This lecture is being recorded

18-452/18-750 Wireless Networks and Applications

Lecture 6: Physical Layer Spread Spectrum and OFDM

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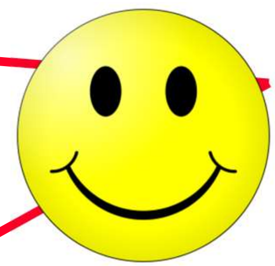
http://www.cs.cmu.edu/~prs/wirelessS21/

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

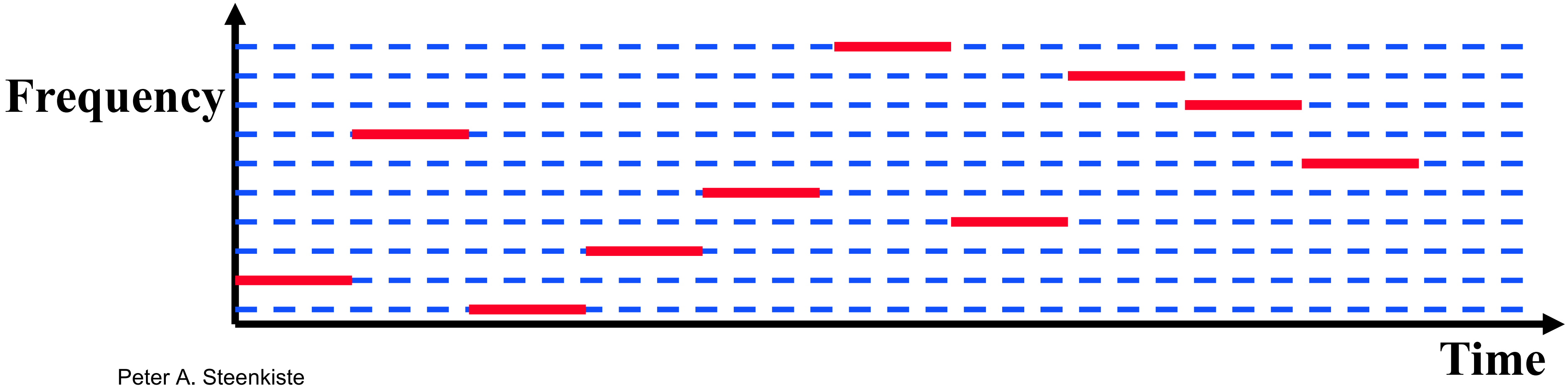


Spread Spectrum

- 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)

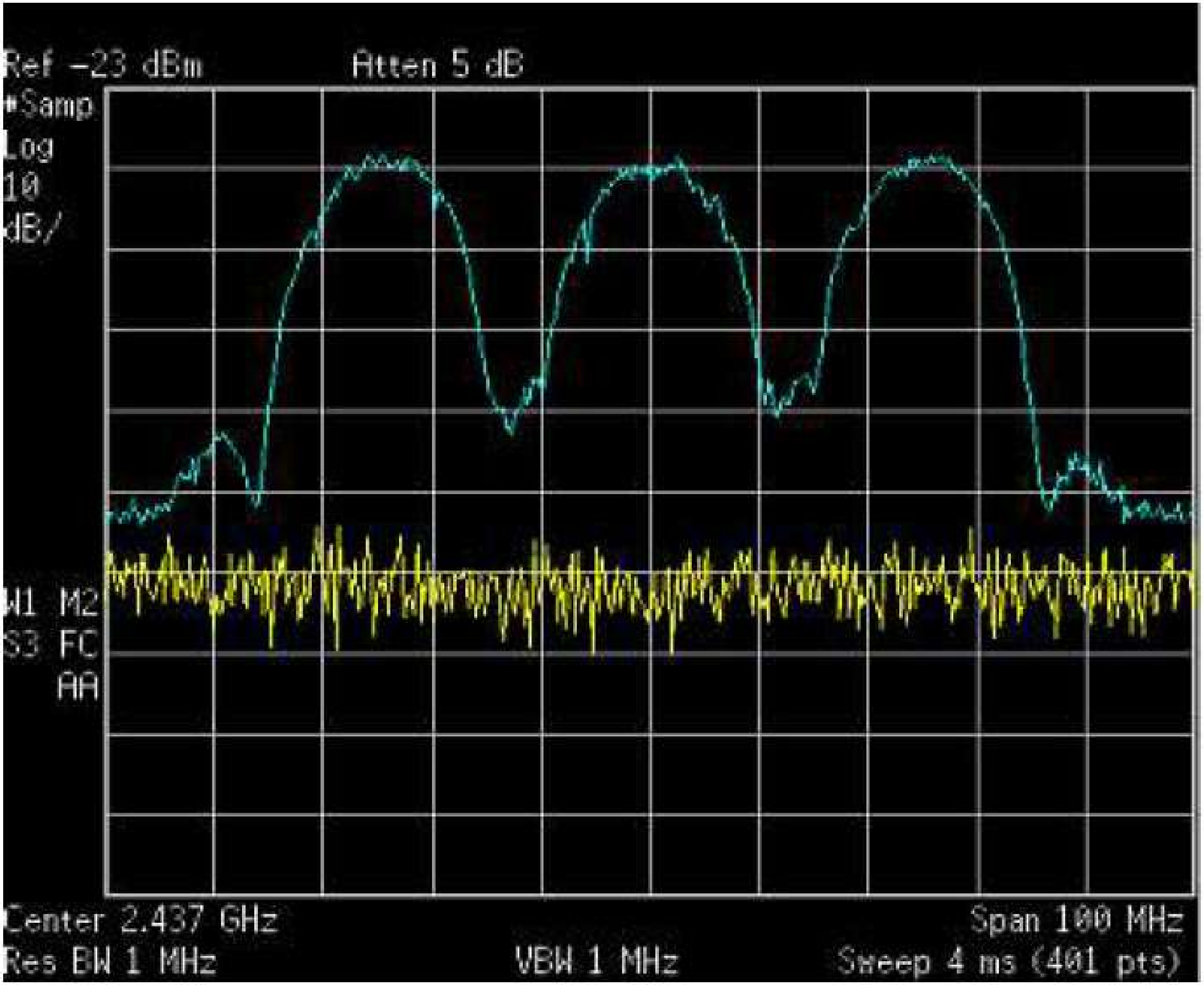
- Have the transmitter hop between a seemingly random sequence of frequencies
  - » Each frequency has the bandwidth of the original signal
- Dwell time is the time spent on one frequency
- Spreading code determines the hopping sequence
  - » Must be shared by sender and receiver (i.e., standardized)
  - » Using different spreading codes minimizes interference



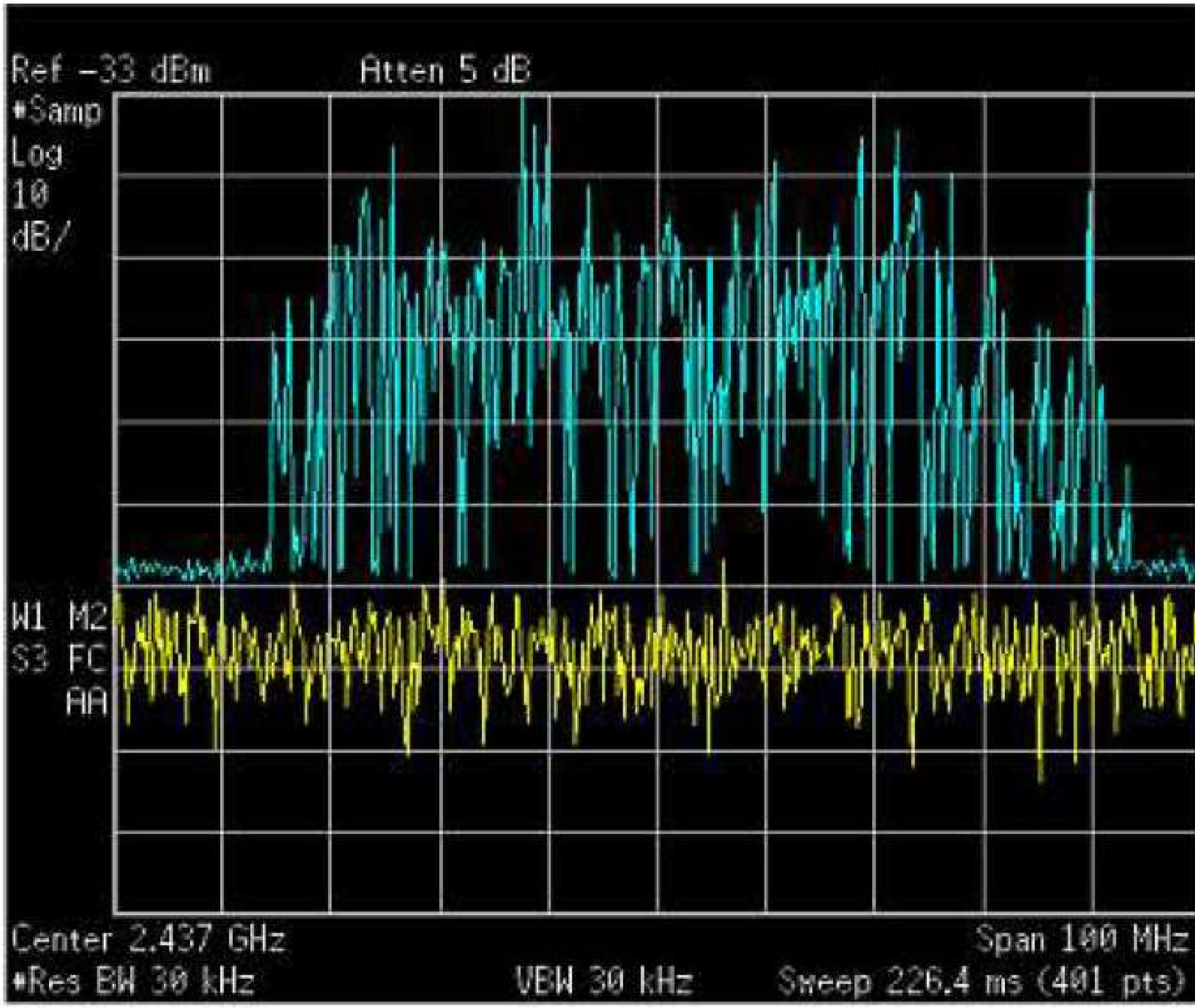
Example: Bluetooth

- 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

802.11 Spectrogram

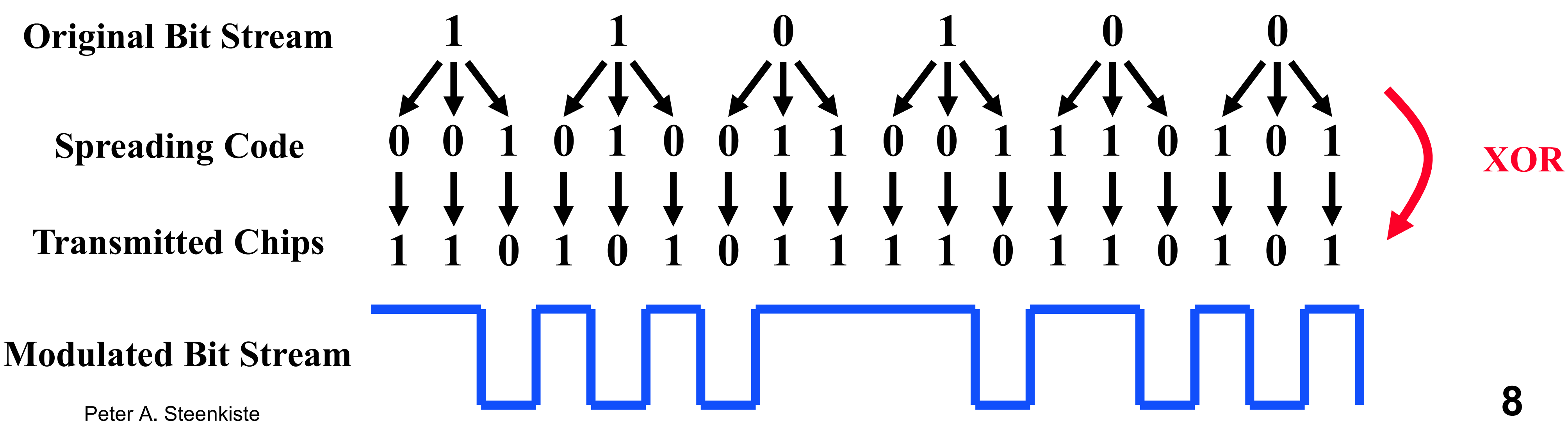


Frequency Hopping Spectrogram

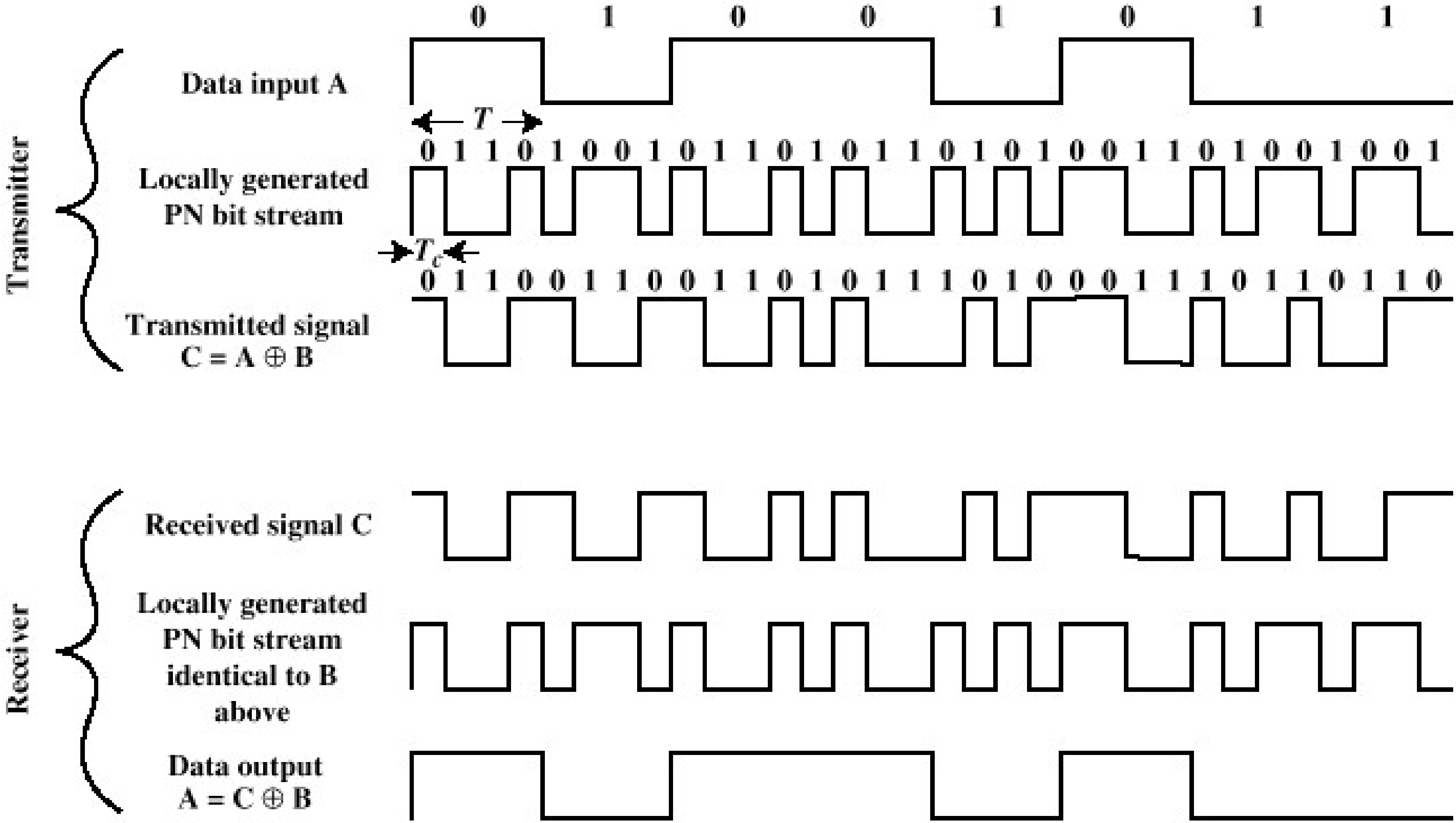


Direct Sequence Spread Spectrum (DSSS)

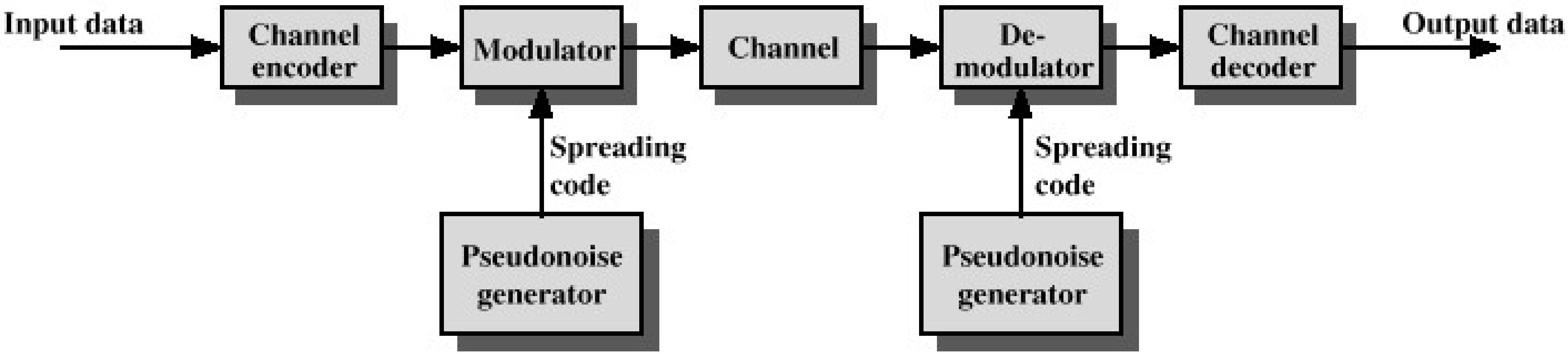
- Each bit in original signal is represented by multiple bits (chips) in the transmitted signal
- Spreading code spreads signal across a wider frequency band
  - » Spread is in direct proportion to number of bits used
  - » E.g. exclusive-OR of the bits with the spreading code
- The resulting bit stream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



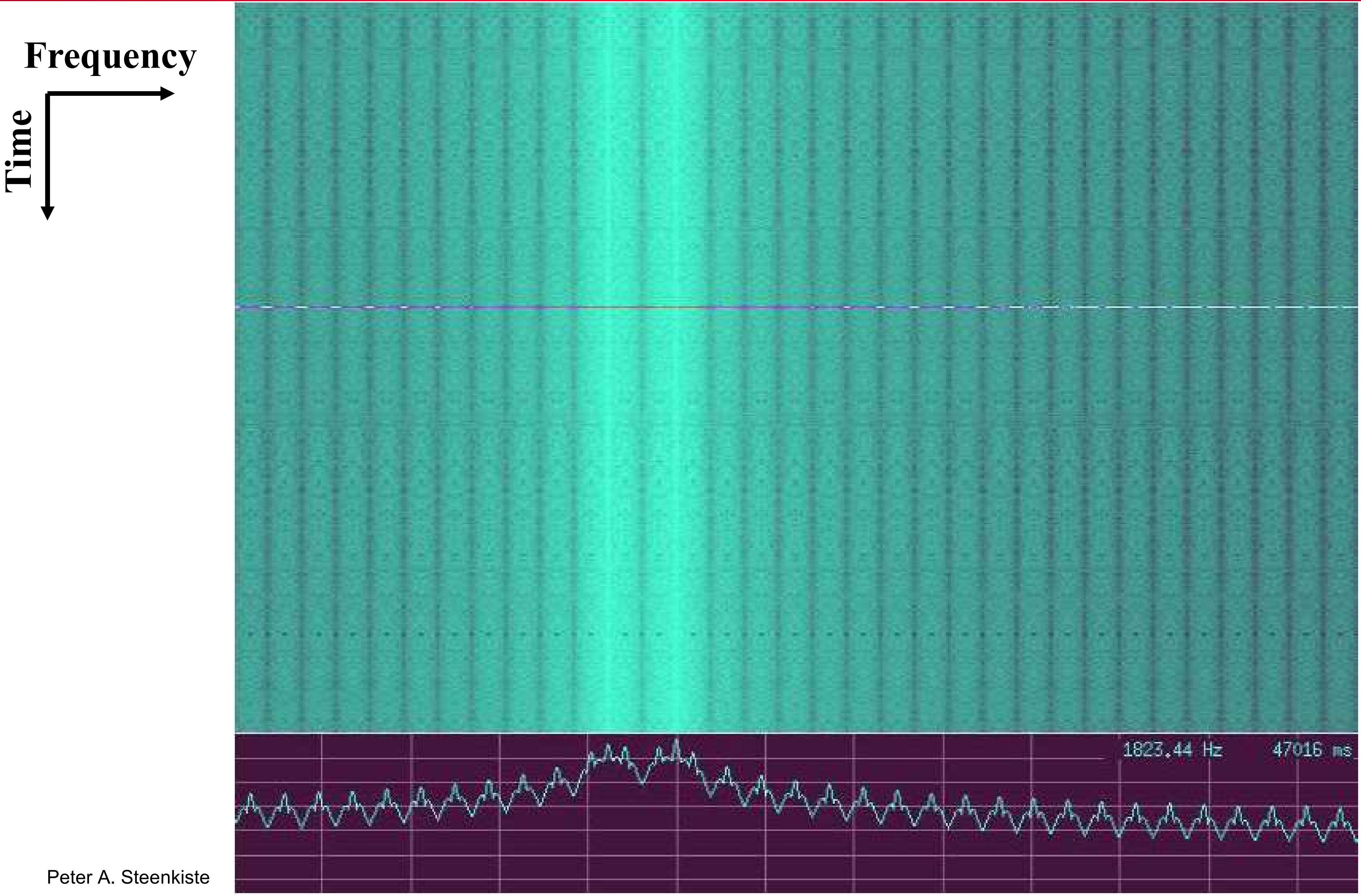
Direct Sequence Spread Spectrum



Spread Spectrum



Spectrogram: DSSS-encoded Signal



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 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)
  - » E.g., Code Division Multiple Access - next

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
  - » Spread spectrum with users use different spreading sequences
  - » Spreading sequences that are orthogonal, i.e. they have minimal overlap
  - » Base station manages spreading codes
- 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 – sharing!

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

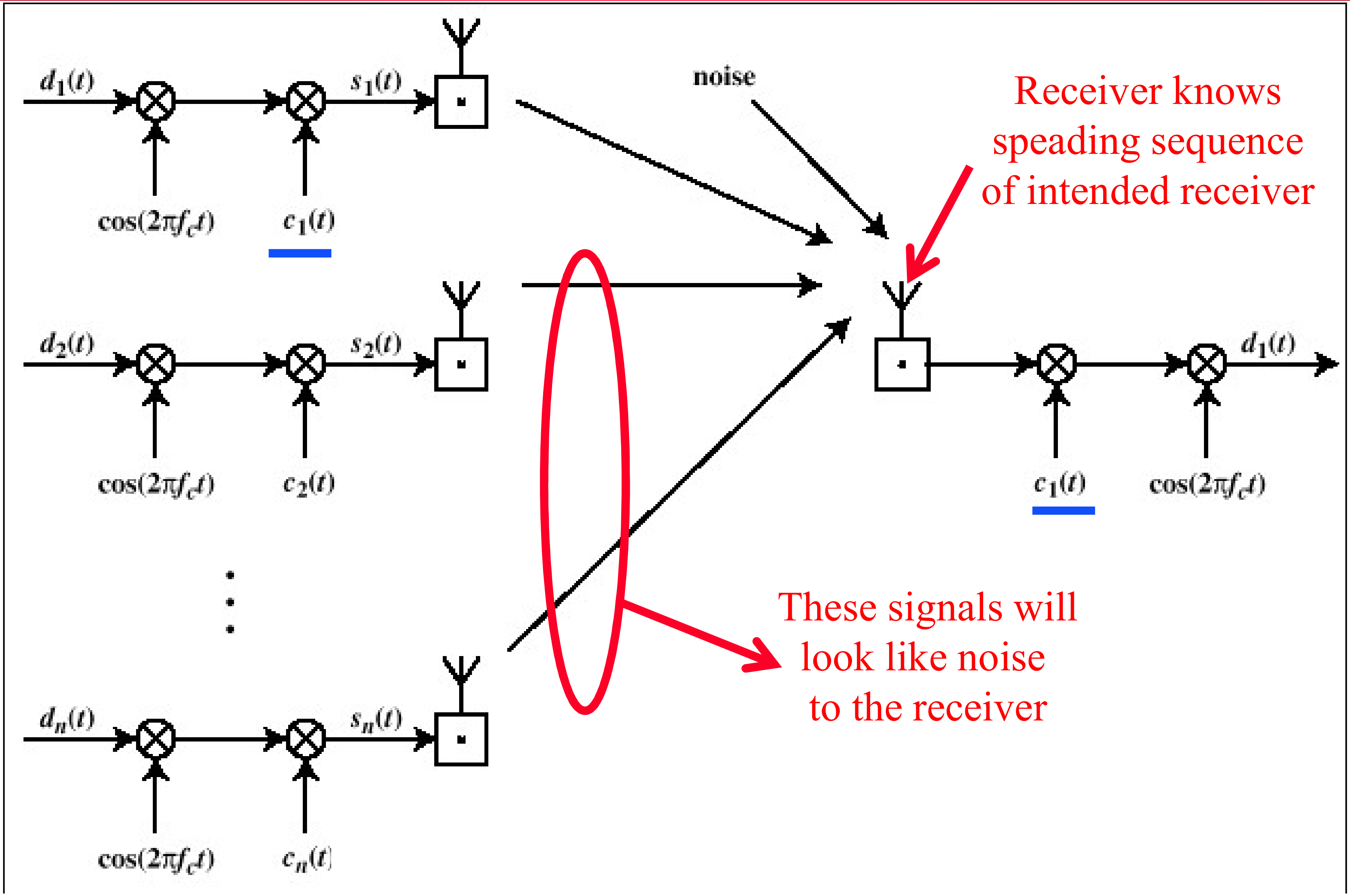
$$S_u(d) = d1 \times c1 + d2 \times c2 + d3 \times c3 + d4 \times c4 + d5 \times c5 + d6 \times c6$$

  - <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



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

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
  - » 3G 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**

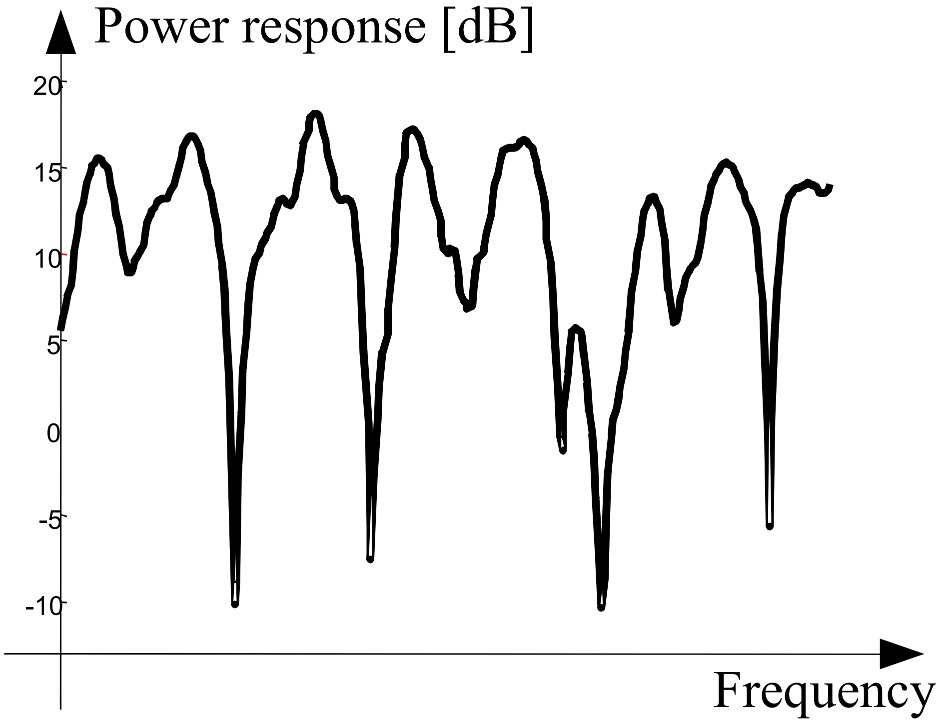
Outline

- 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
  - » This is major issue for wide-band channels only
- 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

Frequency-Selective Radio Channel



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

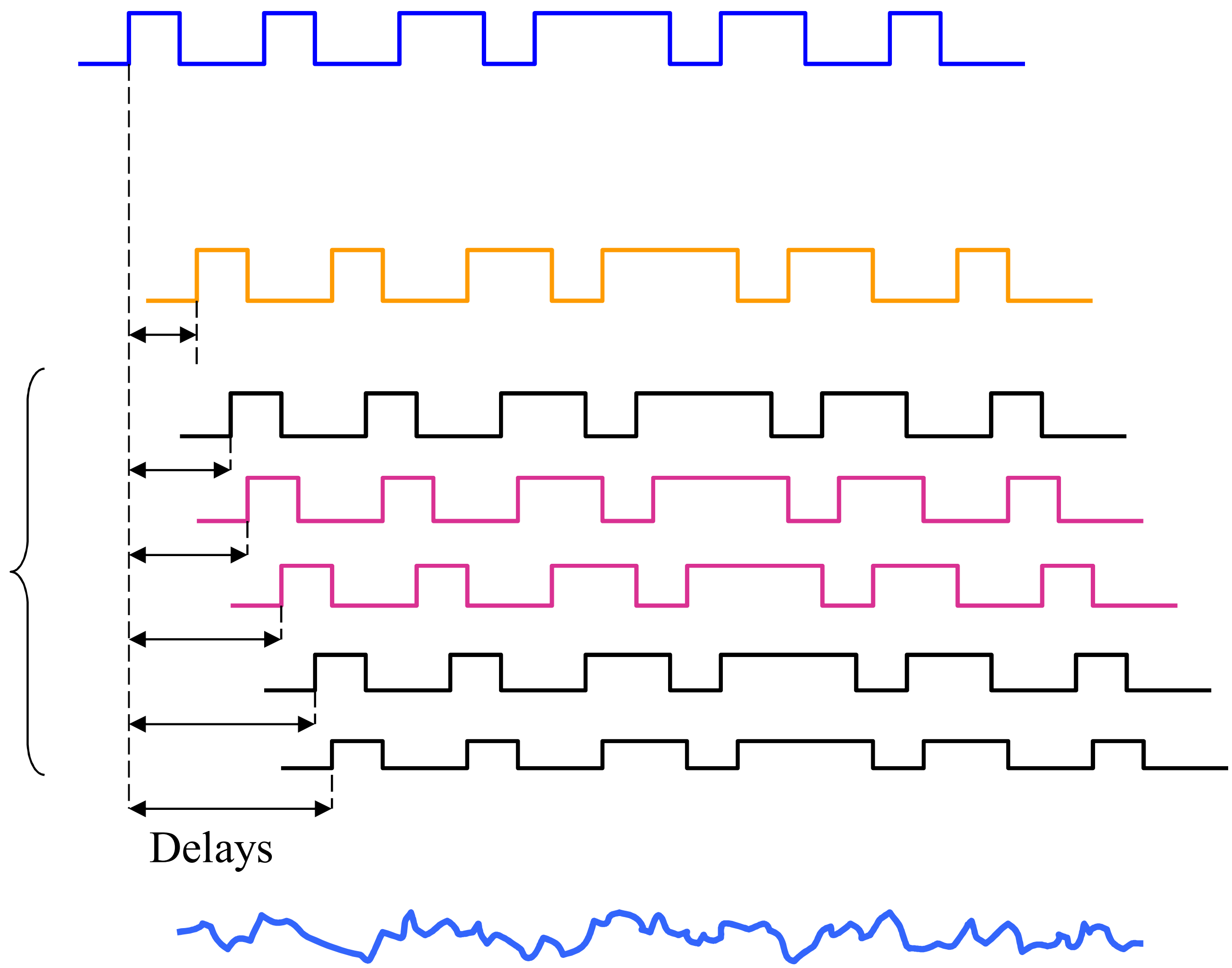
Inter-Symbol-Interference

Transmitted signal:

Received Signals:

Line-of-sight:

Reflected:



The symbols add up on the channel
→ Distortion!

Distributing Bits over Subcarriers

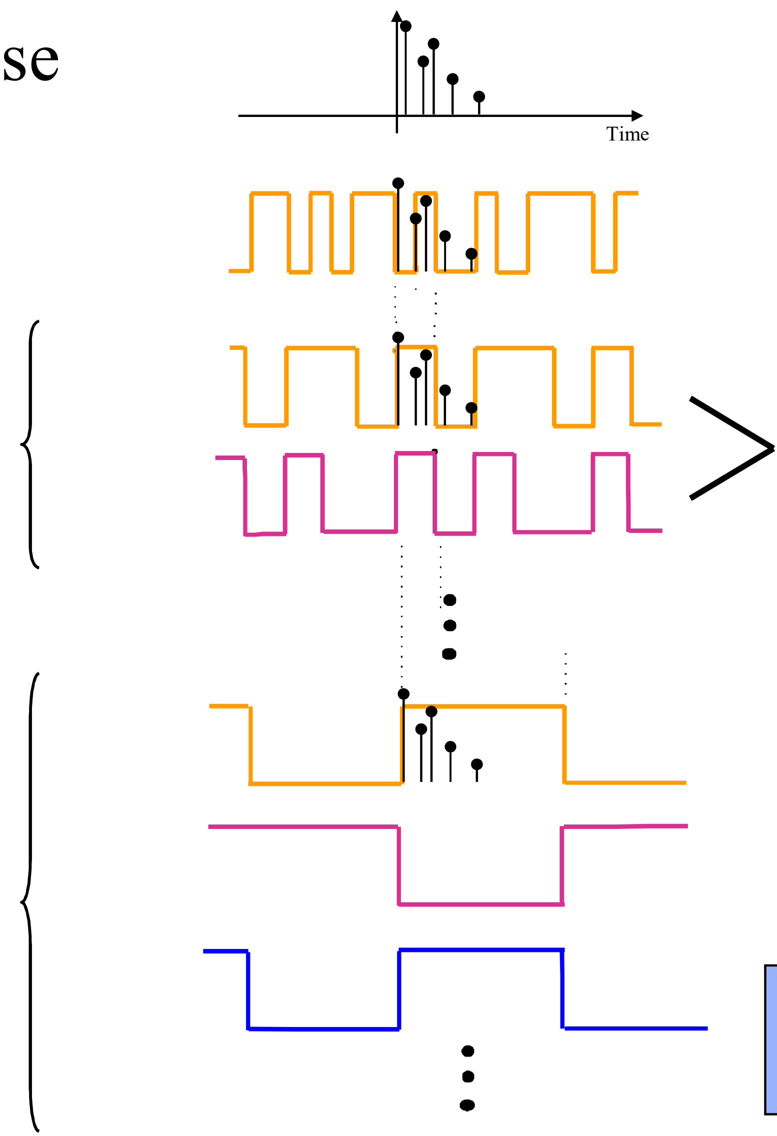
Channel impulse response

Single Carrier

2 Carriers

8 Carriers

⋮



Channels are transmitted at different frequencies (sub-carriers)

Resistance to ISI improves with number of channels

Benefits of Narrow Band Channels

Channel impulse response

Channel transfer function

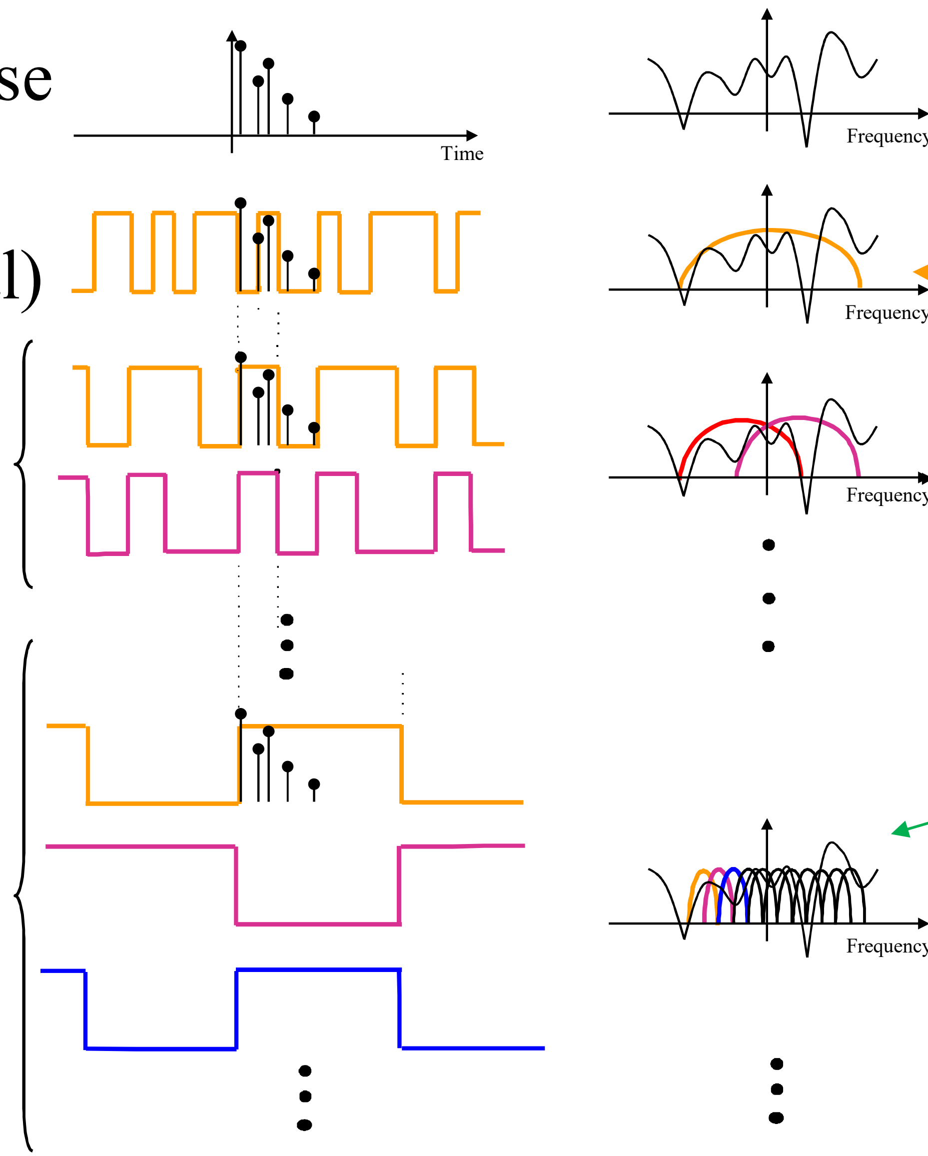
1 Carrier (serial)

Signal is "broadband": Frequency selective fading

2 Carriers

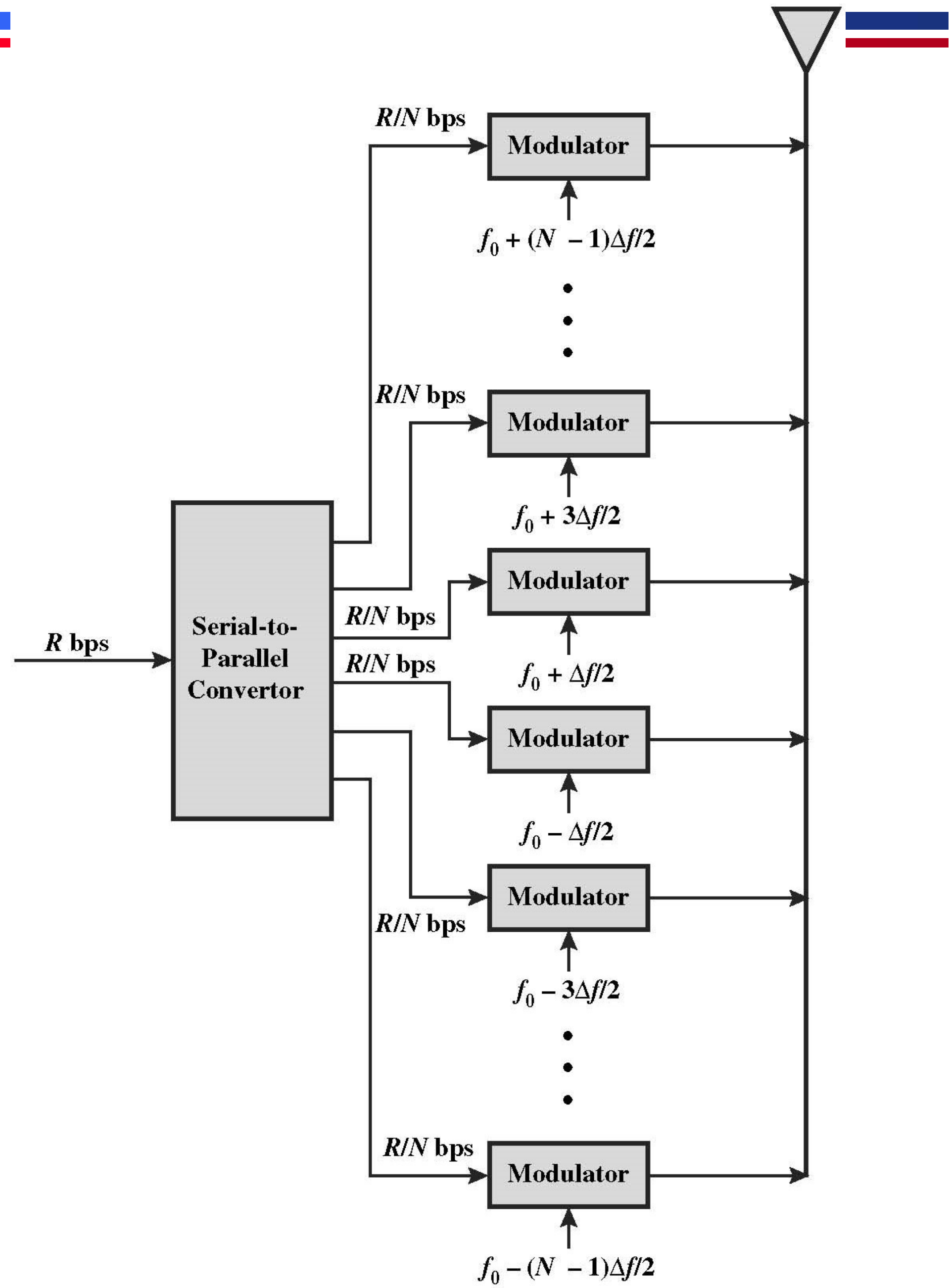
8 Carriers

Sub-carriers are "narrowband": Flat fading in each sub-carrier

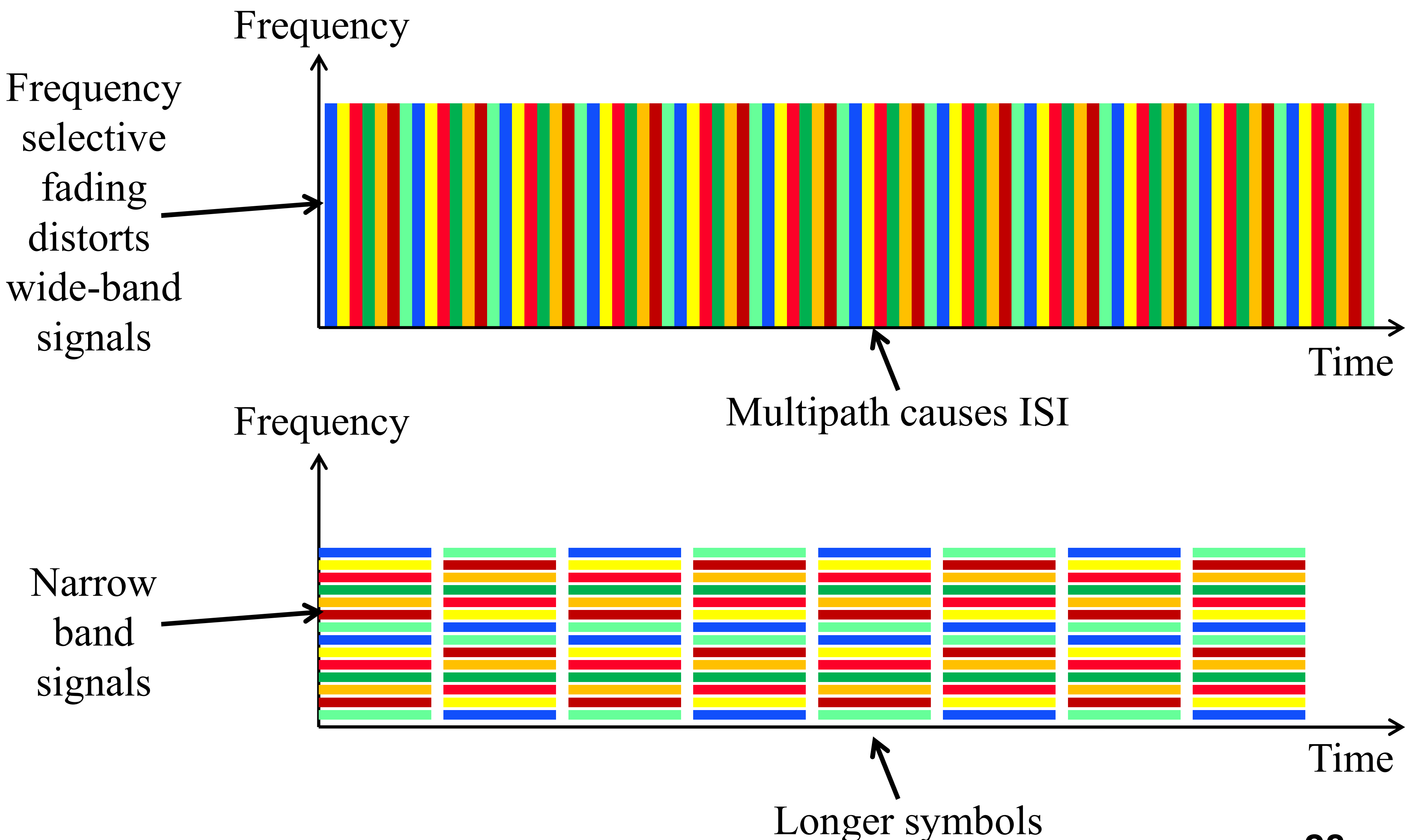


OFDM - Orthogonal Frequency Division Multiplexing

- 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



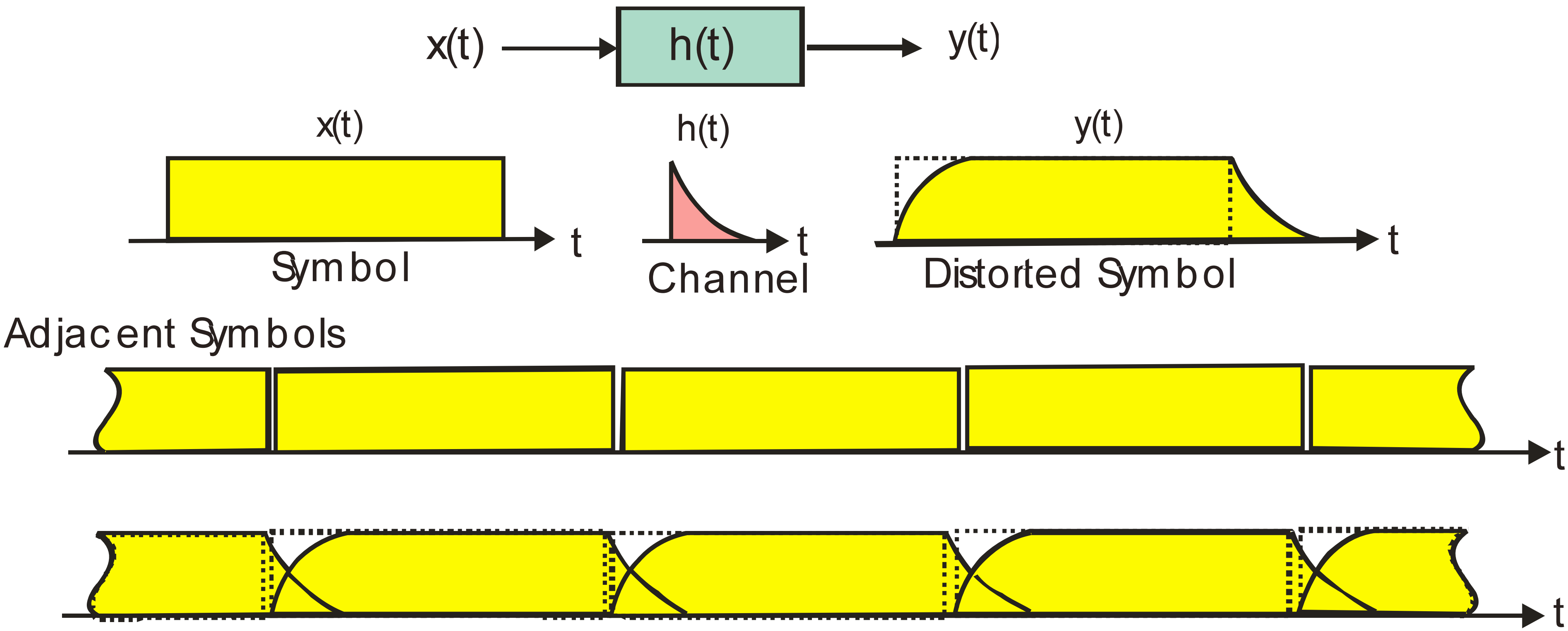
OFDM Transmission



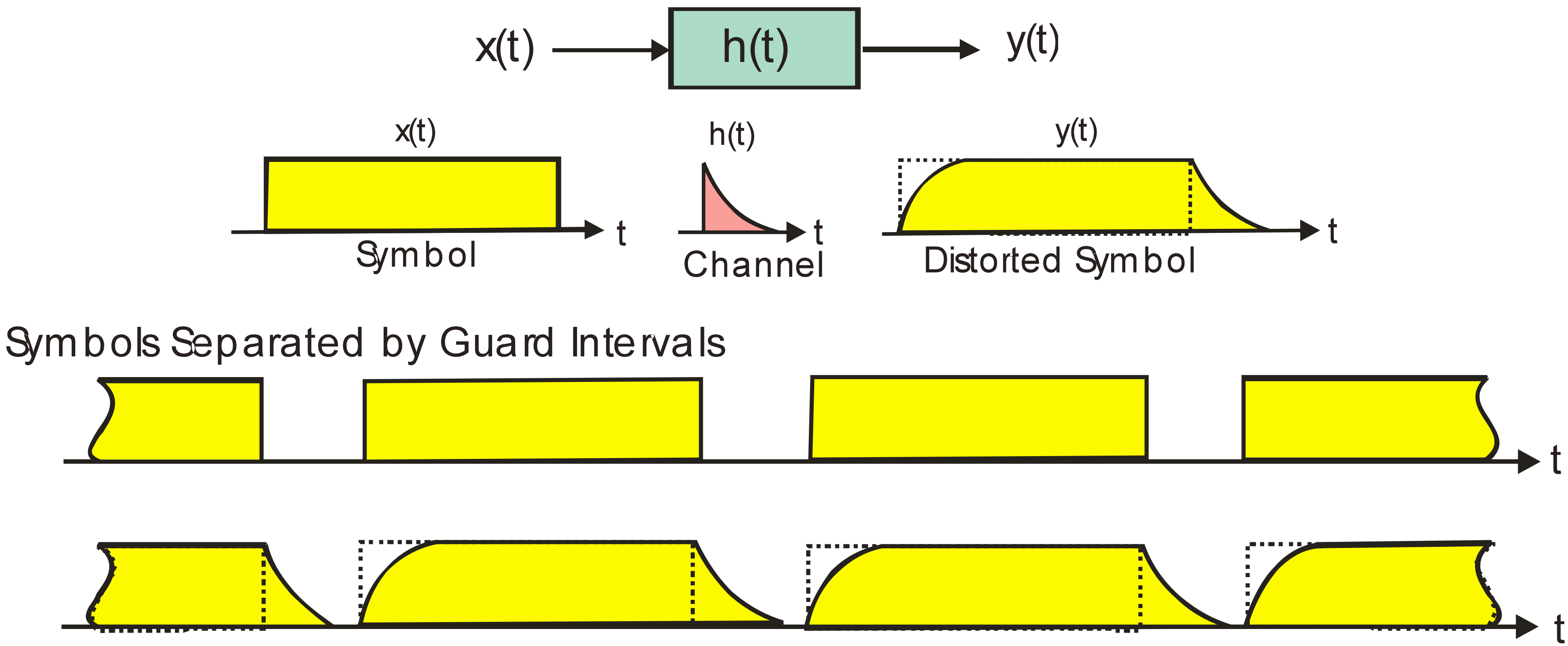
Fighting ISI

- 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

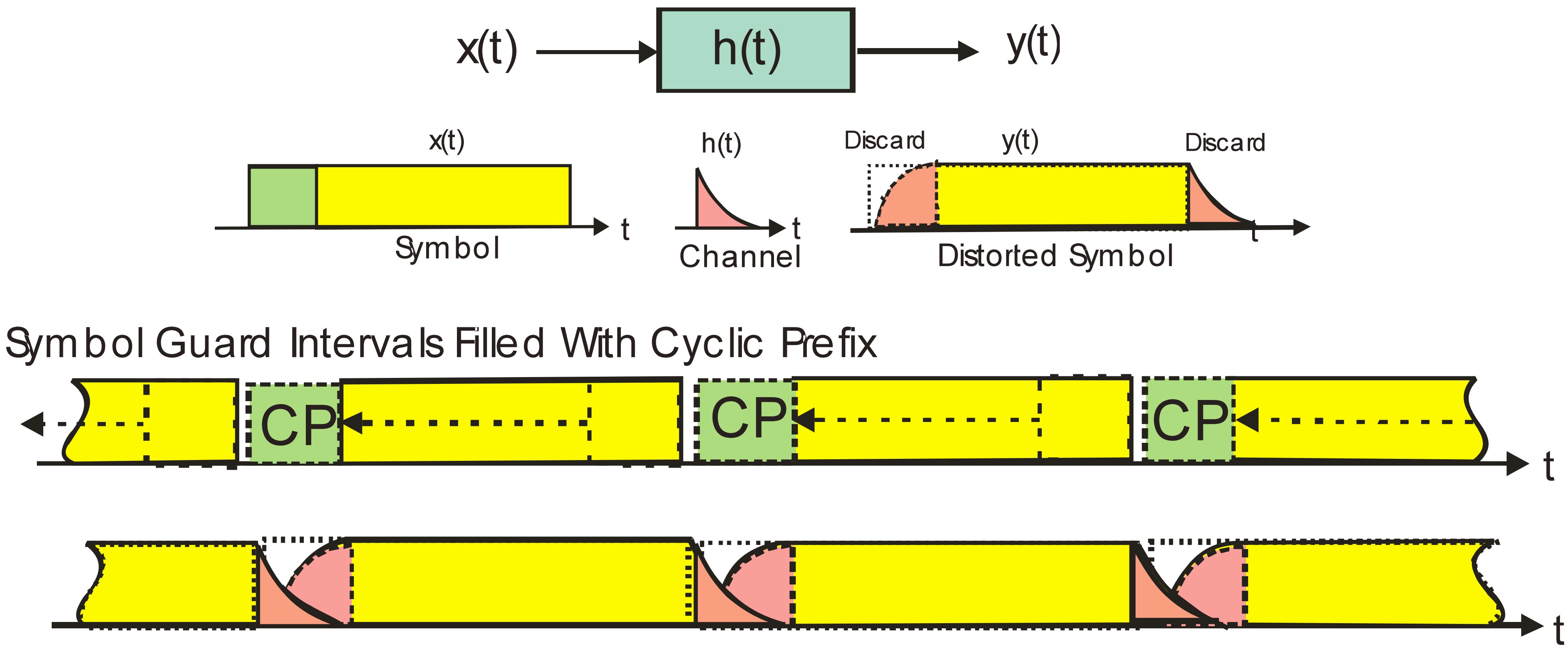
Adjacent Symbol Interference (ASI) Symbol Smearing Due to Channel



Guard Interval Inserted Between Adjacent Symbols to Suppress ASI

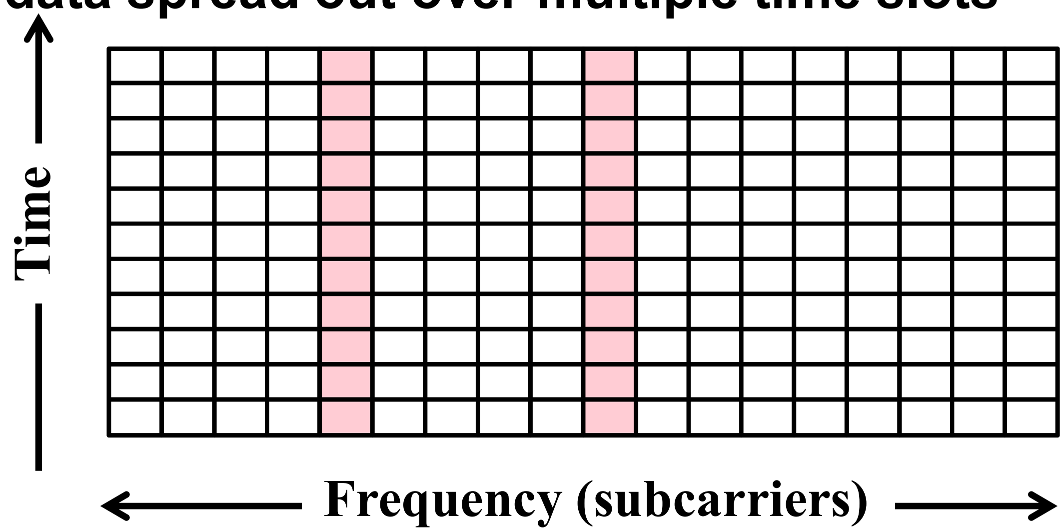


Cyclic Prefix Inserted in Guard Interval to Suppress Adjacent Channel Interference (ACI)



Use of Redundancy in OFDM

- OFDM uses error coding as described earlier
  - » 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



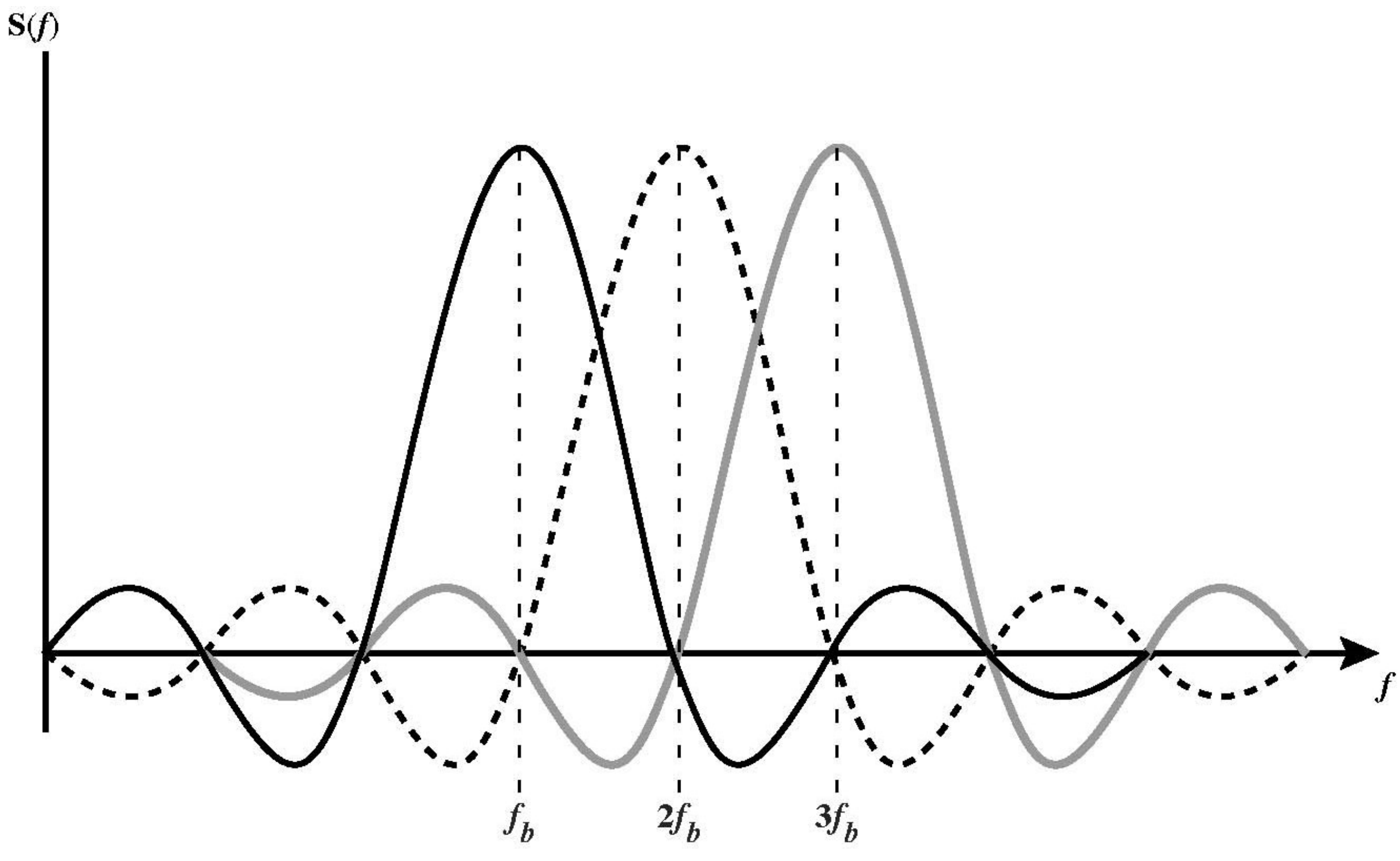
- Combining OFDM with MIMO adds space diversity (discussed later in course)

Implementing OFDM

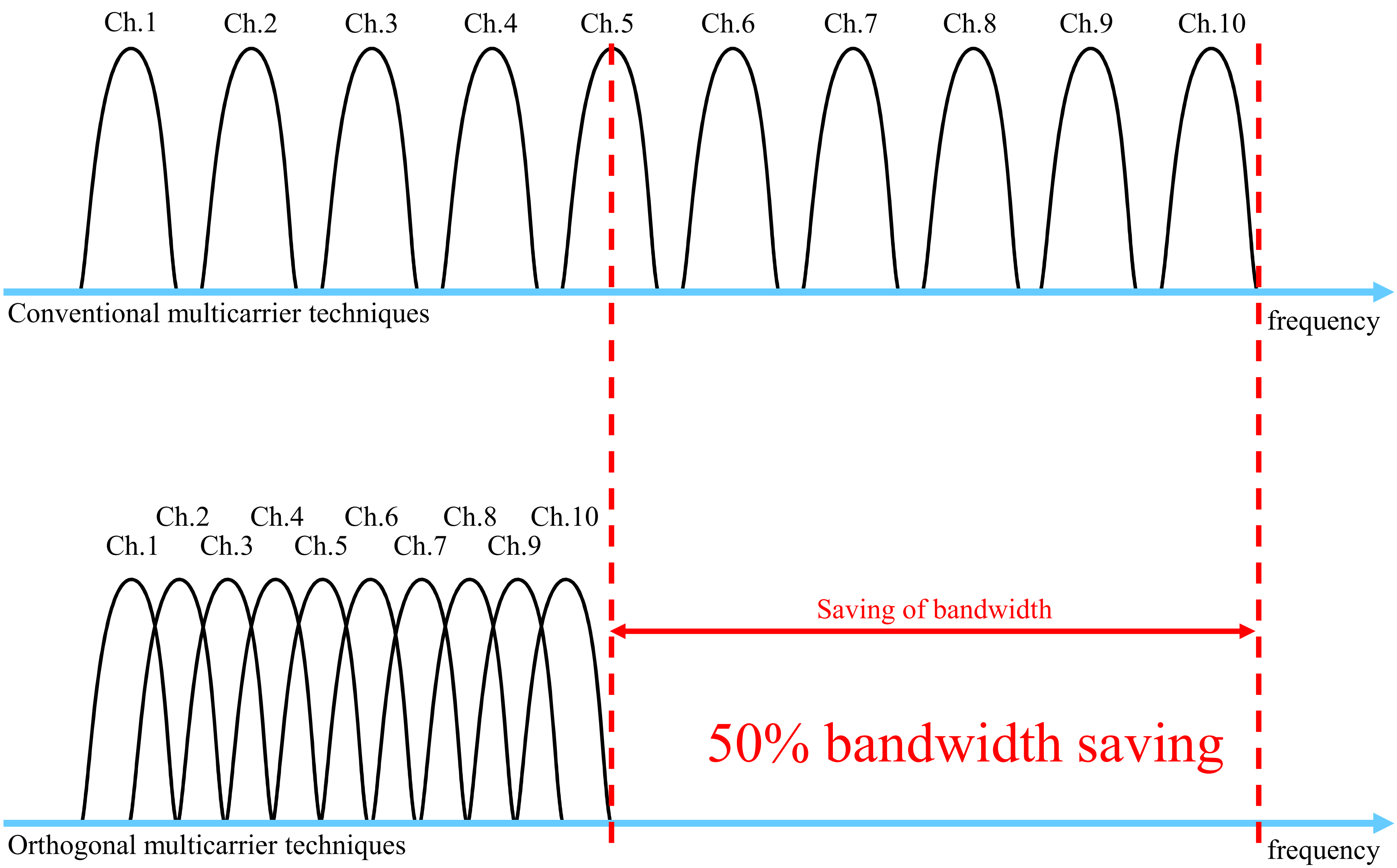
- This is great, but OFDM looks very complicated!
- How many radios do I need?   48?
- How do I get 48 (or more) subcarriers packed very densely?
- Do I need guard bands between the subcarriers, and if so, how wide?
  - » Looks like a lot of wasted spectrum

Subcarriers are “Orthogonal”

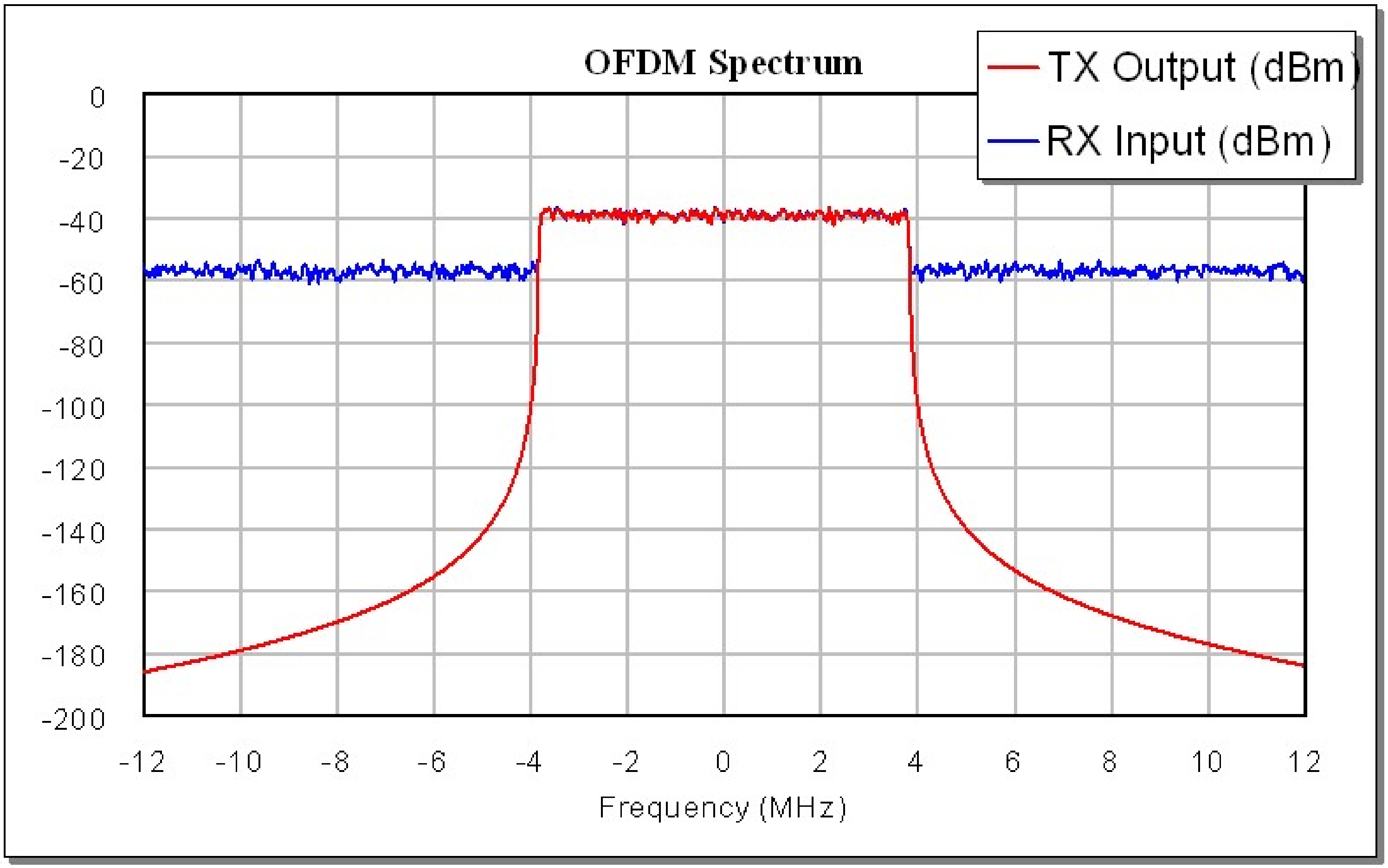
- **Peaks of spectral density of each carrier coincide with the zeros of the other carriers**
  - **Carriers can be packed very densely with minimal interference**
  - **Requires very good control over frequencies**



Densely Packing OFDM Channels



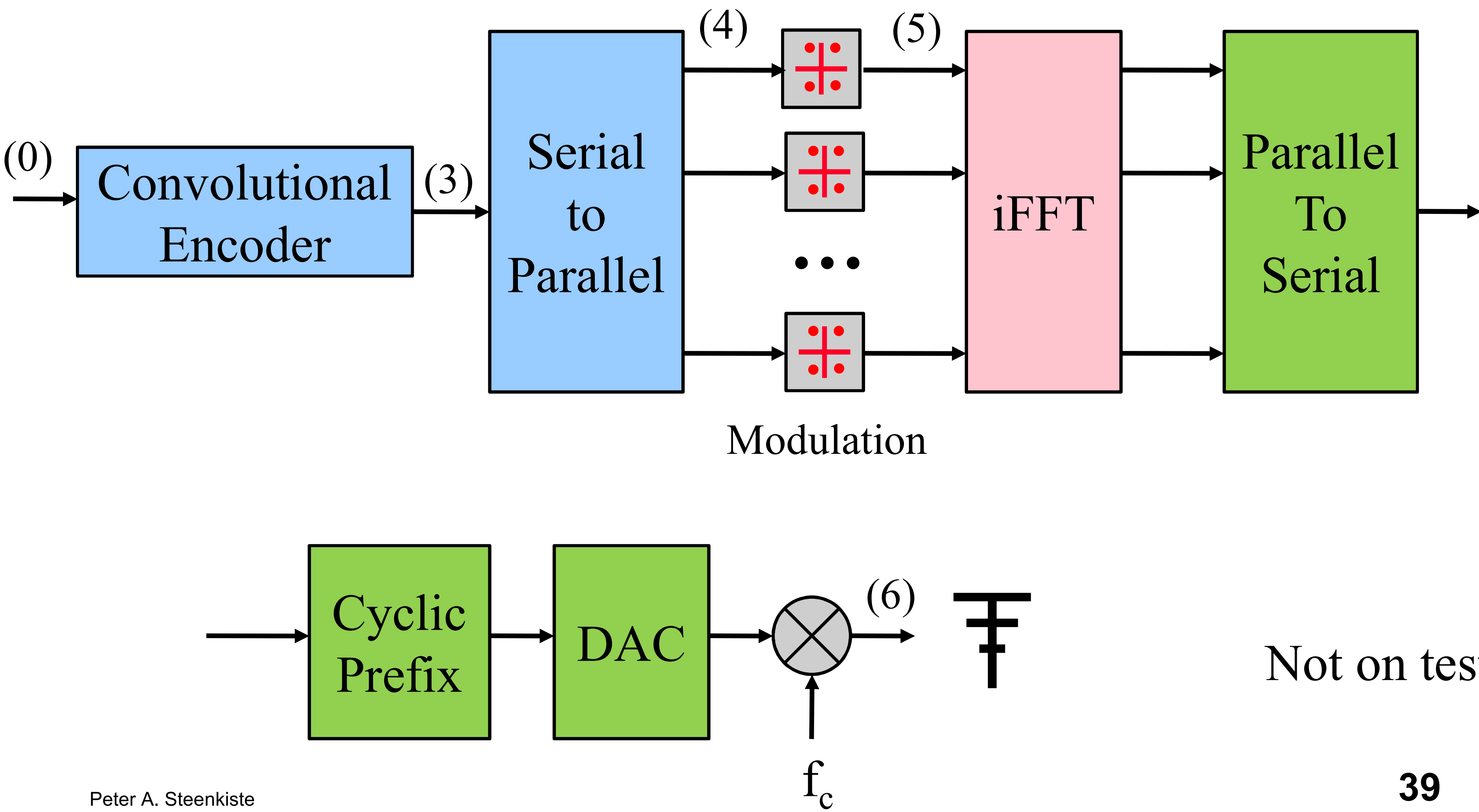
OFDM Spectrum Use



Implementing OFDM

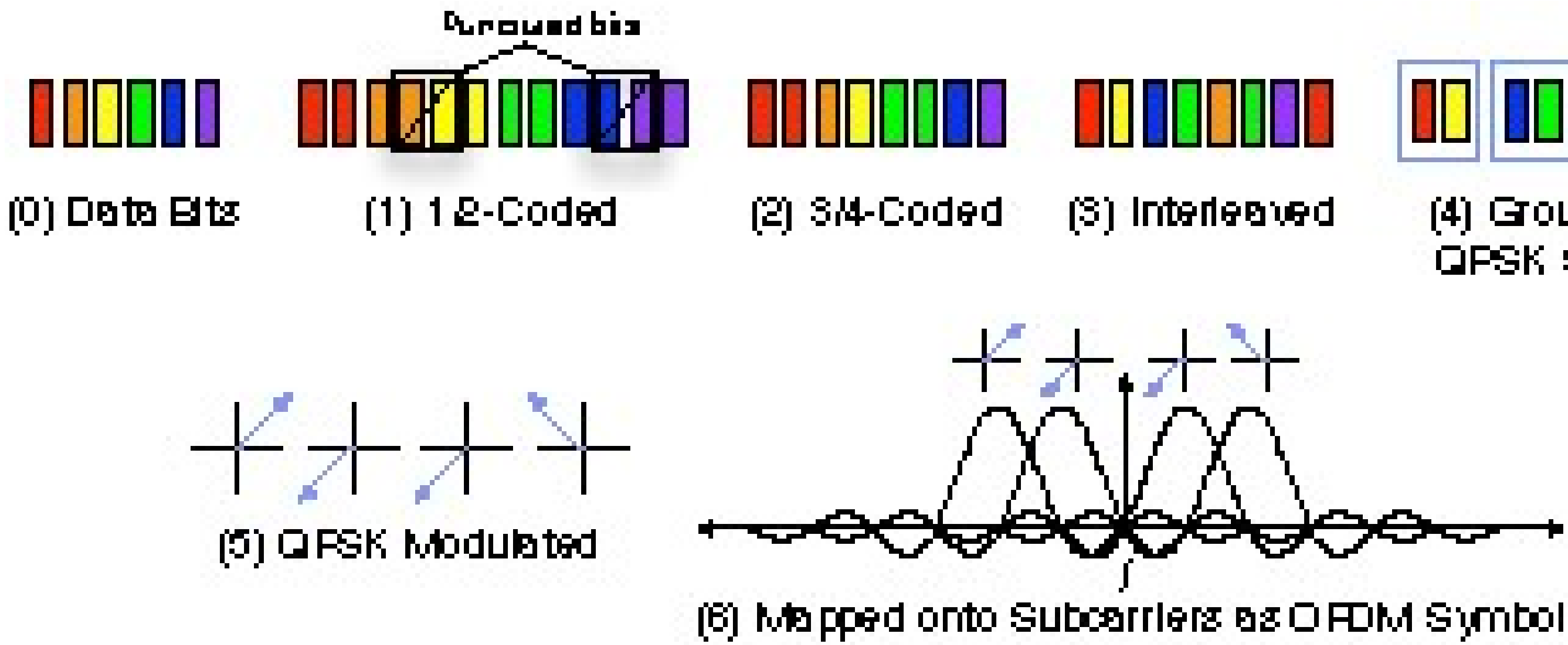
- Naïve approach: modulate individual subcarriers and move them to the right frequency
  - » Not practical: the subcarriers are packed very densely and their spacing must be very precise
  - » Also complicated: lots of signals to deal with!
- How it works: radio modulates the subcarriers and combines 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

OFDM Transmitter



Not on test

OFDM in 802.11



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

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

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

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
  - » More complex radio (but gates 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**