PHY II: The Wireless Channel and OFDM

COS 598a: Wireless Networking and Sensing Systems

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[Parts adapted from P. Steenkiste, D. Tse]

Context: Propagation modes

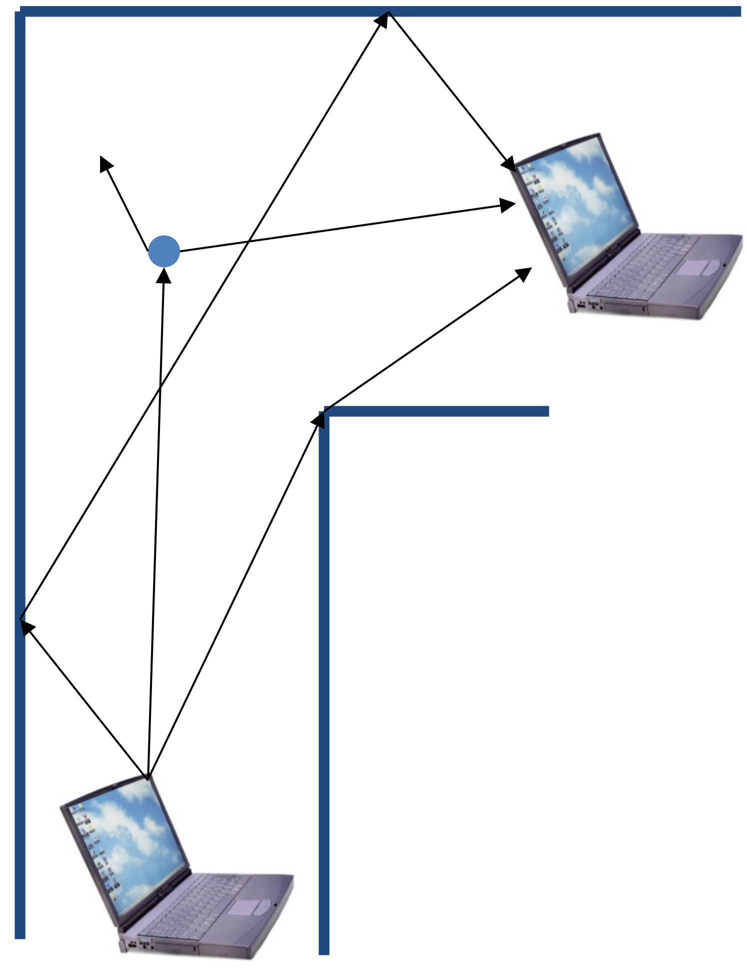
- **Multipath propagation**
  - Most common form of propagation
  - Happens above ~ 30 MHz
  - Subject to many forms of degradation

- Ground-wave propagation
  - More or less follows the contour of the earth
  - For frequencies up to about 2 MHz, e.g. AM radio

- Sky wave propagation
  - Signal "bounces" off the ionosphere back to earth – can go multiple hops
  - Used for amateur radio and international broadcasts

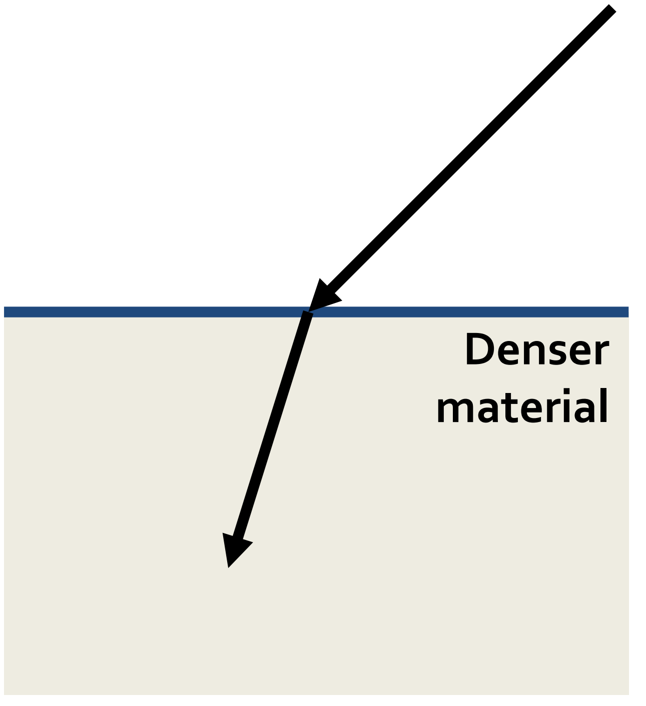
Propagation mechanisms

- Besides line of sight, signal can reach receiver in three other “indirect” ways
- **Reflection:** signal is reflected from a large object
- **Diffraction:** signal is scattered by the edge of a large object – “bends”
- **Scattering:** signal is scattered by an object that is small relative to the wavelength.



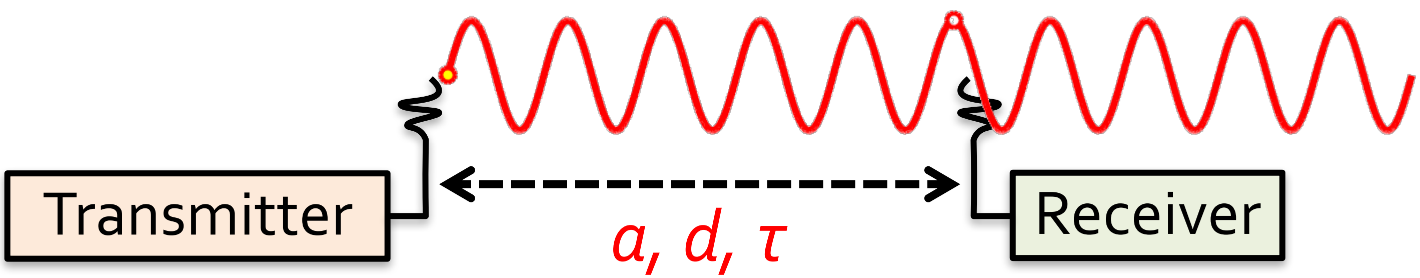
Refraction

- Speed of EM signals depends on the density of the material
  - Vacuum: 3×10^8 m/sec
  - Denser: slower
- Density is captured by ***refractive index***
- Explains "bending" of signals in some environments
  - *e.g.* sky wave propagation
  - *e.g.* propagation through walls



Sinusoidal carrier, line of sight only

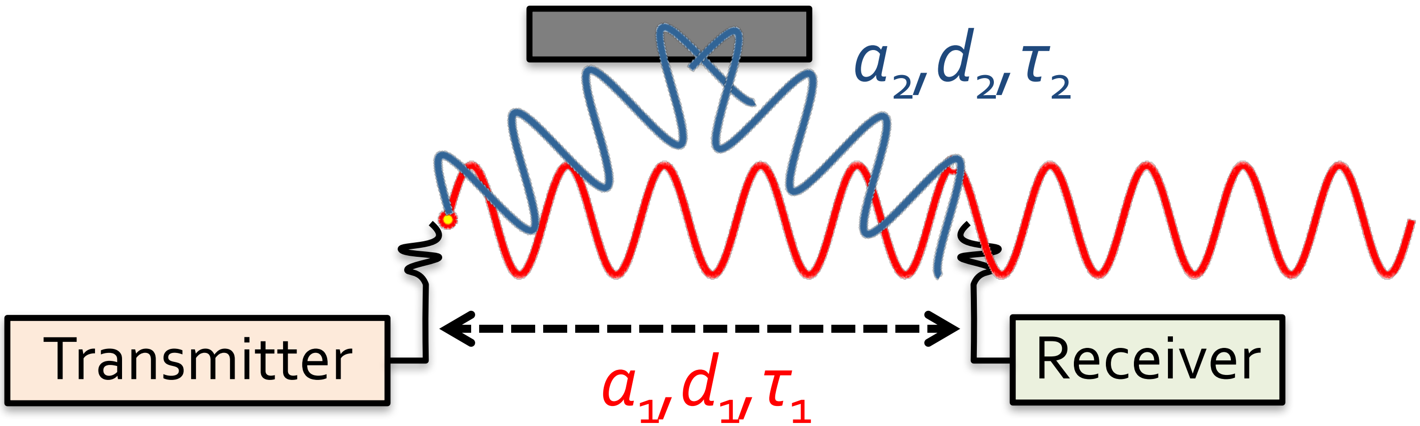
- Transmitted signal: $x(t) = a(t) \cdot \cos(2\pi f_c t + \varphi(t))$



- Path ***attenuation*** a, ***distance*** d, ***time of flight*** τ
  - Complex channel $h = ae^{j2\pi d/\lambda}$

- Received signal: $y(t) = h \cdot x(t) + n(t)$
  - Relation: $\frac{d}{\lambda} = f_c\tau$

Sinusoidal carrier, reflecting path



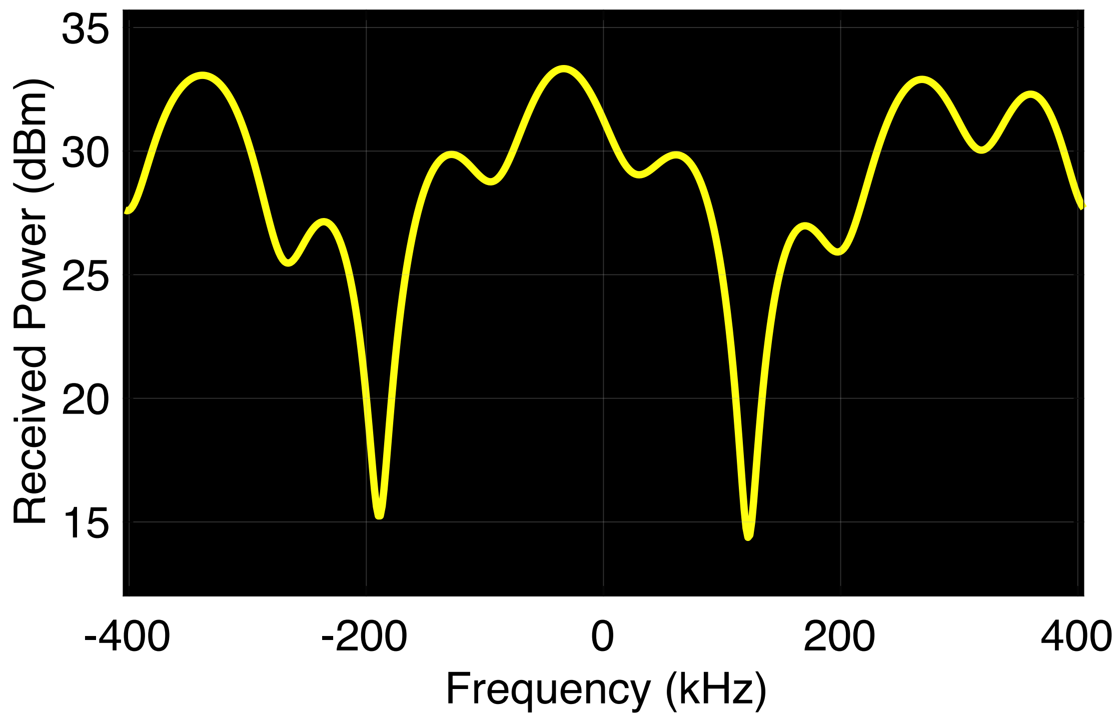
- Channel is now $h = a_1 e^{j2\pi d_1/\lambda} + a_2 e^{j2\pi d_2/\lambda}$

- Suppose $d_2 - d_1 = \lambda/2$ and $d_1 \approx d_2$:
  - Then $h \approx 0$ so **receive approx. zero** (***destructive fading***)

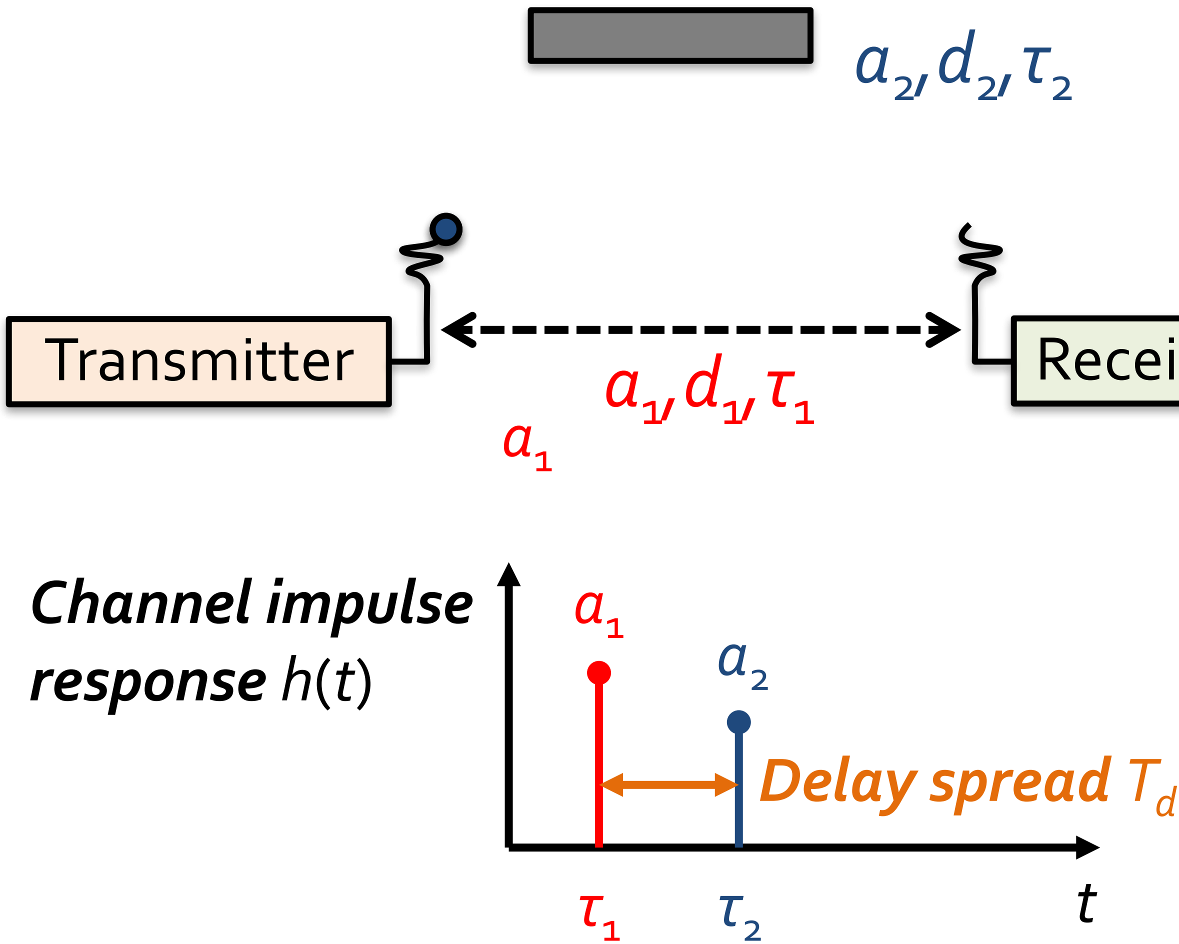
At different λ, h ≠ 0: fading is **selective** in frequency

Multipath causes frequency *selectivity*

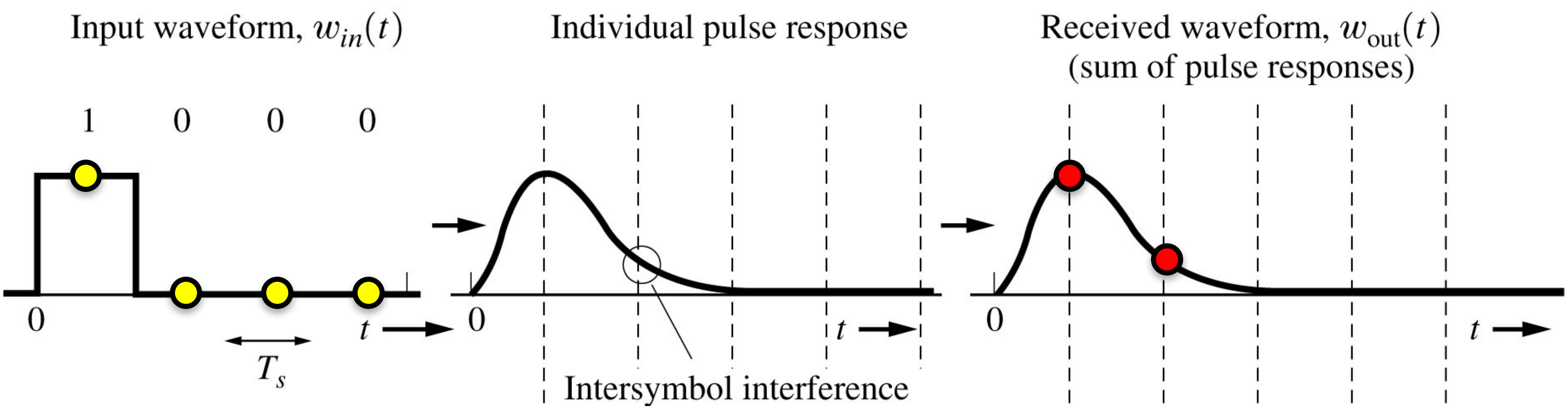
- Interference between reflected and line-of-sight radio waves results in **frequency dependent fading**



What does the channel look like in time?

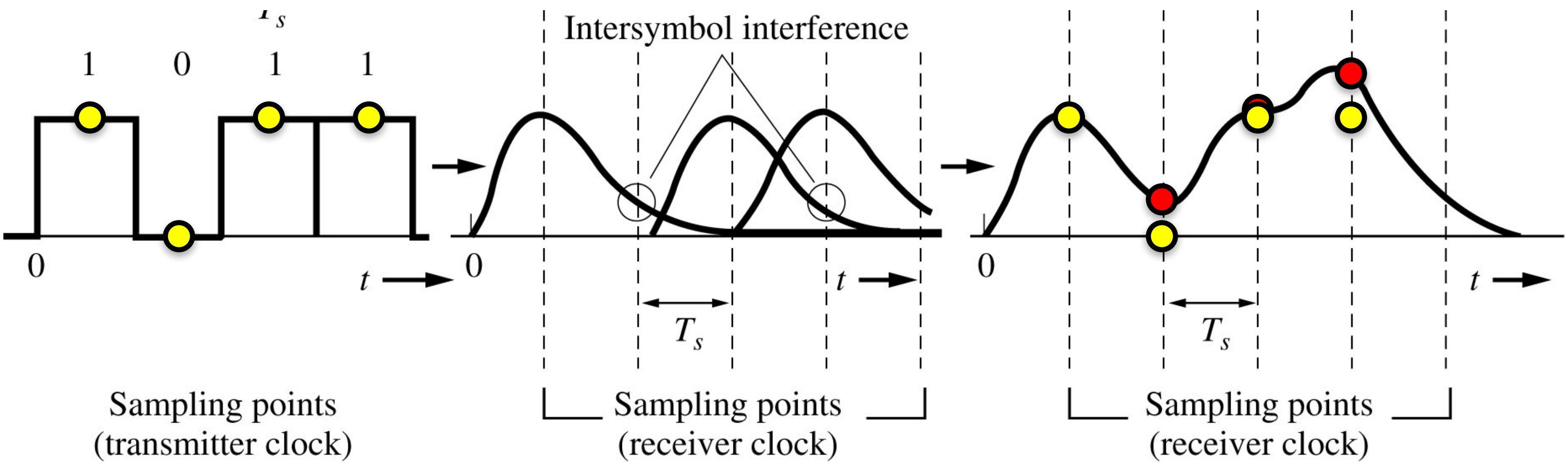


Problem: Inter-symbol interference (ISI)



- Transmitted signal ●
- Received signal with ISI ●

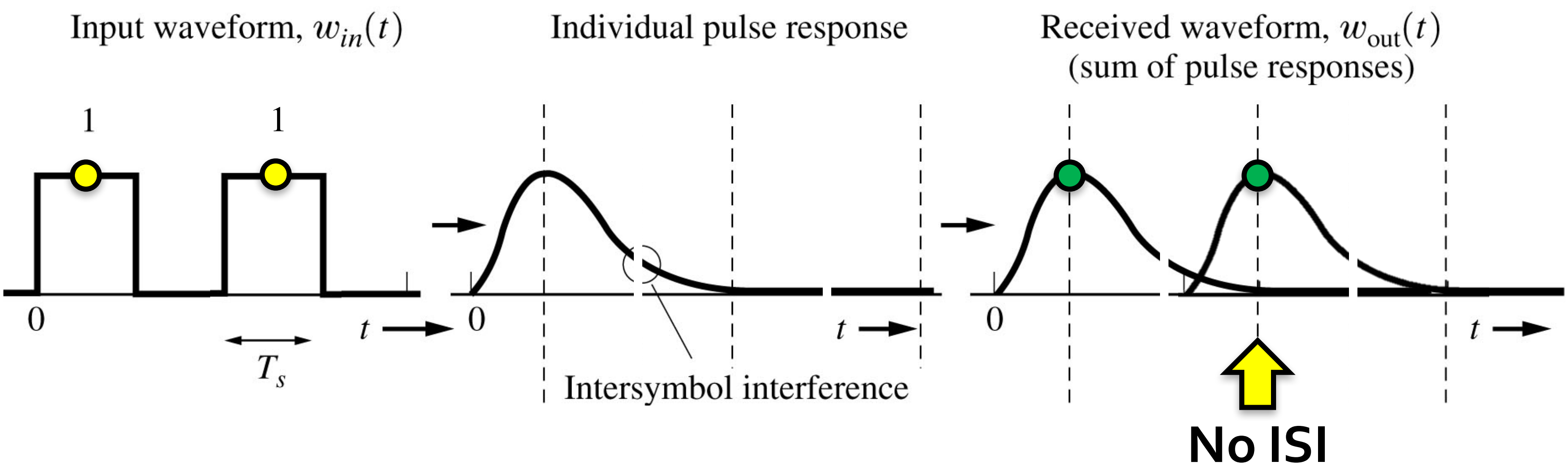
Problem: Inter-symbol interference (ISI)



- Transmitted signal
- Received signal with ISI

- ISI at one symbol **depends on** the value of **other** symbols

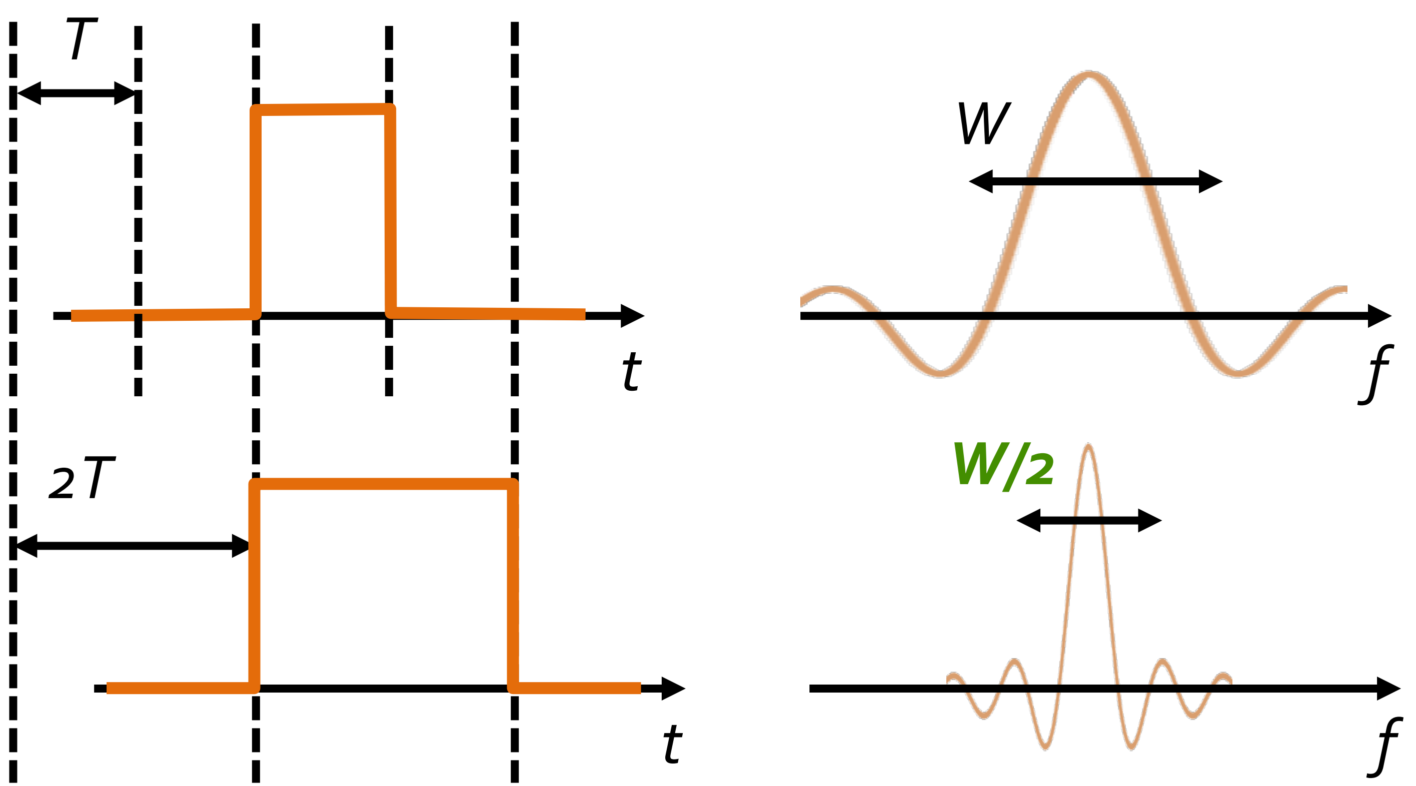
Solution: Slow down



- Transmitted signal
- Received signal

Symbol time determines frequency bandwidth

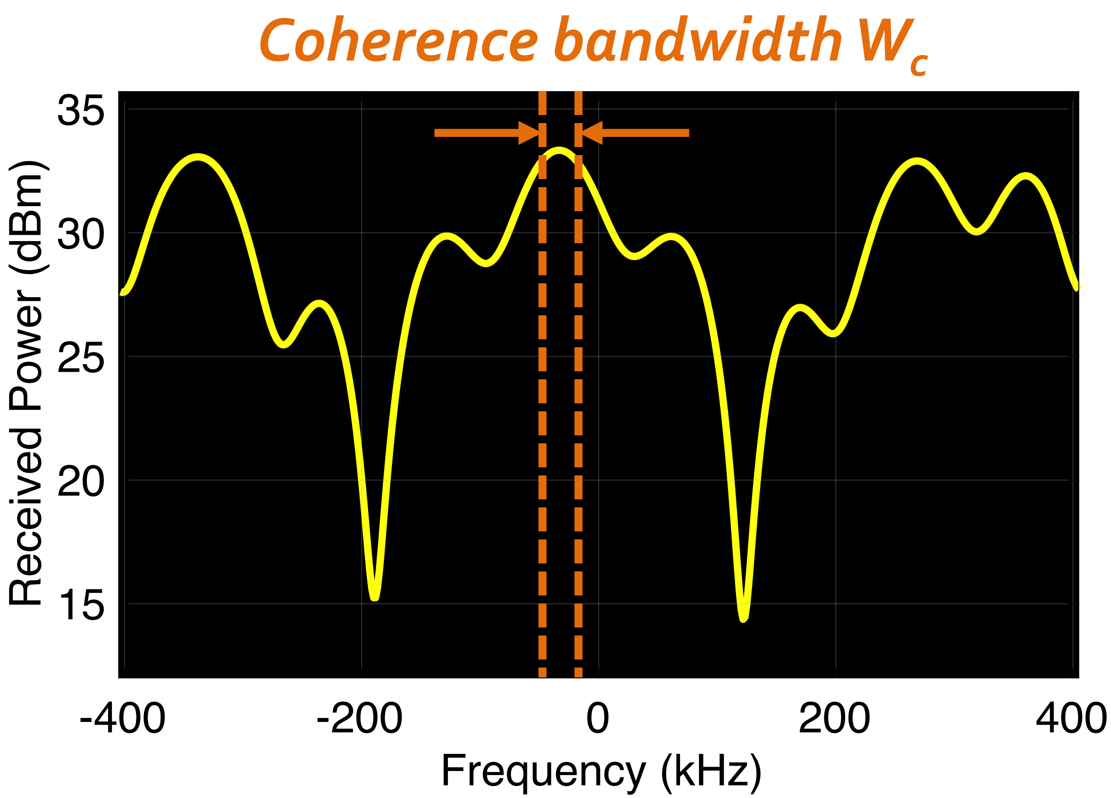
Symbol time



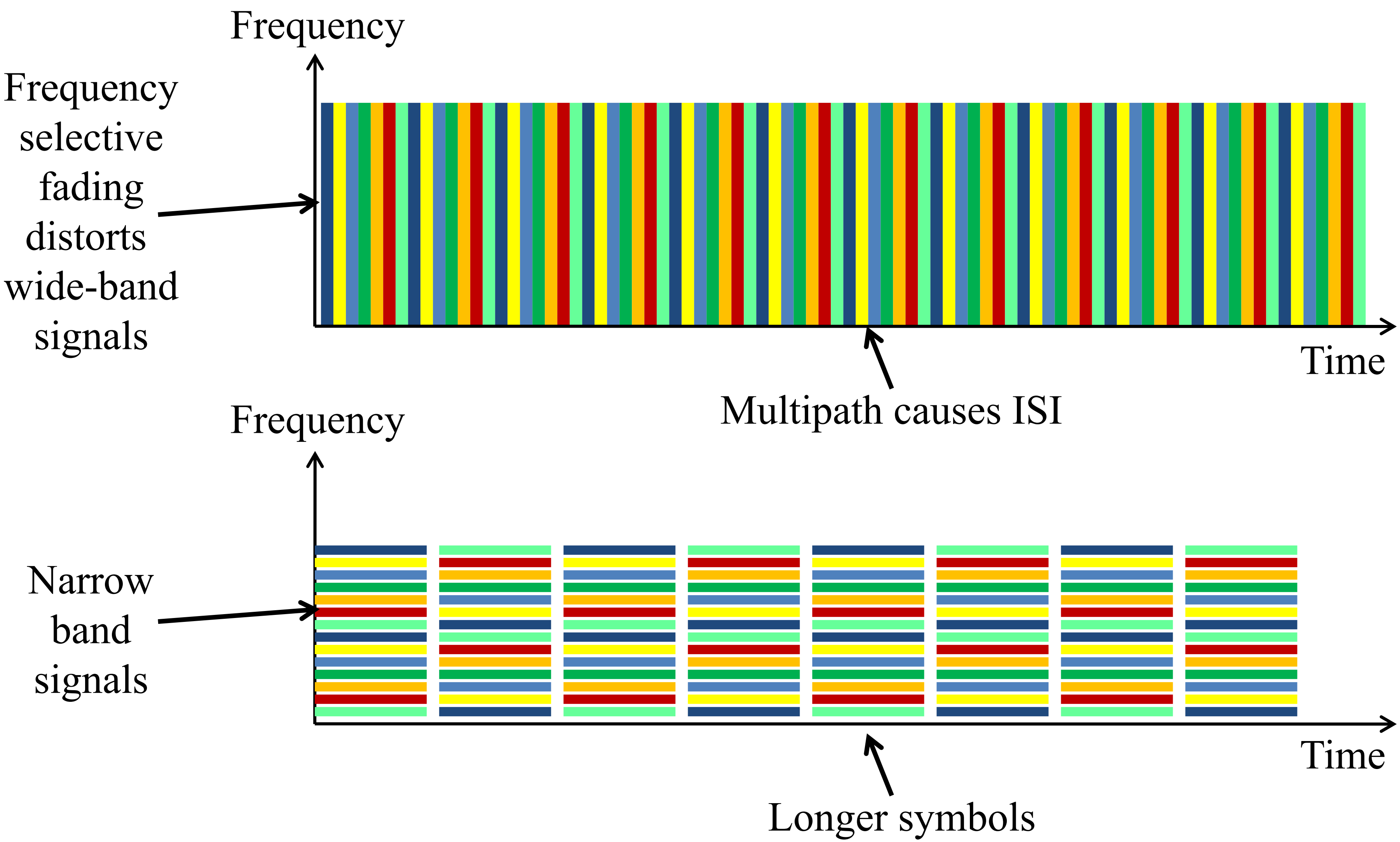
Slowing down by a factor of two **halves the frequency bandwidth** of the sender's signal

A narrowband signal "fits into" the coherence bandwidth

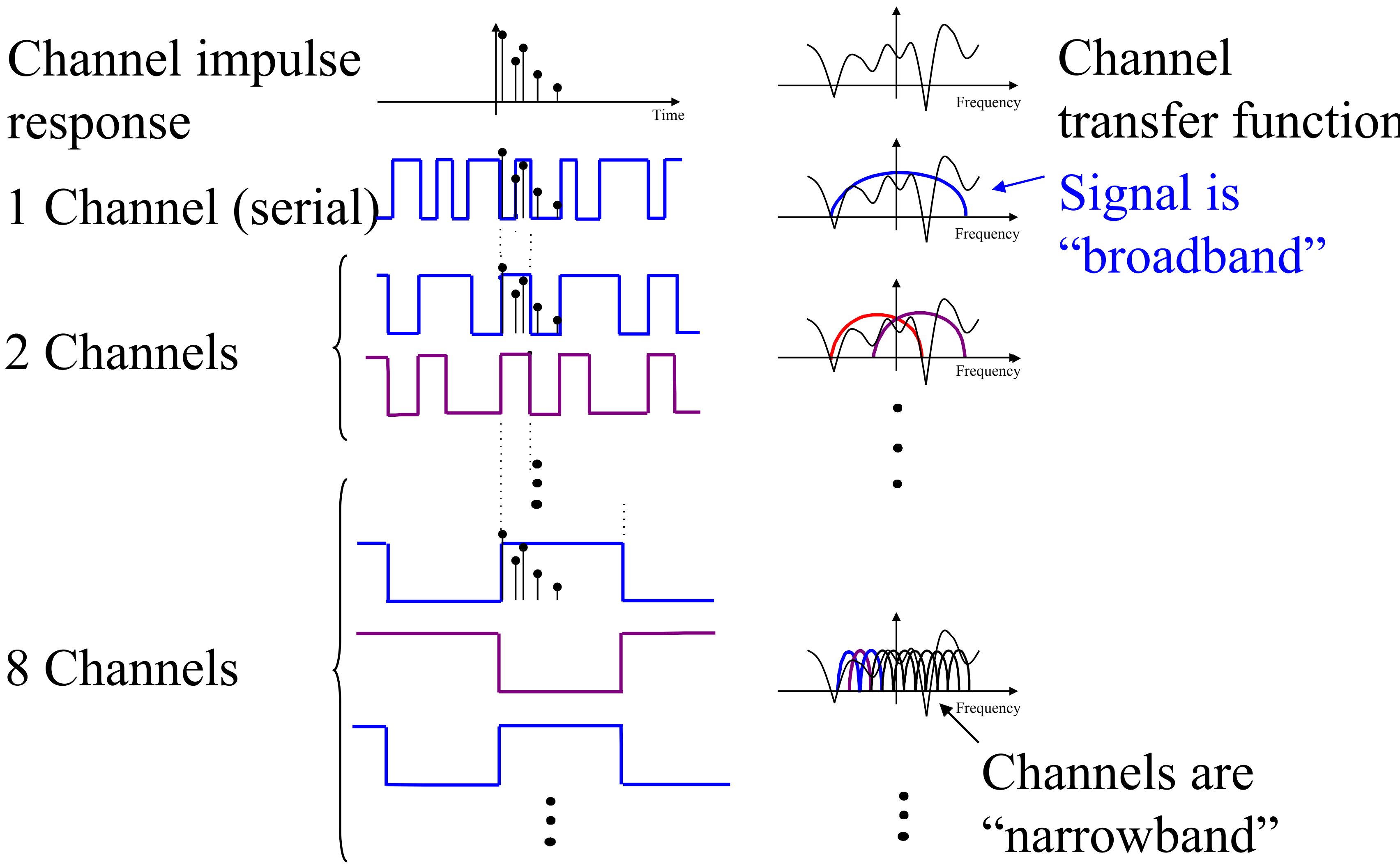
- Over what frequency range is the channel approximately the same? This is the ***coherence bandwidth*** $W_c \approx \frac{1}{2T_d}$



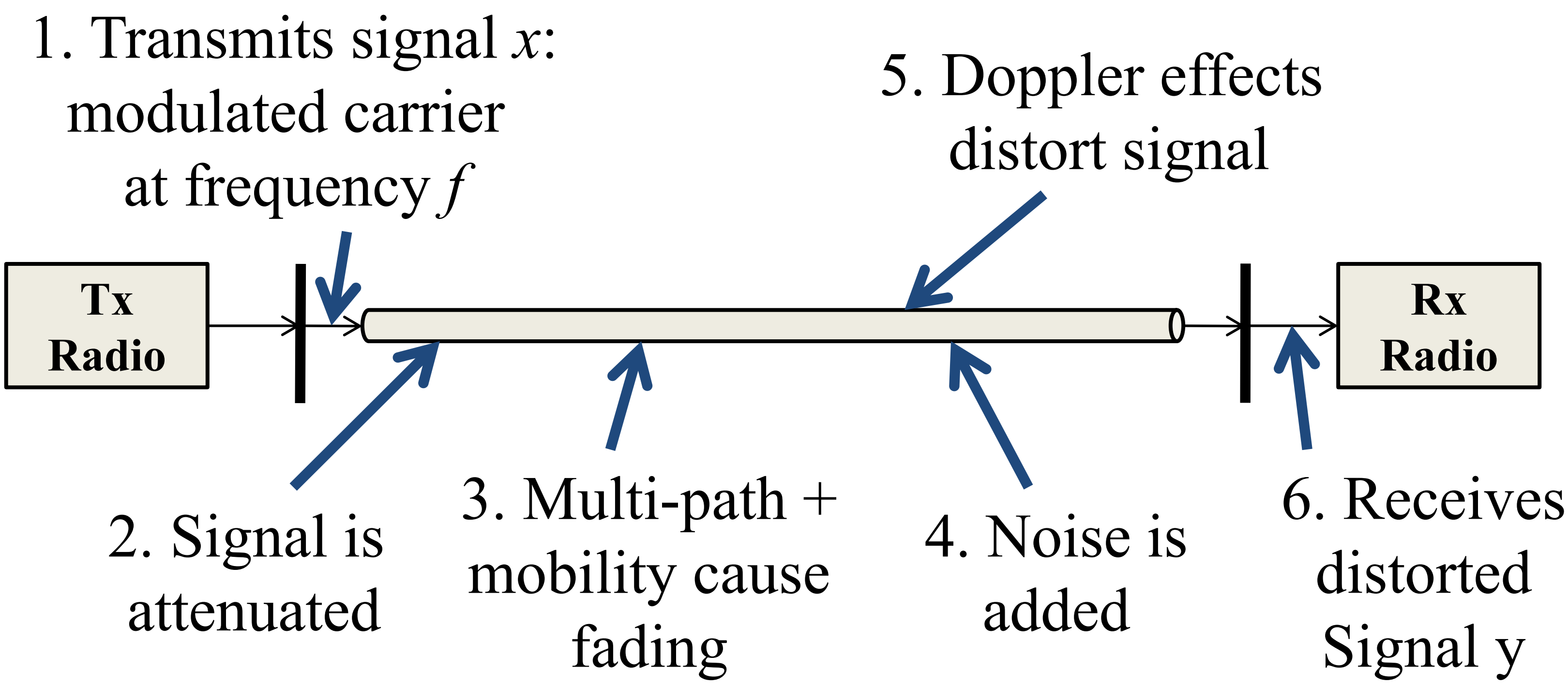
Summary: Wideband versus narrowband



Benefits of narrowband



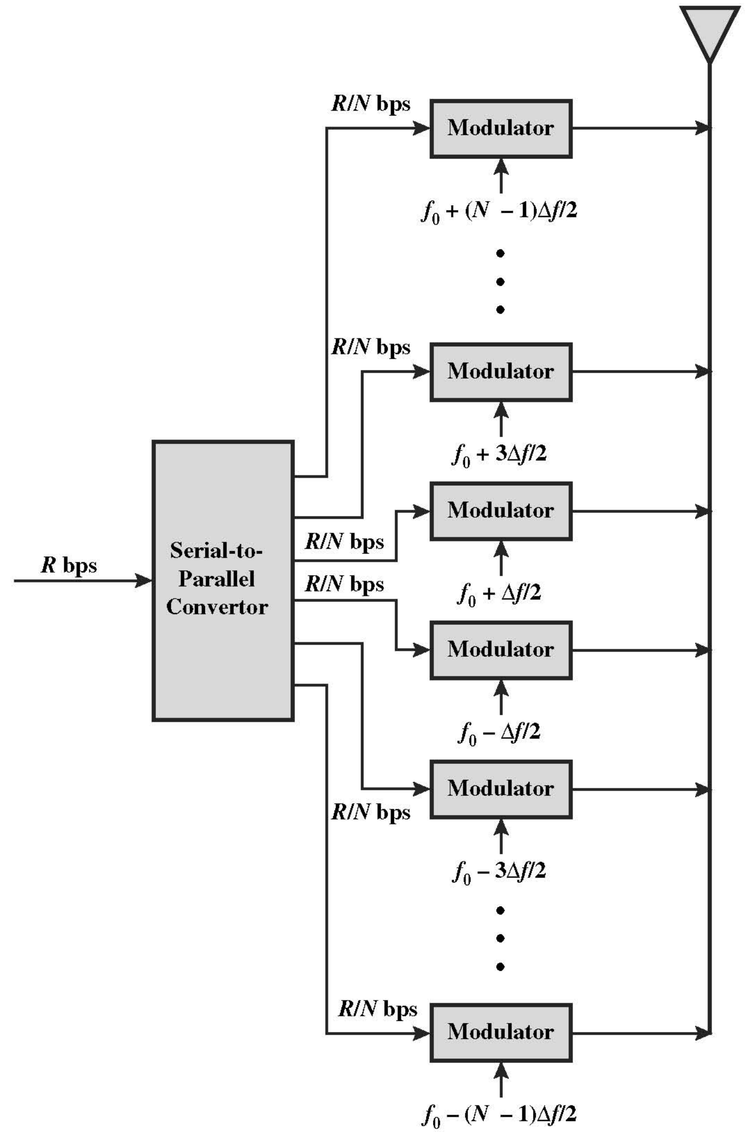
Channel model



$$\mathbf{x} \times \mathbf{h} + \mathbf{n} = \mathbf{y}$$

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
- Challenge is efficiently packing many subcarriers in a band - later



Distributing bits over subcarriers

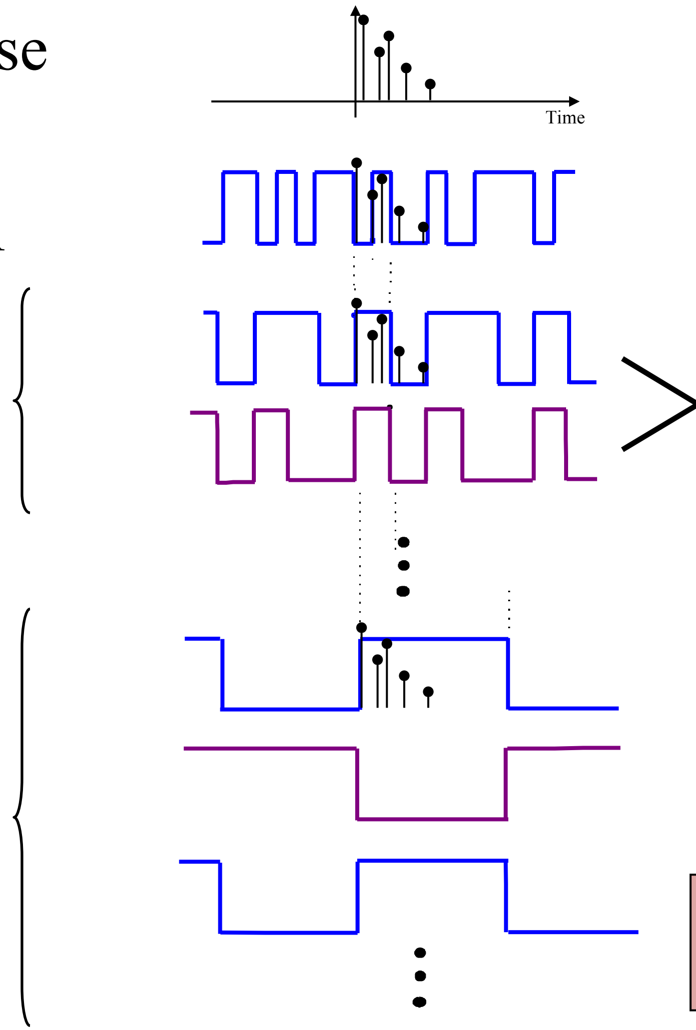
Channel impulse response

Single Channel

2 Channels

8 Channels

⋮

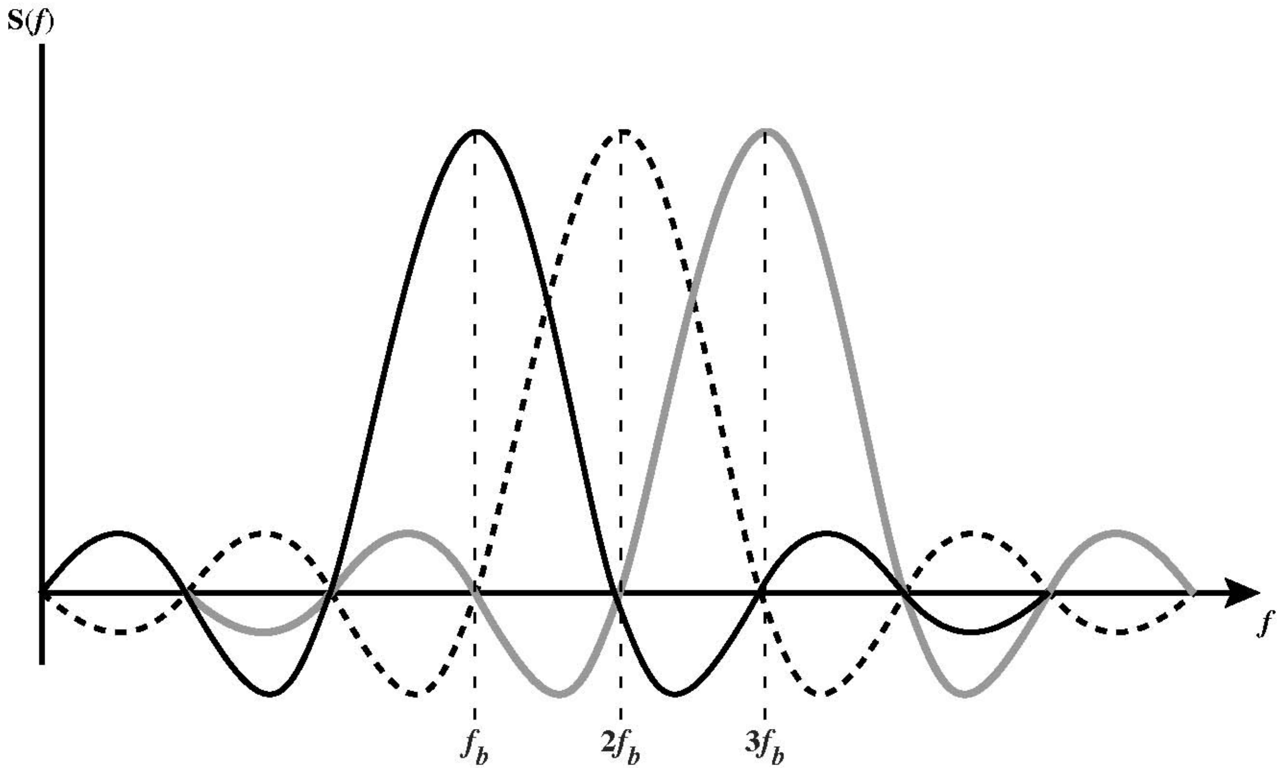


Channels are transmitted at different frequencies (sub-carriers)

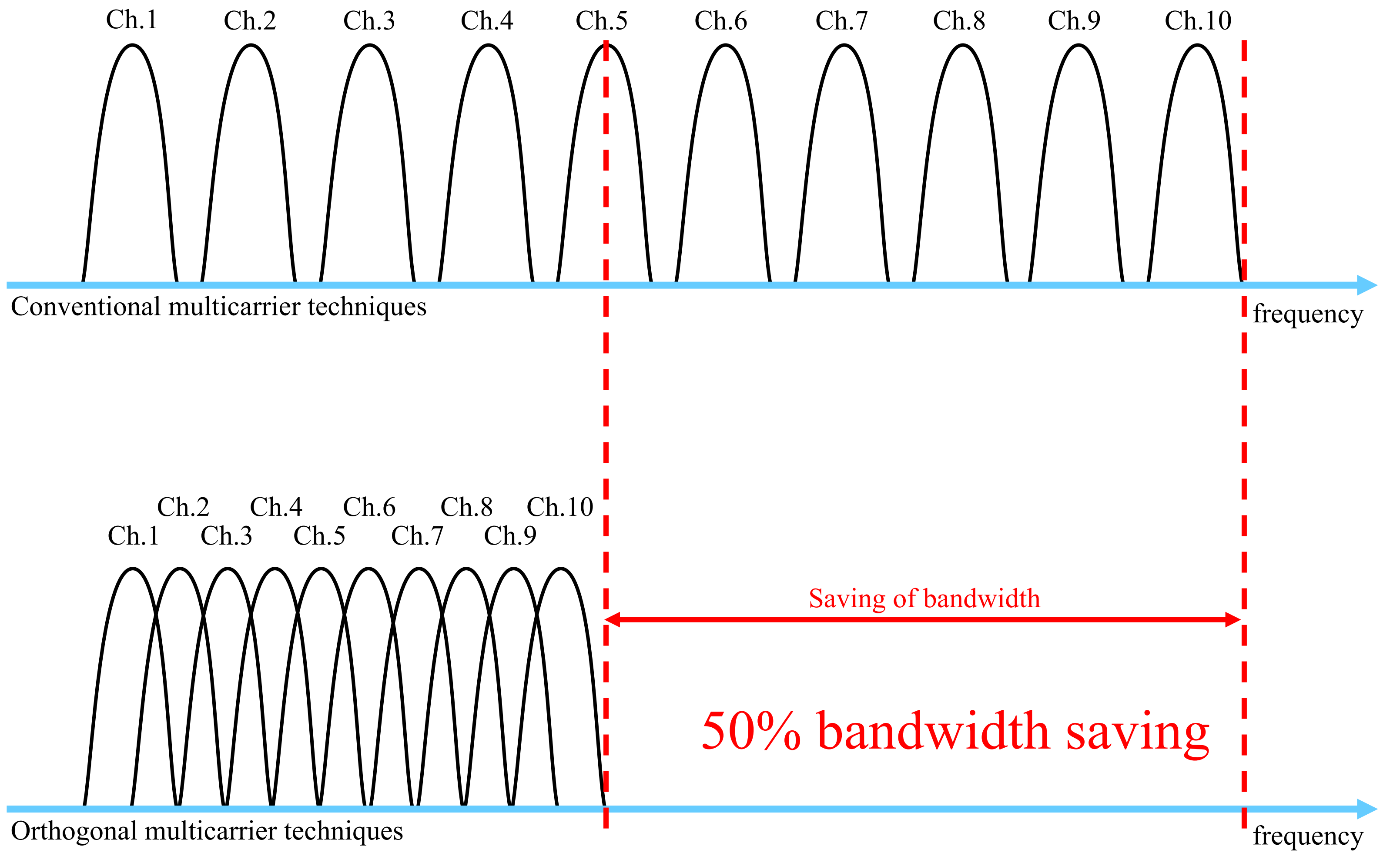
Resistance improves with number of channels

OFDM subcarriers are “Orthogonal”

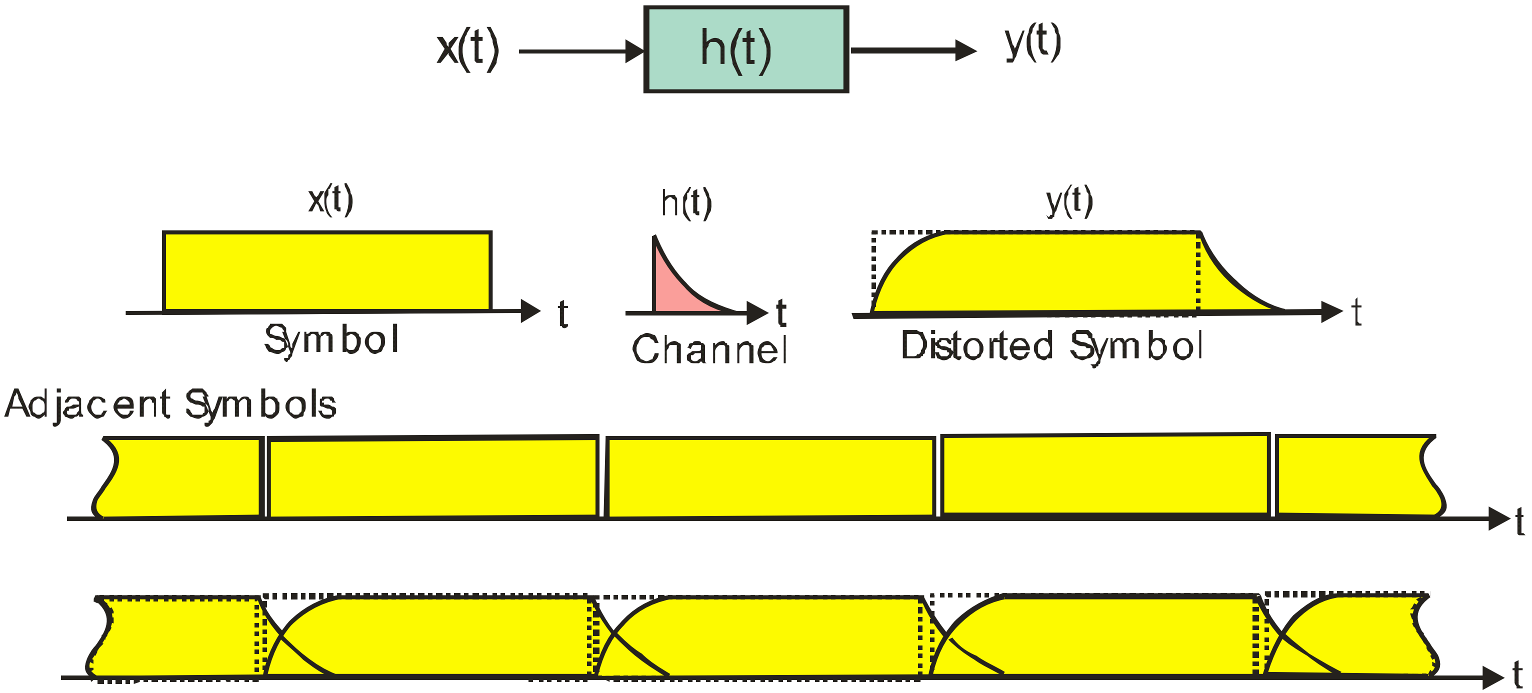
- Peaks of spectral density of each carrier coincide with the zeros of the other carriers
  - Carriers can be packed very densely with minimal interference
  - Requires very good control over frequencies



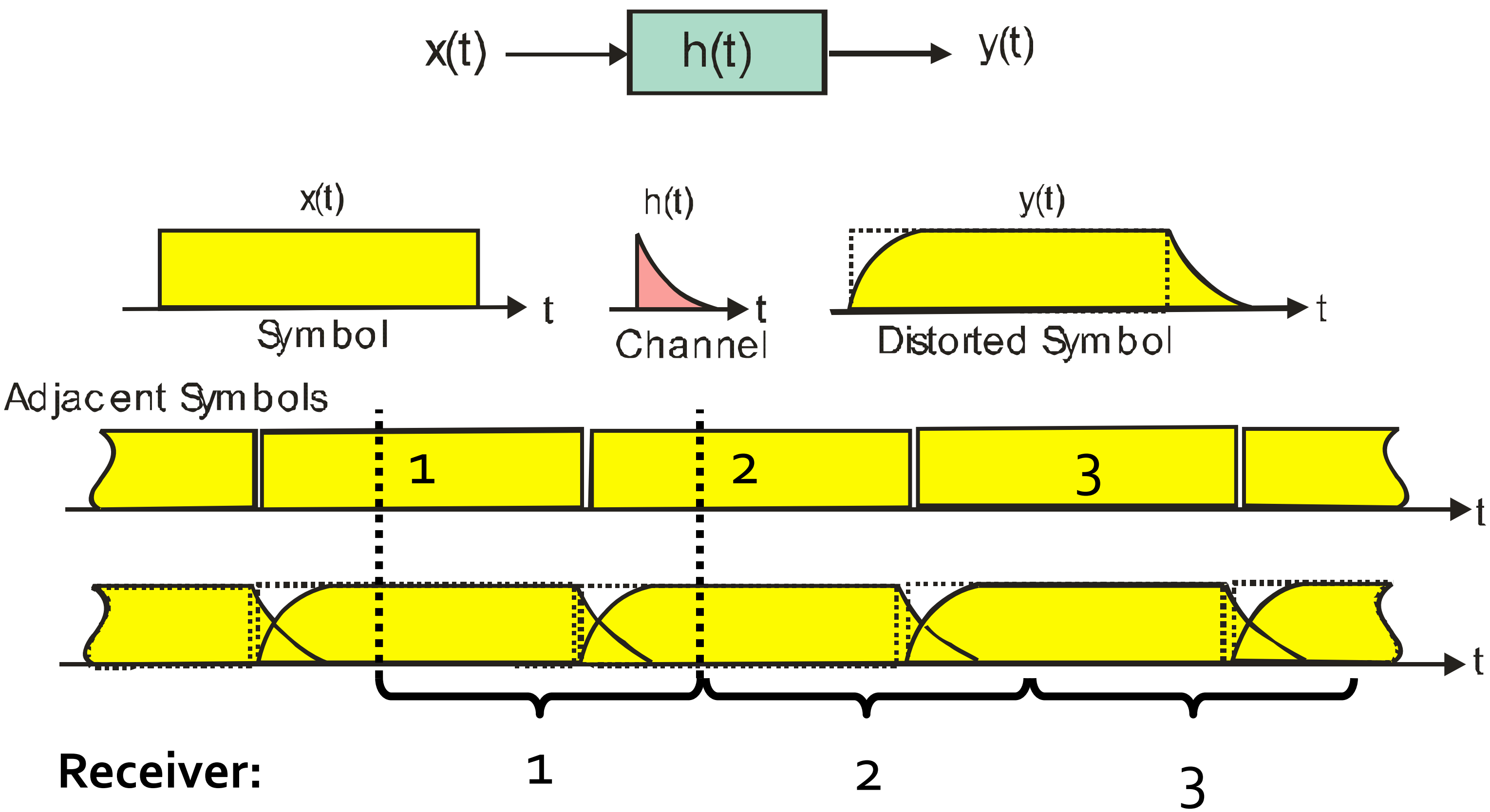
Densely Packing OFDM Channels



Problem: Adjacent Symbol Interference

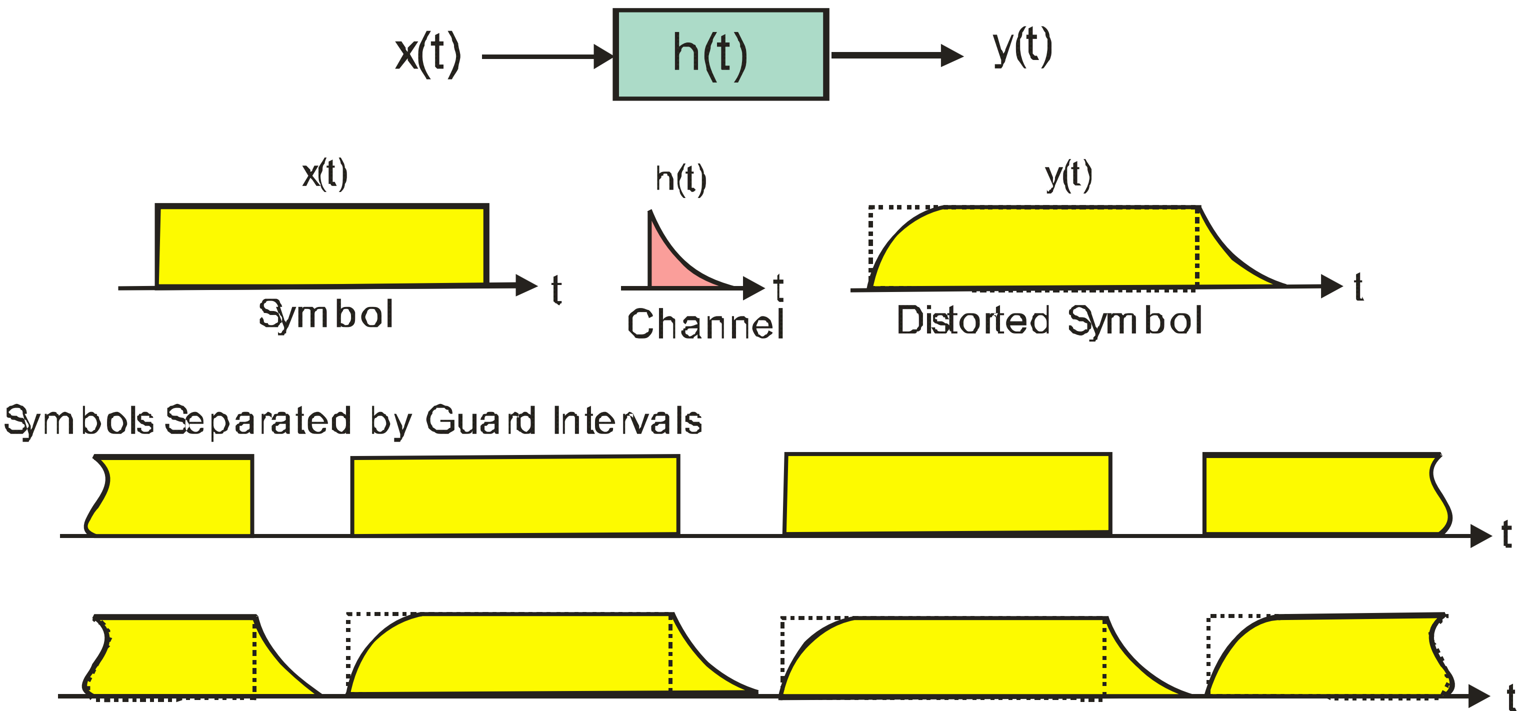


Problem: Receiver synchronization



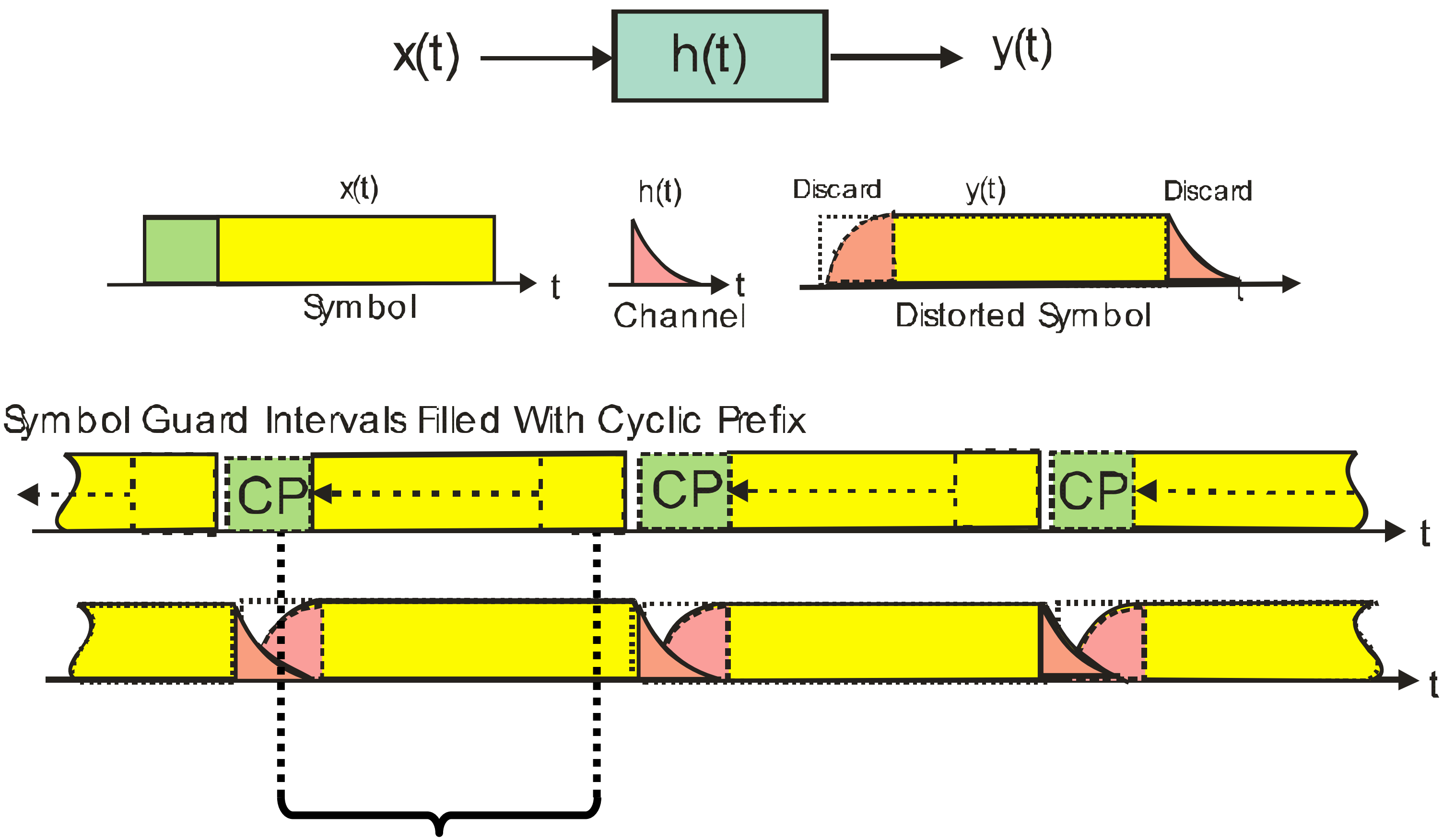
Receiver's view of Symbol 1 contains **actual Symbols 1 and 2**

Interference solution: Inter-symbol guard interval



Guard interval between adjacent symbols **mitigates adjacent symbol interference**

Synchronization solution: Cyclic prefix



Receiver: Symbol OK!

Example: IEEE 802.11a, 802.11g

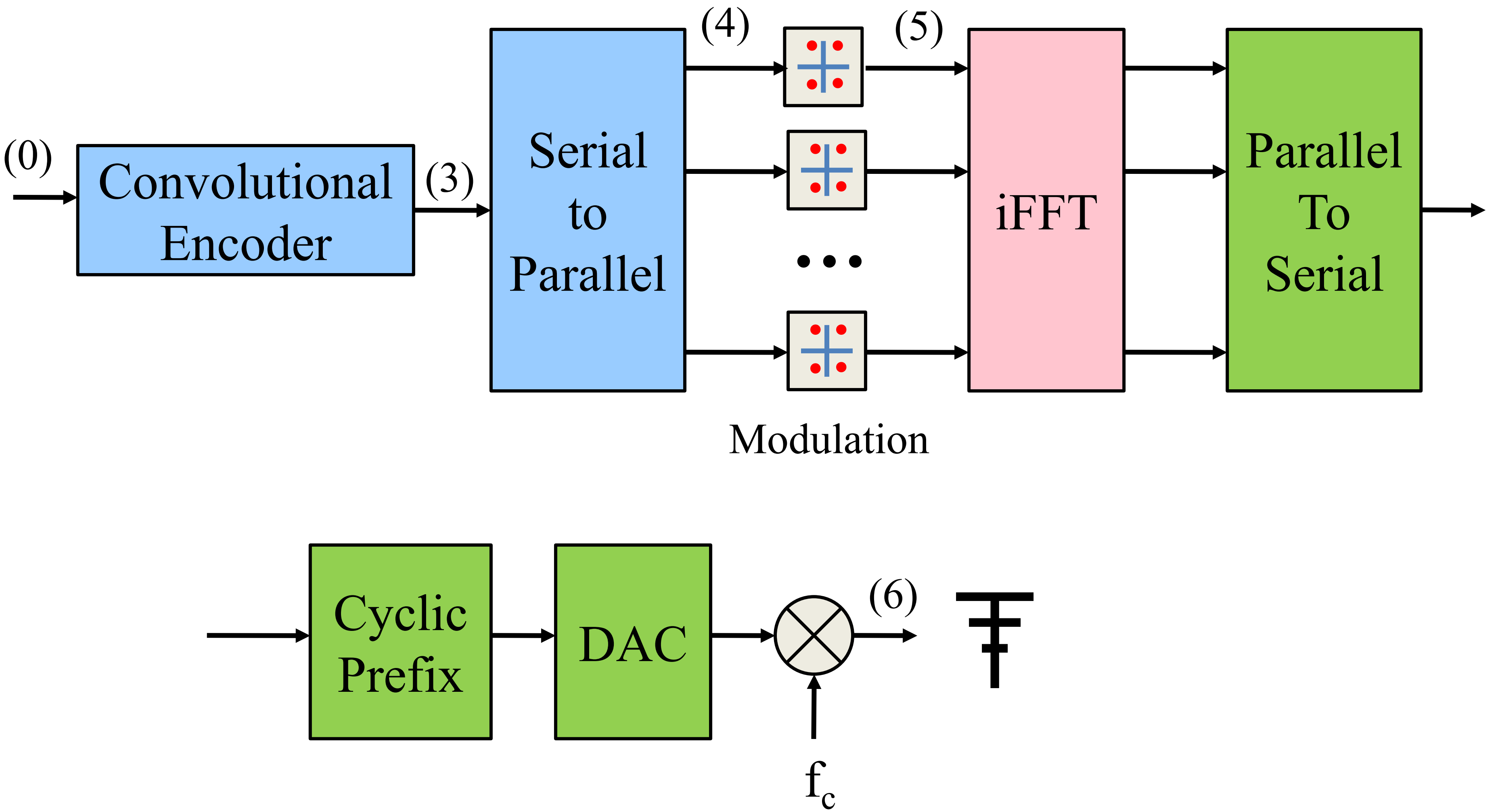
- OFDM with up to 48 subcarriers
  - Subcarrier spacing is 312.5 KHz
  - Subcarriers modulated: BPSK, QPSK, 16-QAM, or 64-QAM

- Uses a convolutional code at a rate of ½, 2/3, ¾ , or 5/6 to provide forward error correction

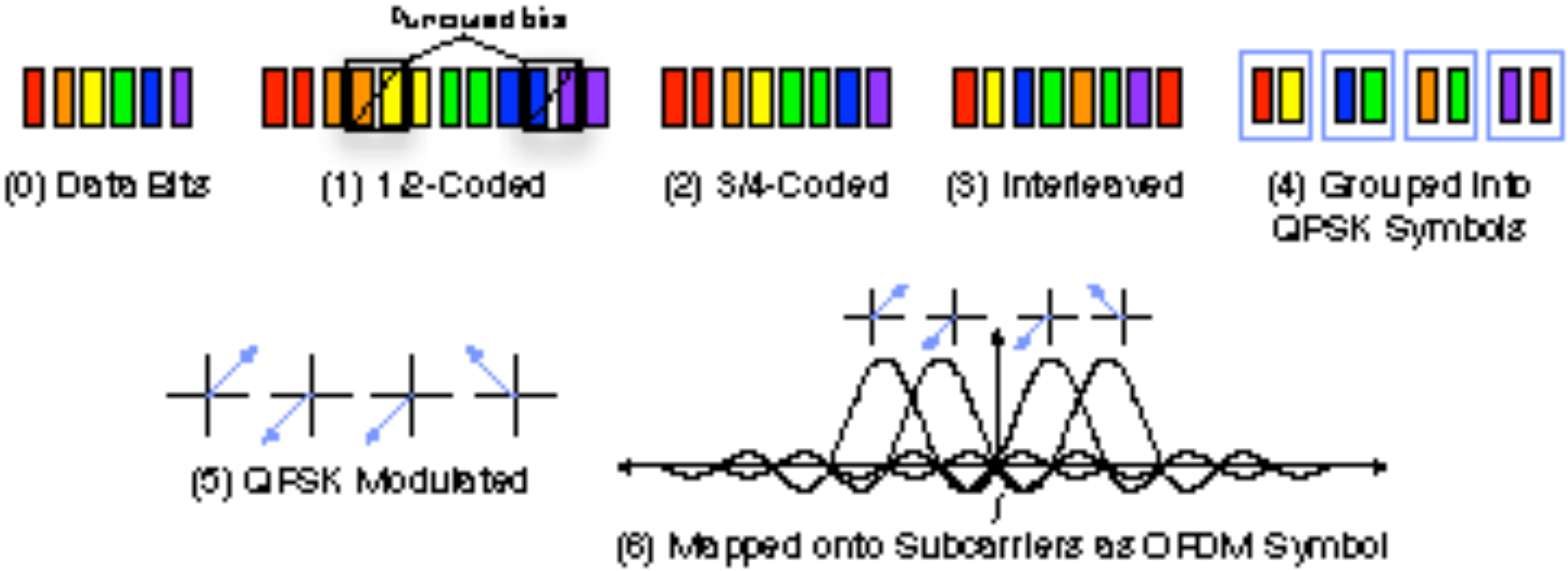
- Results in data rates of 6, 9, 12, 18, 24, 36, 48, and 54 MBps

- Cyclic prefix is 25% of a symbol time (16 vs 64)

OFDM Transmitter



OFDM in 802.11



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