UNIT-I
WIRELESS CHANNELS

LARGE SCALE PATH LOSS:

- Paths can vary from simple line-of-sight to ones that are severely obstructed by buildings, mountains, and foliage.

- Radio channels are extremely random and difficult to analyze.
- Two basic goals of propagation modeling:
- Predict magnitude and rate (speed) of received signal strength fluctuations over short distances/time durations
- Predict **average** received signal strength for given Tx/Rx separation
- characterize received signal strength over distances from 20 m to 20 km
- *Large-scale radio wave propagation model* models
- needed to estimate coverage area of base station
- in general, large scale path loss decays *gradually* with distance from the transmitter
- will also be affected by geographical features like hills and buildings

Free-Space Signal Propagation

- Clear, unobstructed line-of-sight path → satellite and fixed microwave
- Friis transmission formula → Rx power (*Pr*) vs. T-R separation (*d*)

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$

where

- *Pt* = Tx power (W) ,*G* = Tx or Rx antenna gain (unitless)
  - relative to isotropic source (ideal antenna which radiates power uniformly in all directions)

***Effective Isotropic Radiated Power* (*EIRP*)**

$$EIRP = P_t G_t$$

Represents the max. radiated power available from a Tx in the direction of max. antenna gain, as compare to an isotropic radiator.

- *L* = system losses (antennas, transmission lines between equipment and antennas, atmosphere, etc.)
  - unitless
  - *L* = 1 for zero loss

- $L > 1$ in general

λ = wavelength = c / f (m).

d = T-R separation distance (m)

Path Loss (*PL*) in dB:

$$PL_{dB} = 10\log\left(\frac{P_t}{P_r}\right) = -10\log\left(\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2 L}\right)$$

$$= -10\log\left(\frac{G_t G_r \lambda^2}{(4\pi)^2 L}\right) + 10\log\left(d^2\right)$$

$$= -10\log\left(\frac{G_t G_r \lambda^2}{(4\pi)^2 L}\right) + 20\log(d)$$

- $d^2 \rightarrow$ power law relationship
  - P_r decreases at rate of proportional to d^2
  - P_r decreases at rate of 20 dB/decade (for line-of-sight, even worse for other cases)
  - For example, path loses 20 dB from 100 m to 1 km
  - Comes from the d^2 relationship for surface area.
- Close in reference point (d_o) is used in large-scale models

$$P_r(d) = P_r(d_0)\left(\frac{d_0}{d}\right)^2 \quad \text{for } d > d_o > d_f$$

  - d_o : known received power reference point - typically 100 m or 1 km for outdoor systems and 1 m for indoor systems
  - d_f: far-field distance of antenna, we will always work problems in the far-field

D: the largest physical linear dimension of antenna

TWO RAY MODEL:

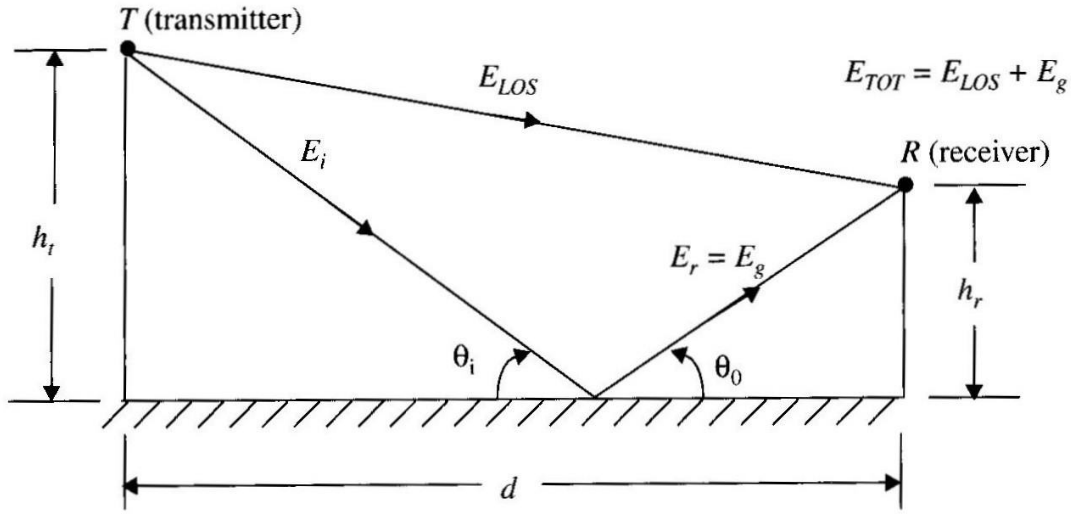


Figure 4.7 Two-ray ground reflection model.

ETOT is the electric field that results from a combination of a direct line-of-sight path and a ground reflected path.

$$\vec{E}_{TOT} = \vec{E}_{LOS} + \vec{E}_g$$

let E_o be $|\vec{E}|$ at reference point d_o then

$$\vec{E}(d,t) = \left(\frac{E_0 d_0}{d}\right)\cos\left(\omega_c\left(t - \frac{d}{c}\right)\right) \quad d > d_0$$

- **For the direct path let $d = d'$; for the reflected path**

  $d = d''$ then

$$\vec{E}_{TOT}(d,t) = \left(\frac{E_0 d_0}{d'}\right)\cos\left(\omega_c\left(t - \frac{d'}{c}\right)\right) + \Gamma\left(\frac{E_0 d_0}{d''}\right)\cos\left(\omega_c\left(t - \frac{d''}{c}\right)\right)$$

- **for large T−R separation : θ_i goes to 0 (angle of incidence to the ground of the reflected wave) and**

  $\Gamma = -1$

- **Phase difference can occur depending on the phase difference between direct and reflected E fields**

The phase difference is θ_Δ due to Path difference , $\Delta = d'' - d'$, between $\bar{E}_{LOS}$ and $\bar{E}_g$ **.**

$$\text{Equation (4.40): } \Delta = d'' - d' = \sqrt{(h_t + h_r)^2 + d^2} - \sqrt{(h_t - h_r)^2 + d^2}$$

- **From two triangles with sides *d* and ($h_t + h_r$) or ($h_t - h_r$)**

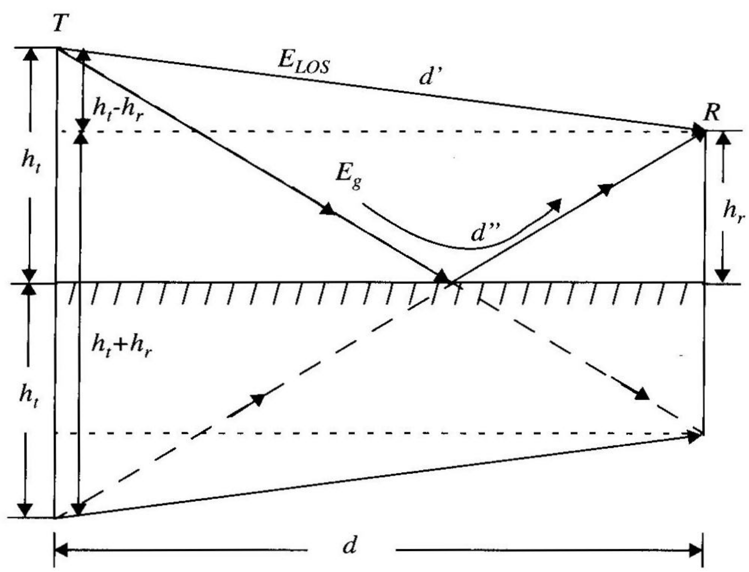


Figure 4.8 The method of images is used to find the path difference between the line-of-sight and the ground reflected paths.

- **for large distances** $d >> \sqrt{h_t h_r}$ **it can be shown that**

$$\left.\vec{E}_{TOT}(d)\right| \approx \frac{4\pi E_0 d_0 h_t h_r}{\lambda d^2}$$

$$P_r \approx \frac{P_t G_t G_r h_t^2 h_r^2}{d^4}$$

Two-ray path loss model:
PL (dB)= 40 log d – [10 log G_t + 10 log G_r + 20 log h_t + 20 log h_r]

Now d^4 instead of d^2 for free space

- $P_r \propto \frac{1}{d^4} P_r$

- $\boxed{P_r(d) = P_r(d_0)\left(\frac{d_0}{d}\right)^4}$

Predictable Link Budget Design using Path Loss Models

Most RF propagation models are derived from combined

(i) analytical studies

(ii) experimental methods

Empirical Approach – measured data is fitted to a curve or an

analytical expression

- uses field measurements

- implicitly accounts for all factors (known and unknown)
- model generally not valid for all frequencies or environments

- Classical Models have evolved to predict large scale path loss
- used to estimate receive signal strength as a function of distance
- used along with noise analysis techniques used to predict SNR

for RF mobile systems

3.9.1 Log Distance Path Loss Model

- average received power decreases logarithmically with distance
- theory & measurements indicate validity for indoors & outdoors

(1) Average Large Scale Path Loss Model

- **distance dependent** mean path loss - over significant distances

$$\overline{PL}(d) = \frac{P_r(d)}{P_t(d)} \propto \left(\frac{d}{d_0}\right)^n \qquad (3.67)$$

$$\overline{PL}(dB) = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right) \qquad (3.68)$$

d_0 = close in reference distance, often determined emperically
d = transmitter - receiver separation
n = path loss exponent - indicates rate of path loss increase with d_0

3.9.2 Log Normal Shadowing

- **surrounding clutter** isn't considered by log distance model
- averaged received power (eqn 3.68) is inconsistent with measured data
- measured $PL(d)$ at any location is random, with **log normal** distribution about $\overline{PL}(d)$ (normal distribution of $\log_{10}(\bullet)$)

$$PL(d) = \overline{PL}(d) + X_\sigma$$

$$PL(d)\ (dB) = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma \qquad (3.69a)$$

$$P_r(d)\ (\mathrm{dB}) = P_t(d)\ (\mathrm{dB}) - PL(d)\ (\mathrm{dB}) \qquad (3.69b)$$

- antenna gains included in $PL(d)$
- X_σ = zero-mean Gaussian distributed random variable *(in dB)*
- σ = standard deviation of X

Log Normal Distribution - describes random shadowing effects

- for specific Tx-Rx, measured signal levels have normal distribution about distance dependent mean (in dB)
- occurs over many measurements with same Tx-Rx & different clutter standard deviation, σ (also measured in dB)

Lognormal Model For Local Shadowing

- typically, σ_{dB} ranges from *5-12*
- let u = **median path loss** (dB) at distance d from transmitter
  → distribution x_{dB} of observed path loss has pdf given by:

$$\mathbf{Pr}[x_{dB} = x] = f(x_{dB}) = \frac{1}{\sqrt{2\pi\sigma_{dB}}} \exp-\left(x_{dB} - u/2\sigma_{dB}^2\right)$$

it follows that $\mathbf{Pr}(x_{dB} > x) = \int_x^\infty f(x_{dB})dx_{dB}$

$$= \int_x^\infty \frac{1}{\sqrt{2\pi\sigma_{dB}}} \exp-\left(x_{dB} - u/2\sigma_{dB}^2\right)$$

3.9.3 Determination of % Coverage Area

- in a given coverage area, let γ = desired receive signal level – could be determined by receiver sensitivity (or visa versa)
- random shadowing effects cause some locations at d to have received power, $P_r(d) < \gamma$

Determine boundary coverage vs % area covered within a boundary, assuming

- a circular coverage area with radius R from base station
- **likelihood** of coverage at cell boundary is known (given)
- $d = r$ represents radial distance from transmitter

useful service area (coverage area): $U(\gamma)$ = *% area* with $P_r(d) > \gamma$

$$U(\gamma) = \frac{1}{2\pi R^2}\int \Pr[P_r(r) > \gamma]\, dA$$

$$U(\gamma) = \frac{1}{2\pi R^2}\int_0^{2\pi}\int_0^{R} \Pr[P_r(r) > \gamma]\, r\; dr\, d\theta \qquad (3.73)$$

SMALL SCALE FADING:

Multi-Path in the radio channel creates small-scale fading. The three most important effects are:

- Rapid changes in signal strength over a small travel distance or time interval
- Random frequency modulation due to varying Doppler shifts on different multi-path signals
- Time dispersion (echoes) caused by multi-path propagation delays

PARAMETERS OF MOBILE MULTIPATH CHANNELS:

- Time dispersion parameters
    - Mean excess delay
    - Rms delay spread
    - Excess delay spread (X dB)
- Coherence bandwidth

- Doppler spread and coherence time

Time Dispersion Parameters

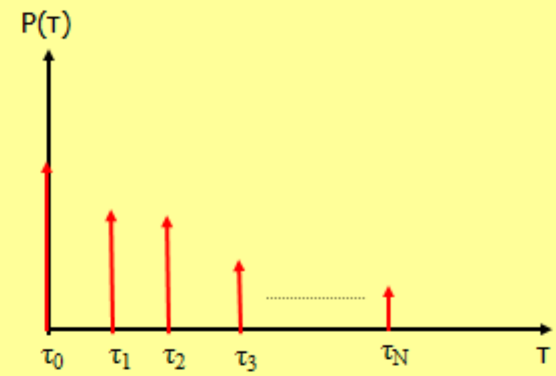
Mean Excess Delay

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

RMS Delay Spread

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

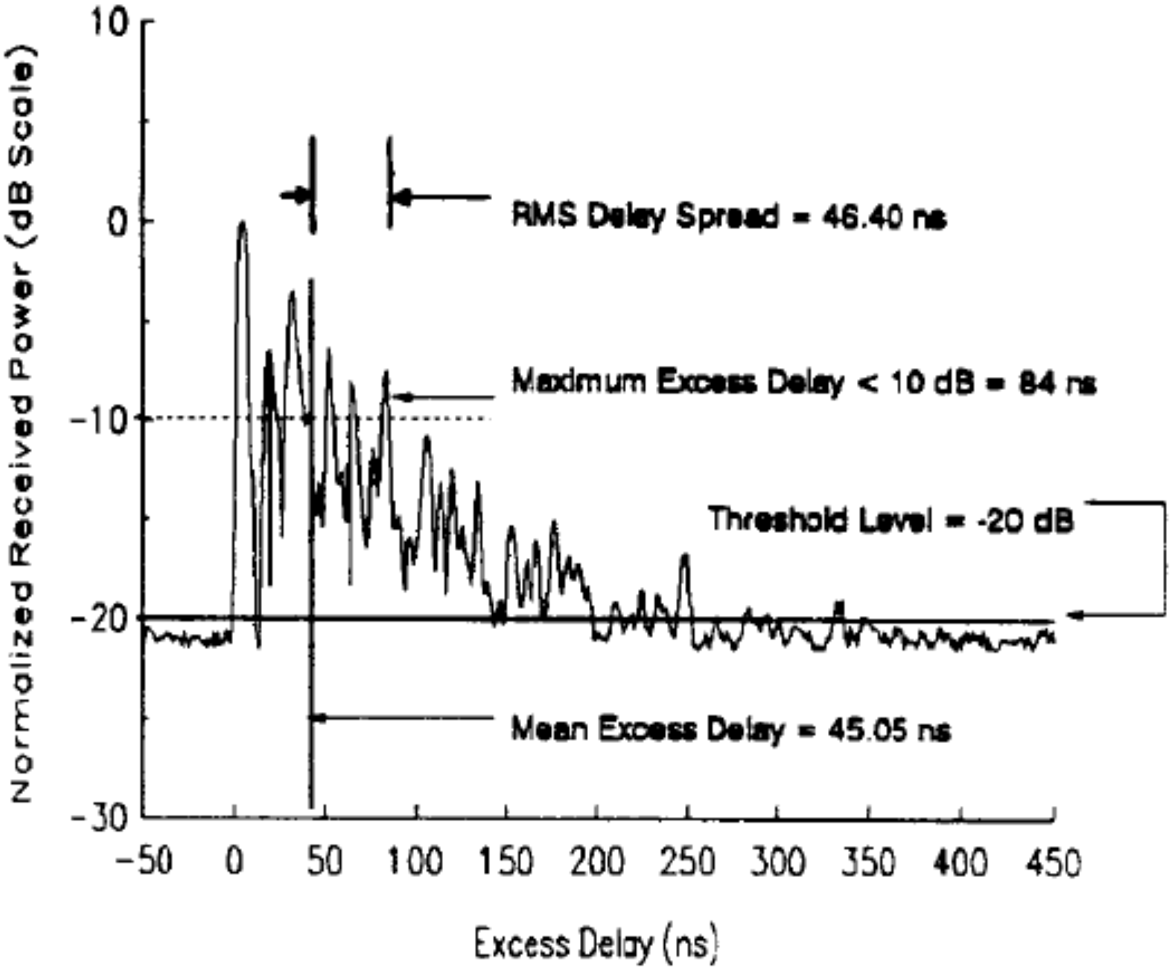
$$\overline{\tau^2} = \frac{\sum_k P(\tau_k)\tau_k^2}{\sum_k P(\tau_k)}$$



Power Delay Profile

Note: These delays are measured relative to the first detectable signal (multi-path component) arriving at the receiver at $\tau_0 = 0$

Maximum Excess Delay (XdB) or Excess Delay Spread (XdB):
Time delay during which multi-path energy falls to X dB below the maximum (Note that the strongest component does not necessarily arrive at τ_0)


RMS Delay Spread = 46.40 ns
Maximum Excess Delay < 10 dB = 84 ns
Threshold Level = -20 dB
Mean Excess Delay = 45.05 ns
Normalized Received Power (dB Scale)
Excess Delay (ns)
10
0
-10
-20
-30
-50
0
50
100
150
200
250
300
350
400
450

Coherence Bandwidth

A statistical measure of the range of frequencies over which the channel is can be considered to be "flat" (i.e., a channel which passes all spectral components with approximately equal gain and linear phase)

Coherence Bandwidth over which the frequency correlation function is 0.9

$$B_C = \frac{1}{50\sigma_\tau}$$

Coherence Bandwidth over which the frequency correlation function is 0.5

$$B_C = \frac{1}{5\sigma_\tau}$$

Doppler Shift

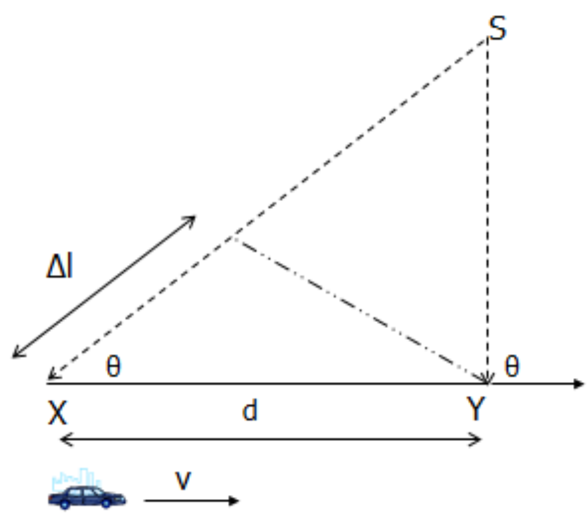
The difference in path lengths traveled by the wave from source S to the mobile at X and Y is Δl

Note: Assume SX, SY >>d such that angle of arrival is nearly equal at X and Y

$$\Delta l = d \cos\theta = v\Delta t \cos\theta$$

Phase Difference due to variation in path lengths

$$\Delta\varphi = \frac{2\pi v\Delta t}{\lambda} = \frac{2\pi v\Delta t}{\lambda}\cos\theta$$



Doppler Shift is Given by

$$f_d = \frac{1}{2\pi}\frac{\Delta\varphi}{\Delta t} = \frac{v}{\lambda}\cos\theta$$

Doppler Spread and Coherence Time

- Doppler spread and coherence time are parameters which describe the time varying nature of the channel
- Doppler spread B_D is a measure of spectral broadening due to the Doppler shift associated with mobile motion
- Coherence time is a statistical measure of the time duration over which the channel impulse response is essentially invariant

Coherence Time is inversely proportional to Doppler spread

$$T_C \approx \frac{1}{f_m}$$

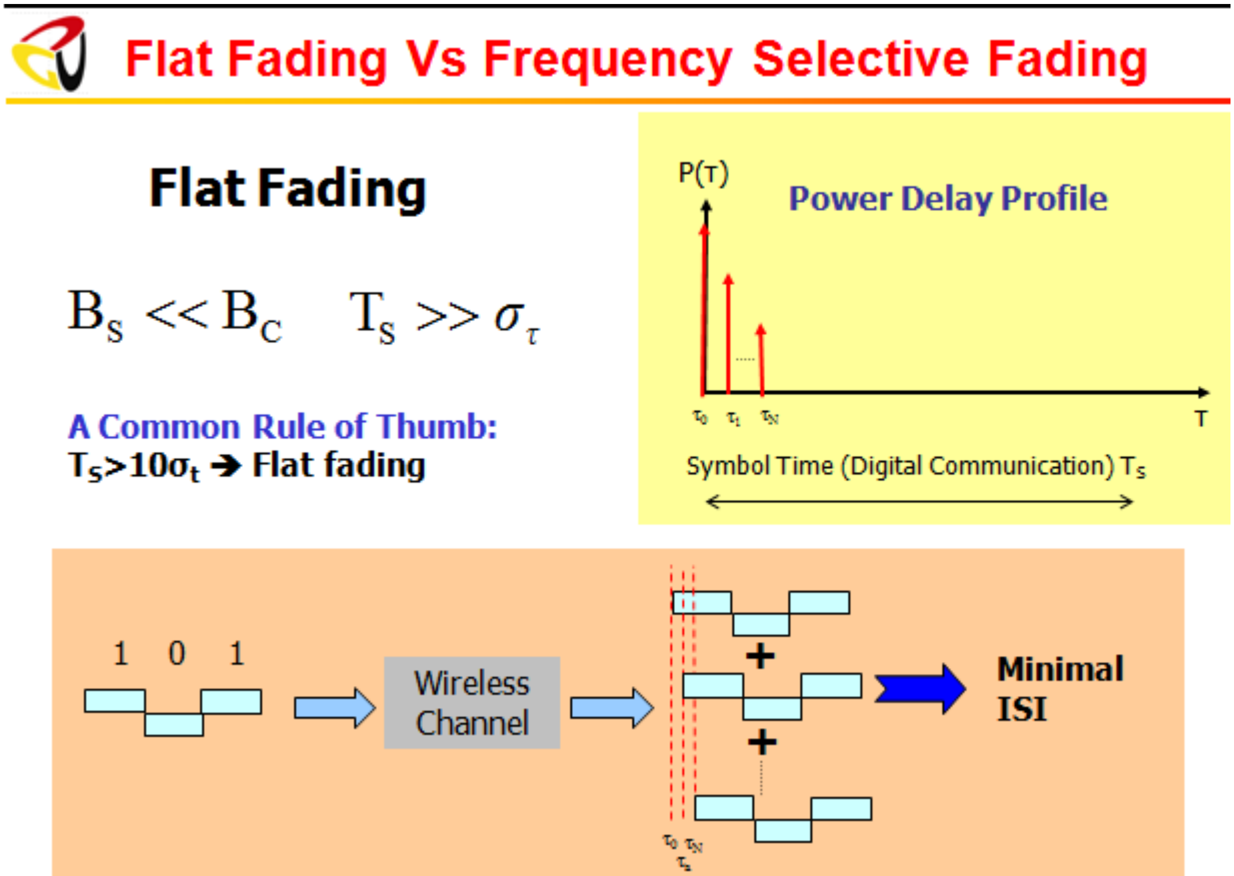
Coherence Time over which the time correlation function is 0.5

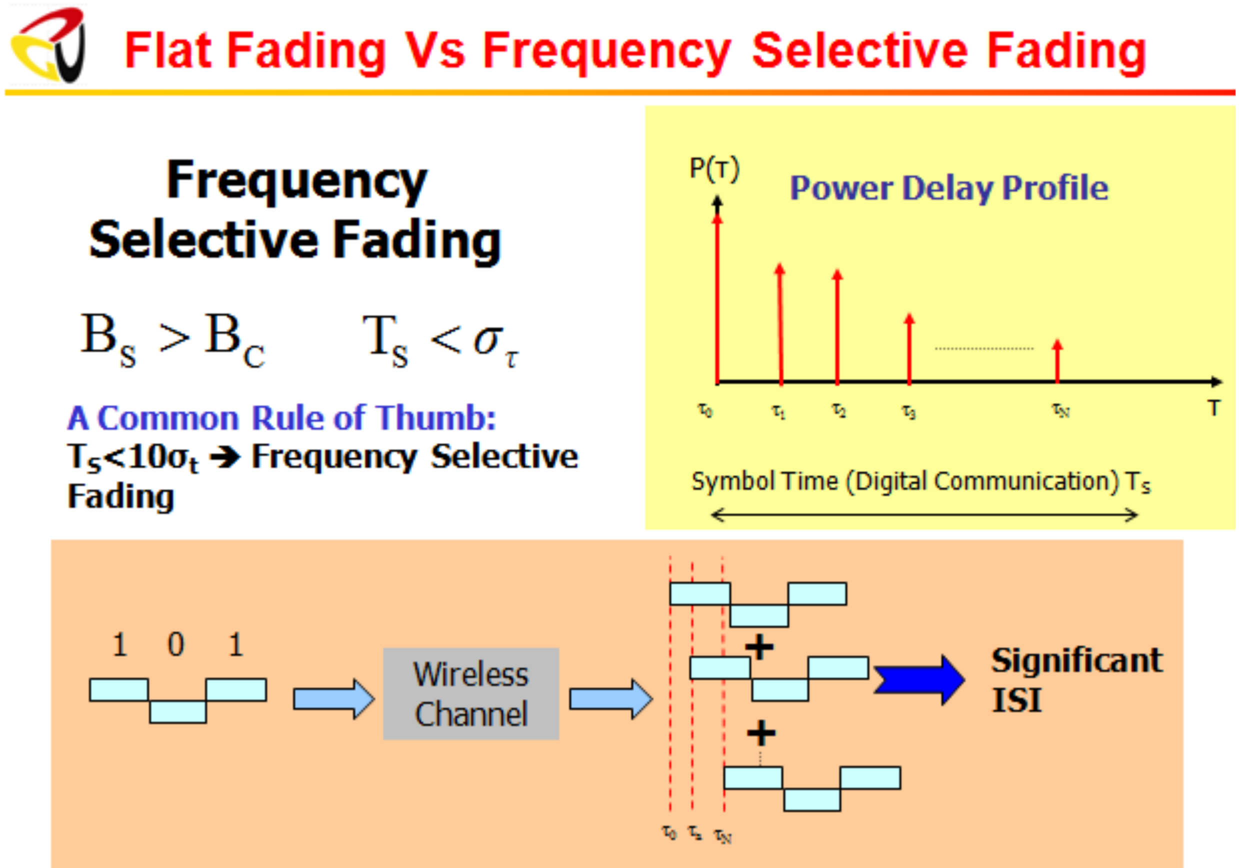
$$T_C \approx \frac{9}{16\pi f_m}$$

where f_m is the maximum Doppler shift given by $f_m = v/\lambda$

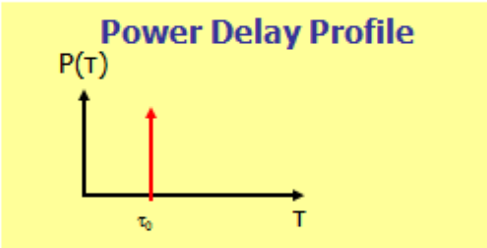
A Common Rule:

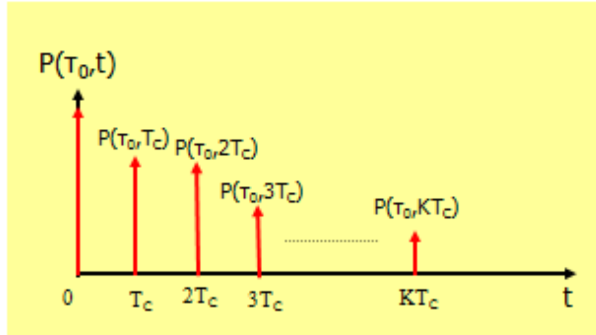
$$T_C = \sqrt{\frac{9}{16\pi f_m}\frac{1}{f_m}} = \frac{0.423}{f_m}$$


Flat Fading Vs Frequency Selective Fading
Flat Fading
$B_S << B_C \quad T_S >> \sigma_\tau$
A Common Rule of Thumb:
$T_S > 10\sigma_t \rightarrow$ Flat fading
P(τ)
Power Delay Profile
τ_0 τ_1 τ_N
T
Symbol Time (Digital Communication) T_S
1 0 1
Wireless Channel
+
+
τ_0 τ_N
Minimal ISI


Flat Fading Vs Frequency Selective Fading
Frequency Selective Fading
$B_S > B_C$
$T_S < \sigma_\tau$
A Common Rule of Thumb:
$T_S < 10\sigma_t$ ➔ Frequency Selective Fading
P(τ)
Power Delay Profile
τ0
τ1
τ2
τ3
τN
T
Symbol Time (Digital Communication) T_S
1 0 1
Wireless Channel
+
+
Significant ISI

Slow Fading Vs Fast Fading





- Consider a wireless channel comprised of a single path component.
- The power delay profile reflects average measurements
- $P(\tau_0)$ shall vary as the mobile moves

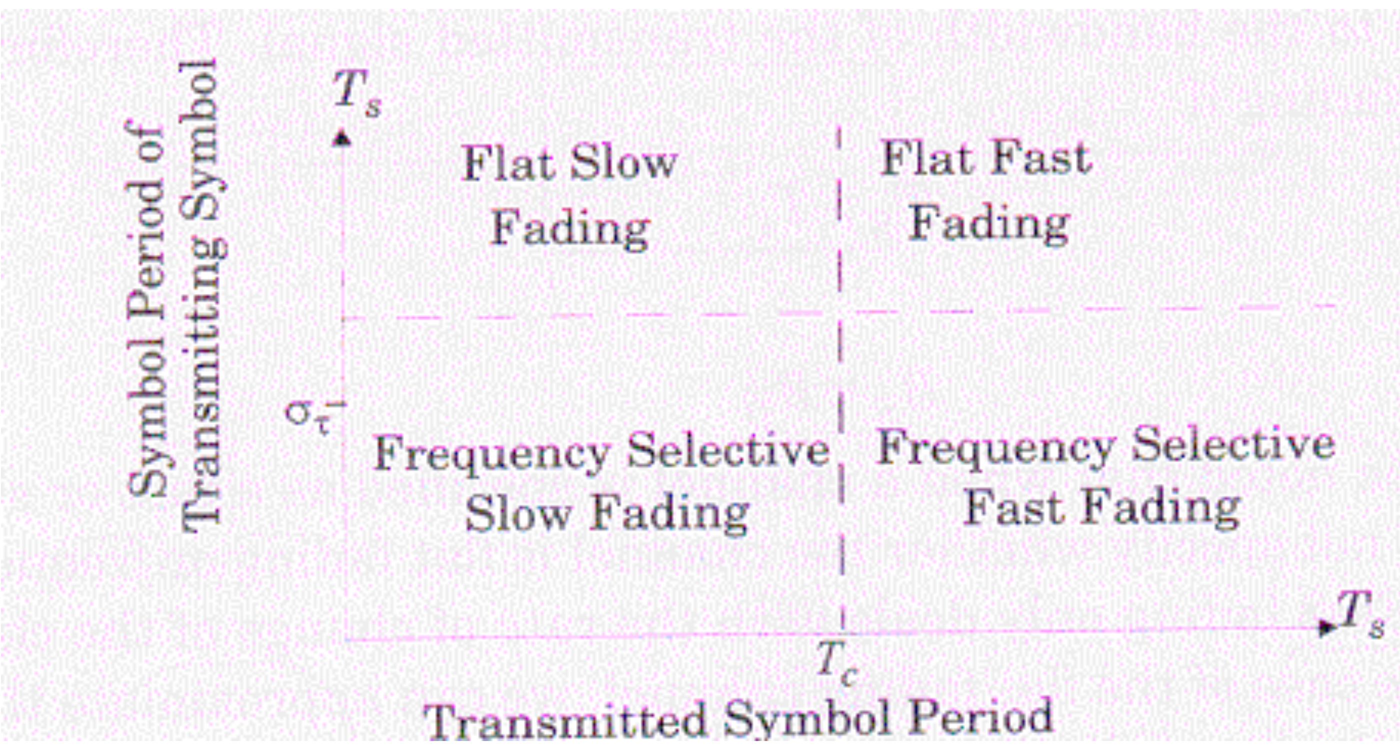
Fast Fading

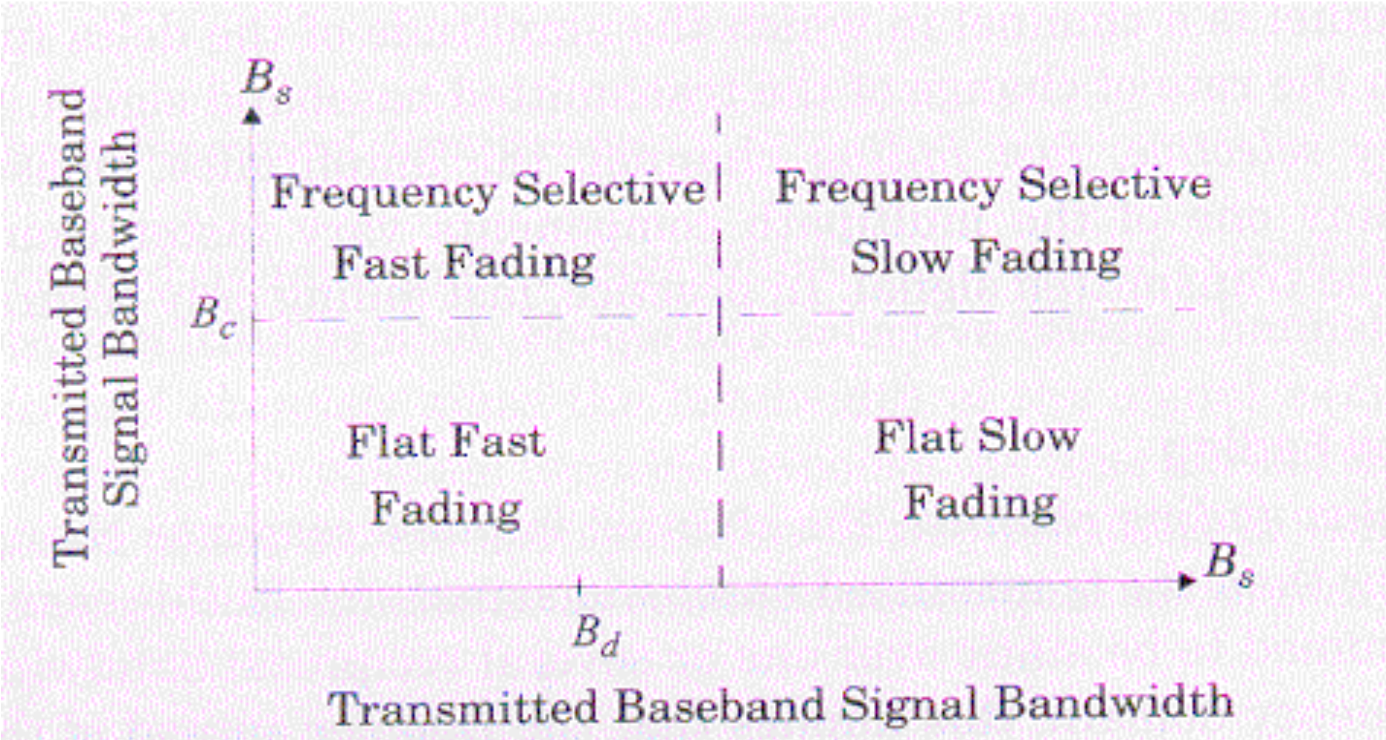
$T_S > T_C$ $\quad B_S < B_D$

Frequency dispersion
(time selective fading)

Slow Fading

$T_S \ll T_C$ $\quad B_S \gg B_D$




B_s
Frequency Selective
Fast Fading
Frequency Selective
Slow Fading
B_c
Flat Fast
Fading
Flat Slow
Fading
B_s
B_d
Transmitted Baseband Signal Bandwidth
Transmitted Baseband
Signal Bandwidth