Small-Scale Fading

PROF. MICHAEL TSAI

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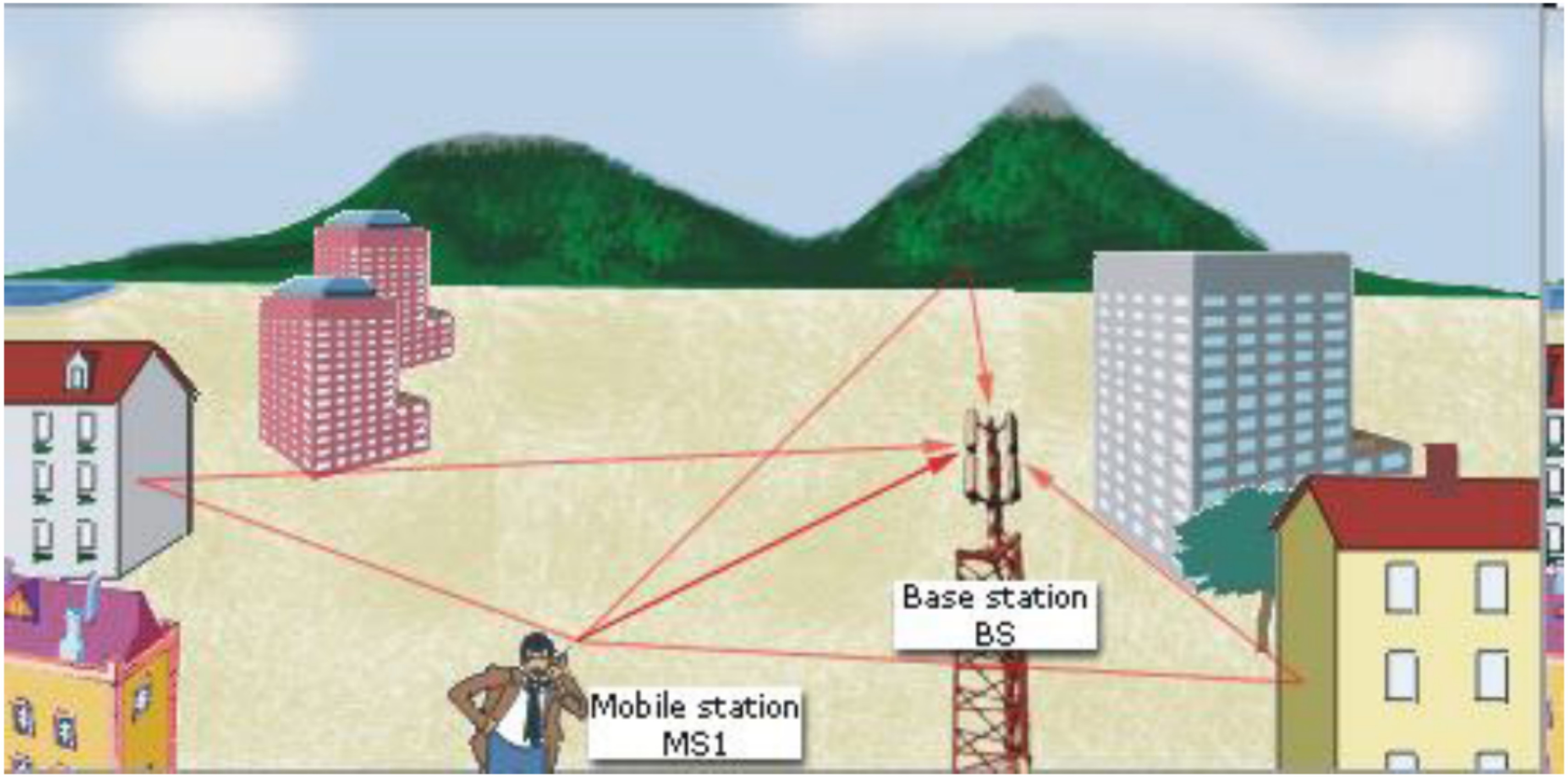
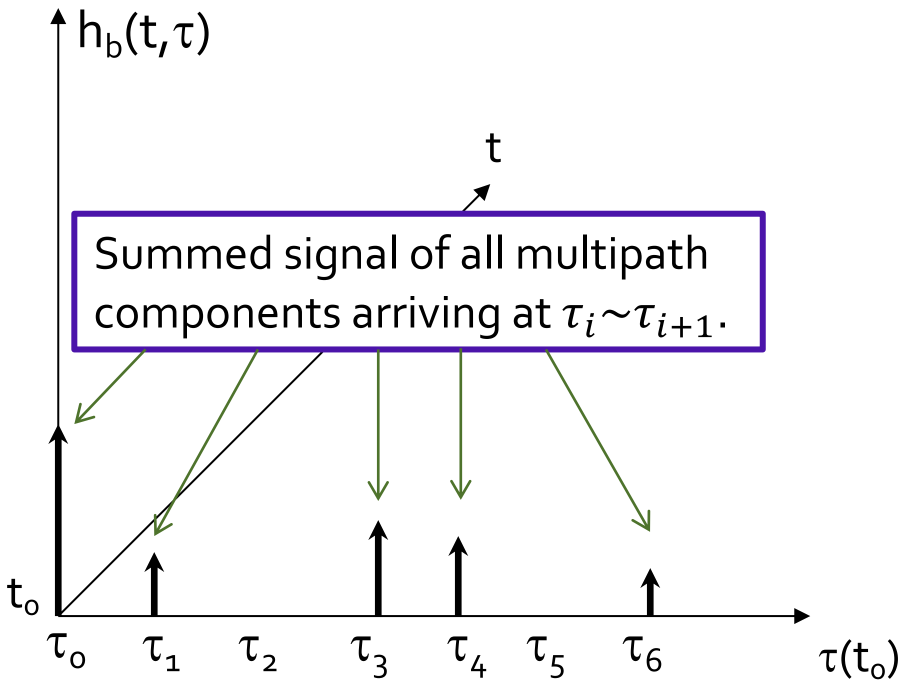
Multipath Propagation



RX just sums up all Multi Path Component (MPC).

Multipath Channel Impulse Response

An example of the time-varying discrete-time impulse response for a multipath radio channel



Excess delay: the delay with respect to the first arriving signal (τ)

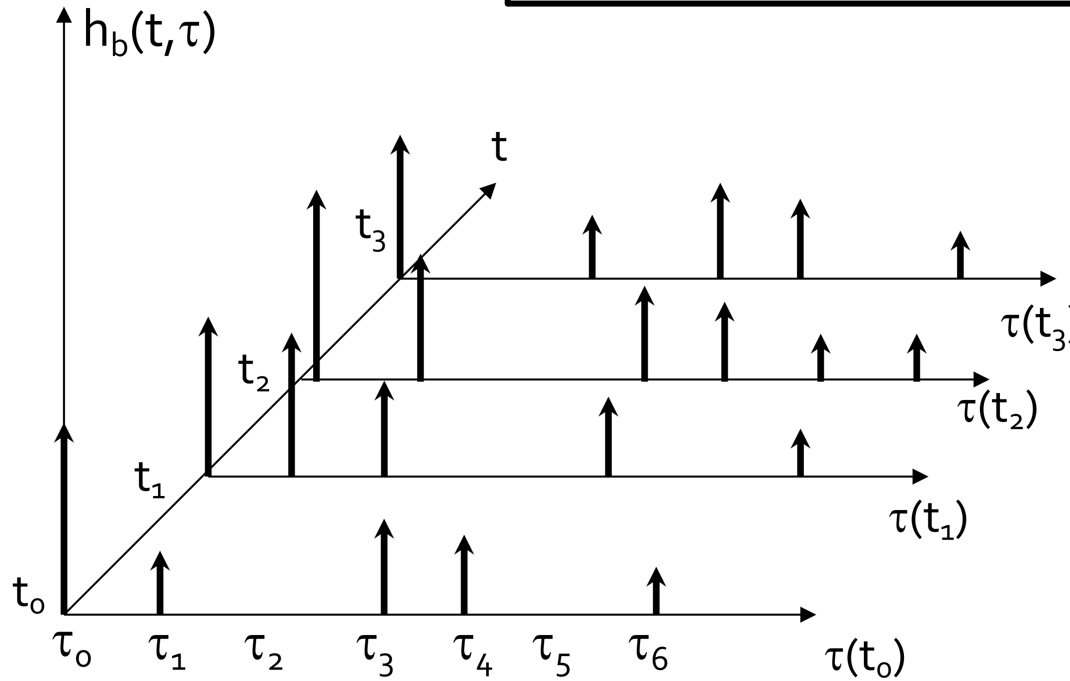
Maximum excess delay: the delay of latest arriving signal

The channel impulse response when $t = t_0$ (what you receive at the receiver when you send an impulse at time t_0)

$\tau_0 = 0$, and represents the time the first signal arrives at the receiver.

Time-Variant Multipath Channel Impulse Response

Because the transmitter, the receiver, or the reflectors are moving, the impulse response is time-variant.



Multipath Channel Impulse Response

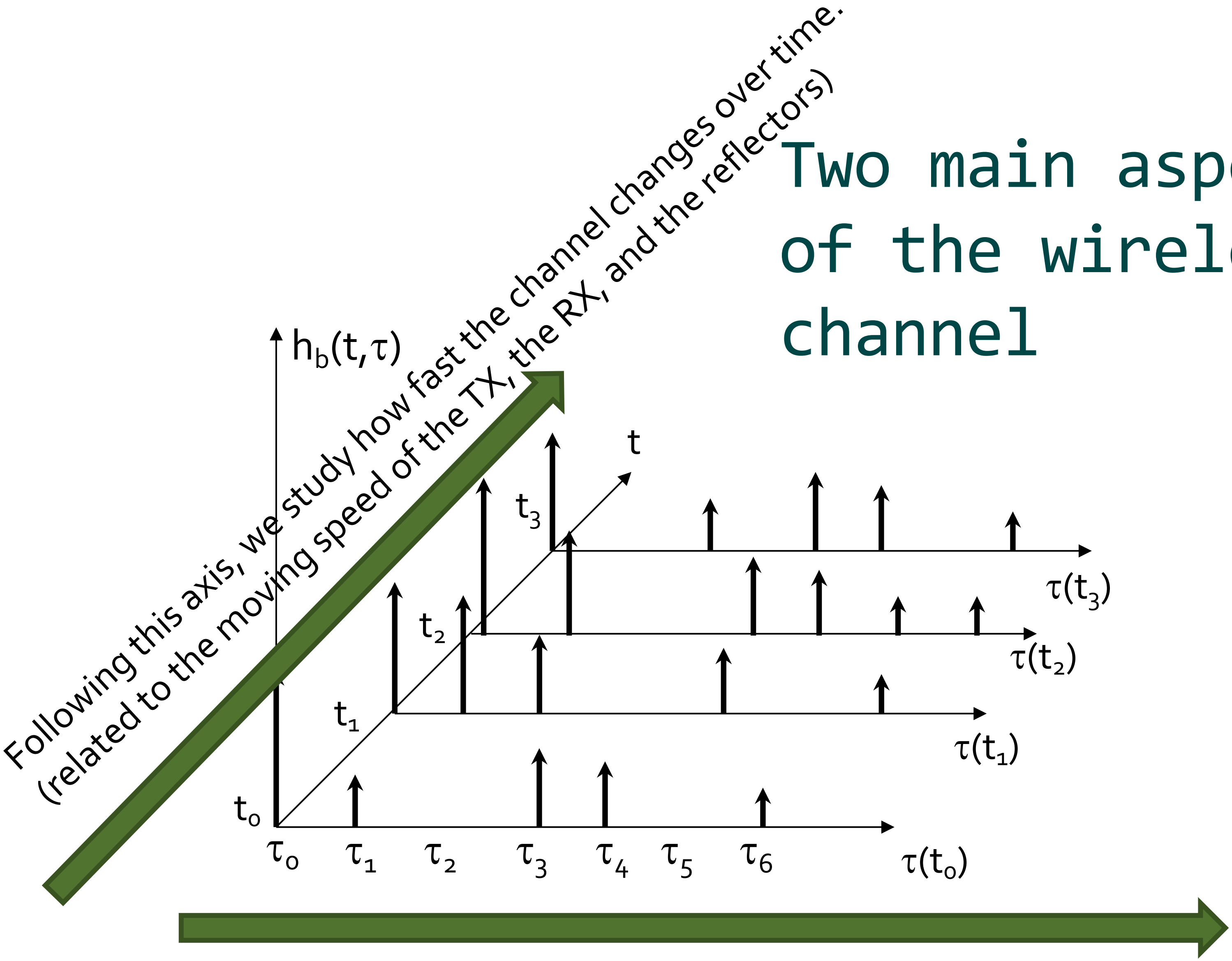
- **The channels impulse response is given by:**

$$h_b(t,\tau) = \overbrace{\sum_{i=0}^{N-1}}^{\text{Summation over all MPC}} \underbrace{a_i(t,\tau)}_{\text{Amplitude change (mainly path loss)}} \exp\left[-j\left\{\underbrace{2\pi f_c \tau(t_i)}_{\text{Phase change due to different arriving time}} + \overbrace{\phi_i(t,\tau)}^{\text{Additional phase change due to reflections}}\right\}\right]\delta\left(t-\tau_i(t)\right)$$

- **If assumed time-invariant (over a small-scale time or distance):**

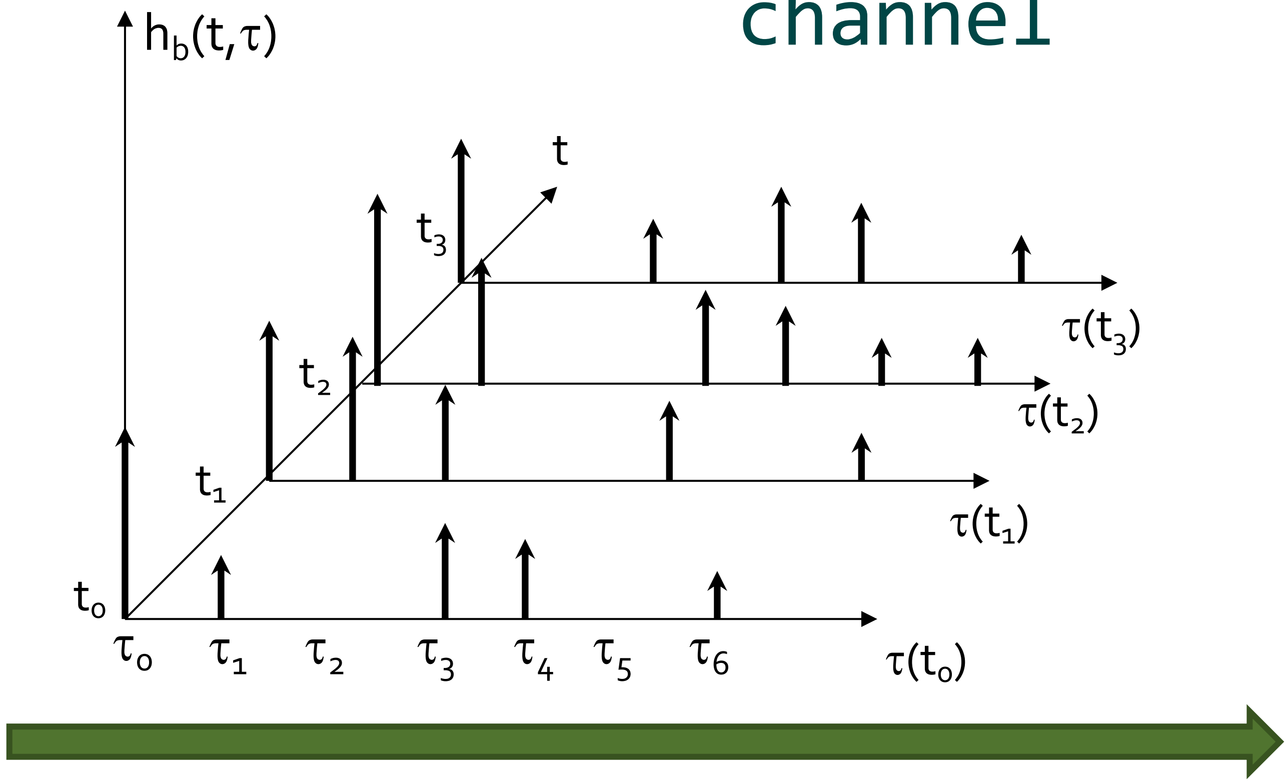
$$h_b(\tau) = \sum_{i=0}^{N-1} a_i \exp\left[-j\theta_i\right]\delta\left(\tau-\tau_i\right)$$

Two main aspects of the wireless channel



Following this axis, we study how "spread-out" the impulse response are. (related to the physical layout of the TX, the RX, and the reflectors at a single time point)

Two main aspects of the wireless channel



Following this axis, we study how “spread-out” the impulse response are.
(related to the physical layout of the TX, the RX, and the reflectors at a single time point)

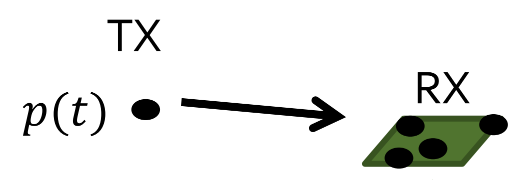
Power delay profile

- **To predict $h_b(\tau)$ a probing pulse p(t) is sent s.t.**

$$p(t) \approx \delta(t - \tau)$$

- **Therefore, for small-scale channel modeling, POWER DELAY PROFILE is found by computing the spatial average of $|h_B(t;\tau)|^2$ over a local area.**

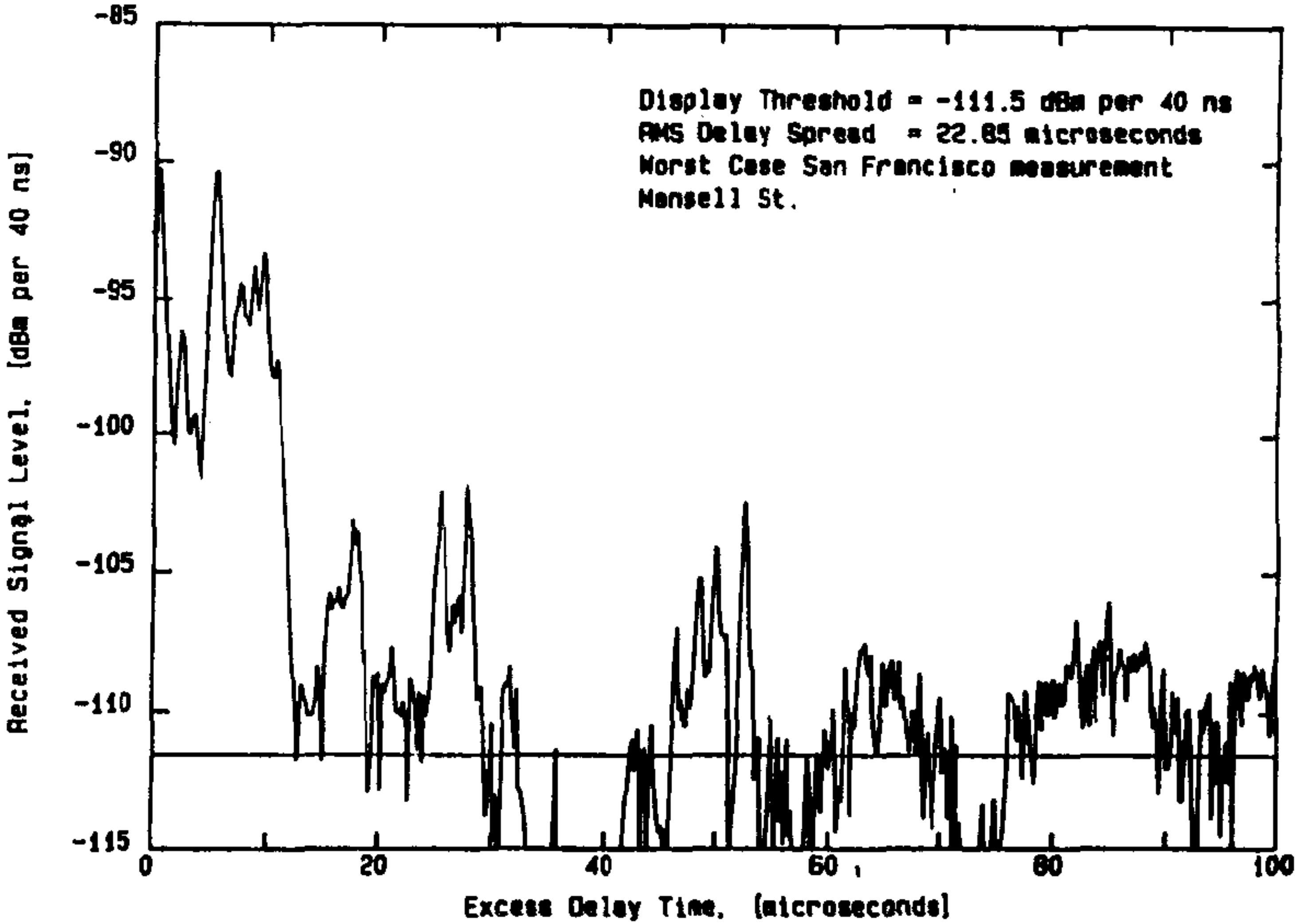
$$P(t;\tau) \approx k|h_b(t;\tau)|^2$$



Average over
several measurements
in a local area

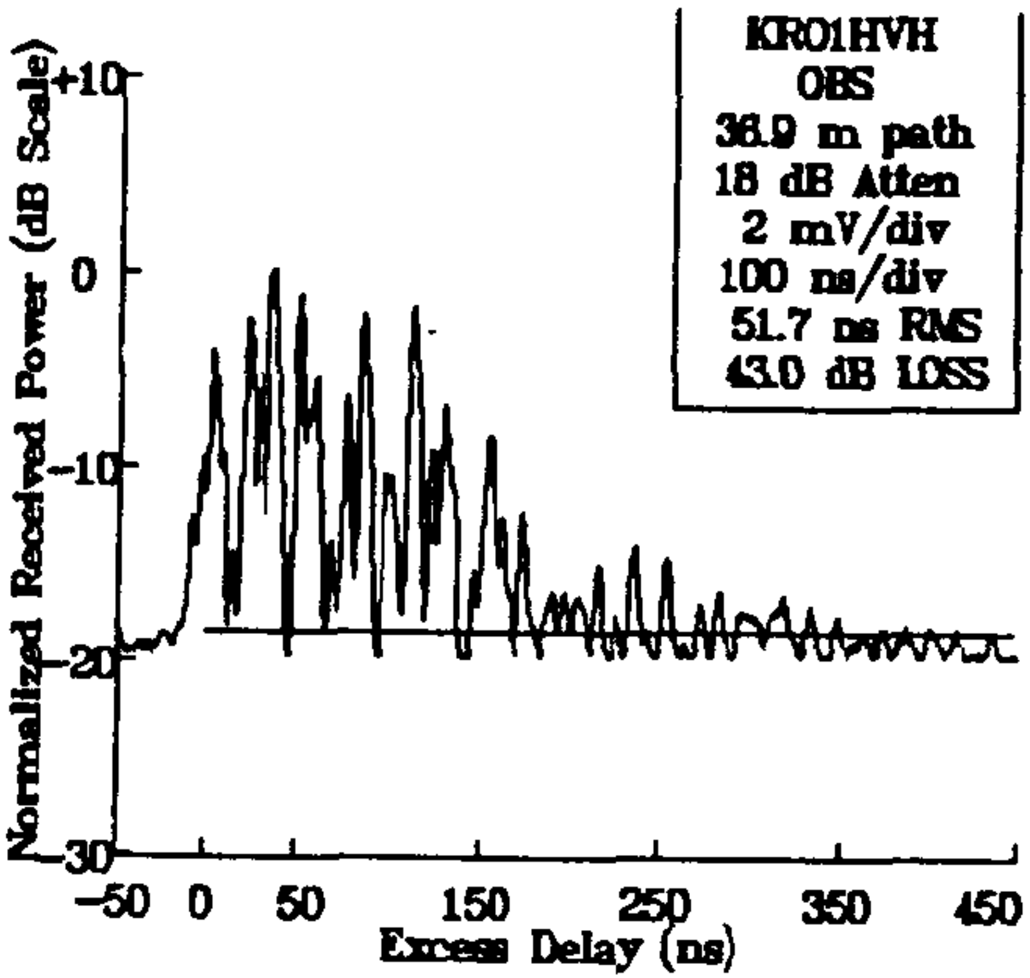
Example: power delay profile

From a 900 MHz cellular system in San Francisco



Example: power delay profile

Inside a grocery store at 4 GHz



Time dispersion parameters

- **Power delay profile is a good representation of the average "geometry" of the transmitter, the receiver, and the reflectors.**
- **To quantify "how spread-out" the arriving signals are, we use time dispersion parameters:**

Already talked about this

  - Maximum excess delay: the excess delay of the latest arriving MPC
  - Mean excess delay: the "mean" excess delay of all arriving MPC
  - RMS delay spread: the "standard deviation" of the excess delay of all arriving MPC

Time dispersion parameters

- **Mean Excess Delay**

First moment of the power delay profile

$$\bar{\tau} = \frac{\sum_k a_k^2 \tau_k}{\sum_k a_k^2} = \frac{\sum_k P(\tau_k)\tau_k}{\sum_k P(\tau_k)}$$

- **RMS Delay Spread**

Square root of the second central moment of the power delay profile

$$\sigma_\tau = \sqrt{\overline{\tau^2} - (\bar{\tau})^2}$$

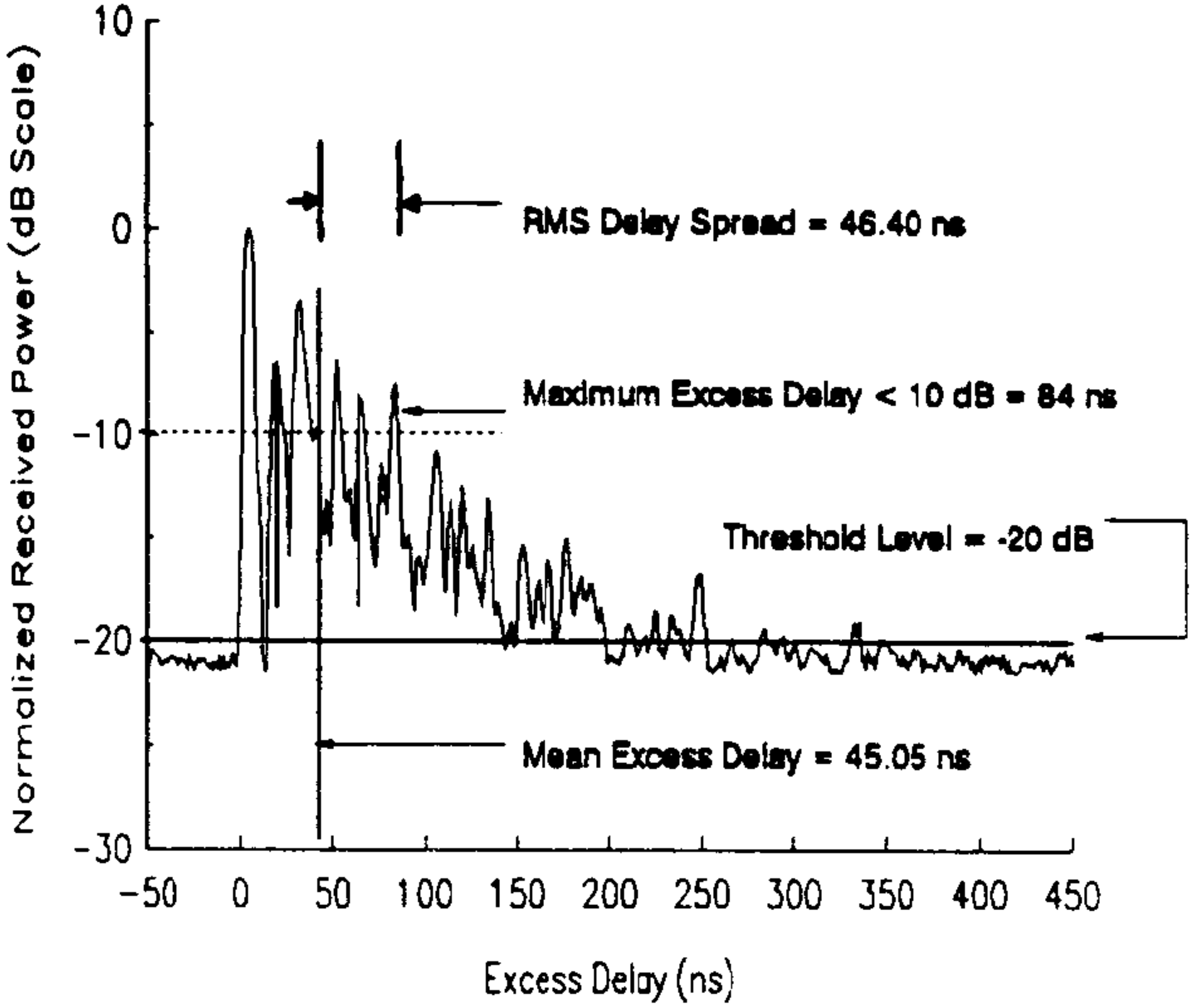
$$\overline{\tau^2} = \frac{\sum_k a_k^2 \tau_k^2}{\sum_k a_k^2} = \frac{\sum_k P(\tau_k)\tau_k^2}{\sum_k P(\tau_k)}$$

Second moment of the power delay profile

Time dispersion parameters

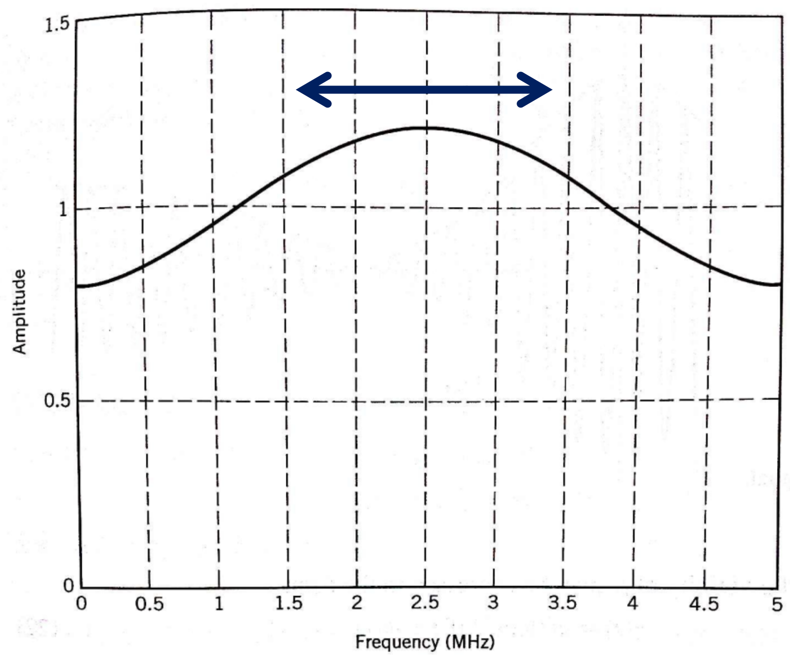
- **Maximum Excess Delay:**
  - Original version: the excess delay of the **latest** arriving MPC
  - In practice: the latest arriving could be smaller than the noise
  - No way to be aware of the “latest”
- **Maximum Excess Delay (practical version):** ?
  - The time delay during which multipath energy falls to X dB below the maximum.
- **This X dB threshold could affect the values of the time-dispersion parameters**
  - Used to differentiate the noise and the MPC
  - Too low: noise is considered to be the MPC
  - Too high: Some MPC is not detected

Example: Time dispersion parameters



Coherence Bandwidth

- **Coherence bandwidth is a statistical measure of the range of frequencies over which the channel can be considered "flat"**
  → a channel passes all spectral components with approximately <u>equal gain and linear phase</u>.



Coherence Bandwidth

- **Bandwidth over which Frequency Correlation function is above 0.9**

$$B_c \approx \frac{1}{50\sigma_\tau}$$

- **Bandwidth over which Frequency Correlation function is above 0.5**

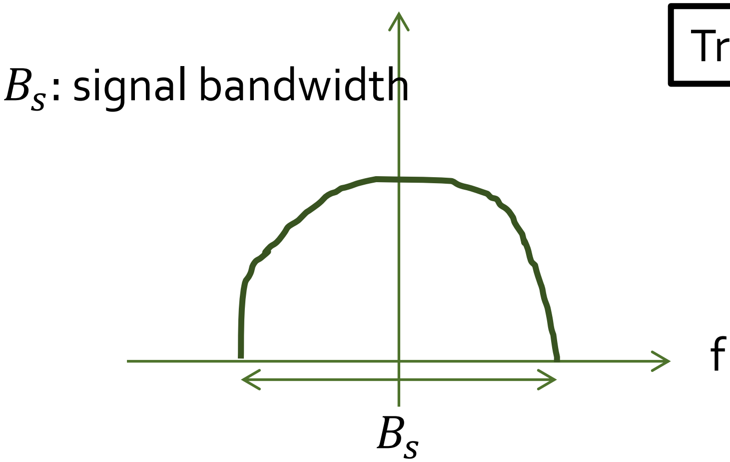
$$B_c \approx \frac{1}{5\sigma_\tau}$$

Those two are approximations derived from empirical results.

Typical RMS delay spread values

Environment	Frequency (MHz)	RMS Delay Spread (σ_τ)	Notes	Reference
Urban	910	1300 ns avg. 600 ns st. dev. 3500 ns max.	New York City	[Cox75]
Urban	892	10-25 μs	Worst case San Francisco	[Rap90]
Suburban	910	200-310 ns	Averaged typical case	[Cox72]
Suburban	910	1960-2110 ns	Averaged extreme case	[Cox72]
Indoor	1500	10-50 ns 25 ns median	Office building	[Sal87]
Indoor	850	270 ns max.	Office building	[Dev90a]
Indoor	1900	70-94 ns avg. 1470 ns max.	Three San Francisco buildings	[Sei92a]

Signal Bandwidth & Coherence Bandwidth



Transmitted Signal

$$T_s \approx \frac{1}{B_s}$$

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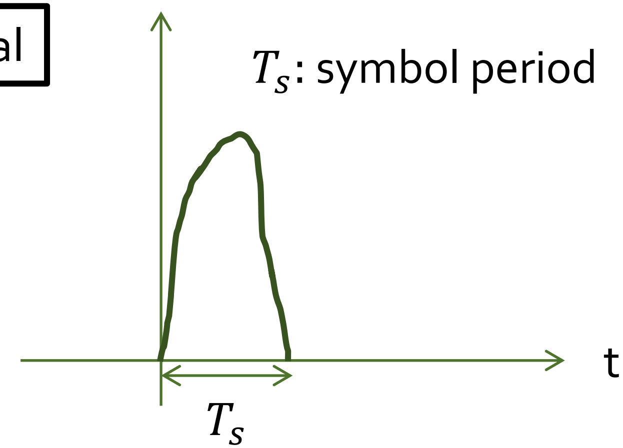
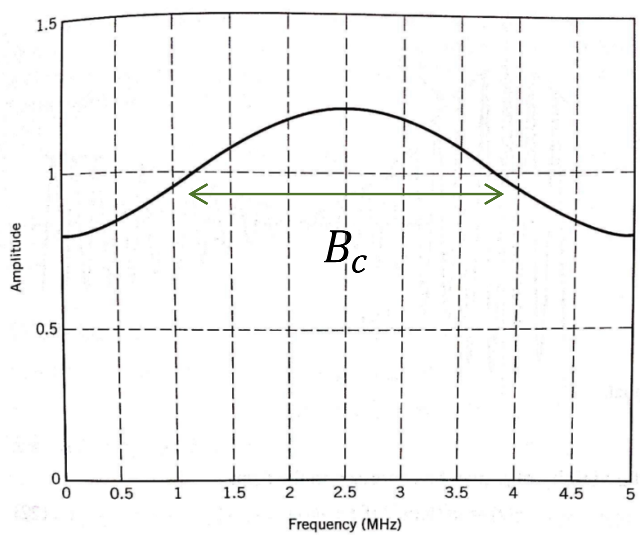
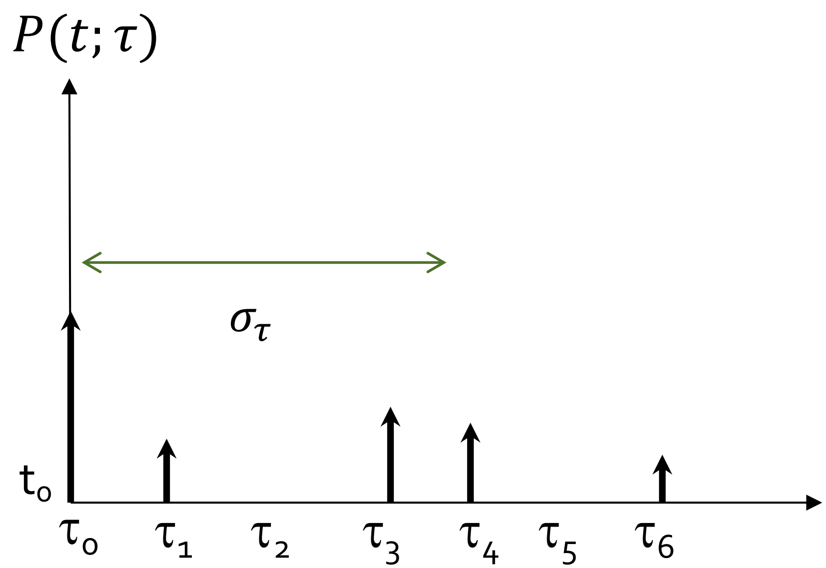
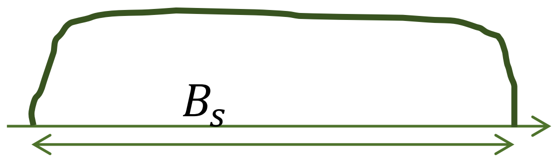




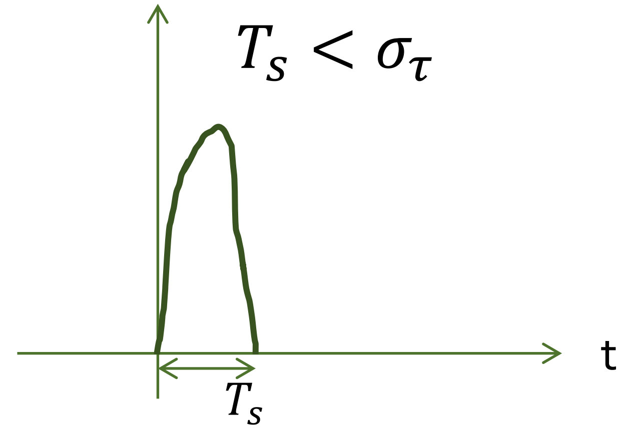


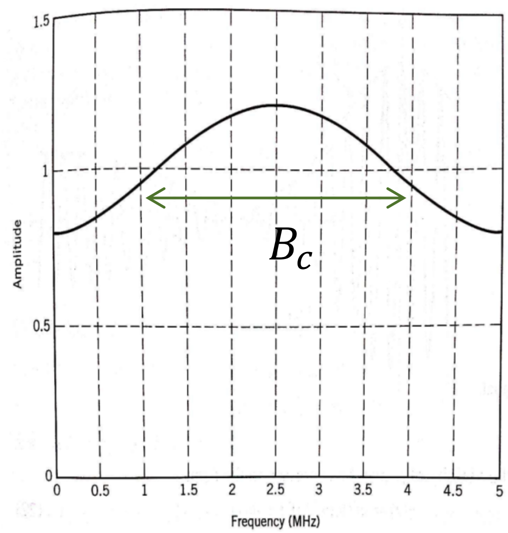
Frequency-selective fading channel

$B_s > B_c$



TX signal





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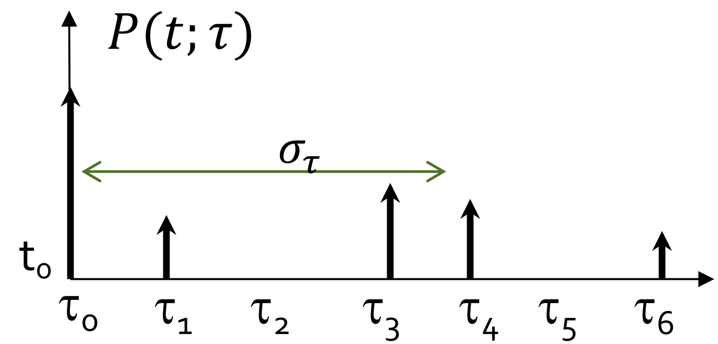
Channel



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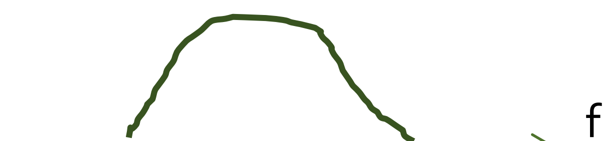
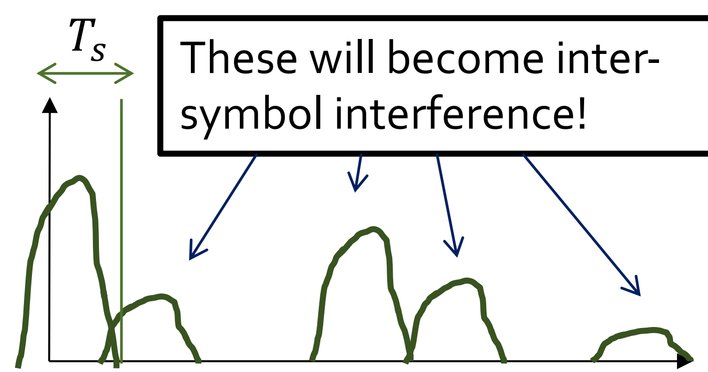
RX signal

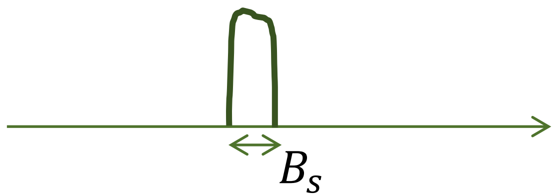




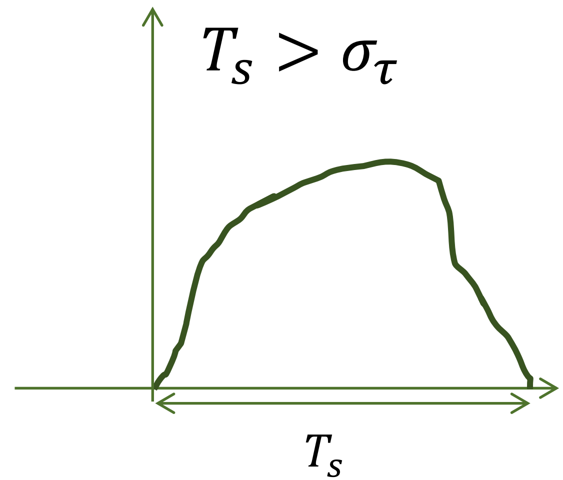
Flat fading channel

$B_s < B_c$

$T_s > \sigma_\tau$



TX signal



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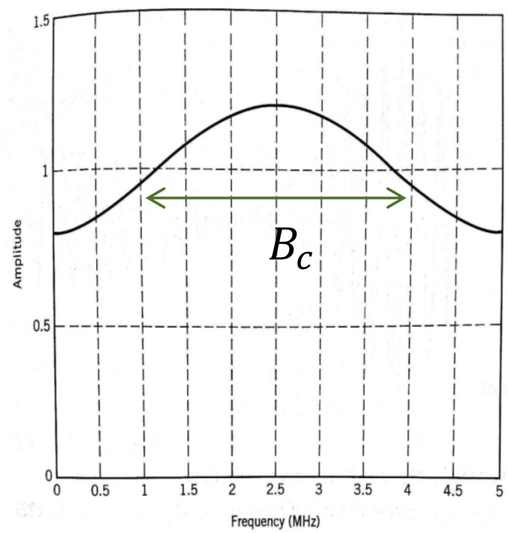
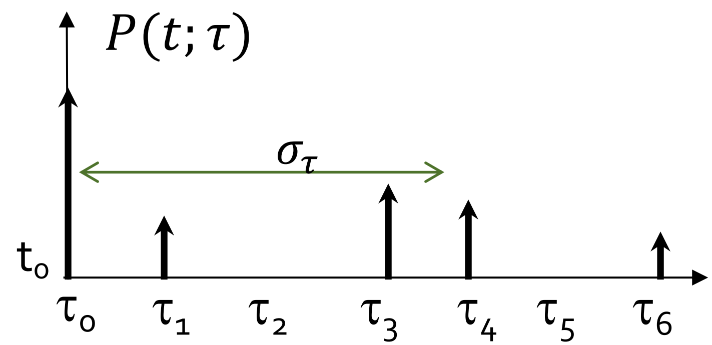


Channel



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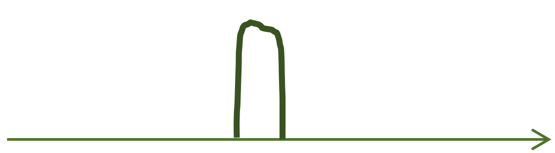
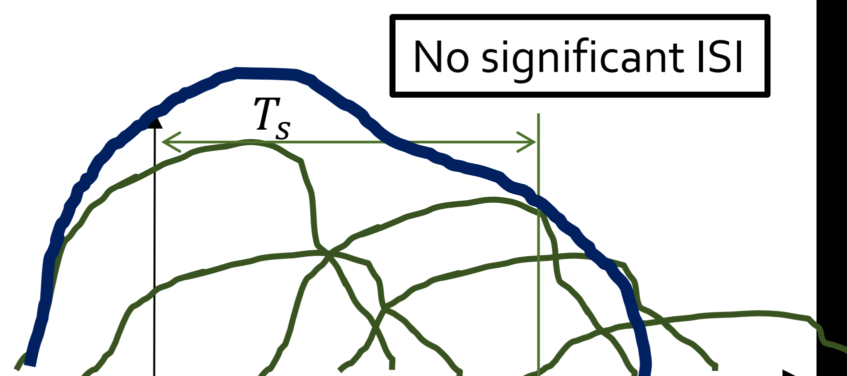


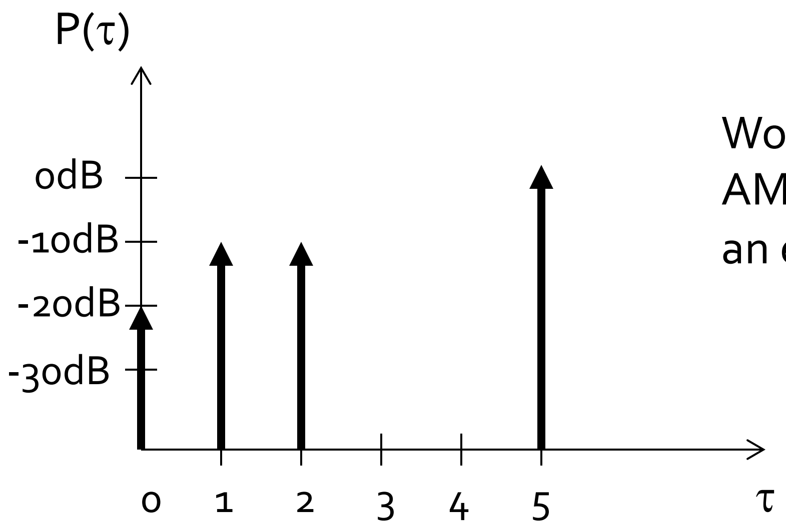
RX signal



Equalizer 101

- **An equalizer is usually used in a frequency-selective fading channel**
  - When the coherence bandwidth is low, but we need to use high data rate (high signal bandwidth)
- **Channel is unknown and time-variant**
  - Step 1: TX sends a known signal to the receiver
  - Step 2: the RX uses the TX signal and RX signal to estimate the channel
  - Step 3: TX sends the real data (unknown to the receiver)
  - Step 4: the RX uses the estimated channel to process the RX signal
  - Step 5: once the channel becomes significantly different from the estimated one, return to step 1.

Example



Would this channel be suitable for AMPS or GSM without the use of an equalizer?

$$\text{Mean Excess Delay} = \bar{\tau} = \frac{\sum_k P(\tau_k)\tau_k}{\sum_k P(\tau_k)} = \frac{5(1)+2(0.1)+1(0.1)+0(0.01)}{1+0.1+0.1+0.01} = 4.38\mu s$$

$$\overline{\tau^2} = \frac{\sum_k P(\tau_k)\tau_k^2}{\sum_k P(\tau_k)} = \frac{(1)5^2+(0.1)2^2+(0.1)1^2+(0.01)0^2}{1+0.1+0.1+0.01} = 21.07\mu s^2$$

Example

- **Therefore:**

$$\text{RMS Delay Spread} = \sigma_\tau = \sqrt{\overline{\tau^2} - (\overline{\tau})^2} = \sqrt{21.07 - (4.38)^2} = 1.37\mu s$$

$$\text{Coherence Bandwidth} = B_C = \frac{1}{5\sigma_\tau} = \frac{1}{5(1.37\mu s)} = 146KHz$$

- **Since B_C > 30KHz, AMPS would work without an equalizer.**
- **GSM requires 200 KHz BW > B_C → An equalizer would be needed.**