Mobile Radio Communications

Course 3: Radio wave propagation

Propagation mechanisms

- free space propagation
- reflection
- diffraction
- scattering

LARGE SCALE: average attenuation

$$dx >> \lambda$$

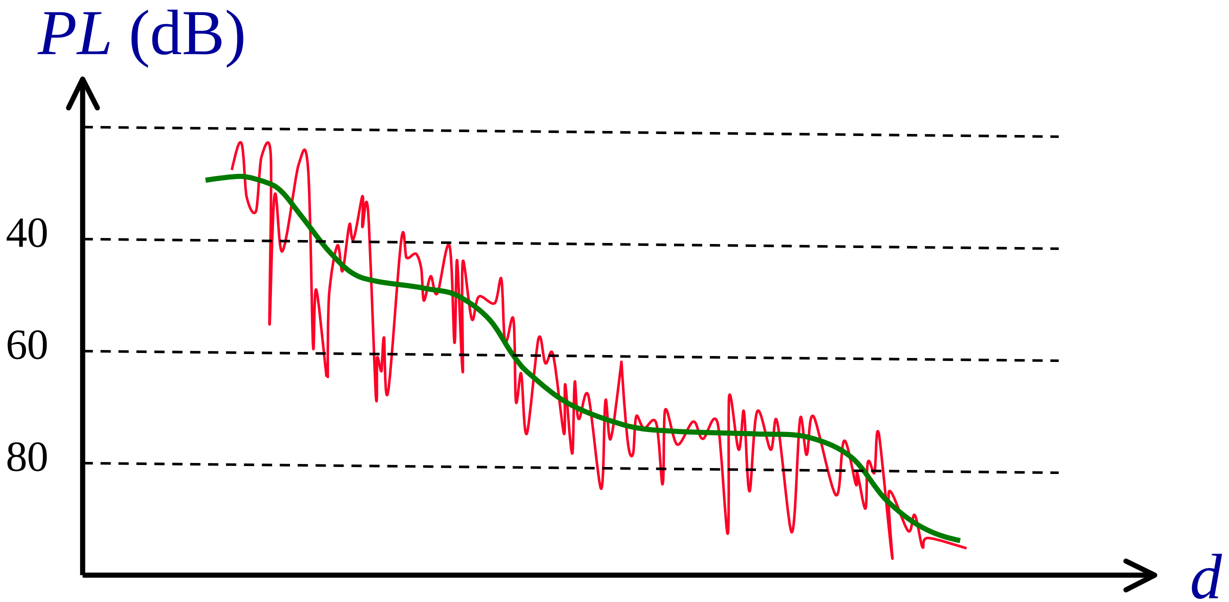
$$dt >> T_S$$

SMALL SCALE: short-term variations in position and time

$$dx \approx \lambda$$

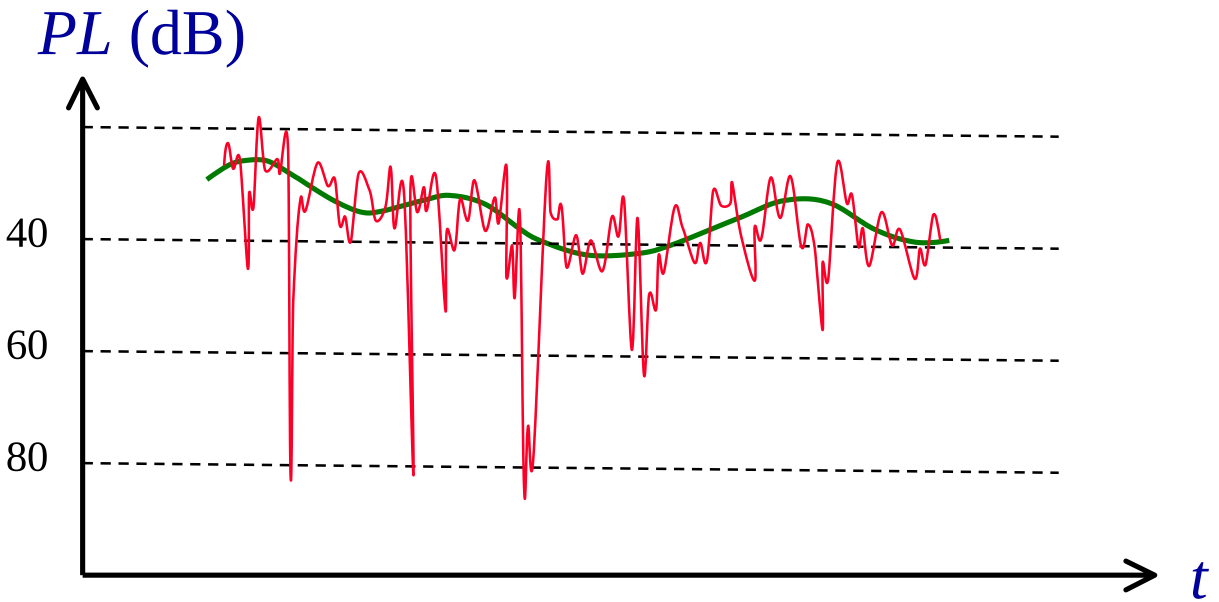
$$dt \approx T_S$$

Large-scale/small scale variations <u>space</u>



Large-scale/small scale variations

time



Free-space propagation

***P*:**	**power**
***G*:**	**antenna gain**
***d*:**	**separation distance**
***L*:**	**system loss**

$$P_R(d) = \frac{P_T \cdot G_T \cdot G_R \cdot \lambda^2}{(4\pi)^2 \cdot d^2 \cdot L}$$

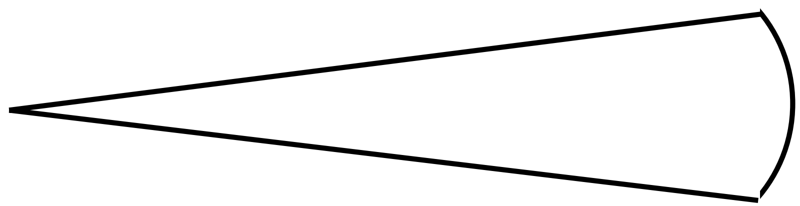
Antenna gain

- **isotropic: G=1**
- **directional: G(θ)**

$$G = \frac{4\pi A_e}{\lambda^2}$$

EIRP: effective isotropic radiated power

(received power as if received from isotropic source)



$$EIRP = G_T \cdot P_T$$

Free-space path loss

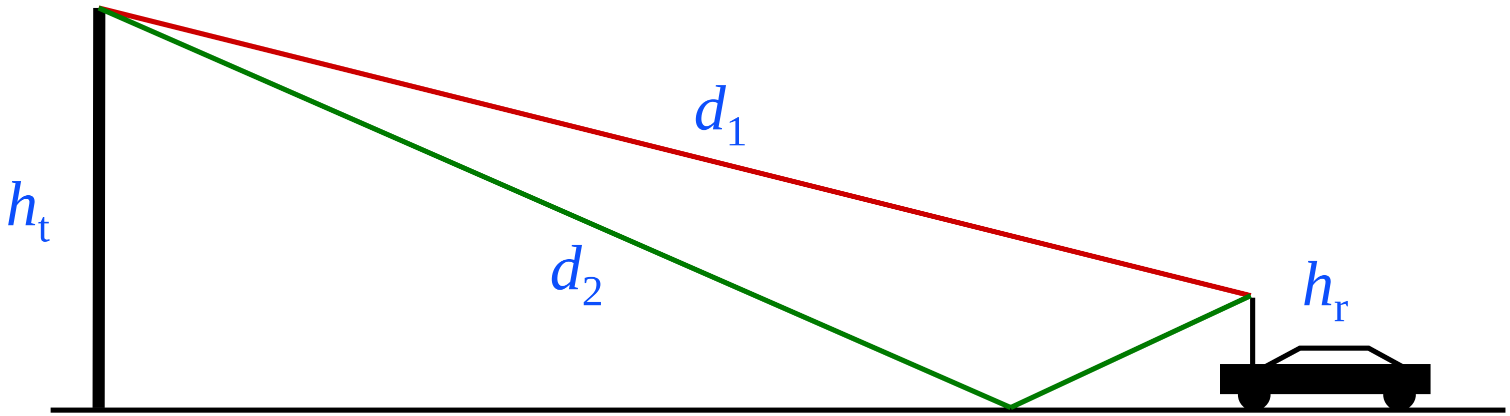
$$PL = 10\log\frac{P_T}{P_R}$$

$$= 20\log\frac{4\pi}{\lambda} + 20\log d$$

$$= PL(d_0) + 20\log\frac{d}{d_0}$$

attenuation 20 dB/dec

Ground wave reflection



$$E_{tot} = \frac{\alpha}{d_1}\cos(\omega_c t) + \Gamma\frac{\alpha}{d_2}\cos(\omega_c t + \Delta\theta)$$

Ground wave reflection

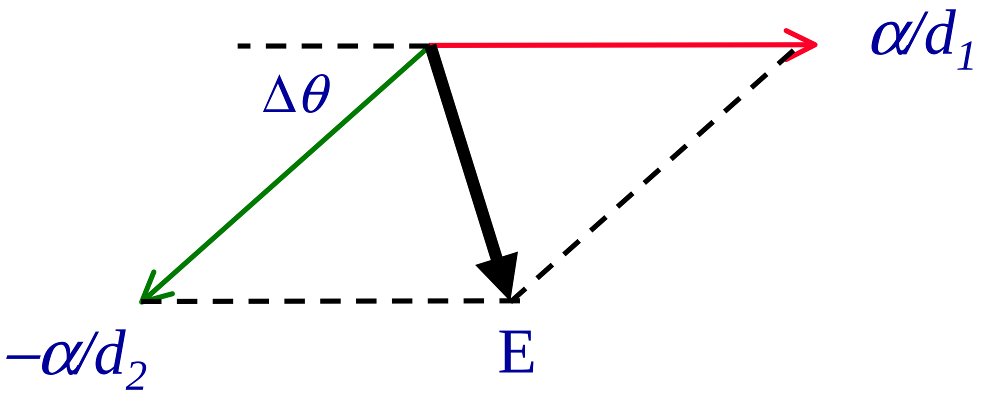
$$\Delta = d_2 - d_1$$

$$= \sqrt{d^2 + (h_t + h_r)^2} - \sqrt{d^2 + (h_t - h_r)^2}$$

$$\approx \frac{2h_t h_r}{d} \qquad d >> h$$

$$\Delta\theta \approx \frac{4\pi h_t h_r}{\lambda d}$$

Ground wave reflection



$$E^2 = \left(\frac{\alpha}{d}\right)^2 \left\{(1-\cos\Delta\theta)^2 + \sin^2\Delta\theta\right\}$$

$$= \left(\frac{\alpha}{d}\right)^2 (2 - 2\cos 2\Delta\theta) \approx \left(\frac{\alpha}{d}\right)^2 (\Delta\theta)^2$$

Ground wave reflection

$$E \approx \left(\frac{\alpha}{d}\right)\frac{4\pi h_t h_r}{\lambda d}$$

$$P_r = |E|^2 \frac{A_e}{120\pi} \approx \beta \frac{(h_t h_r)^2}{d^4}$$

$$A_e \approx G \frac{\lambda^2}{4\pi}$$

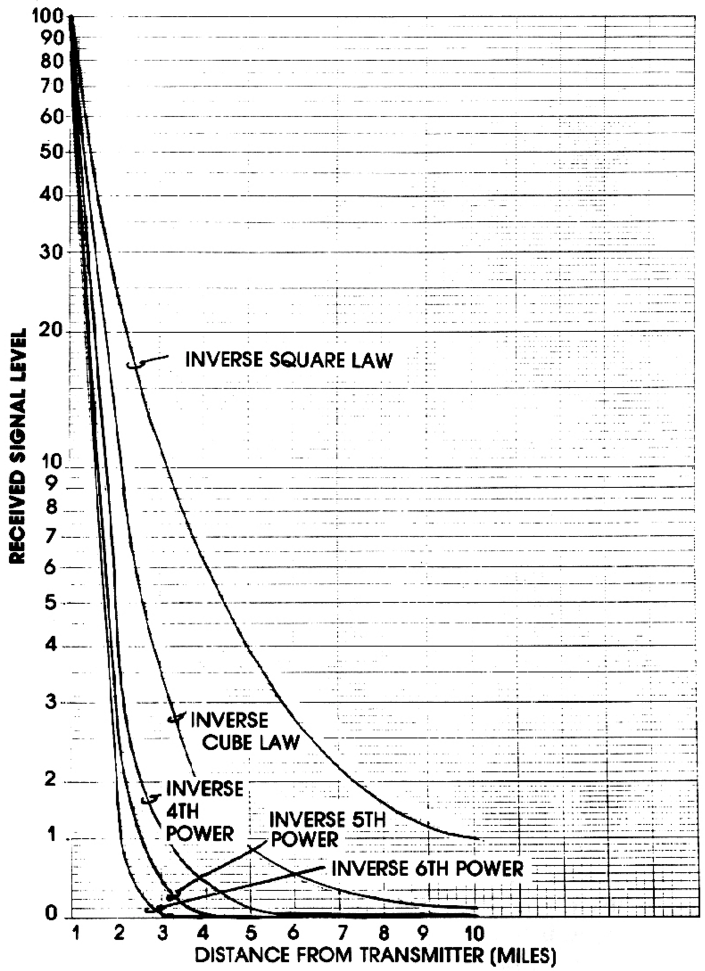
Two-ray path loss model

$$PL = 40\log d -$$

$$(10\log G_t + 10\log G_r + 20\log h_t + 20\log h_r)$$

attenuation 40 dB/dec

Path loss exponent



Log-distance path loss model

$$\overline{PL} = PL(d_0) + 10n \log \frac{d}{d_0}$$

d: T-R distance

d_0: close-in reference distance

n: path loss exponent ranging from 1 to 6

Okumura path loss model

$$L_{50} = L_F + A_{mu}(f,d) - G(h_t) - G(h_r) - G_{AREA}$$

$$G(h_t) = 20\log(\frac{h_t}{200}) \qquad 10\text{m} < h_t < 1000\text{m}$$

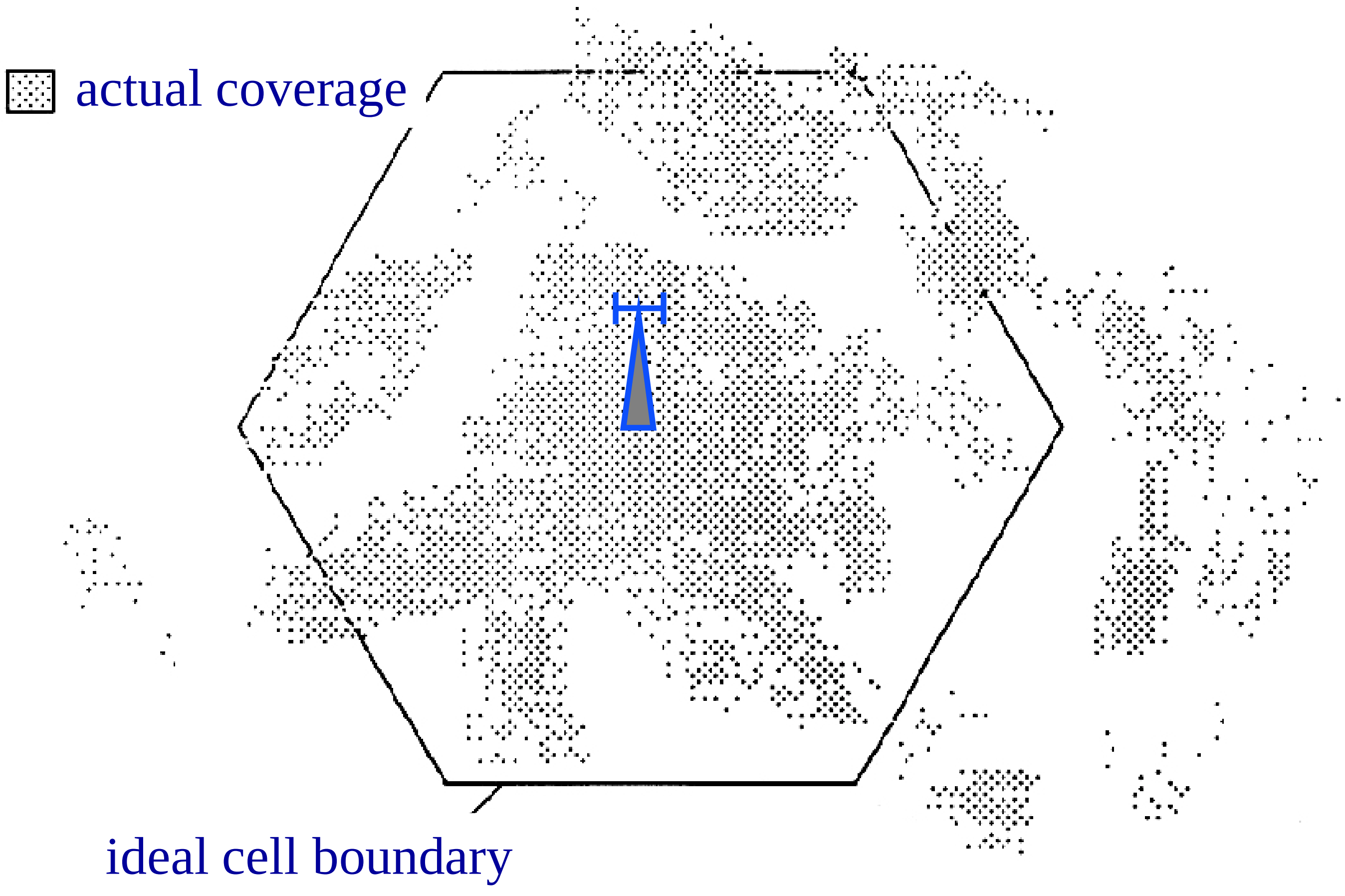
$$G(h_r) = 10\log(\frac{h_r}{3}) \qquad h_r < 3\text{m}$$

$$G(h_r) = 20\log(\frac{h_r}{3}) \qquad 3\text{m} < h_t < 10\text{m}$$

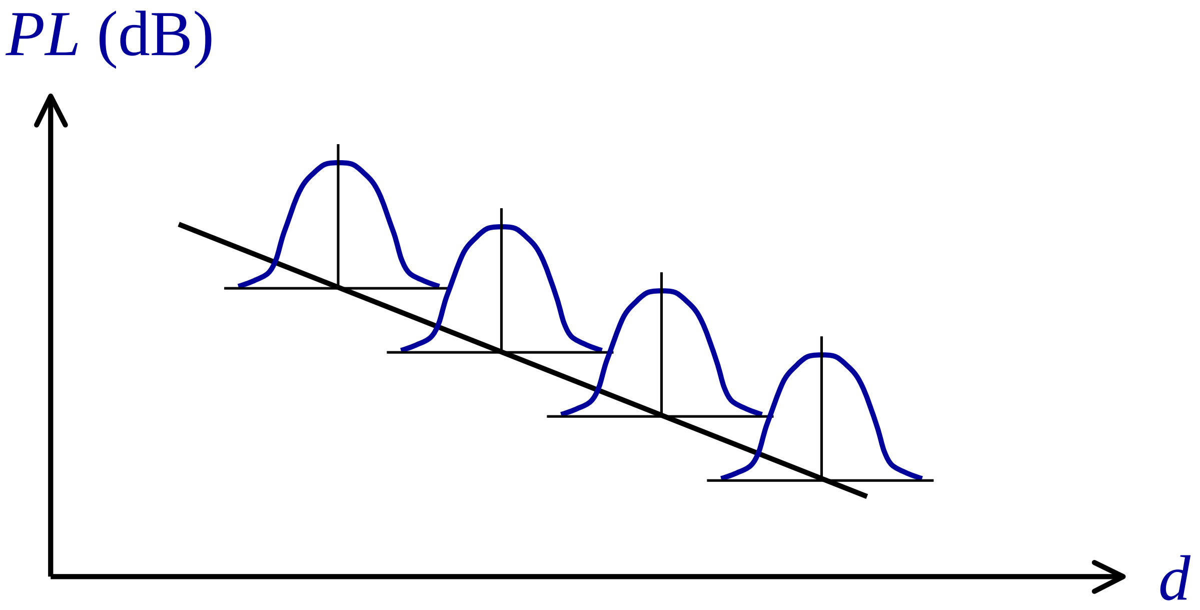
Hata path loss model

$$L_{50} = 69.55 + 26.16 \log f_c - 13.82 \log h_t - a(h_r)$$
$$+ (44.9 - 6.55 \log h_t) \log d + C(f_c)$$

Coverage area



Log-normal shadowing



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

Log-normal shadowing

$$X = N(0, \sigma)$$

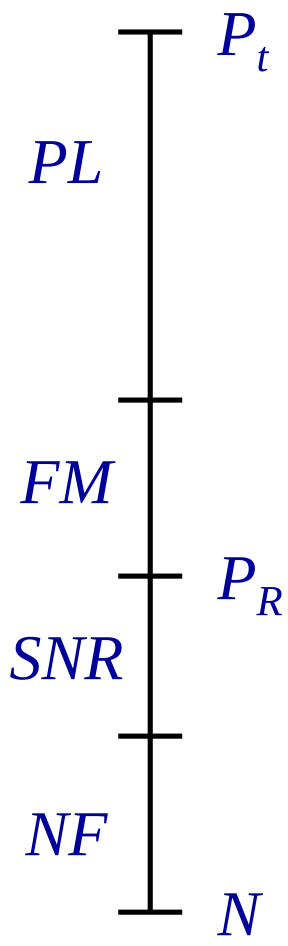
zero-mean Gaussion with standard dev. σ

outdoor: σ=6-9dB

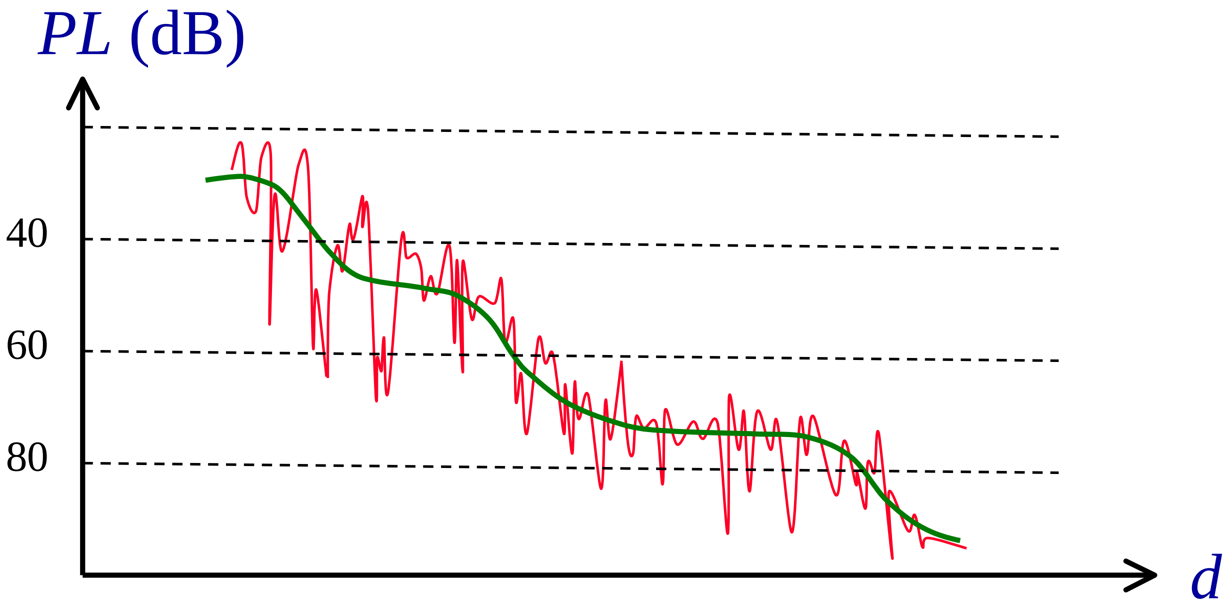
indoor: σ=2-12dB

Link budget

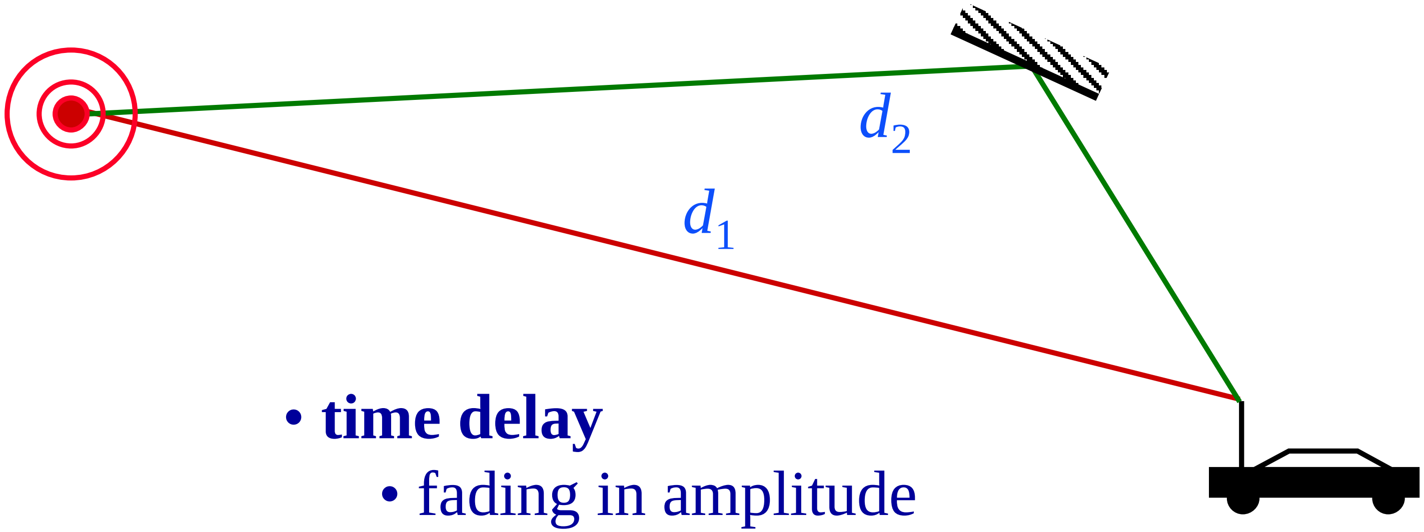
P_t:	permitted transmit power
P_r:	required receive power
PL:	path loss
N:	noise floor
NF:	noise factor
FM:	fading margin
SNR:	required signal-to-noise ratio



Multipath fading



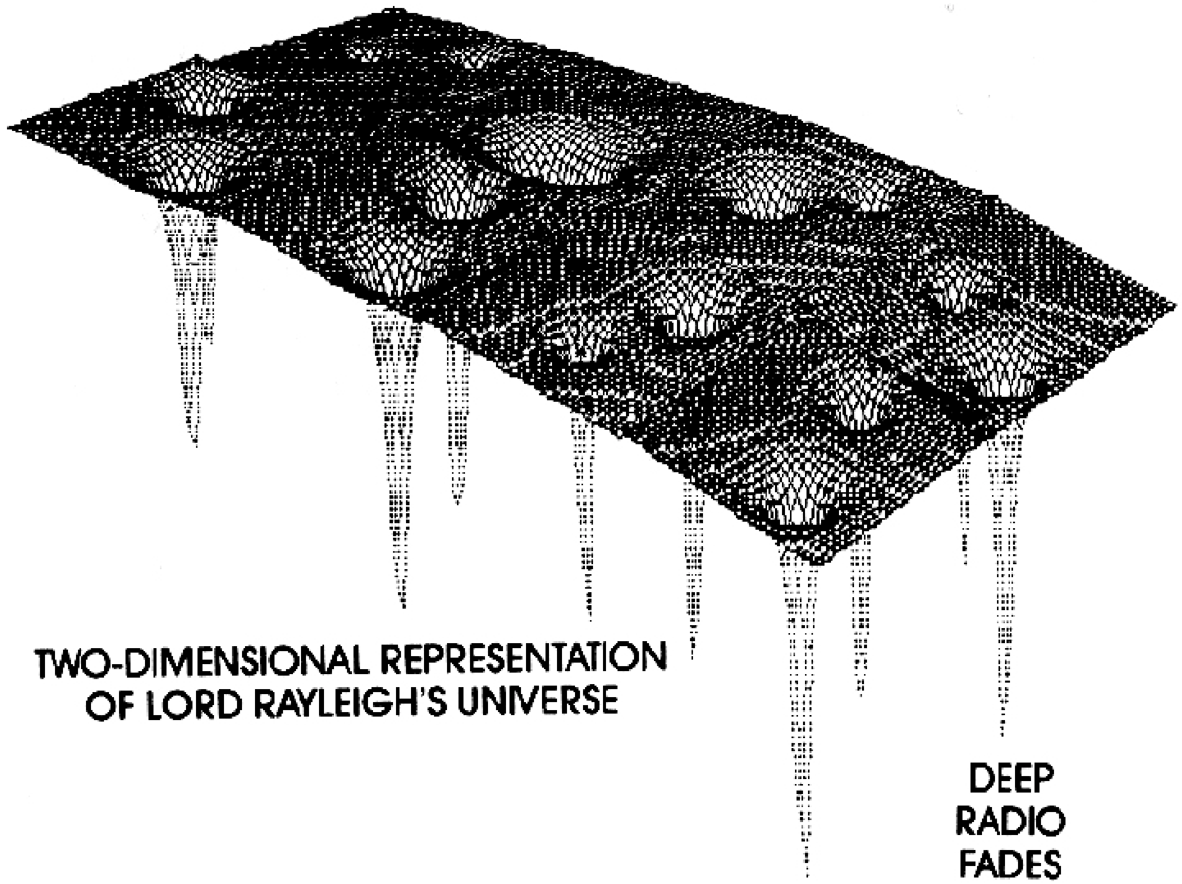
Multipath effects



- **time delay**
  - fading in amplitude
  - dispersion (echoes)

- **Doppler spread**
  - speed
  - angle of arrival

Delay space phenomenon



Fading

$$\Delta d \approx \lambda$$

$$\Delta \tau \approx \frac{\lambda}{c} = \frac{1}{f_c}$$

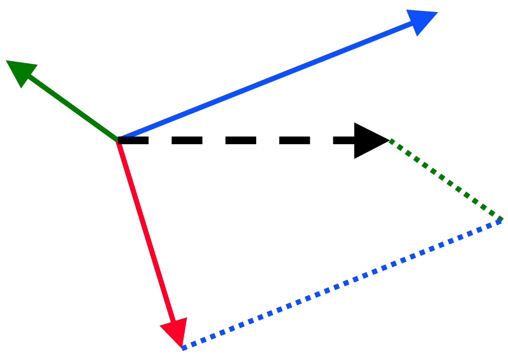
$$\Delta \theta \approx \pi$$

RF waves

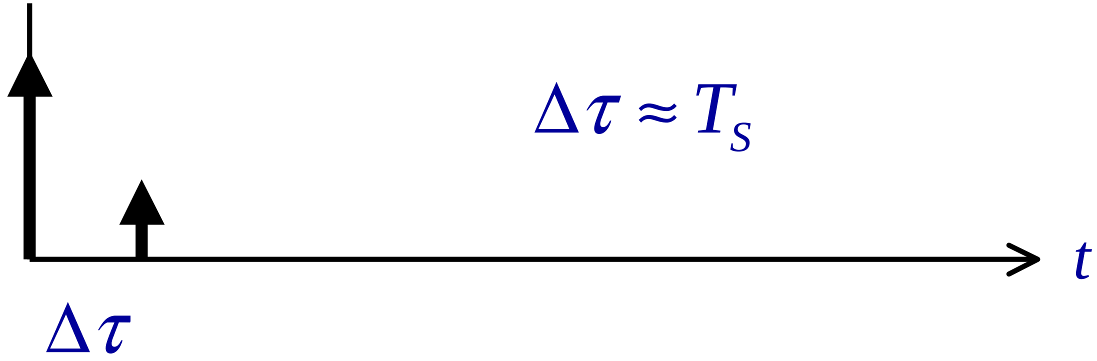
$$s_1 = r_1 \cos \theta_1$$

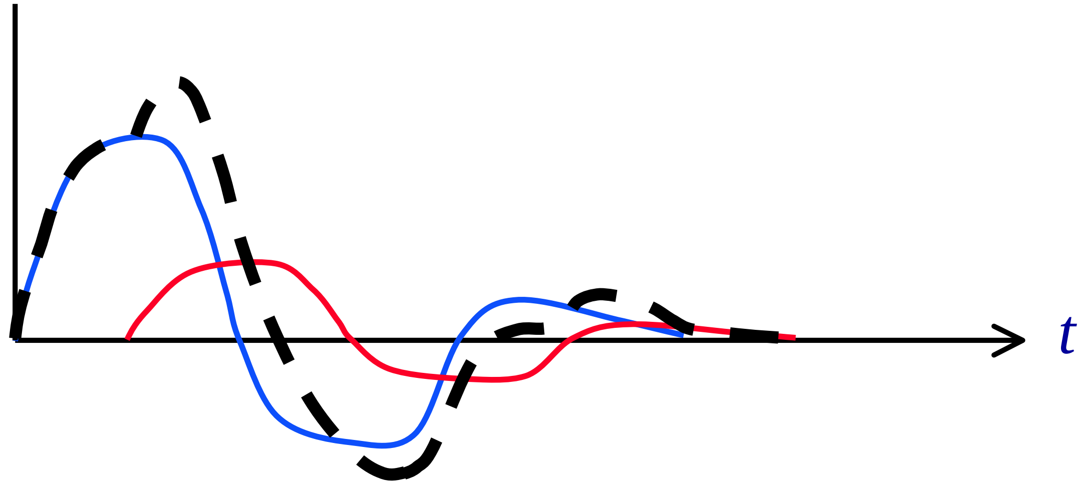
$$s_2 = r_2 \cos \theta_2$$

$$s_3 = r_3 \cos \theta_3$$

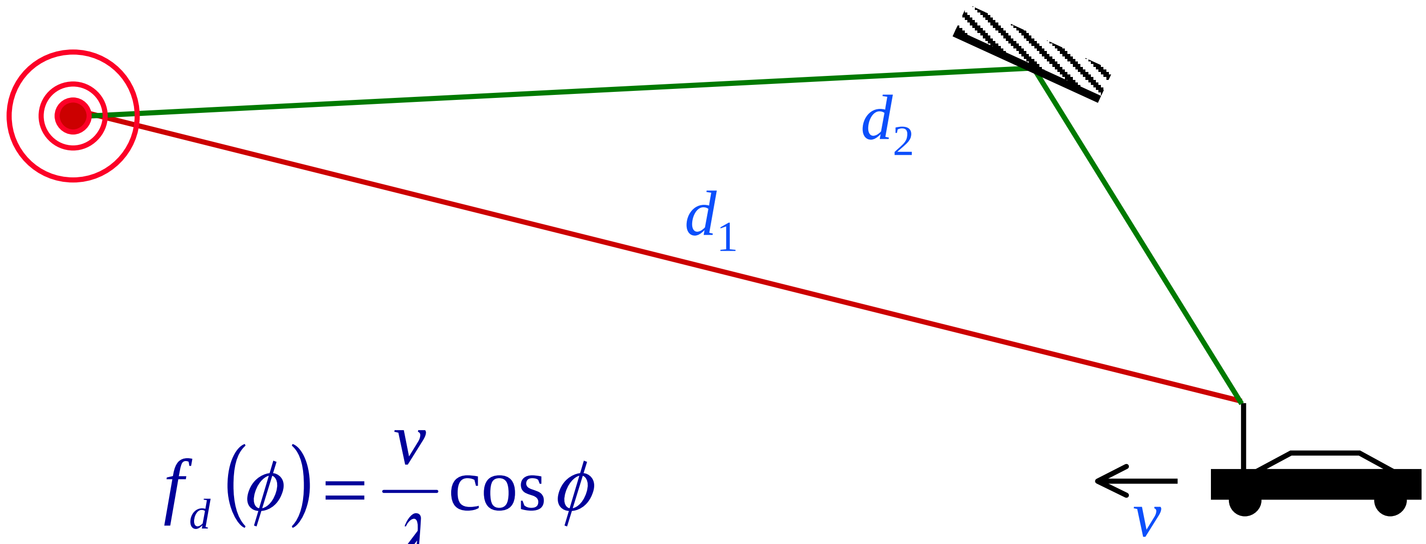


Time dispersion





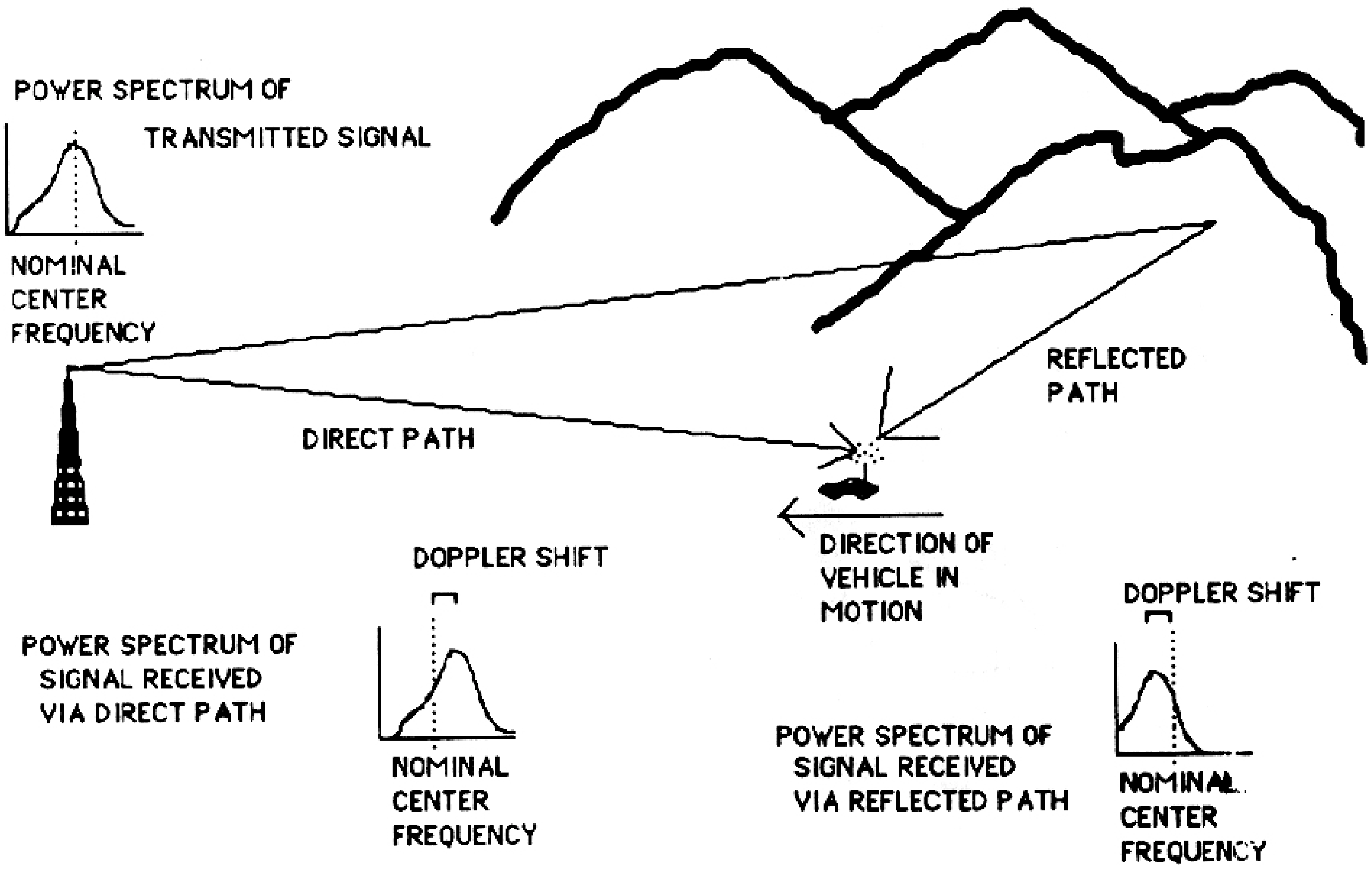
Doppler spread



$$f_d(\phi) = \frac{v}{\lambda}\cos\phi$$

$$0 \le \phi \le \pi \quad \Rightarrow \quad -\frac{v}{\lambda} \le f_d \le \frac{v}{\lambda}$$

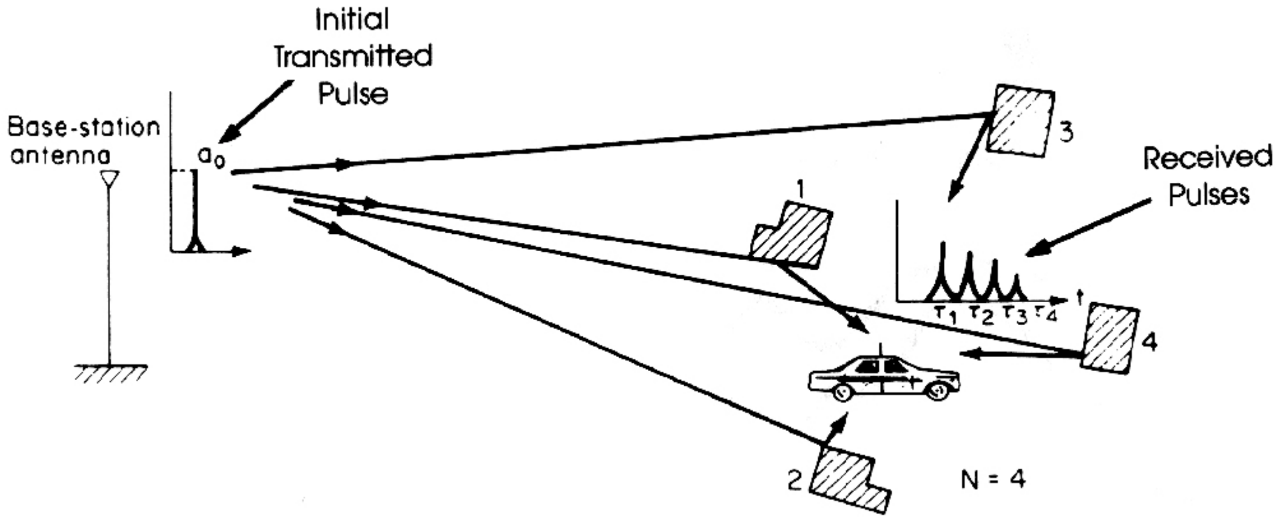
Doppler shifts



Doppler spread

v (km/h)	f_c (MHz)	f_d (Hz)
50	900	40
100	900	80
50	2010	90
100	2010	180

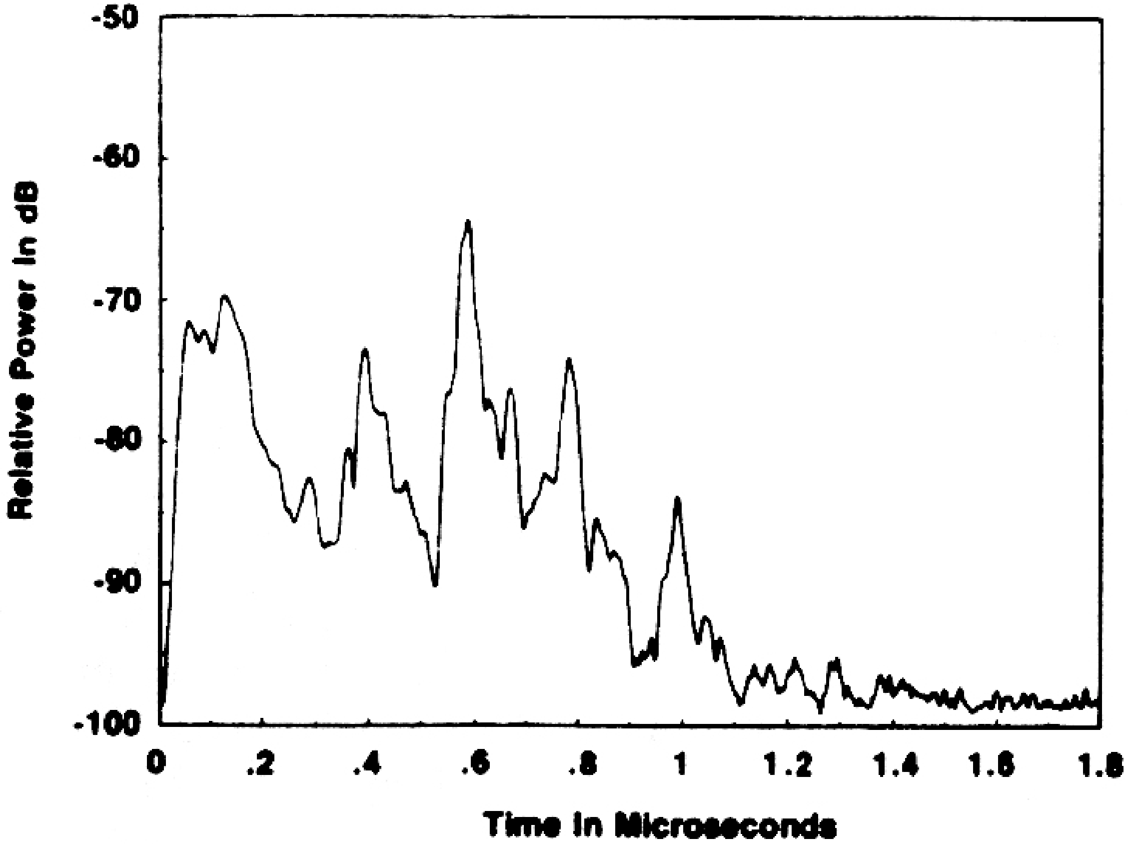
Delay profile



(a)

(b)

Measured delay profile



Impulse response model

time-variant, linear system: $h(t,\tau)$

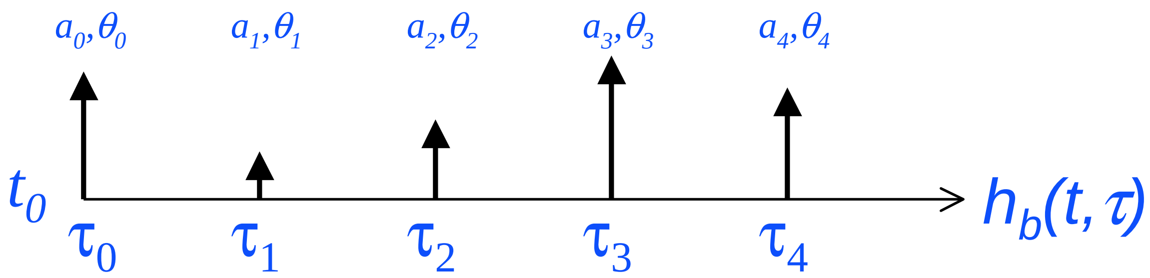
t: **time variant due to motion (ms to s)**
τ: **time dispersion (ns to μs)**

filter representation:

$$y(t) = x(t) * h(t,\tau)$$

FIR representation

$$h_b(t,\tau) = \sum_{i=0}^{N-1} a_i(t) \exp\{-j\theta_i(t)\}\delta(\tau - \tau_i)$$

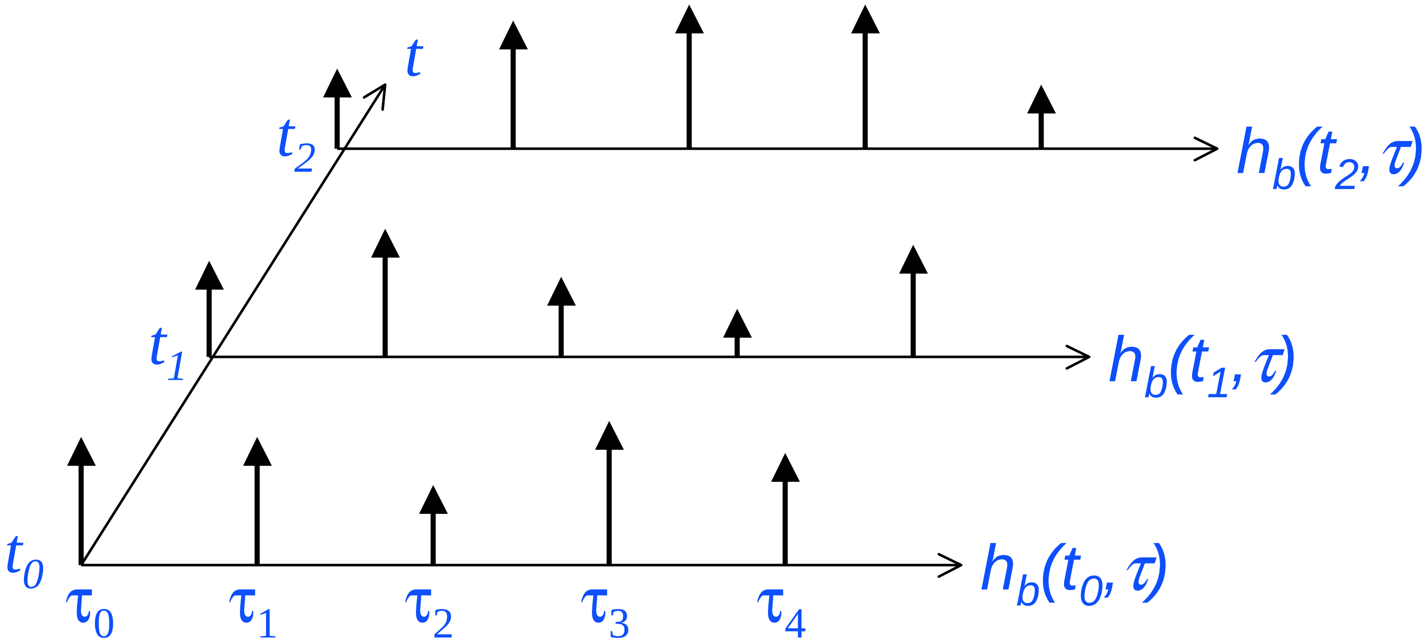


$BW_{signal} < 1/(2\Delta\tau)$

$\tau 0$: excess delay reference

$N\Delta\tau$: maximum excess delay

FIR representation



Power delay profile

$$\left|h_b(t,\tau)\right|^2$$

- measured in local area
- spatial averaging (2-6m)

Time dispersion parameters

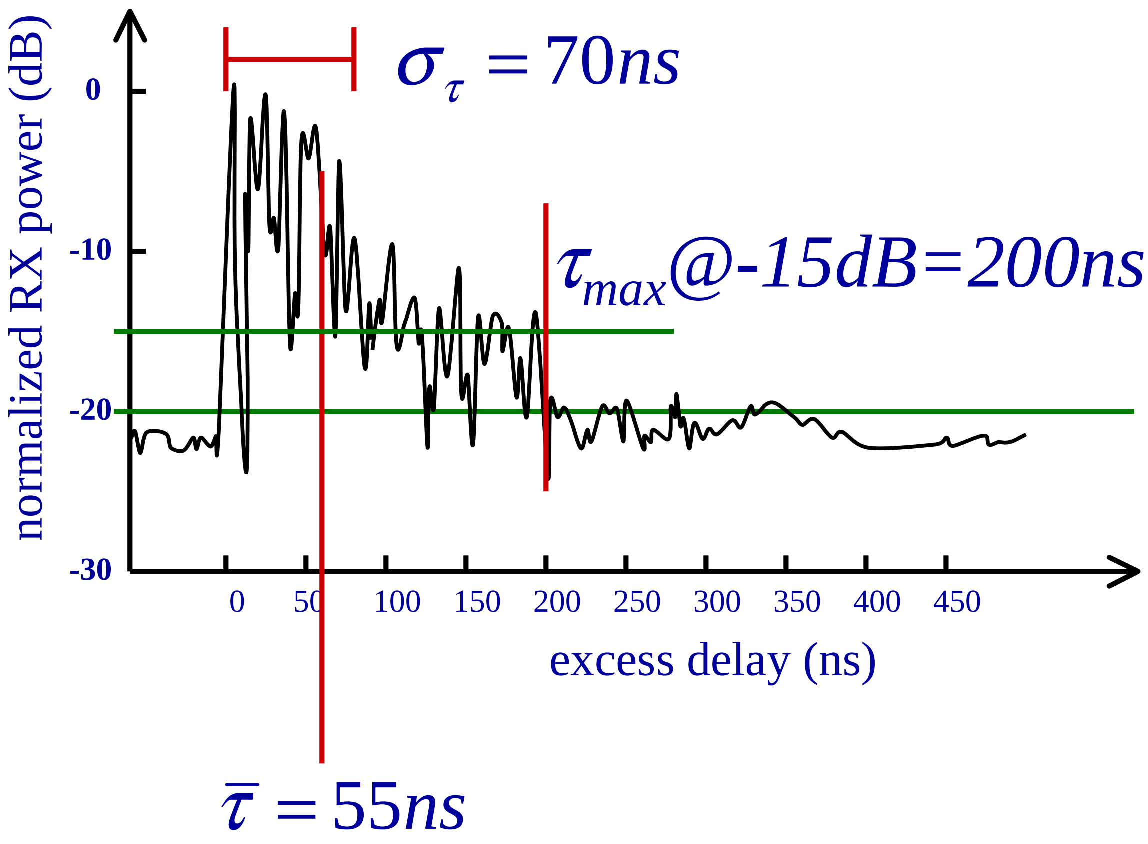
$$\bar{\tau} = \frac{\sum_k P(\tau_k)\tau_k}{\sum_k P(\tau_k)} \qquad \overline{\tau^2} = \frac{\sum_k P(\tau_k)\tau_k^2}{\sum_k P(\tau_k)}$$

mean excess delay: $\bar{\tau}$

rms delay spread: $\sigma_\tau = \sqrt{\overline{\tau^2} - (\bar{\tau})^2}$

maximum excess delay: τ **where** $P \le P_{max}$

Time dispersion example



Time dispersion values

environment	f (MHz)	σ_τ
urban	900	10-25μs
suburban	900	200-300ns
indoor	1500	70-90ns

Coherence bandwidth

$$h(t,\tau) \leftrightarrow H(f)$$

B_c: Δf where frequencies become uncorrelated

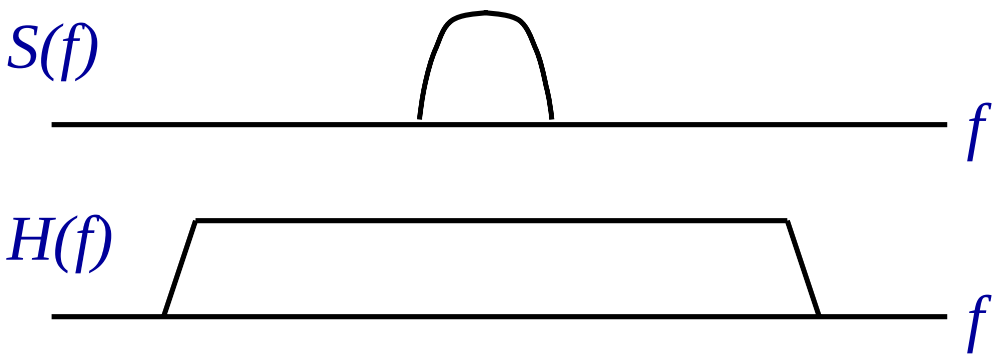
corr.>0.5

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

Flat fading

All frequency components fade identically.

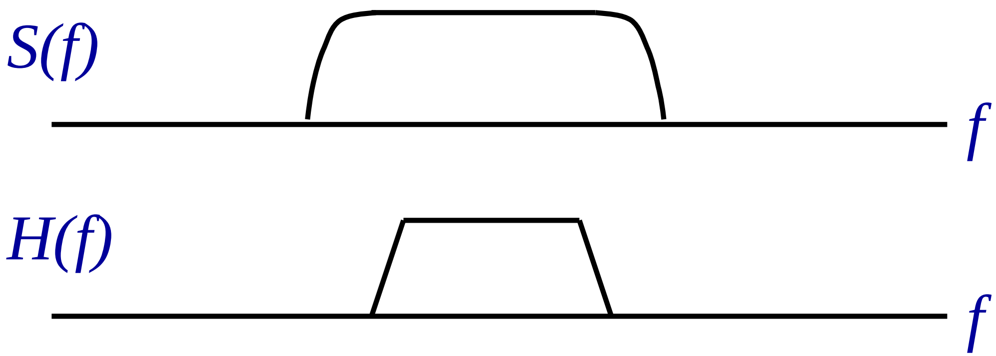
$$B_s << B_c \qquad T_s >> \sigma_\tau$$



Frequency-selective fading

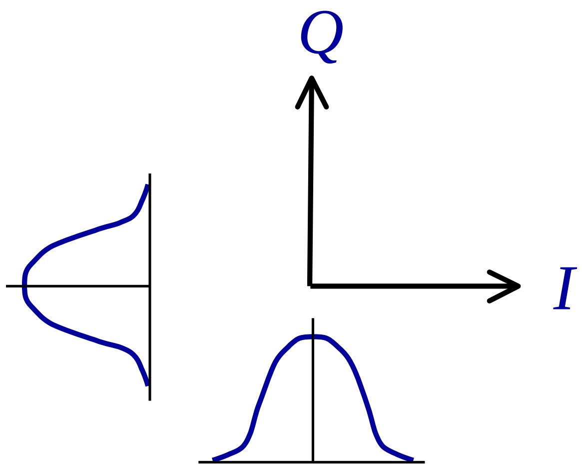
Different frequency components fade differently.

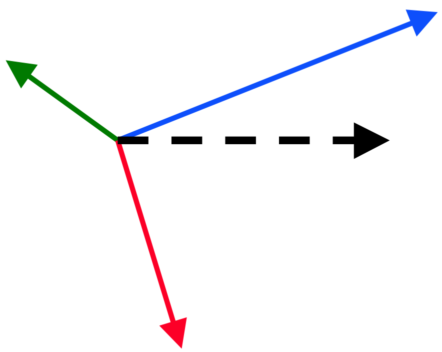
$B_s > B_c$ $T_s < \sigma_\tau$



Rayleigh fading

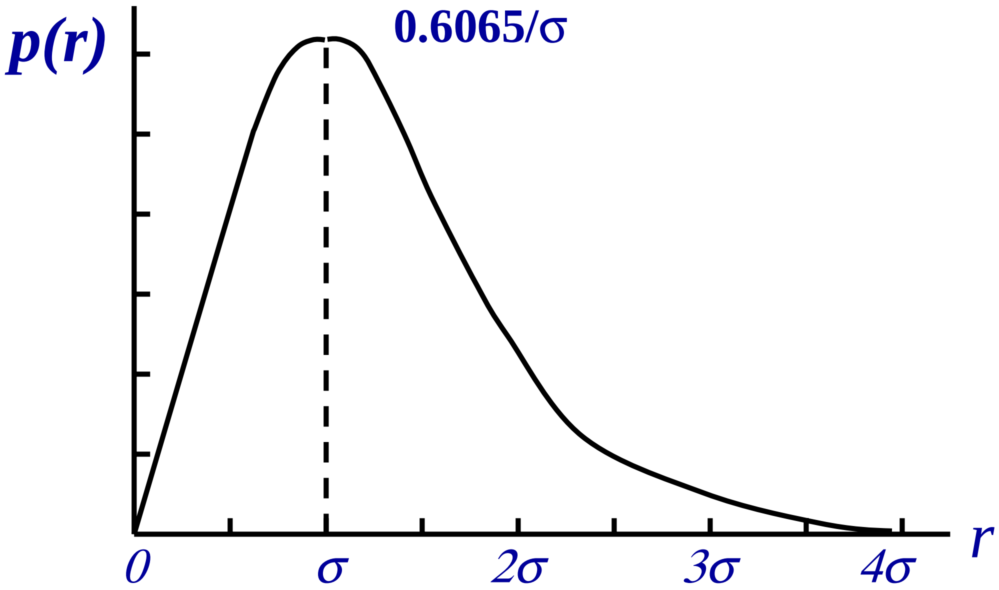
- Amplitude fading
- *N* i.i.d. components: resultant Normally (Gaussian) distributed
- Gaussian distribution on *I* and *Q* gives Rayleigh on envelope





Rayleigh distribution

$$p(r) = \frac{r}{\sigma^2} \exp\left(-\frac{r^2}{2\sigma^2} \right) \quad (r \geq 0)$$

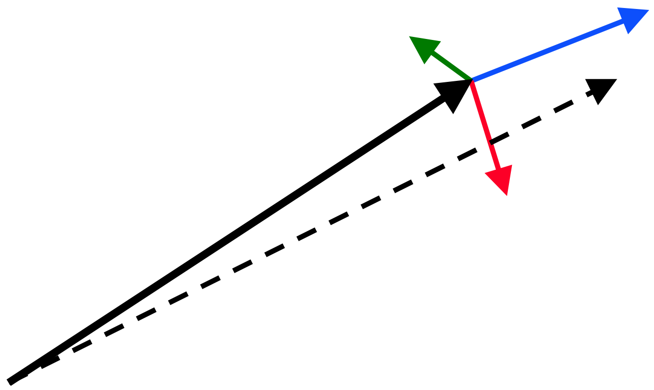


$$\bar{r} = 1.2533\sigma$$

$$\sigma_r^2 = 0.4292\sigma^2$$

Rician fading

- **Amplitude fading**
- **One dominant component + *N* i.i.d. components: resultant Rician distributed**



Rician distribution

$$p(r) = \frac{r}{\sigma^2} \exp\left(-\frac{r^2 + A^2}{2\sigma^2}\right) I_0\left(\frac{Ar}{\sigma^2}\right) \quad (A, r \geq 0)$$

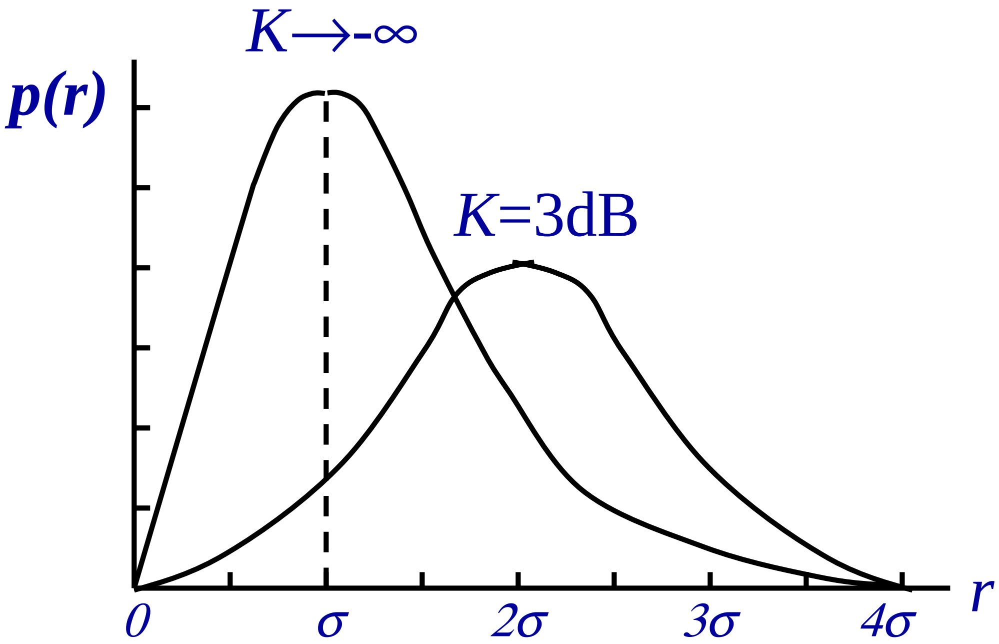
***A*: amplitude of dominant component**
I_0: zero-order Bessel function

Rician factor: $K = \dfrac{A^2}{2\sigma^2}$

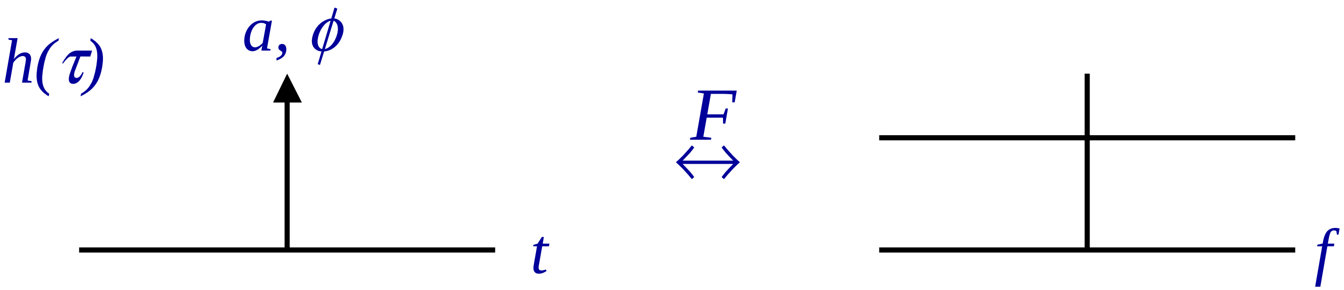
Rician distribution

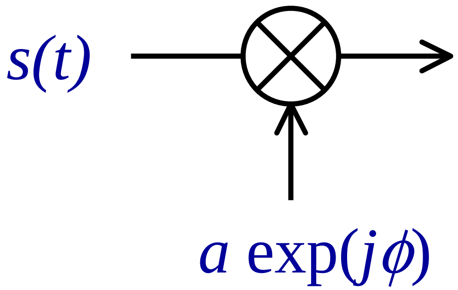
$K \to -\infty$: approaching Rayleigh

$K \to \infty$: approaching $N(A,\sigma)$



Modeling: flat fading

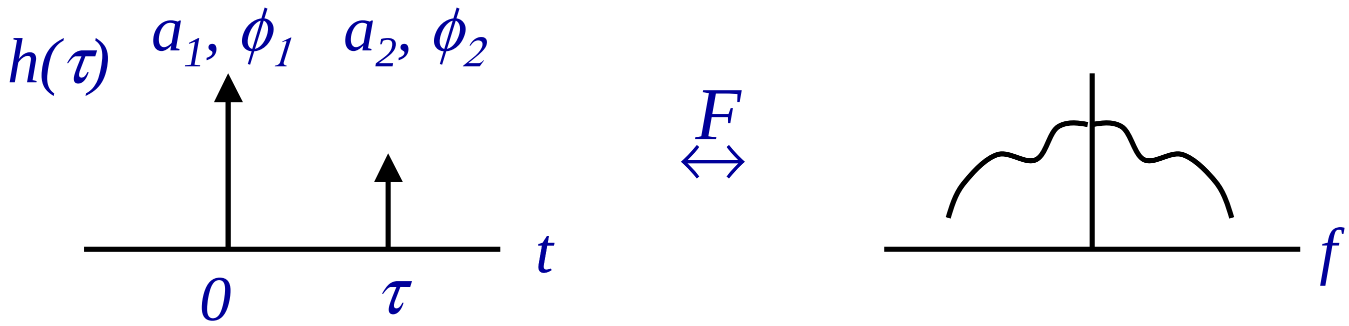


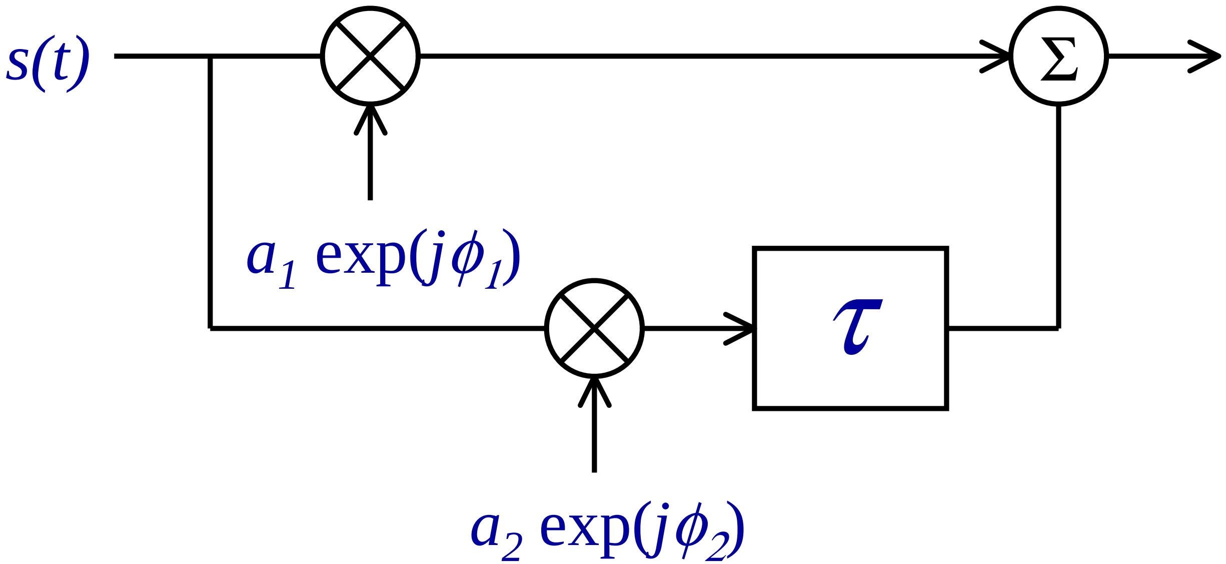


a: Rayleigh dist.

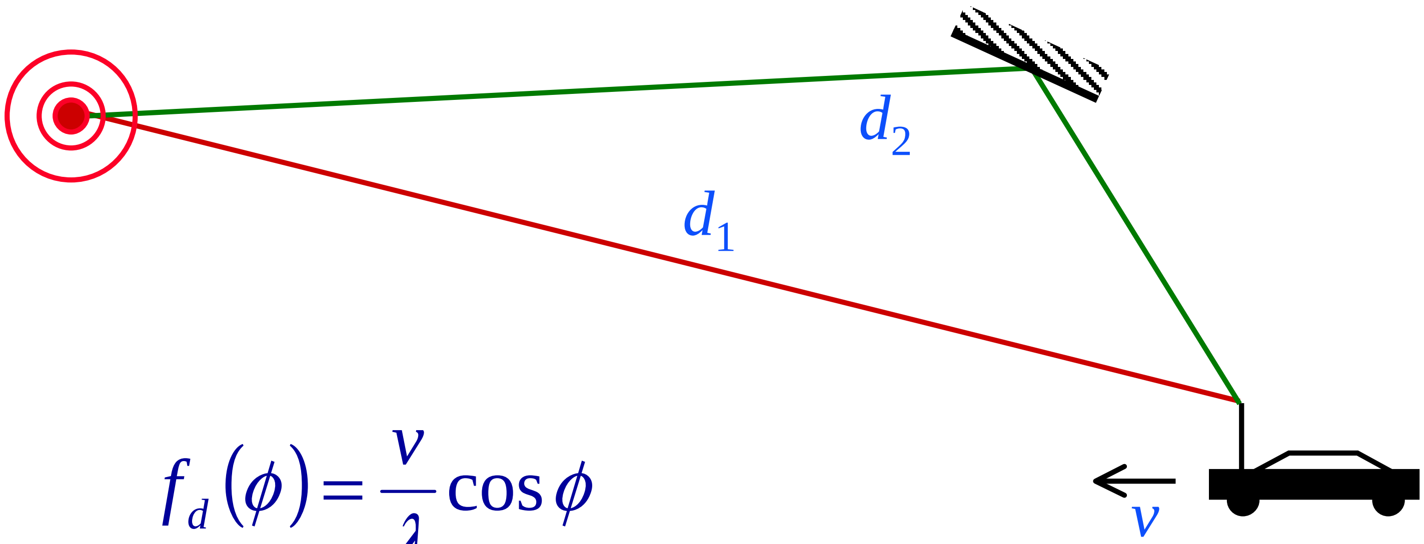
ϕ: uniform (0,2π]

Modeling: 2-ray fading





Doppler spread



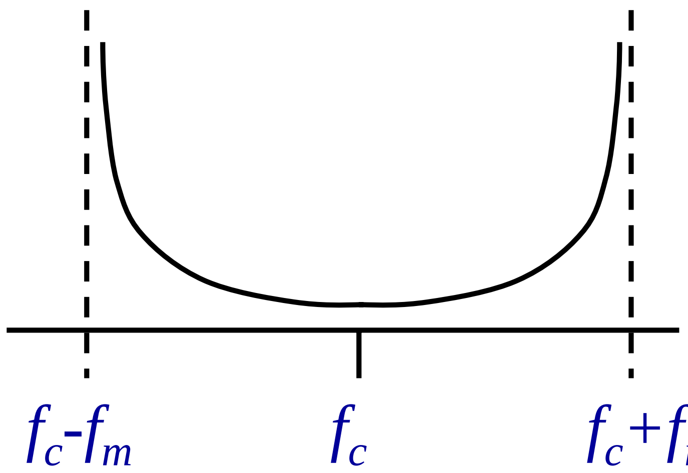
$$f_d(\phi) = \frac{v}{\lambda}\cos\phi$$

$$0 \le \phi \le \pi \quad \Rightarrow \quad -\frac{v}{\lambda} \le f_d \le \frac{v}{\lambda}$$

Doppler power spectrum

$$S_D(f) = \frac{\alpha}{f_m \sqrt{1 - \left(\frac{f - f_c}{f_m}\right)^2}}$$

$$f_m = \frac{v}{\lambda}$$



Coherence time

$$S_D(f) \leftrightarrow h_D(t)$$

***T_c*: *Δt* where samples become uncorrelated**

$$T_c \approx \frac{1}{2 f_m}$$

Slow and fast fading

Fast fading:

$B_s < B_D$ $T_s > T_c$

Slow fading:

$B_s >> B_D$ $T_s << T_c$

Slow/fast - flat/freq-sel. fading

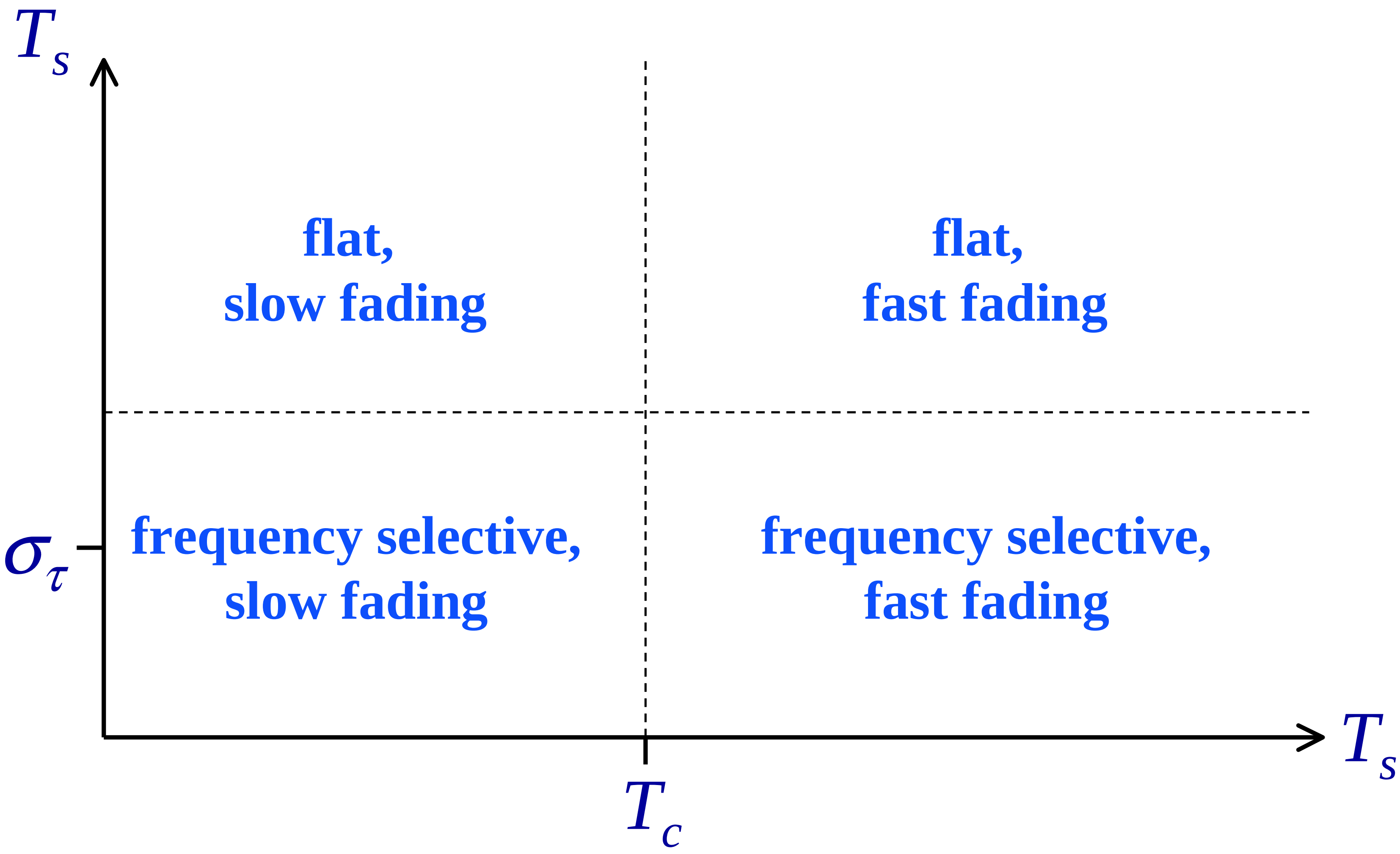
Flat / frequency selective fading:

Echo pattern $h(t,\tau)$

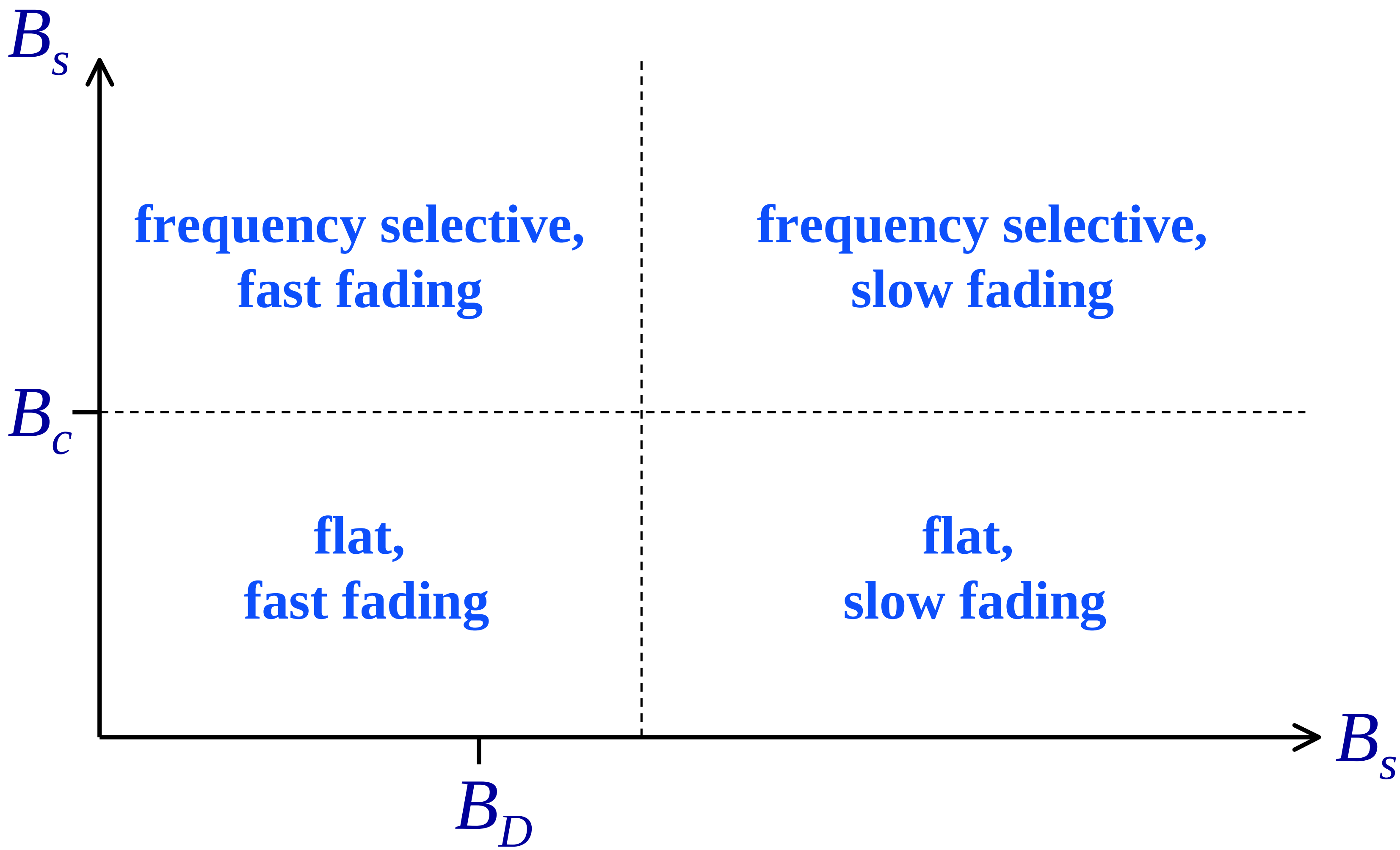
Fast / slow fading:

Motion effects $h(t,\tau)$

Slow/fast - flat/freq-sel. fading



Slow/fast - flat/freq-sel. fading



Multipath time scales

- **Amplitude fading:** $dt \approx \dfrac{1}{f_c}$ **(i.e. *dt*=1ns)**
- **Time dispersion:** $dt \approx \dfrac{\Delta d}{c}$ **(i.e. *dt*=1μs)**
- **Doppler spread:** $dt \approx \dfrac{1}{f_d}$ **(i.e. *dt*=10ms)**

FOR NEXT WEEK

- **Read:**

  Chapter 5: §5.1, 5.2 (not 5.2.2, 5.2.3), 5.3 (not 5.3.2, 5.3.3)

  §5.4 - 5.9 (not 5.7.8)

- **Solve problems:**

  Chapter 4: 4.2, 4.3, 4.5, 4.18, 4.21