Wireless OFDM Systems

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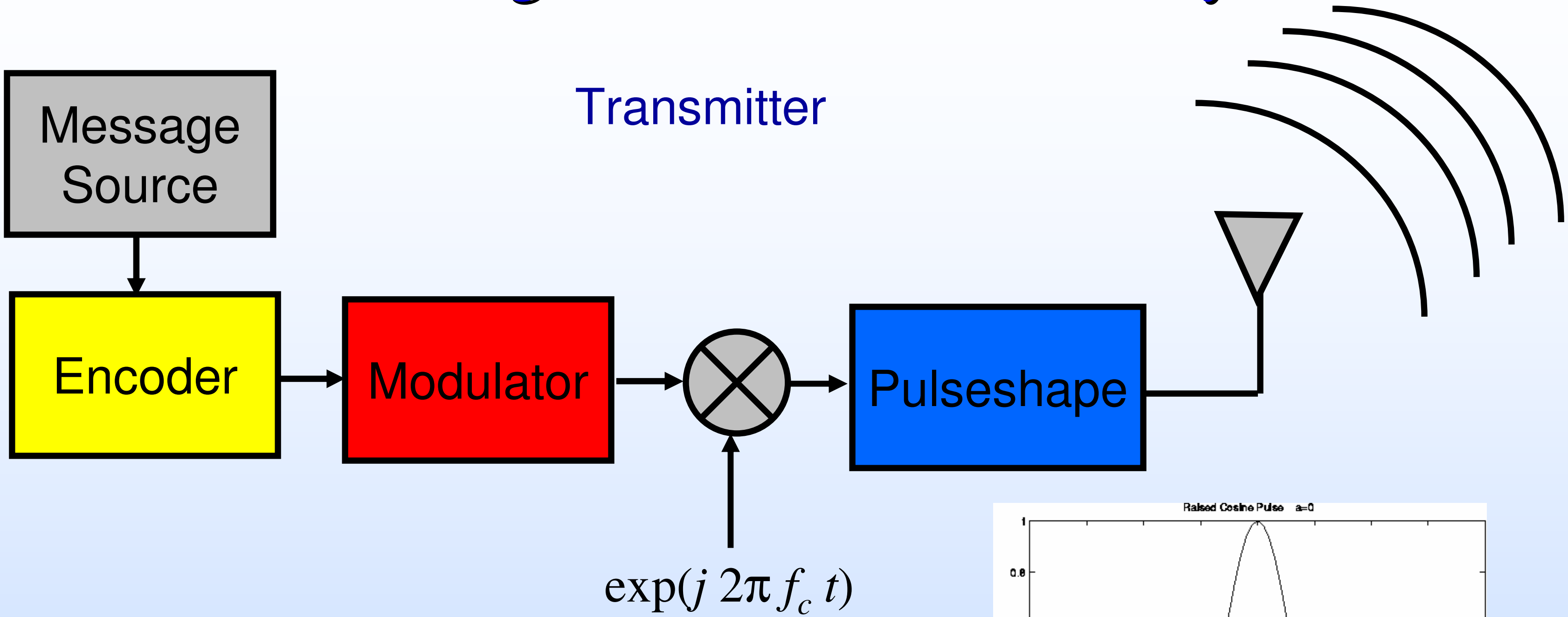
OFDM Systems & Applications

Standard	*Meaning*	*Carrier Freq.*	*Rate (Mbps)*	*Applications*
DAB	**Digital Audio Broadcasting**	**FM radio**	**0.008-0.384**	**Audio broadcasting**
DVB-T	**Digital Video Broadcasting**	**UHF**	**3.7-32**	**Digital TV broadcasting**
DVB-H	**Digital Video Broadcasting**	**UHF**	**13.7**	**Digital broadcasting to handheld**
IEEE 802.11a	**Wireless LAN / WiFi**	**5.2 GHz**	**6 - 54**	**Wireless Internet**
IEEE 802.11g	**Wireless LAN / WiFi**	**2.4 GHz**	**6 – 54**	**Wireless Internet**
IEEE 802.11n	**Wireless LAN (High Speed)**	**2.4 GHz - ??**	**6 – 100**	**Wireless Internet**
IEEE 802.16	**Broadband Wireless Access**	**2.1 GHz & others**	**0.5 – 20**	**Fixed / Mobile Wireless Internet**
IEEE 802.20	**Mobile Broad. Wireless Access**	**3.5 GHz**	**~ 1**	**Mobile Internet / Voice?**

Orthogonal Frequency Division Multiplexing (OFDM)

- **Digital modulation scheme**
- **Wireless counterpart to discrete multitone transmission**
- **Used in a variety of applications**
  - **Broadcast**
  - **High-speed internet access**

Wireless Digital Communication System

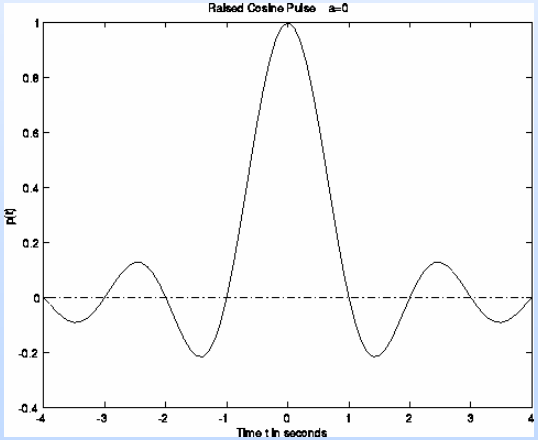


Carrier frequency f_c examples

FM radio 88.5-107.7 MHz
(0.2 MHz station spacing)

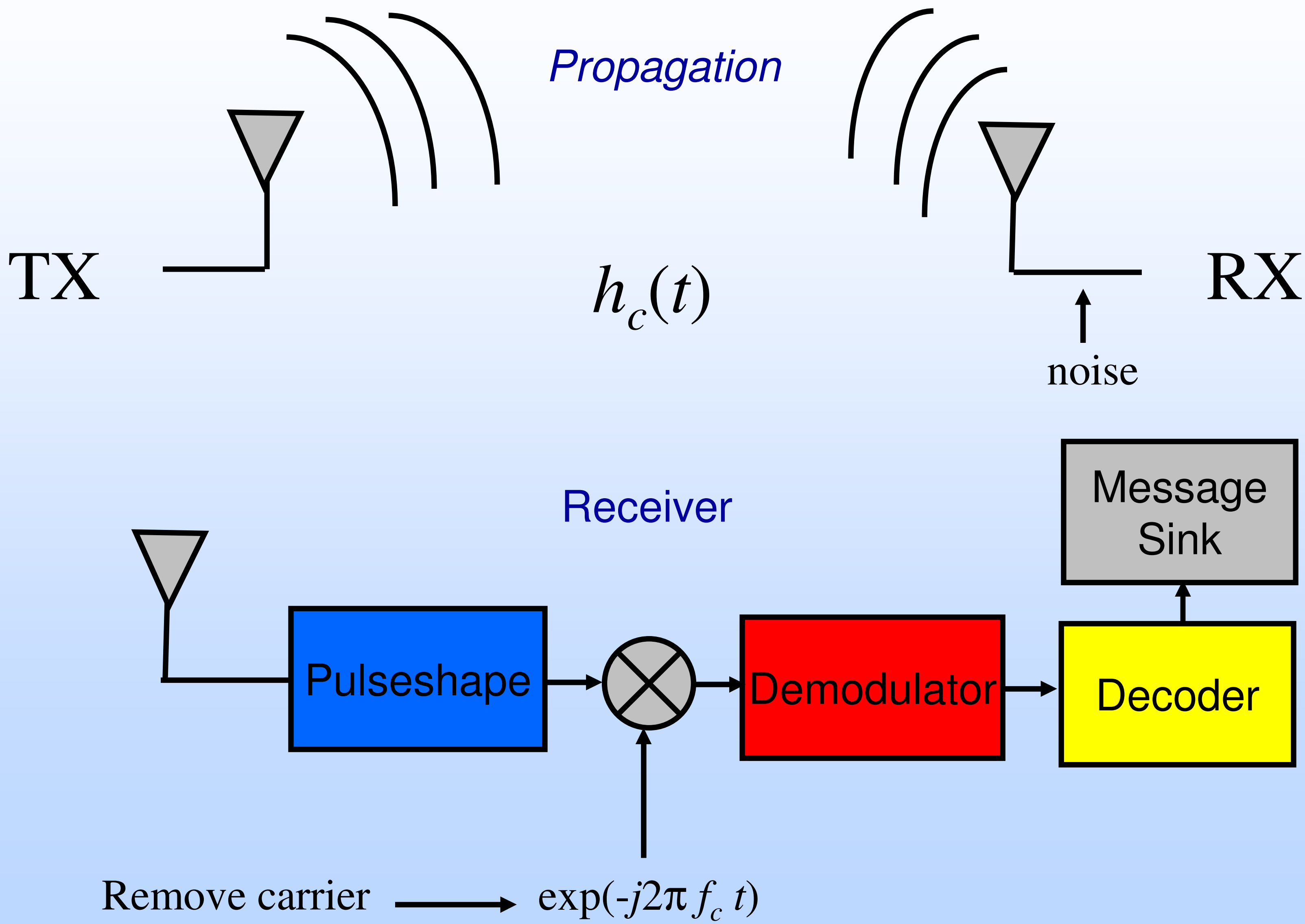
Analog cellular 900 MHz

Digital cellular 1.8 GHz

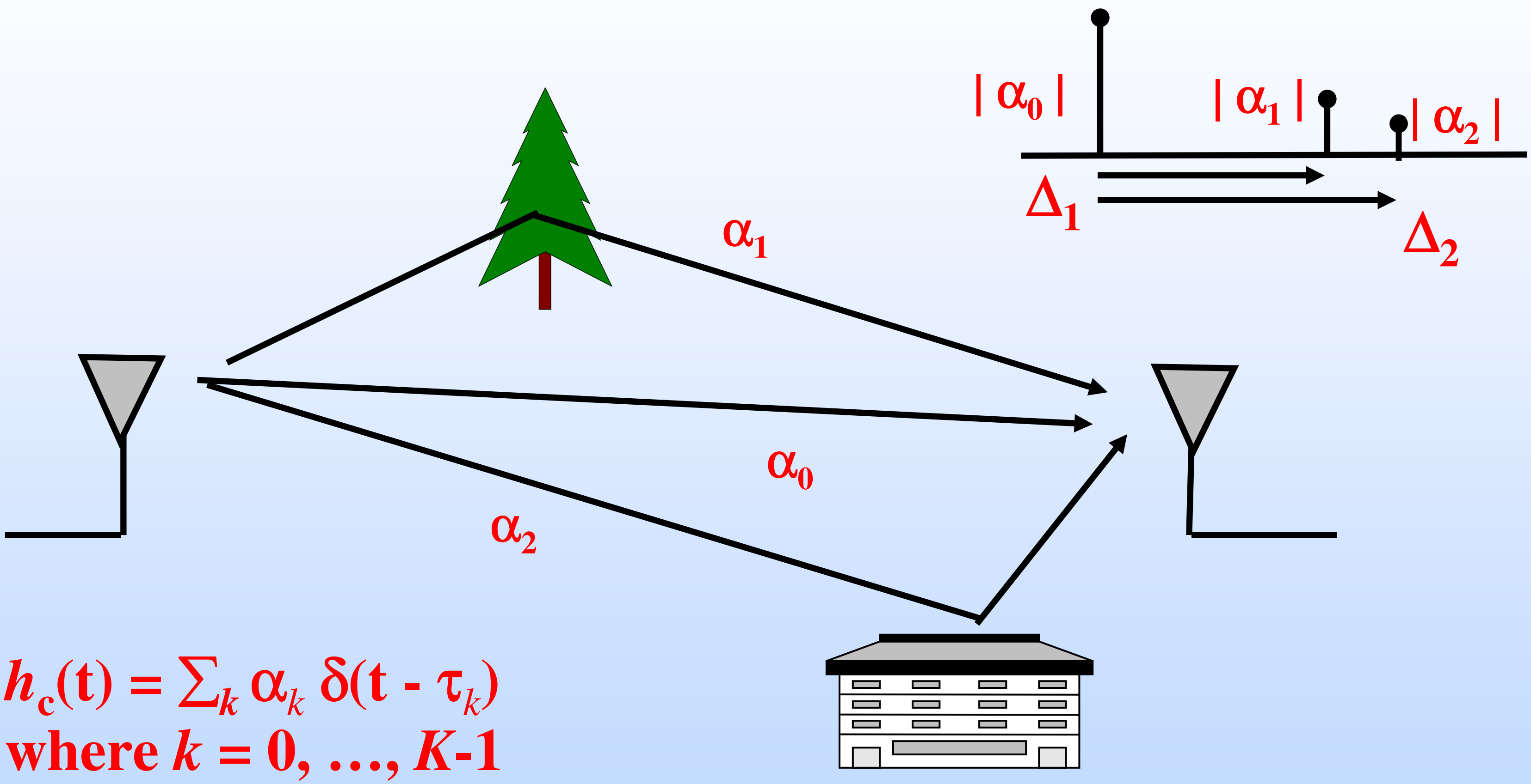


Raised cosine
pulse shaping filter

Wireless Digital Communication System



Multipath Propagation – Simple Model



- $h_c(t) = \sum_k \alpha_k\, \delta(t - \tau_k)$
  where $k = 0, \ldots, K-1$

  α_k : path gain (complex)

  $\tau_0 = 0$ normalize relative delay of first path

  $\Delta_k = \tau_k - \tau_0$ difference in time-of-flight

Equivalent Propagation Channel

convolution

$$h_{\text{eff}}(t) = g_{\text{tr}}(t) \otimes h_c(t) \otimes g_{\text{rx}}(t)$$

transmit filters

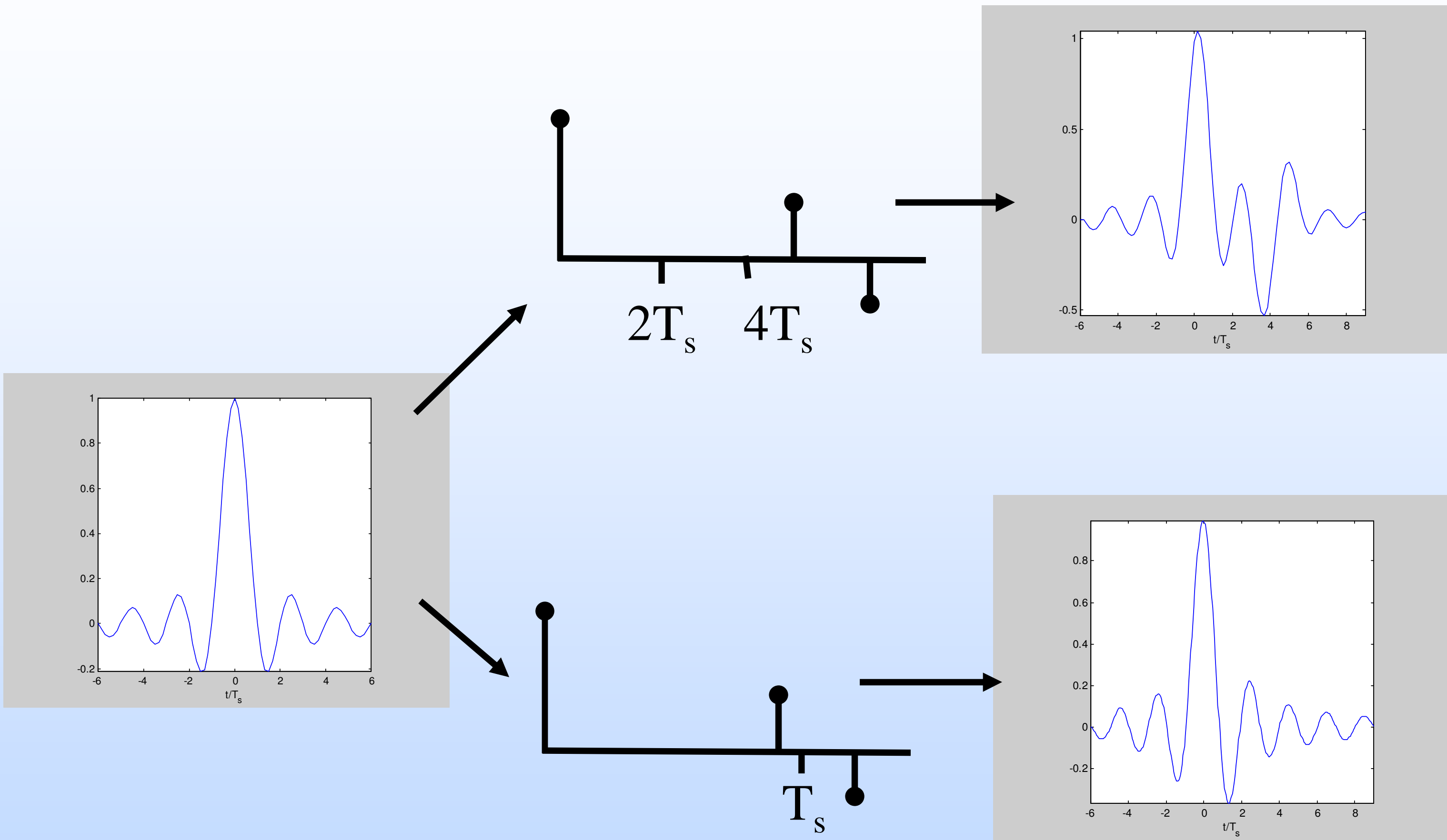
multipath channel

receive filters

- **Effective channel at receiver**
  - Propagation channel
  - Transmit / receive filters
- **$h_c(t)$ typically *random* & changes with time**

⇒ Must estimate and re-estimate channel

Impact of Multipath: Delay Spread & ISI



Max delay spread = effective number of symbol periods occupied by channel

Requires equalization to remove resulting ISI

Effective Delay Spread

- **Delay spread depends on difference in path lengths**
- **Effective delay spread: function of the maximum difference**

	Cell size	***Max Delay Spread***
Pico cell	**0.1 km**	**300 ns**
Micro cell	**5 km**	**15 us**
Macro cell	**20 km**	**40 us**

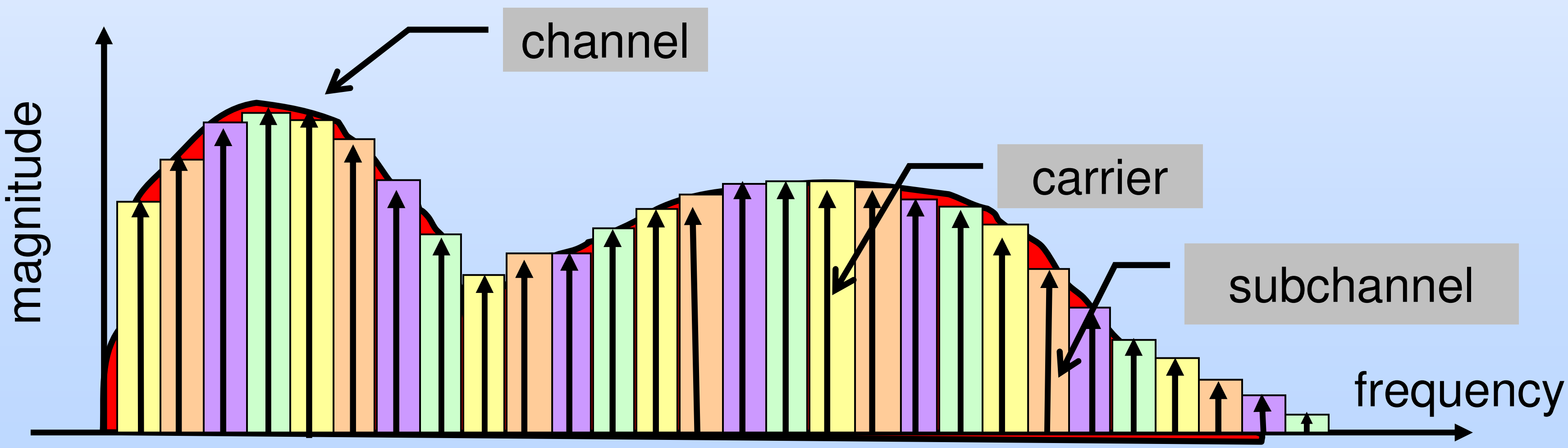
- **Sampling period T_s determines effect of delay spread**

	Sampling Period	***Channel taps***	***Application***
802.11a	**50 ns**	**6**	**WLAN**
DVB-T	**160 ns**	**90**	**Audio**
DAB	**600 ns**	**60**	**TV broadcast**

Radio waves travel ~ 1 ns / ft

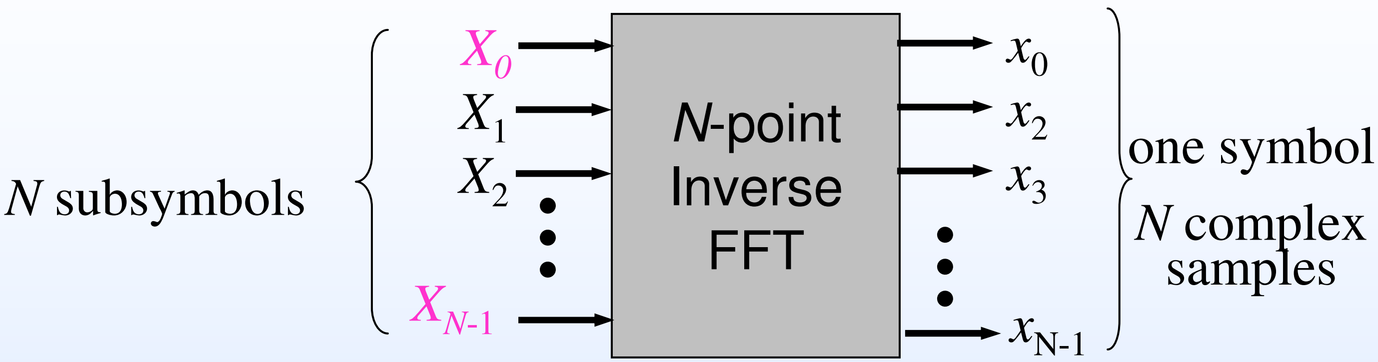
Multicarrier Modulation

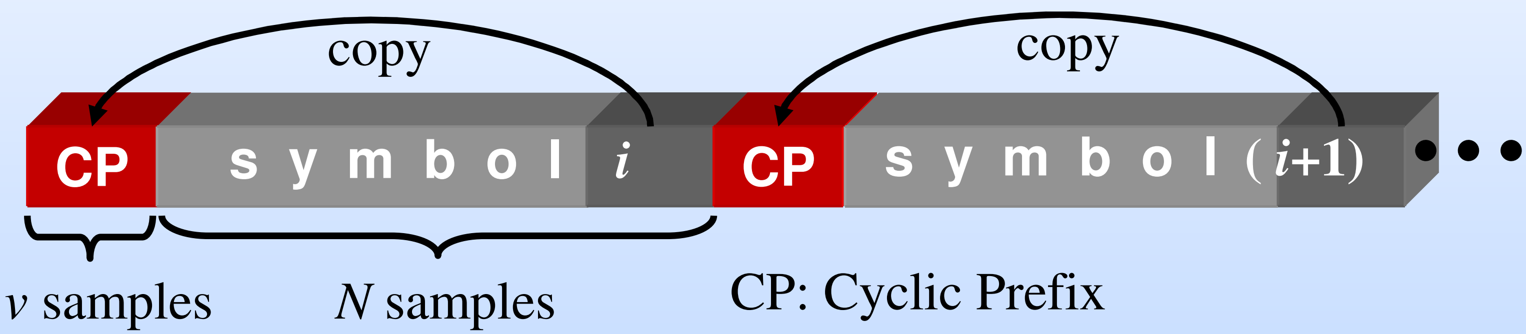
- **Divide broadband channel into narrowband subchannels**
  - No ISI in *subchannels* if constant gain in every subchannel and if ideal sampling
- **Orthogonal Frequency Division Multiplexing**
  - Based on the fast Fourier transform
  - Standardized for DAB, DVB-T, IEEE 802.11a, 802.16a, HyperLAN II
  - Considered for fourth-generation mobile communication systems



Subchannels are 312 kHz wide in 802.11a and HyperLAN II

An OFDM Symbol

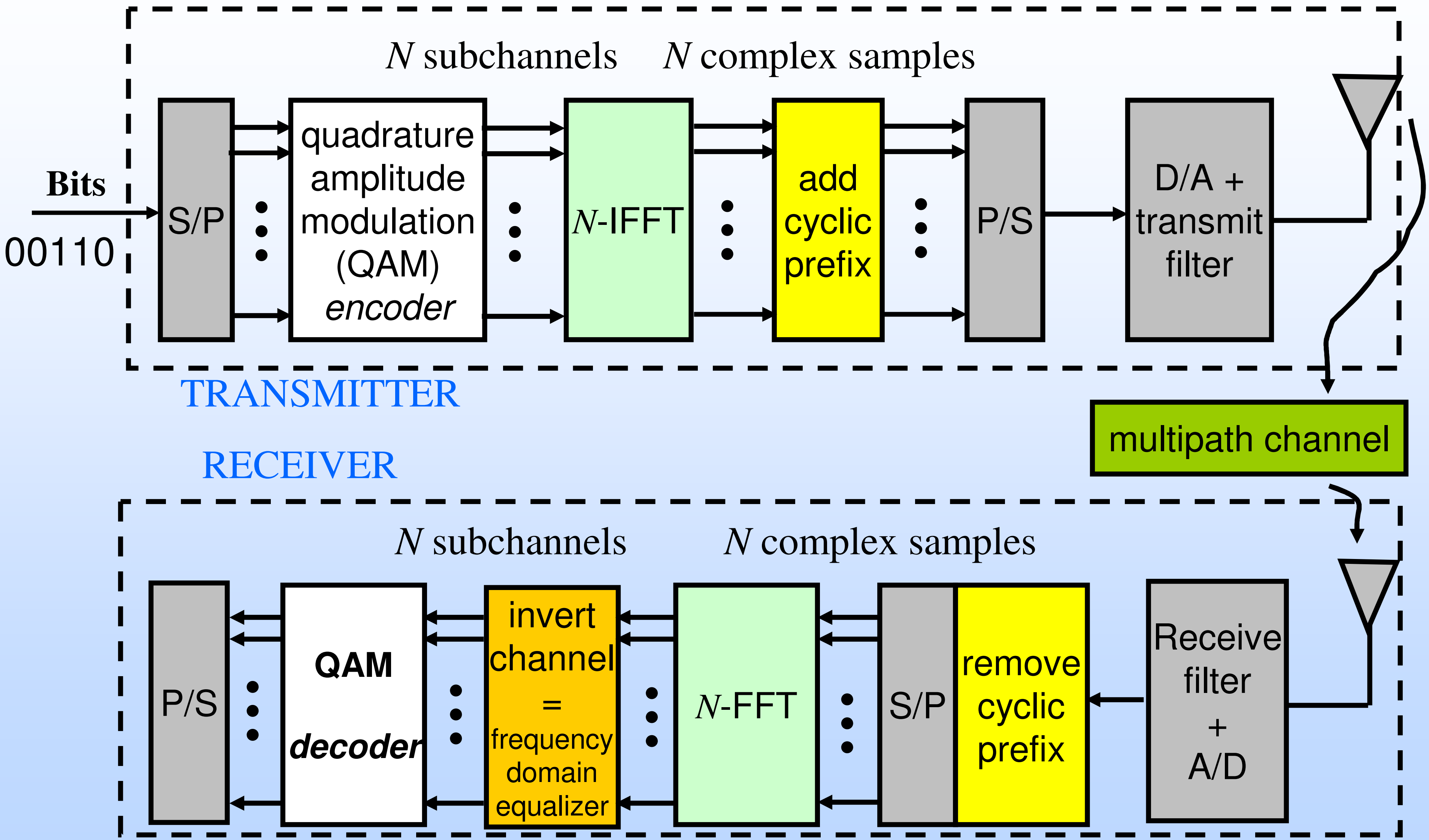




- **Key difference with DMT ⇨ *N* input symbols! Why?**
- **Bandpass transmission allows for complex waveforms**
  - **Transmit:** $y(t) = \mathrm{Re}\{(I(t) + j\,Q(t)) \exp(j 2\pi f_c t)\}$

$$= I(t) \cos(2\pi f_c t) - Q(t) \sin(2\pi f_c t)$$

An OFDM Modem



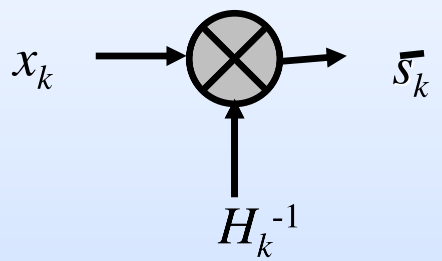
Frequency Domain Equalization

- For the k^{th} carrier:

$$x_k = H_k\, s_k + v_k$$

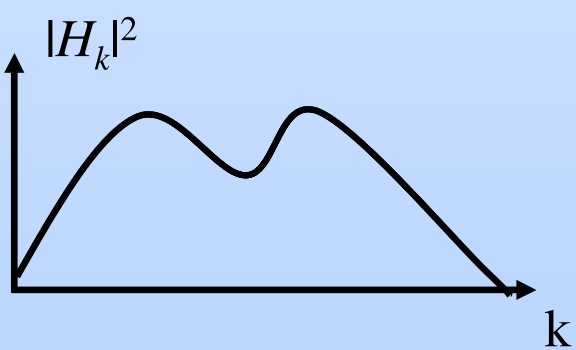
where $H_k = \sum_n h_k(nT_s) \exp(j2\pi\, k\, n \,/\, N)$ where $n = 0, \ldots,. N\text{-}1$

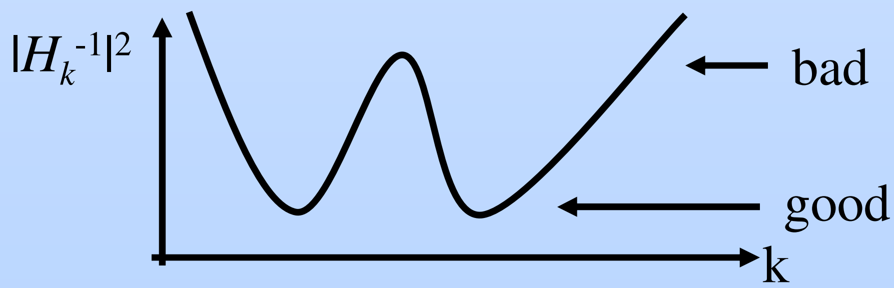
- Frequency domain equalizer



- Noise enhancement factor

$$\hat{\sigma}_k^2 = \sigma_k^2 |H_k^{-1}|^2$$





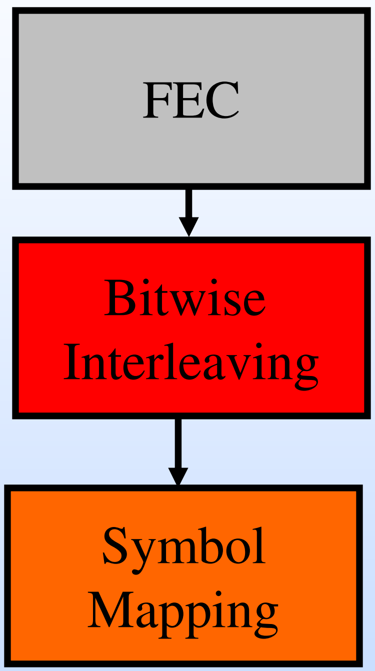
DMT vs. OFDM

- **DMT**
  - Channel changes very slowly ~ 1 s
  - Subchannel gains known at transmitter
  - Bitloading (sending more bits on *good* channels) increases throughput
- **OFDM**
  - Channel may change quickly ~ 10 ms
  - Not enough time to convey gains to transmitter
  - Forward error correction mitigates problems on bad channels

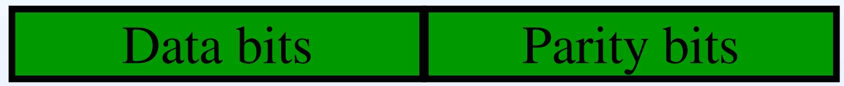
Coded OFDM (COFDM)

- **Error correction is *necessary* in OFDM systems**
- **Forward error correction (FEC)**
  - Adds redundancy to data stream
  - Examples: convolutional codes, block codes
  - Mitigates the effects of bad channels
  - Reduces overall throughput according to the coding rate k/n
- **Automatic repeat request (ARQ)**
  - Adds error detecting ability to data stream
  - Examples: 16-bit cyclic redundancy code
  - Used to detect errors in an OFDM symbol
  - Bad packets are retransmitted (hopefully the channel changes)
  - Usually used with FEC
  - Minus: Ineffective in broadcast systems

Typical Coded OFDM Encoder



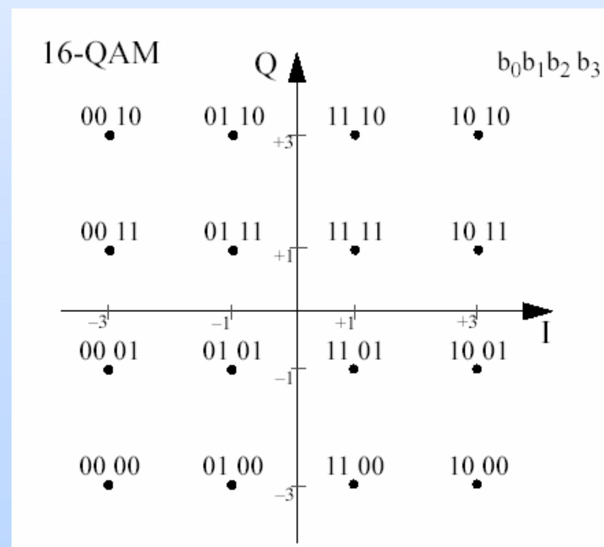
- Reed-Solomon and/or convolutional code



Rate 1/2

- Intersperse coded and uncoded bits

- Map bits to symbols



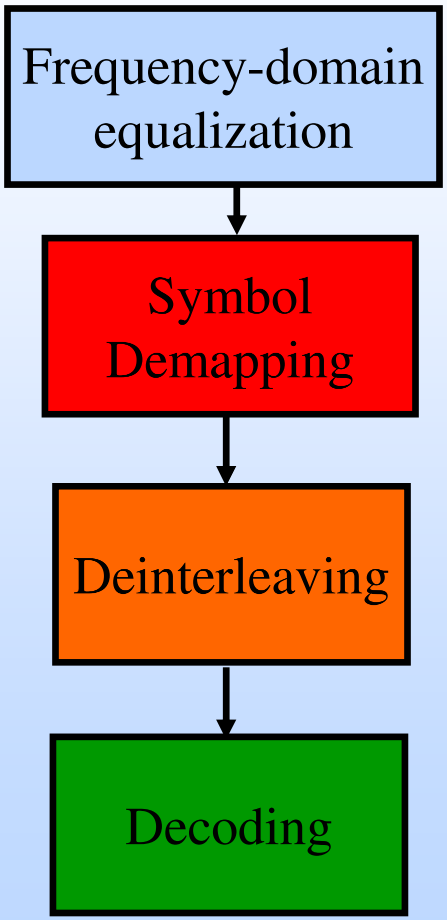
Example: IEEE 802.11a

Data rate (Mbits/s)	Modulation	Coding rate (R)	Coded bits per subcarrier (N_{BPSC})	Coded bits per OFDM symbol (N_{CBPS})	Data bits per OFDM symbol (N_{DBPS})
6	BPSK	1/2	1	48	24
9	BPSK	3/4	1	48	36
12	QPSK	1/2	2	96	48
18	QPSK	3/4	2	96	72
24	16-QAM	1/2	4	192	96
36	16-QAM	3/4	4	192	144
48	64-QAM	2/3	6	288	192
54	64-QAM	3/4	6	288	216

- **IEEE 802.11 employs adaptive modulation**
  - Code rate & modulation depends on distance from base station
  - Overall data rate varies from 6 Mbps to 54 Mbps

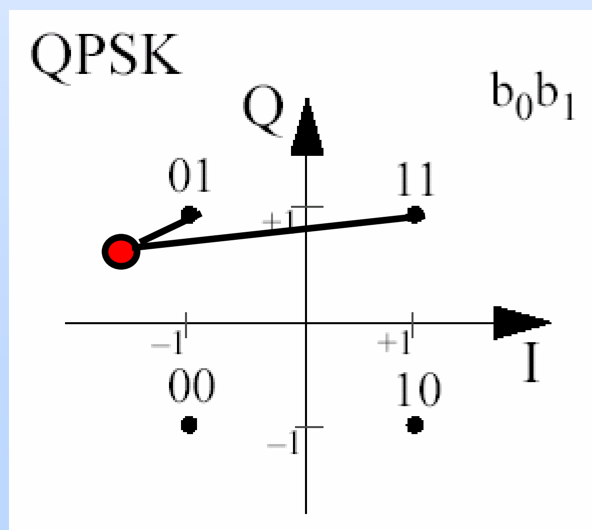
Reference: IEEE Std 802.11a-1999

Typical Coded OFDM Decoder



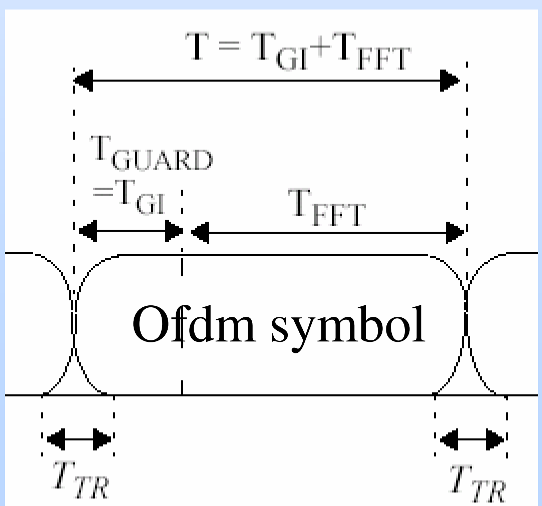
- **Symbol demapping**
  - Produce soft estimate of each bit
  - Improves decoding

$$
\begin{aligned}
L(b_k) &= \log\left(\frac{Pr(x|b_k=1)}{Pr(x|b_k=0)}\right) \\
&\approx \log\left(\frac{\max_{s_k} Pr(x|b_k=1, s_k)}{\max_{s_k} Pr(x|b_k=0, s_k)}\right)
\end{aligned}
$$

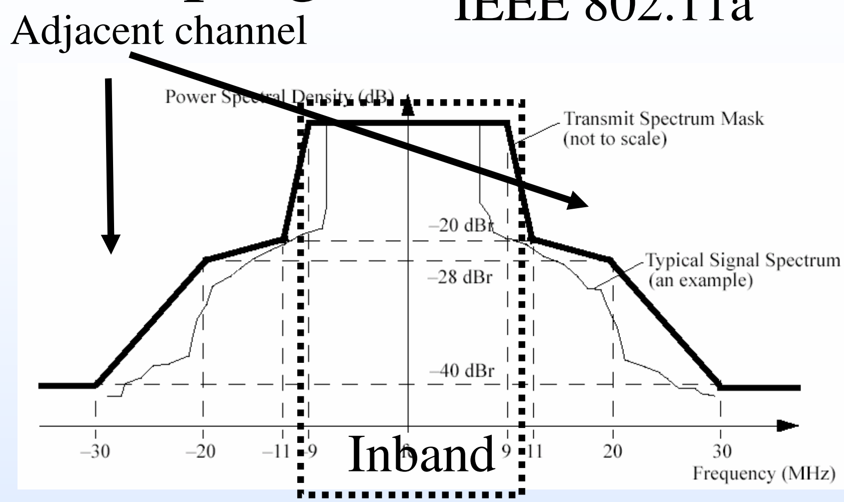


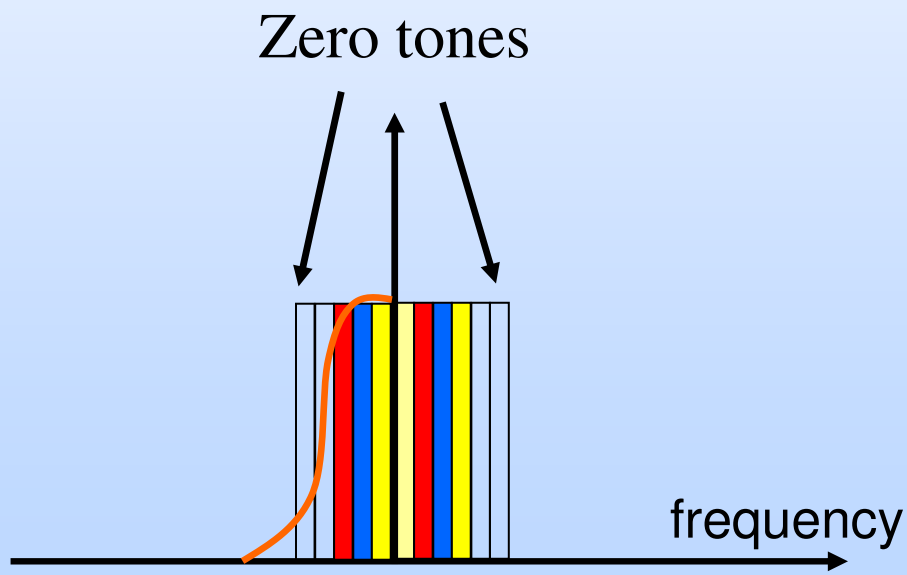
Spectrum Shaping

- **FCC manages spectrum**
- **Specifies power spectral density mask**
  - Adjacent channel interference
  - Roll-off requirements
- **Implications to OFDM**
  - Zero tones on edge of band
  - Time domain windowing ‘smoothes’ adjacent symbols



IEEE 802.11a

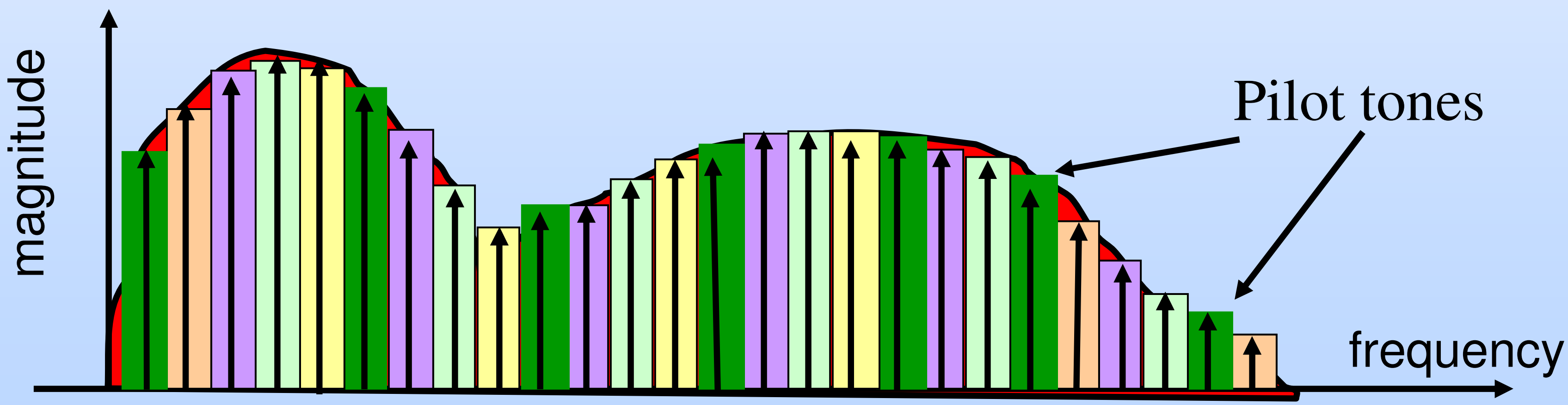




Reference: Std 802.11a

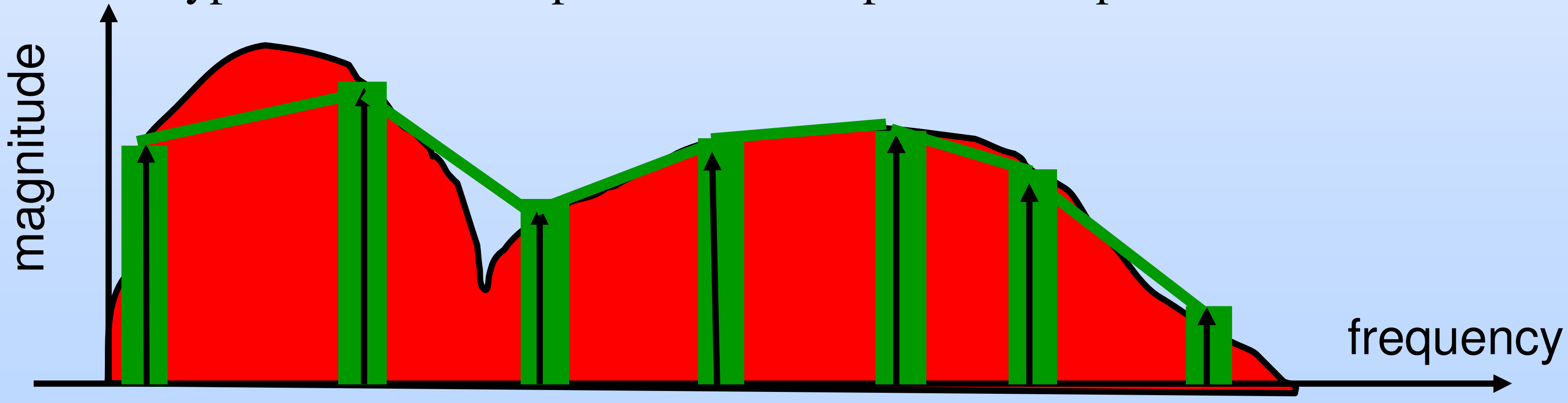
Ideal Channel Estimation

- **Wireless channels change frequently ~ 10 ms**
- **Require frequent channel estimation**
- **Many systems use pilot tones – known symbols**
  - Given s_k, for $k = k_1, k_2, k_3, \ldots$ solve $x_k = \sum_{l=0}^{L} h_l\, e^{-j2\pi k\, l/N}\, s_k$ for h_l
  - Find $H_k = \sum_{l=0}^{L} h_l\, e^{-j2\pi k\, l\, /\, N}$ (significant computation)
- **More pilot tones**
  - Better noise resiliance
  - Lower throughput (pilots are *not* informative)



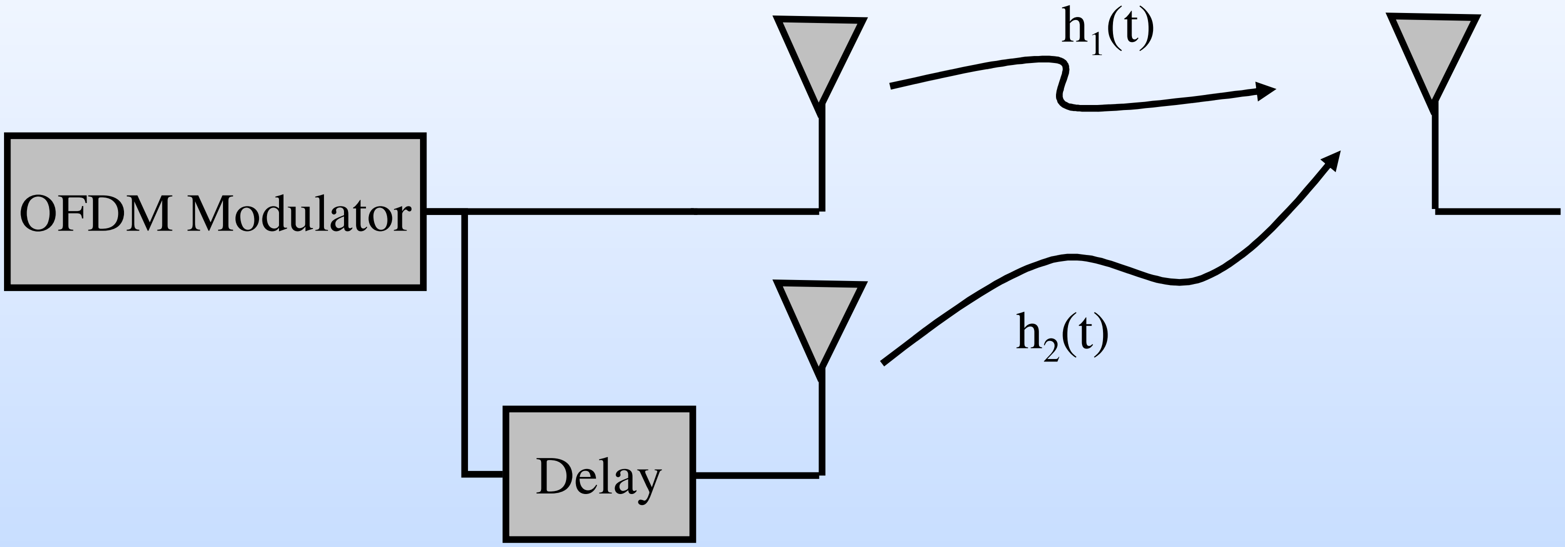
Channel Estimation Via Interpolation

- **More efficient approach is interpolation**
- **Algorithm**
  - For each pilot k_i find $H_{ki} = x_{ki} / s_{ki}$
  - Interpolate unknown values using interpolation filter
  - $H_m = \alpha_{m,1} H_{k1} + \alpha_{m,2} H_{k2} + \ldots$
- **Comments**
  - Longer interpolation filter: more computation, timing sensitivity
  - Typical 1dB loss in performance in practical implementation



OFDM and Antenna Diversity

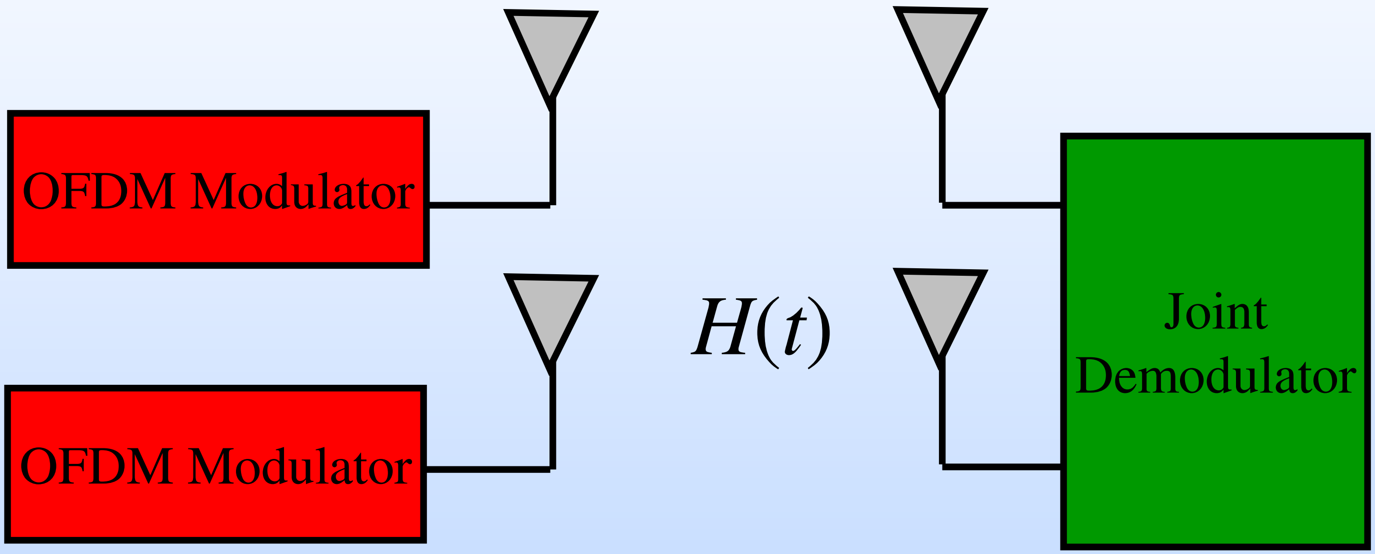
- **Wireless channels suffer from multipath fading**
- **Antenna diversity is a means of compensating for fading**
- **Example *Transmit Delay Diversity***



- **Equivalent channel is $h(t) = h_1(t) + h_2(t - D)$**
- **More channel taps = more diversity**
  - **Choose *D* large enough**

OFDM and MIMO Systems

- **Multiple-input multiple-output (MIMO) systems**
  - Use multiple transmit and multiple receive antennas
  - Creates a *matrix* channel



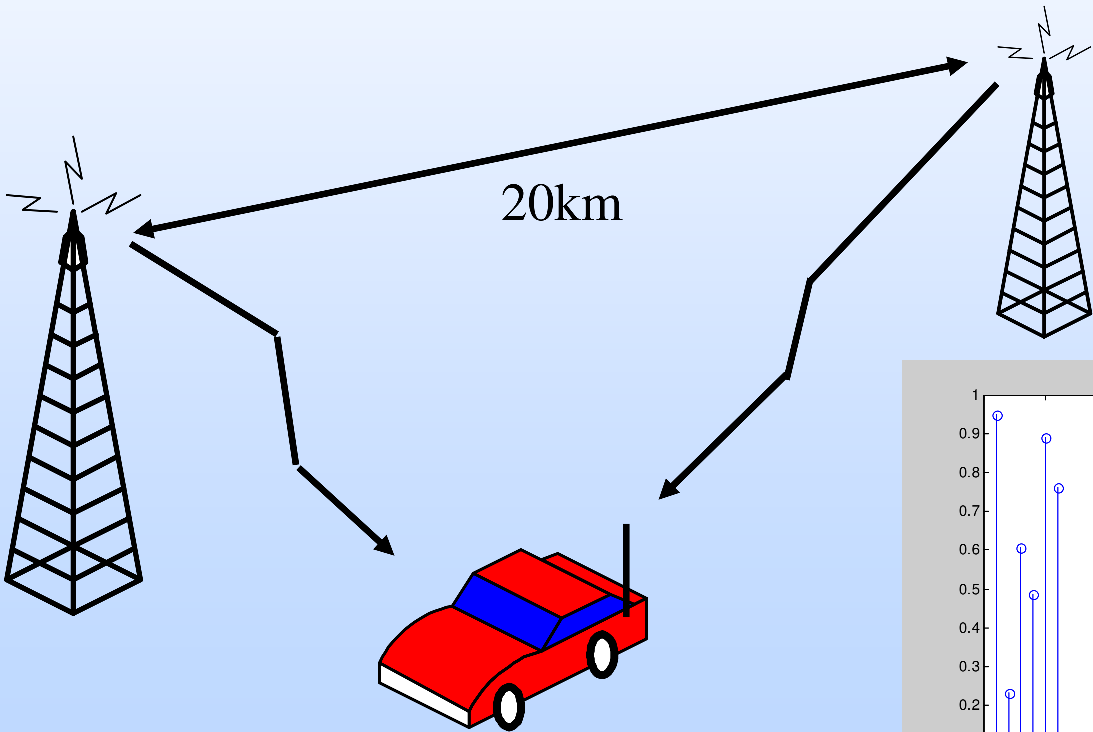
- **Equivalent system for k^{th} tone**

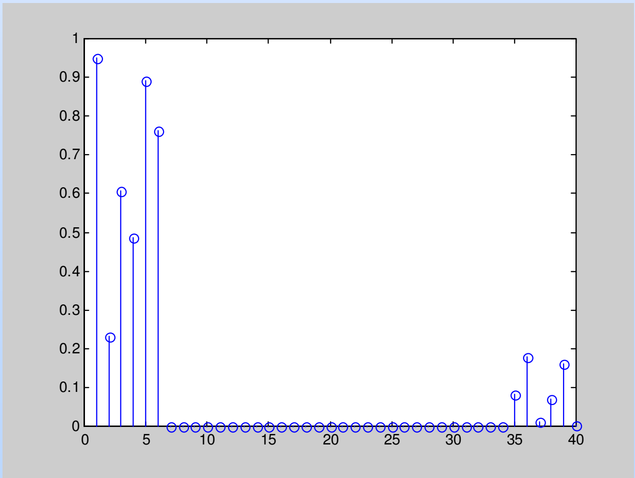
$$\mathbf{x}_k = \mathbf{H}_k \, \mathbf{s}_k + \mathbf{v}_k$$

- **Vector inputs & outputs!**
- **See Wireless Sys. Innovations Lab Web page for more info**

Why OFDM in Broadcast?

- **Enables Single Frequency Network (SFN)**
  - Multiple transmit antennas geographically separated
  - Enables same radio/TV channel frequency throughout a country
  - Creates artificially large delay spread – OFDM has no problems!



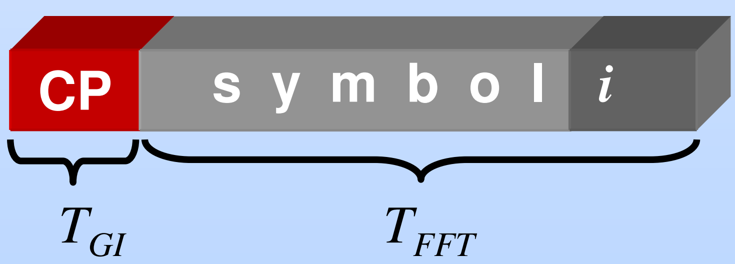


Why OFDM for High-Speed Internet Access?

- **High-speed data transmission**
  - Large bandwidths -> high rate, many computations
  - Small sampling periods -> delay spread becomes a serious impairment
  - Requires *much lower* BER than voice systems
- **OFDM pros**
  - Takes advantage of multipath through simple equalization
- **OFDM cons**
  - Synchronization requirements are much more strict
    - Requires more complex algorithms for time / frequency synch
  - Peak-to-average ratio
    - Approximately 10 log N (in dB)
    - Large signal peaks require higher power amplifiers
    - Amplifier cost grows nonlinearly with required power

Case Study: IEEE 802.11a Wireless LAN

- **System parameters**
  - FFT size: 64
  - Number of tones used 52 (12 zero tones)
  - Number of pilots 4 (data tones = 52-4 = 48 tones)
  - Bandwidth: 20MHz
  - Subcarrier spacing : Δ_f = 20 MHz / 64 = 312.5 kHz
  - OFDM symbol duration: $T_{FFT} = 1/\Delta_f$ = 3.2us
  - Cyclic prefix duration: T_{GI} = 0.8us
  - Signal duration: $T_{signal} = T_{FFT} + T_{GI}$



Case Study: IEEE 802.11a WLAN

- Modulation: BPSK, QPSK, 16-QAM, 64-QAM
- Coding rate: 1 / 2, 2 / 3, 3 / 4
- FEC: *K*=7 (64 states) convolutional code

Frequency Band (GHz)	Maximum Output Power (6dBi antenna gain) mW
5.15 – 5.25	40
5.25 – 5.35	200
5.725-5.825	800