ECE 598HH: Advanced Wireless Networks and Sensing Systems

Lecture 3: Part 1: Review Wireless Channel

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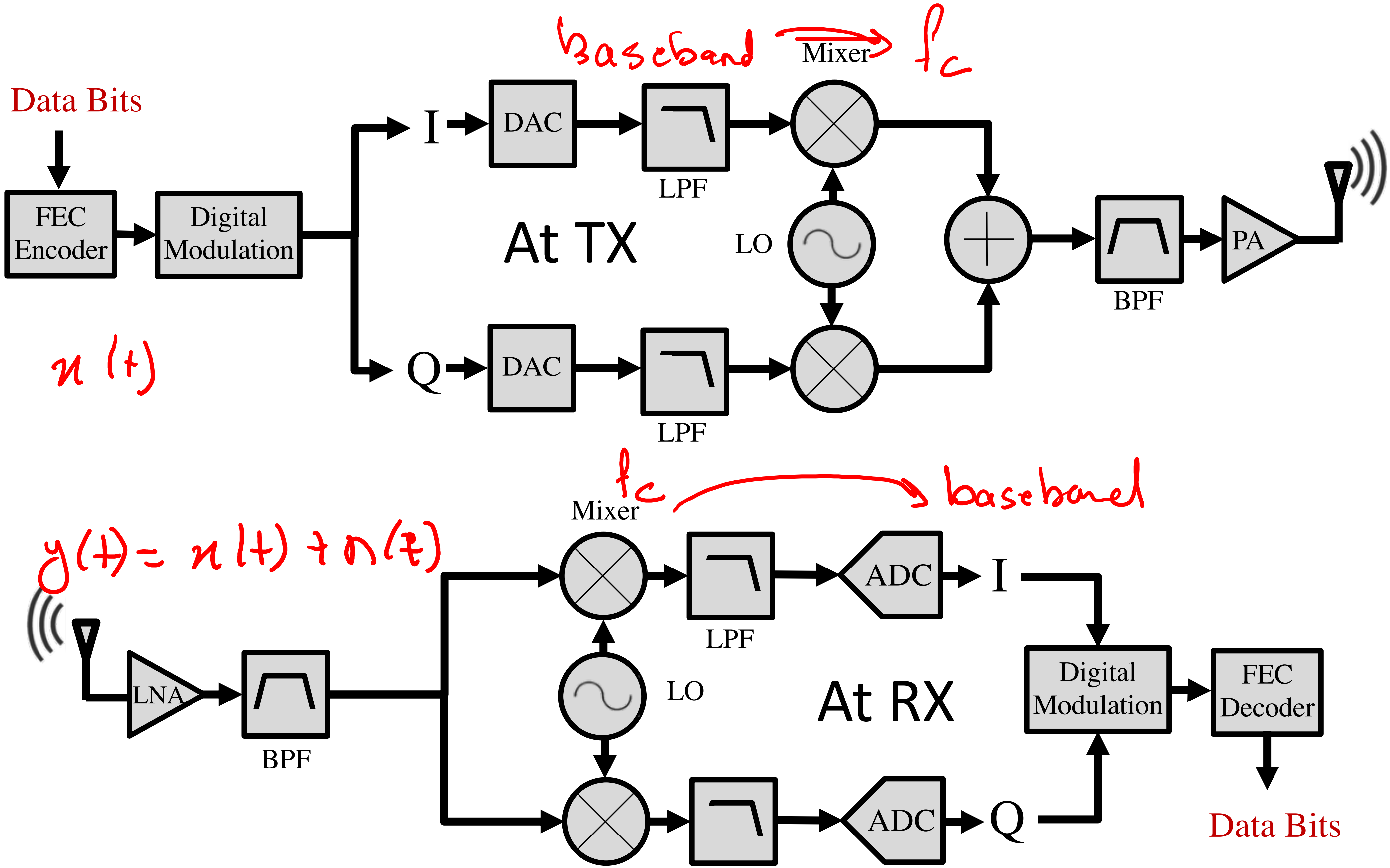
Transmitters & Receivers



Wireless Data Rates

- *Data Rate*
  - *Bandwidth: Samples/sec*
  - *Modulation: Bits/~~sec~~* sample
  - *Coding Rate: Data Bits/Coded Bits*

BER you need
SNR you have

$$Data\ Rate = Bandwidth \times Bits/sample \times Code\ Rate$$

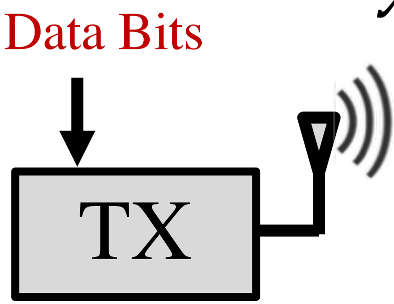
- *Capacity*
  - *Maximum Achievable Data Rate*
  - *Shannon Capacity Theorem:*

$$Capacity = Bandwidth \times \log_2(1 + SNR)$$

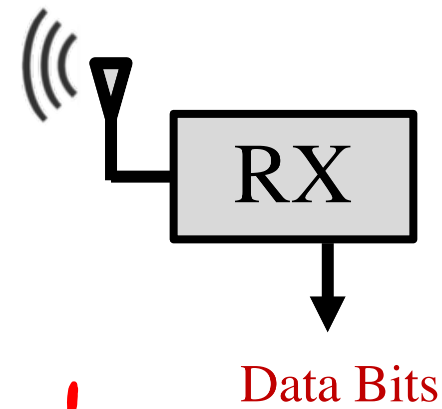
Wireless Channel

wireless channel

$$x(t) \qquad\qquad y(t) = h\,x(t) + n(t)$$



$$h \propto \frac{\lambda}{d} e^{j2\pi d/\lambda}$$



wavelength $= \frac{c}{f_c}$ ↑

Antenna Gain

$\alpha > 2$

① Attenuate

$$P_{Rx} = \frac{G_{Tx}\, G_{Rx}\, \lambda^2}{(4\pi d)^2} P_{Tx}$$

transmit power.

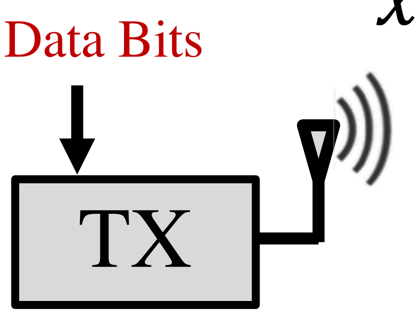
→ distance between TX & RX

$$Path\ Loss\ (dB) = 10\log_{10} P_{Tx}/P_{Rx}$$

$$SNR = \frac{|h|^2 \times |x(t)|^2}{|n(t)|^2} = \frac{|h|^2 P_{Tx}}{N}$$

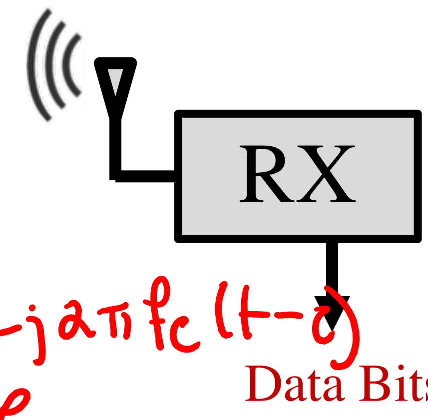
Wireless Channel

$x(t)$



$$h \propto \frac{\lambda}{d}\, e^{j2\pi d/\lambda}$$

$y(t) = h\,x(t) + n(t)$



$x(t)\, e^{j2\pi f_c t} \longrightarrow x(t-\tau)\, e^{-j2\pi f_c (t-\tau)}$

$e^{+j2\pi f_c \tau}\, x(t)\, \underbrace{e^{-j2\pi f_c t} \times e^{j2\pi f_c t}}_{\text{down conversion}}$

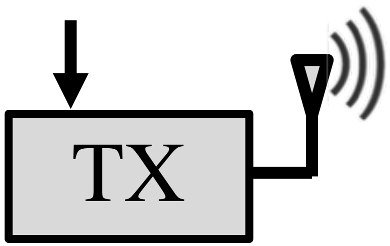
$\tau = \frac{d}{c}$; $f_c = \frac{c}{\lambda}$

$= \underbrace{e^{+j2\pi \frac{d}{\lambda}}}_{\text{channel phase}}\, x(t)$

Channel Estimation & Correction

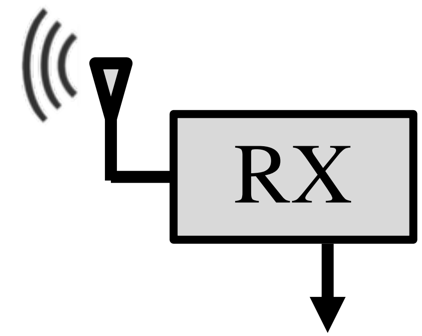
Data Bits

$x(t)$

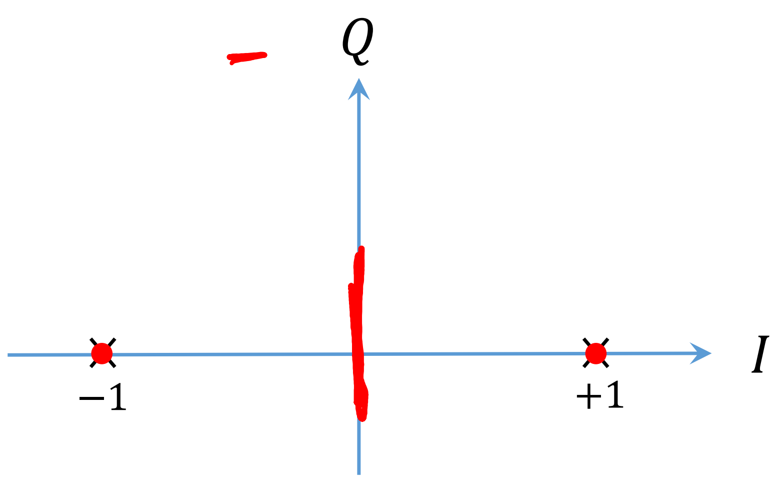


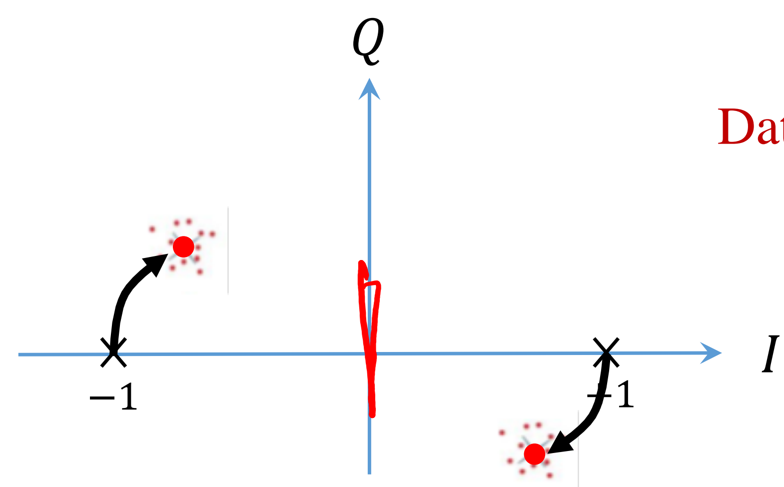
$$h \propto \frac{\lambda}{d}\, e^{j2\pi d/\lambda} \quad \text{mod } 2\pi$$

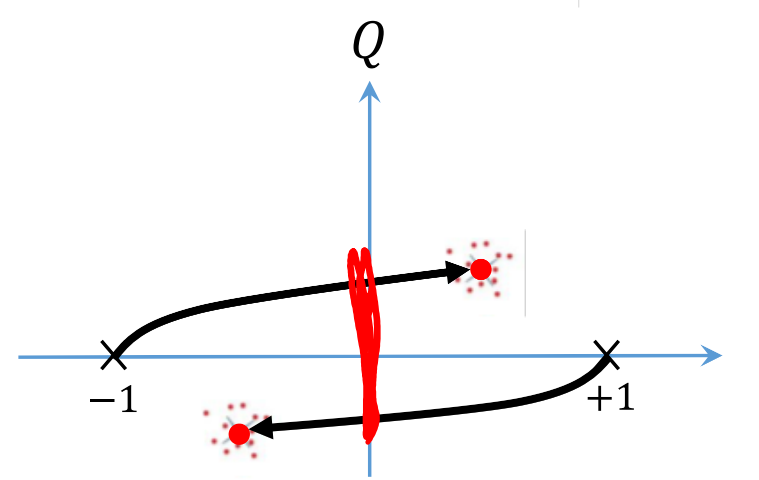
$y(t) = h\, x(t) + n(t)$



Data Bits







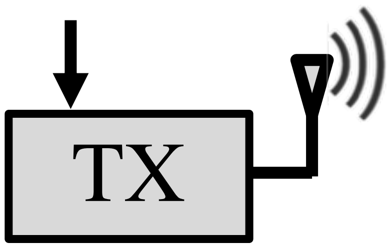
How to estimate and correct for channel?

Send Preamble Bits

Channel Estimation & Correction

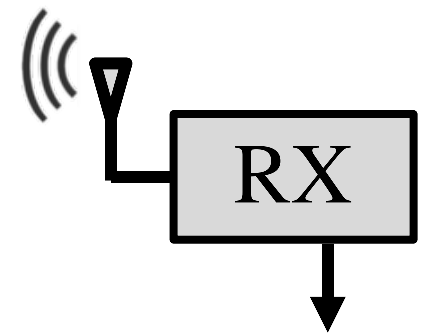
$x(t)$

Data Bits



$$h \propto \frac{\lambda}{d}\, e^{j2\pi d/\lambda}$$

$$y(t) = h\,x(t) + n(t)$$



Data Bits

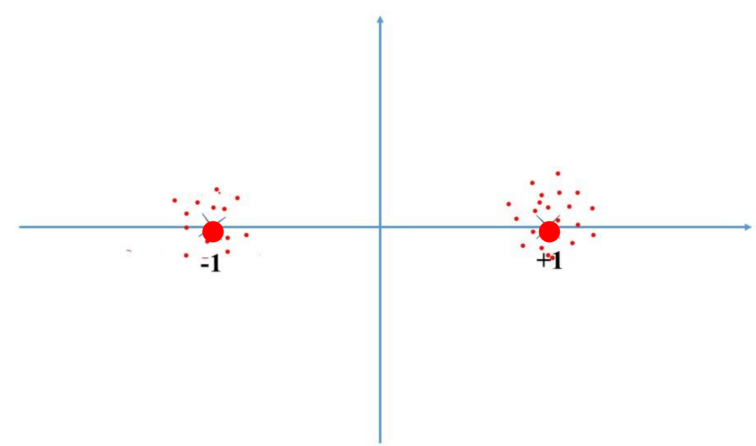
Preamble Bits: Known bits

$x(0) = 1 \longrightarrow y(0) = h + n(0)$

$x(1) = 1 \longrightarrow y(1) = h + n(1)$

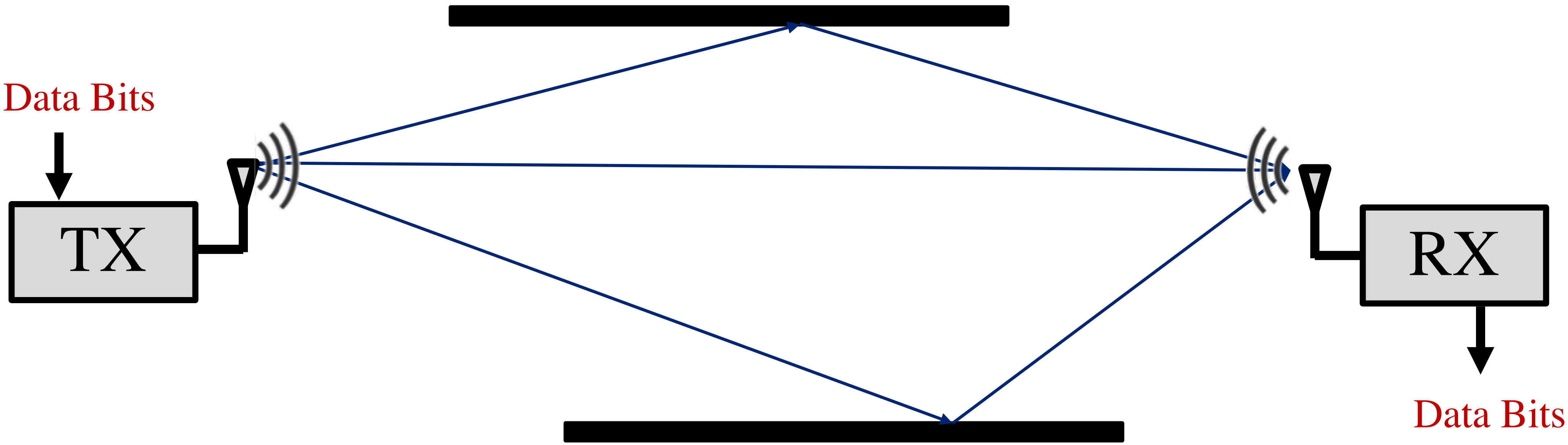
$x(2) = -1 \longrightarrow y(2) = -h + n(2)$

Estimate channel: $\tilde{h} = \sum_k \frac{y(k)}{x(k)}$



Correct channel: $\tilde{x}(t) = \frac{y(t)}{\tilde{h}}$

Multipath Wireless Channel

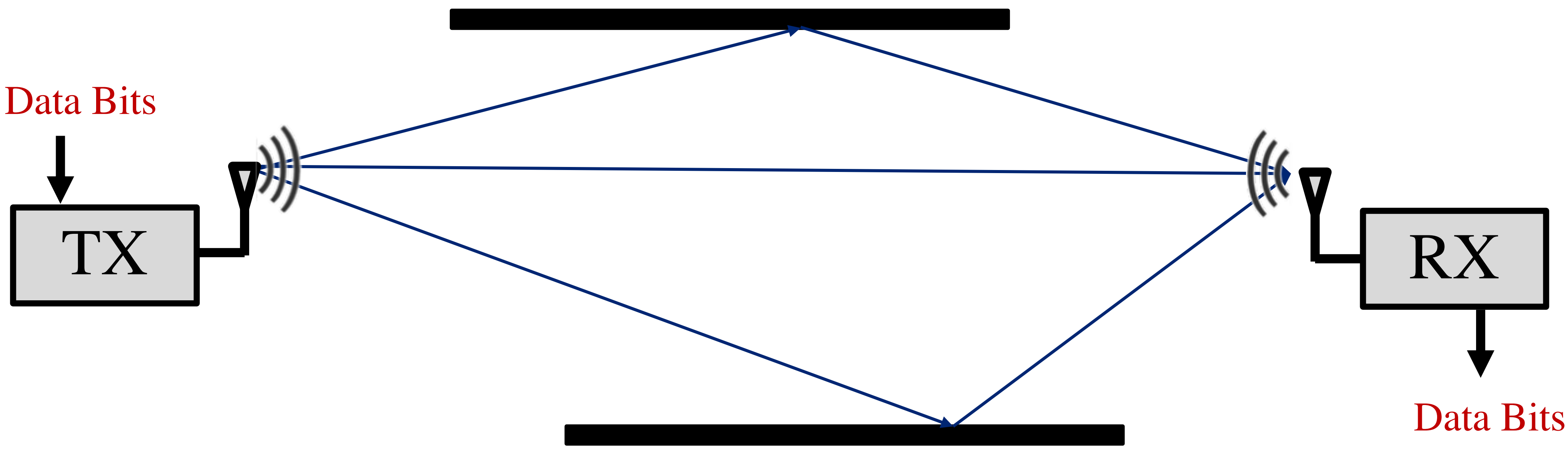


Multipath Propagation: radio signal reflects off objects ground, arriving at destination at slightly different times

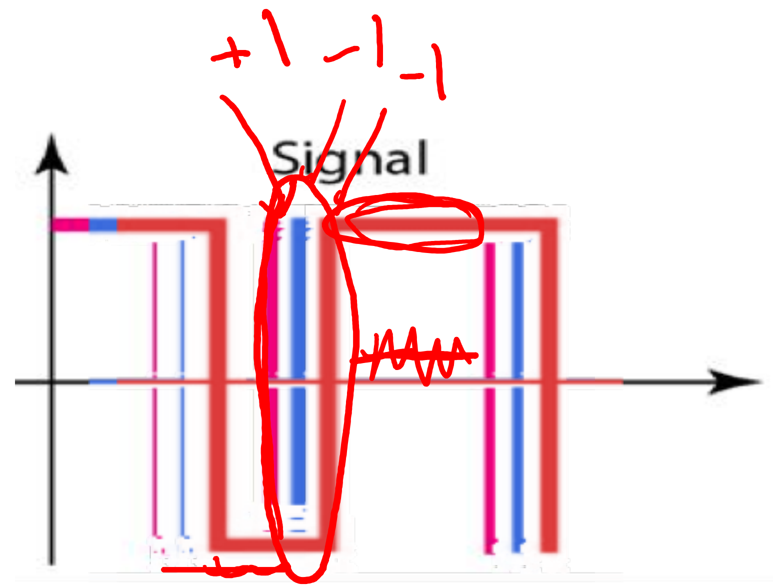
$$y(t) = h_1\, x(t-\tau_1) + h_2\, x(t-\tau_2) + h_3\, x(t-\tau_3)$$

$$y(t) = \sum_k h_k x(t-\tau_k) = h(t) * x(t)$$

Multipath Wireless Channel



- Inter-Symbol-Interference:
  Symbols arriving late interfere with following symbols.



- Channel Fading:
  Paths can sum up destructively or constructively

Multipath Wireless Channel

Example 2 paths with distance $d_1 = 1m, d_2 = 1.06m$:

$$h = h_1 + h_2 = \frac{\lambda}{d_1}\, e^{j2\pi d_1/\lambda} + \frac{\lambda}{d_2}\, e^{j2\pi d_2/\lambda}$$

$$h = \frac{\lambda}{d_1}\, e^{j2\pi d_1/\lambda}\left(1 + \overbrace{\frac{d_1}{d_2}}^{\approx 1}\, e^{j2\pi \overbrace{(d_2-d_1)/\lambda}^{=\pi}}\right)$$

$$\frac{d_1}{d_2} \approx 1 \qquad\qquad \frac{d_2 - d_1}{\lambda} \approx \frac{1}{2} \rightarrow h = 0$$

Multipath Wireless Channel

Example 2 paths with distance $d_1 = 1m, d_2 = 1.06m$:

$$h = h_1 + h_2 = \frac{\lambda}{d_1}\, e^{j2\pi d_1/\lambda} + \frac{\lambda}{d_2}\, e^{j2\pi d_2/\lambda}$$

$@f_1 = 2.5GHz\ (\lambda = 12\ cm)$:

$$h = 0.12\, e^{j\frac{2\pi}{3}} + 0.113\, e^{j\frac{5\pi}{3}} \approx \underline{0.006}$$

$17\times$

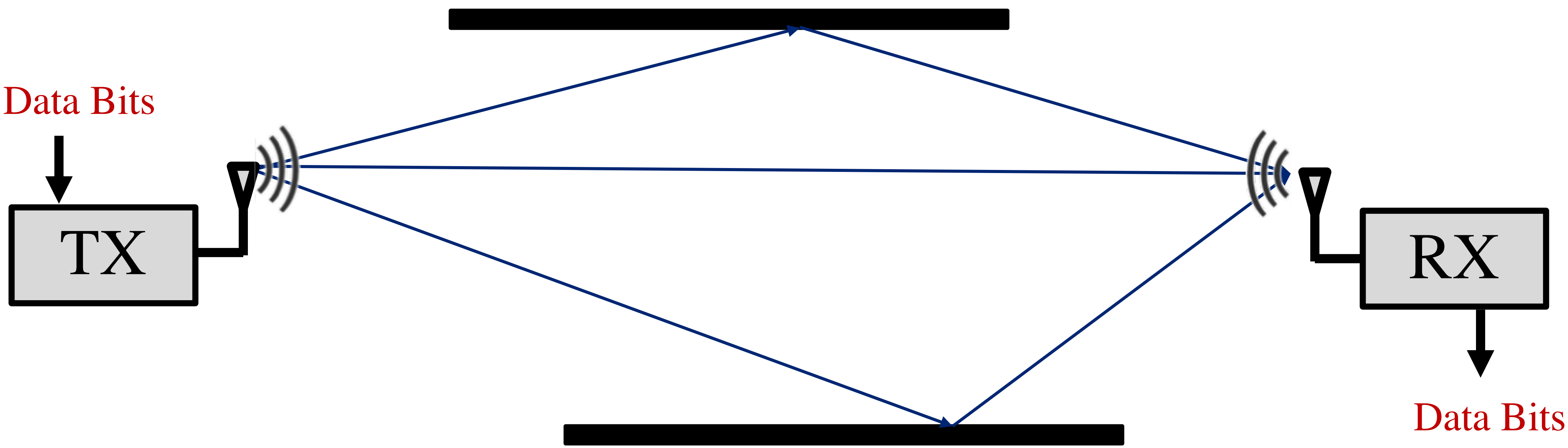
→ 24dB

$@f_2 = 5GHz\ (\lambda = 6\ cm)$:

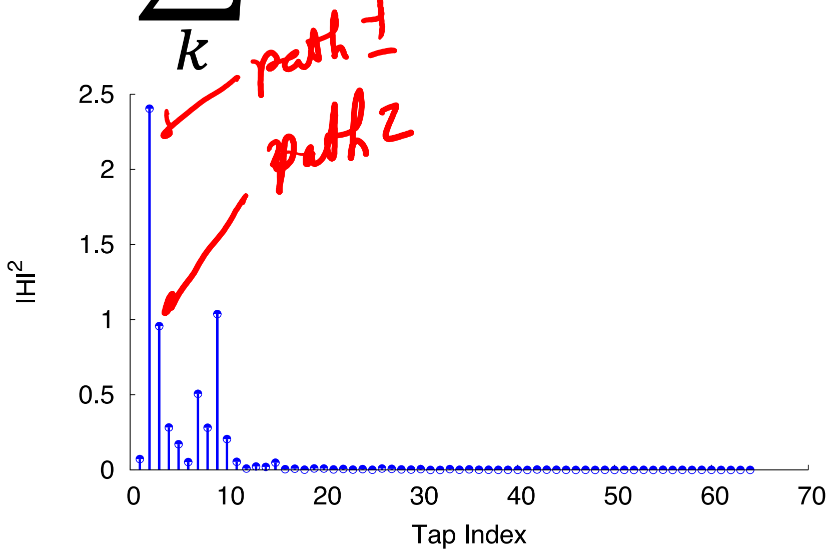
$$h = 0.06\, e^{j\frac{5\pi}{3}} + 0.05\ \ e^{j\frac{5\pi}{3}} \approx 0.116$$

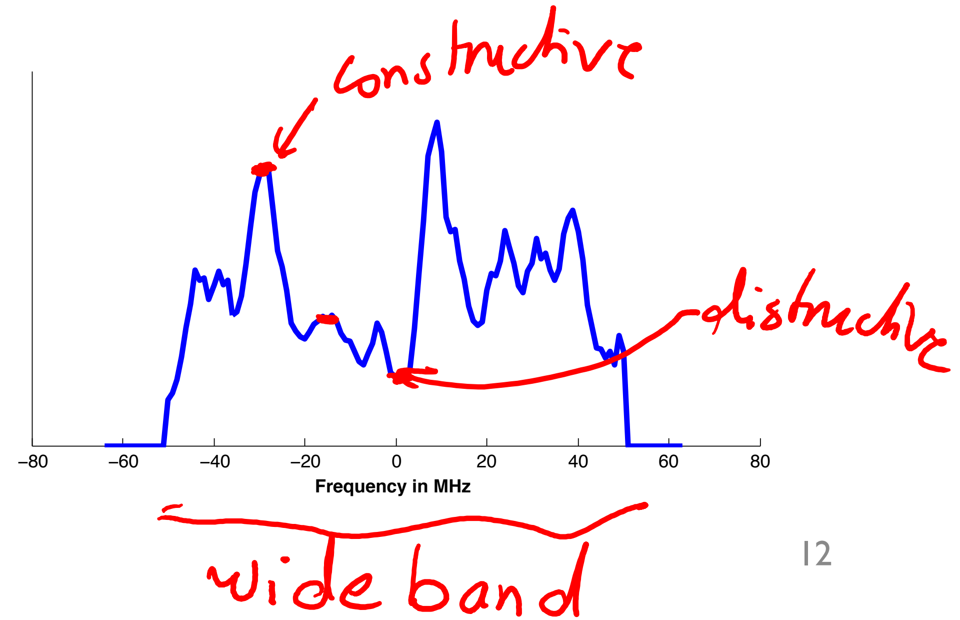
Frequency Selective Fading

Multipath Wireless Channel



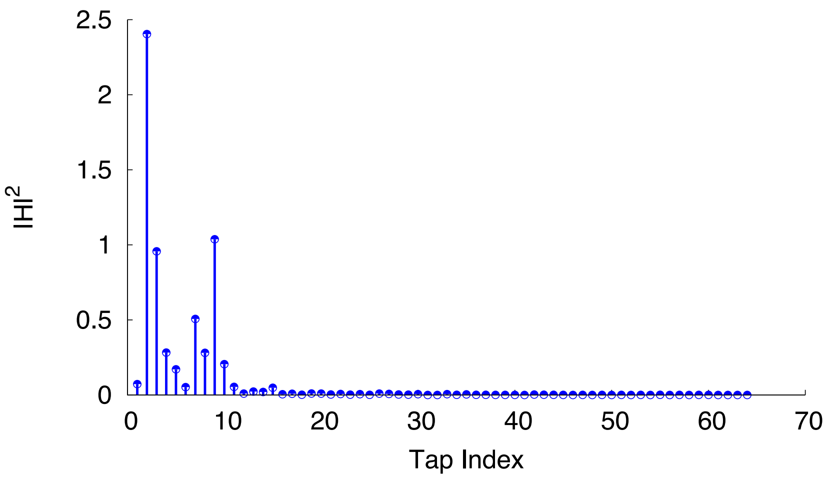
$$y(t) = \sum_k h_k x(t - \tau_k) = h(t) * x(t) \Leftrightarrow H(f)X(f)$$

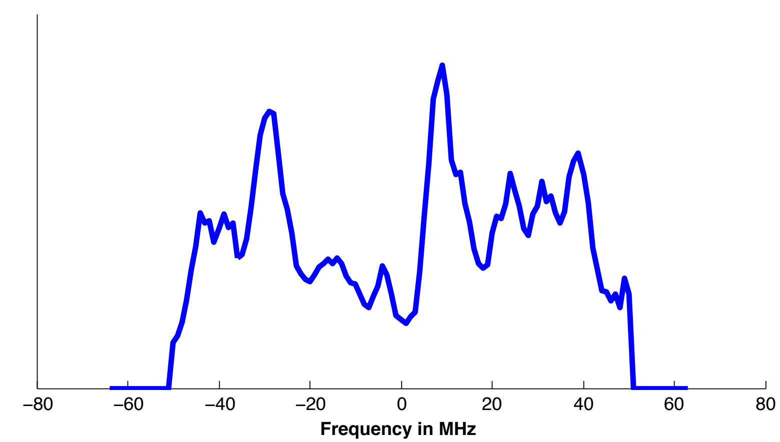




Wide Band vs Narrow Band Channel

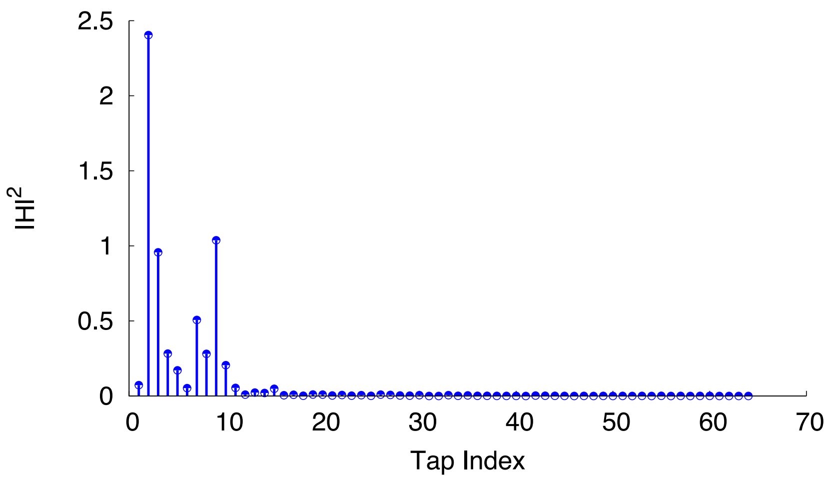
$$y(t) = \sum_k h_k x(t - \tau_k) = h(t) * x(t) \Leftrightarrow H(f)X(f)$$

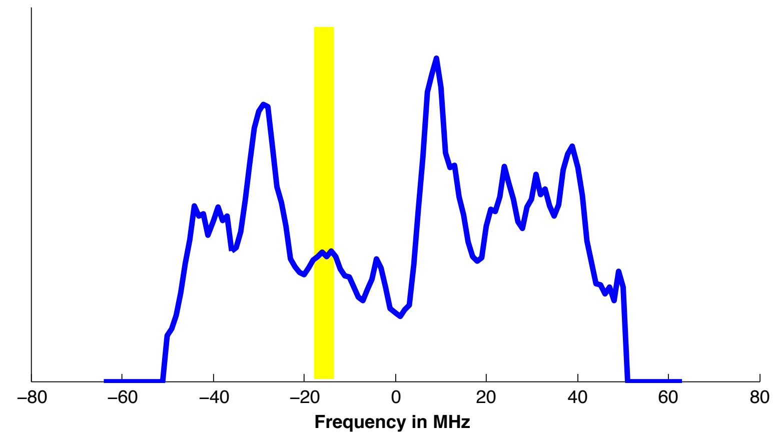




Wide Band vs Narrow Band Channel

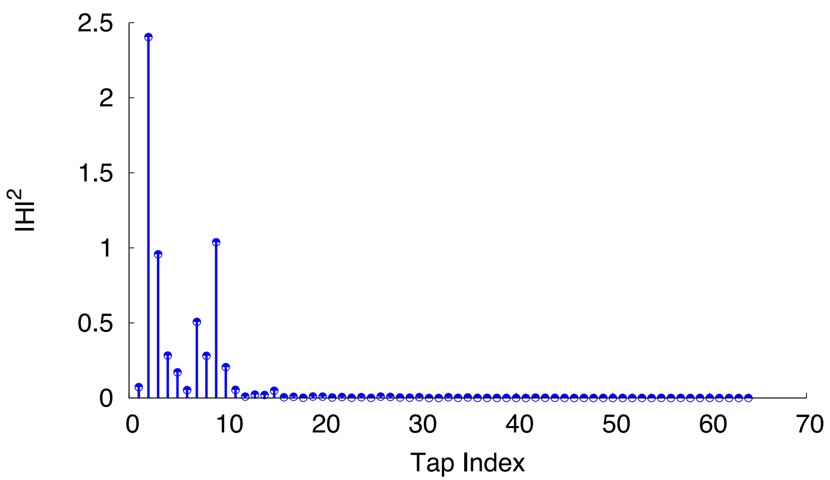
$$y(t) = \sum_k h_k x(t - \tau_k) = h(t) * x(t) \Leftrightarrow H(f)X(f)$$

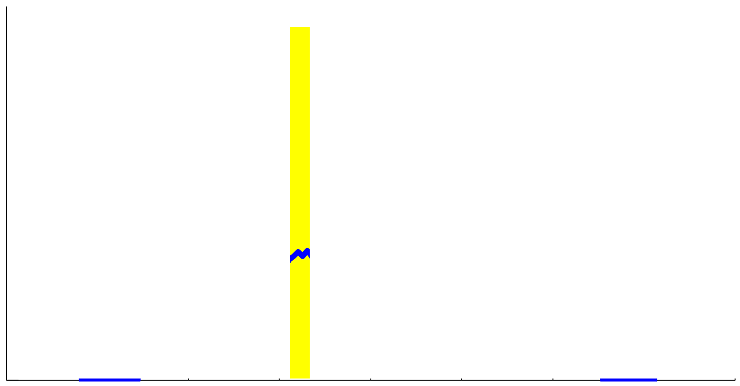




Wide Band vs Narrow Band Channel

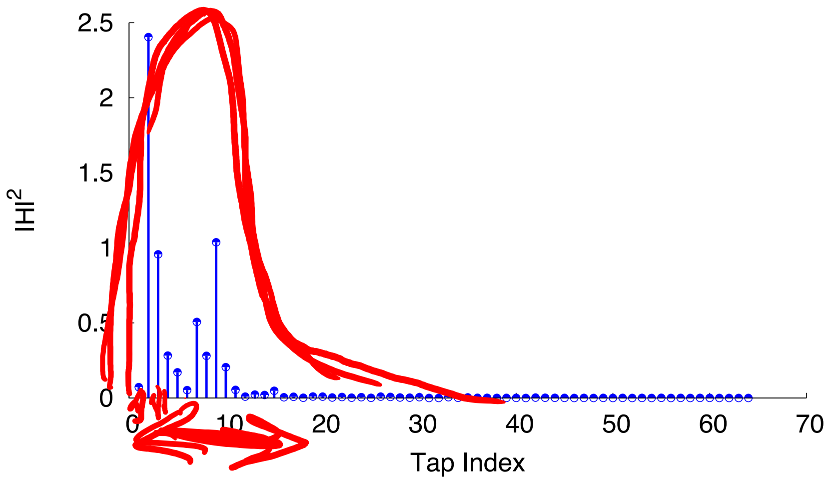
$$y(t) = \sum_k h_k x(t - \tau_k) = h(t) * x(t) \Leftrightarrow H(f)X(f)$$

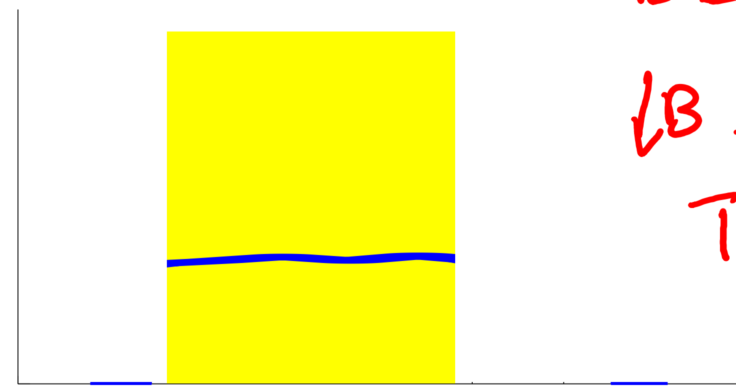




Wide Band vs Narrow Band Channel

$$y(t) = \overbrace{\sum_k h_k}^{=h} x(t - \tau_k) = h(t) * x(t) \Leftrightarrow H(f)X(f)$$





$B = \frac{1}{T}$

$\downarrow B \Rightarrow T \uparrow$

$T > \tau_k$

$$h = h_1 + h_2 = \frac{\lambda}{d_1} e^{j2\pi d_1/\lambda} + \frac{\lambda}{d_2} e^{j2\pi d_2/\lambda}$$

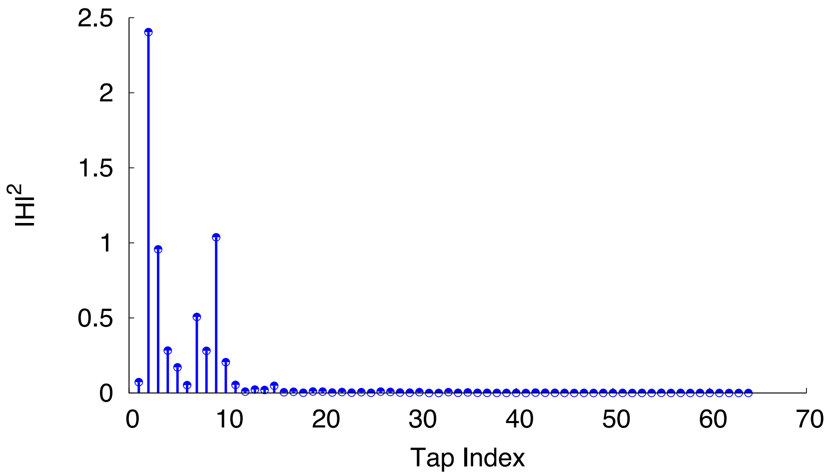
Narrow band channel:

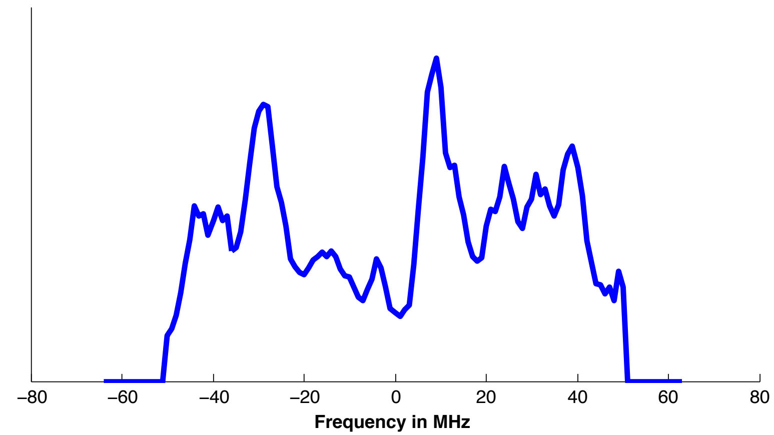
$= \sum h_k$

- same $\lambda = c/f_c$ for all $f \rightarrow h = constant$
- $\Rightarrow$ $y(t) = \boxed{h}\, x(t) \Leftrightarrow h\, X(f)$
- Flat channel

Wide Band vs Narrow Band Channel

$$y(t) = \sum_k h_k x(t - \tau_k) = h(t) * x(t) \Leftrightarrow H(f)X(f)$$





$$H(f) = h_1 + h_2 = \frac{\lambda}{d_1} e^{j2\pi d_1/\lambda} + \frac{\lambda}{d_2} e^{j2\pi d_2/\lambda}$$

Wide band channel:

- h is varies with f → Multi-tap channel
- $y(t) = h(t) * x(t) \Leftrightarrow H(f)X(f)$

Wide Band vs Narrow Band Channel

Narrow band channel:

- Flat channel
- $y(t) = h\,x(t)$

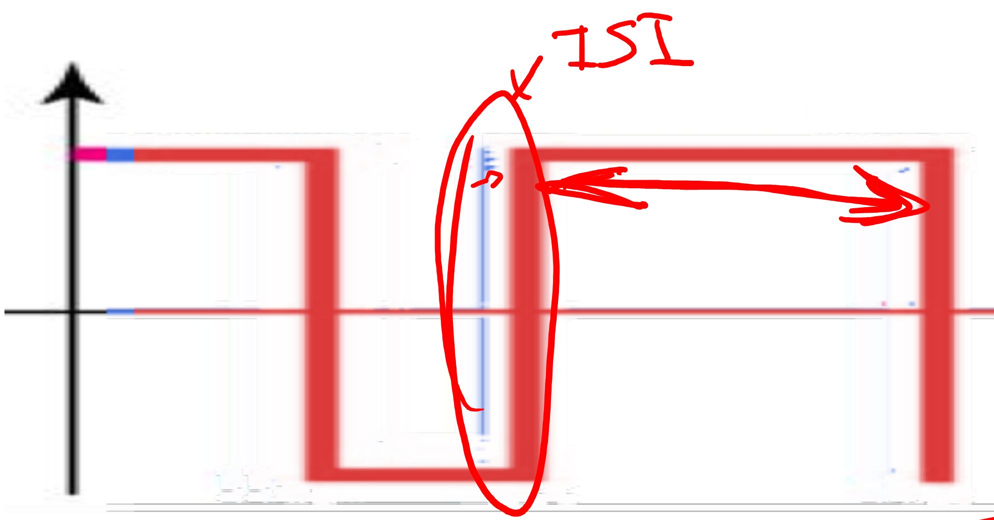
  $\Leftrightarrow h\,X(f)$

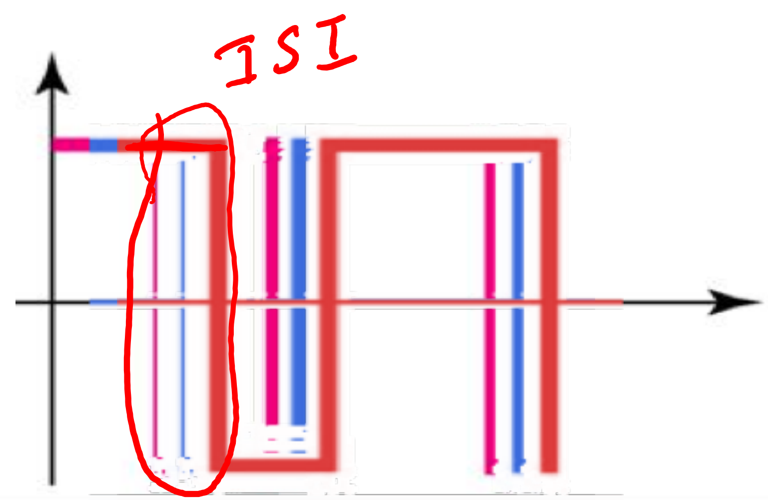
Wide band channel:

- Multi-tap channel
- $y(t) = h(t) * x(t)$

  $\Leftrightarrow \underline{H(f)X(f)}$

$B \Rightarrow \frac{1}{B}$ every symbol





- Solution:

OFDM: Orthogonal Frequency Division Multiplexing

- Idea: transmit symbols in frequency not time.

NEXT LECTURE