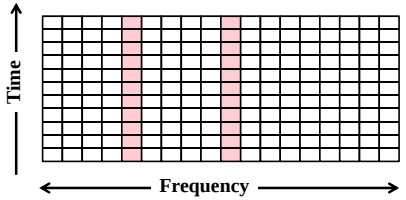


Cyclic Prefix Inserted in Guard Interval to Suppress Adjacent Channel Interference (ACI)



Use of Redundancy in OFDM

- OFDM uses error coding as described earlier
  - » The degree of error coding can be adjusted based on channel conditions
- OFDM offers frequency diversity
  - » Frequency: data is spread out over multiple subcarriers



- Combining OFDM with MIMO adds space diversity

Example: 802.11a

- Uses OFDM with up to 48 subcarriers
  - » Used for data, pilots for control, and guard bands
- 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, ¾, or 5/6 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 vs 64)
- OFDM is also used for the higher 802.11g rates

Discussion

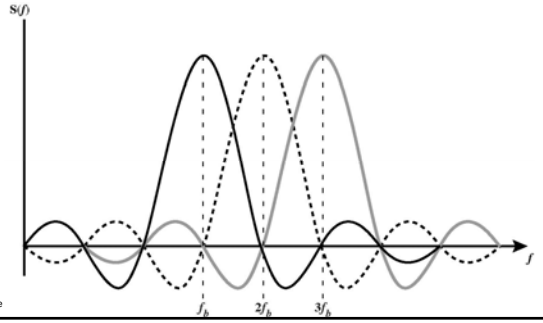
- OFDM is very effective in fighting frequency selective fading and ISI
- Finally a free lunch?
- No – you introduce some overhead
  - » Frequency: you need space between the sub carriers
  - » Time: You need to insert prefixes
- You also add complexity
  - » How do you create many, closely spaced subcarriers?
  - » 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

Implementing OFDM

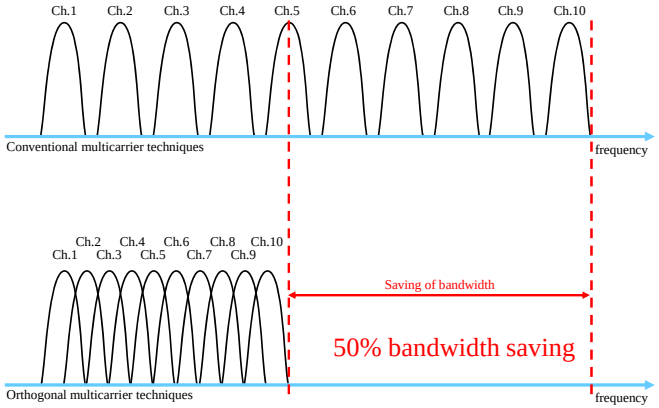
- This is great, but OFDM looks very complicated!
- How do I get 48 (or more) subcarriers packed very densely?
- Do I need guard bands between the subcarriers, and if so, how wide?
- How many radios do I need?

Subcarriers are "Orthogonal"

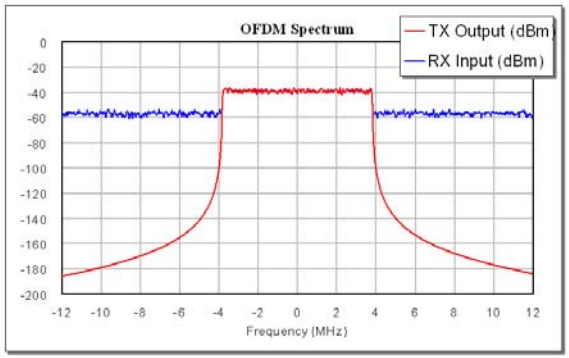
- Peaks of spectral density of each carrier coincide with the zeros of the other carriers
  - » Carriers can be packed very densely with minimal interference
  - » Requires very good control over frequencies



Densely Packing OFDM Channels



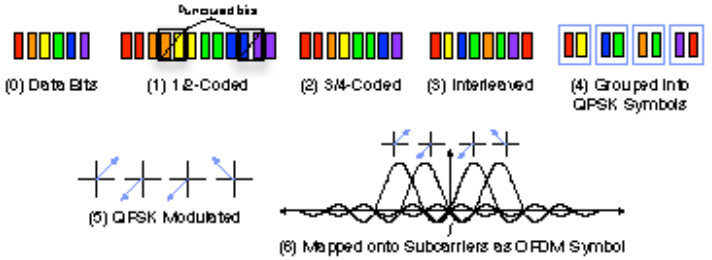
OFDM Spectrum Use



Implementing OFDM

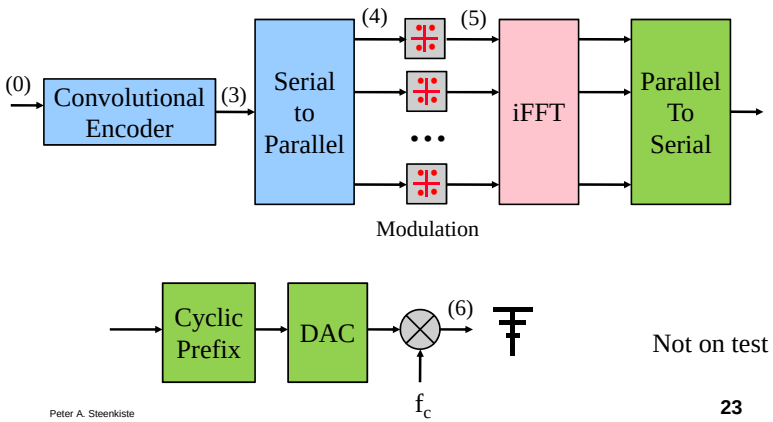
- The naïve approach is to modulate individual subcarriers and move them each to the right frequency
  - » Not practical: the subcarriers are packed very densely and their spacing must be very precise
  - » Also complicated: lots of signals to deal with!
- How it works: Radio modulates the subcarriers and combines them in the digital domain and then converts the signal to the analog domain
  - » The details do not matter for this course

OFDM in 802.11



- Uses punctured code: add redundancy and then drop some bits to reach a certain level of redundancy

OFDM Transmitter



Not on test

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
- 4 microsec symbol duration, including a 0.8 microsec guard interval
- Modulation and coding scheme determines the bit rates
  - » Next slide

MCS for 802.11a

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

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**