Chapter 3
Mobile Radio Propagation

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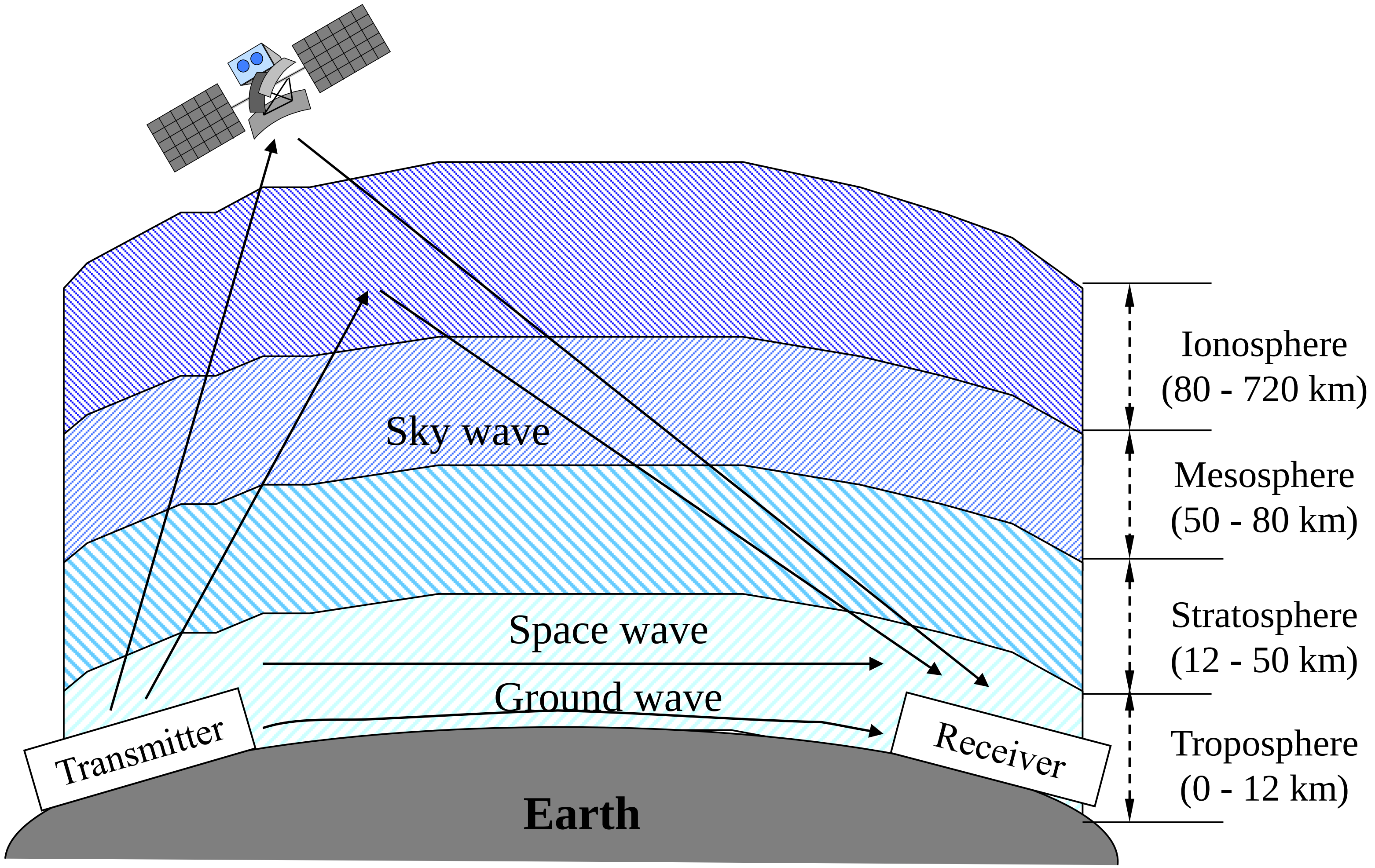
Outline

3.1 Introduction

- For a wireless and mobile system design, it is very important to understand the distinguishing features of mobile radio propagation.
- A wireless mobile channel
  ⇒ modeled as a time-varying communication path between two stations.
  - Multipath propagation channel with fast fading
- Propagation in multipath channels depends on the actual environment, such as:
  - Antenna height
  - Profile of buildings, trees, roads and terrain
- Mobile radio propagation is described by using appropriate statistical techniques.

3.2 Types of Radio Waves

- Propagation of different types of radio waves



Radio Frequency Bands

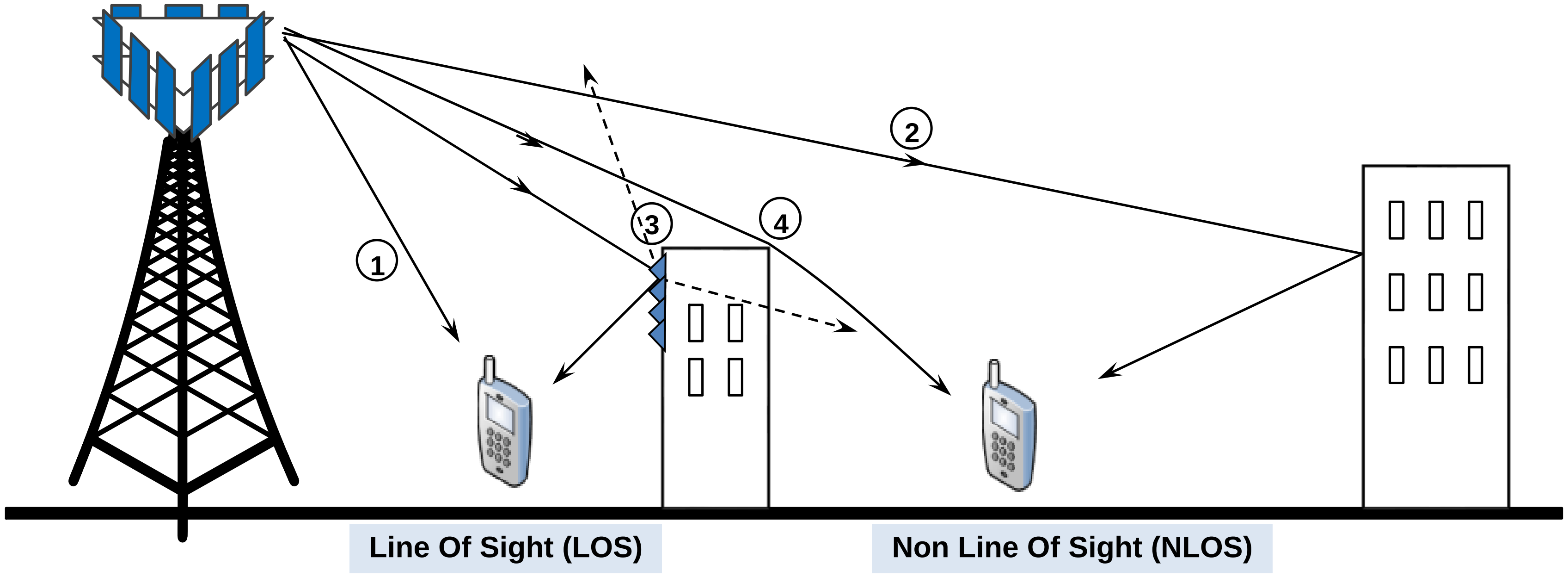
Classification Band	Initials	Frequency Range	Wave Length	Characteristics
Extremely low	ELF	3 Hz - 30 Hz	10^4 – 10^5 km	Ground wave
Super low	SLF	30 Hz – 300 Hz	10^3 – 10^4 km	
Ultra low	ULF	300 Hz - 3 kHz	100 – 10^3 km	
Very low	VLF	3 kHz - 30 kHz	10 – 100 km	
Low	LF	30 kHz - 300 kHz	1 – 10 km	
Medium	MF	300 kHz - 3 MHz	100 m – 1 km	Ground/Sky wave
High	HF	3 MHz - 30 MHz	10 – 100 m	Sky wave
Very high	VHF	30 MHz - 300 MHz	1 – 10 m	Space wave
Ultra high	**UHF**	**300 MHz - 3 GHz**	**10 cm – 1 m**	
Super high	SHF	3 GHz - 30 GHz	1 – 10 cm	
Extremely high	EHF	30 GHz - 300 GHz	1 mm – 1 cm	
Tremendously high	THF	300 GHz - 3000 GHz	0.1 mm - 1 mm	

3.3 Propagation Mechanisms

- **Reflection (반사)**
  - Propagation wave impinges on an object which is large as compared to wavelength (e.g., the surface of the Earth, buildings, walls, etc.)
- **Diffraction (회절)**
  - Radio path between transmitter and receiver obstructed by surface with sharp irregular edges
  - Waves bend around the obstacle, even when LOS (line of sight) does not exist
- **Scattering (산란)**
  - Objects smaller than the wavelength of the propagation wave (e.g. foliage, street signs, lamp posts)

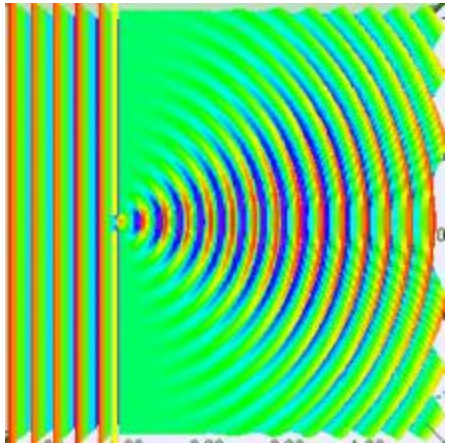
Multipath Propagation

- The received signal consists of several paths.
  1. Direct Path
  2. Reflected Path
  3. Scattered Path
  4. Diffracted Path



Multipath Propagation

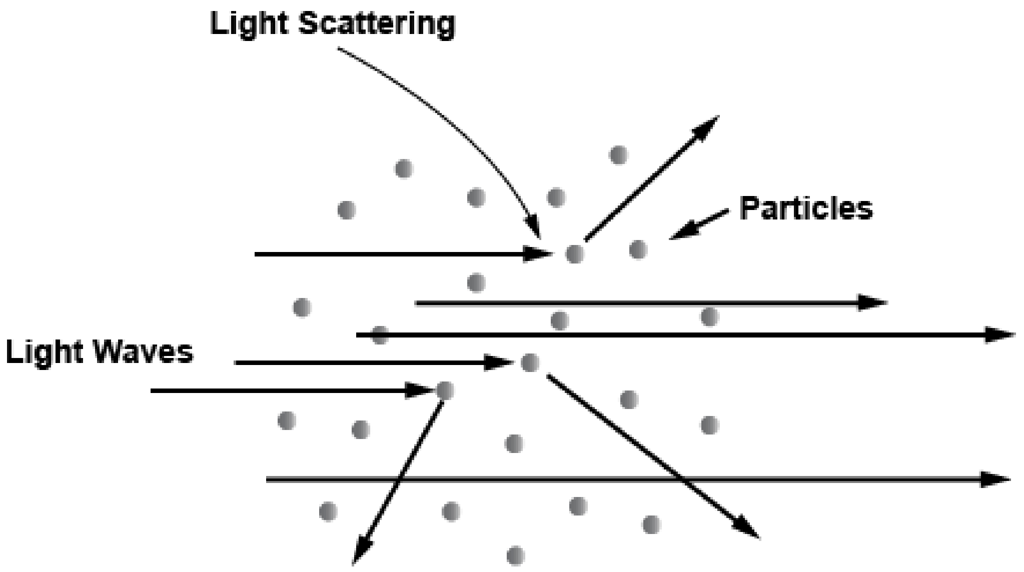
- Reflection
  - It occurs when a propagating electromagnetic wave intrudes upon an object which has very large dimensions when compared to the wavelength of the propagating wave.
  - Reflection occurs from the surface of the earth and from buildings and walls.
- Diffraction
  - Various phenomena which occur when a wave encounters an obstacle.
  - The apparent bending of waves around small obstacles and the spreading out of waves past small openings



Source: https://courses.lumenlearning.com/

Multipath Propagation

- Scattering:
  - It occurs when the medium through which the wave travels consists of objects with dimensions that are small compared to the wavelength, and where the number of obstacles per unit volume is large.
  - Scattered waves are produced by rough surfaces, small objects, or by other irregularities in the channel.



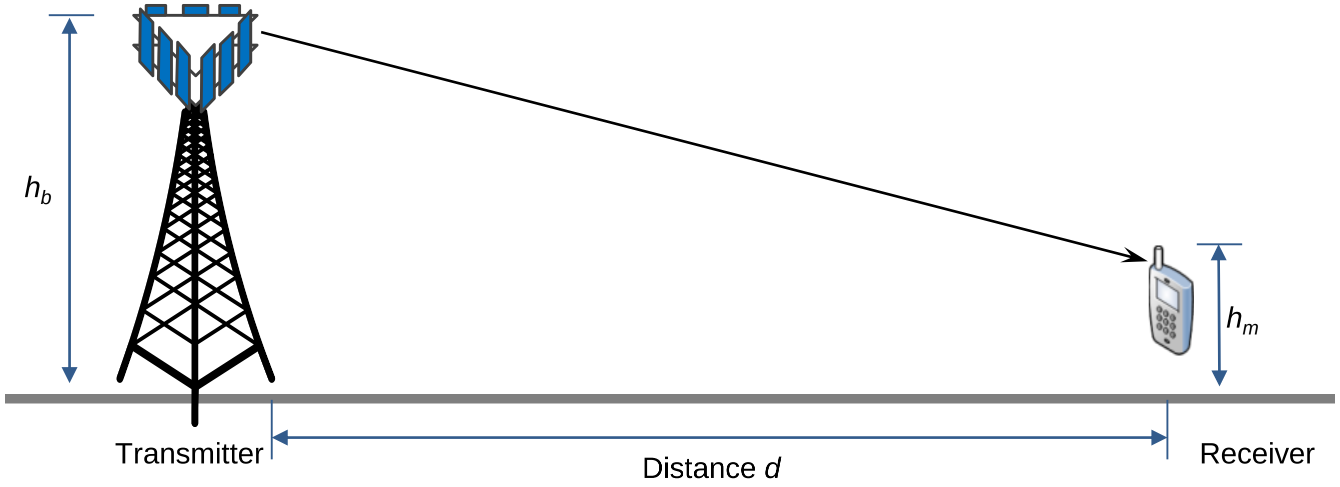
Source: Solid-State Laser Crystal and Device Laboratory

3.4 Free Space Propagation

- The received signal power at distance *d*:

$$P_r = \frac{A_e G_t P_t}{4\pi d^2}$$

  - P_t : transmitting power at an isotropic point source,
  - A_e : effective area,
  - G_t : the transmitting antenna gain.
  - Assuming that the radiated power is uniformly distributed over the surface of the sphere.



3.4 Free Space Propagation

- The received signal power P_r at distance d is given by:

$$P_r = \frac{A_e G_t P_t}{4\pi d^2} \qquad (1)$$

- Relationship between an effective aperture and the receiving antenna gain G_r can be given by

$$G_r = \frac{4\pi A_e}{\lambda^2} \qquad (2)$$

where λ is the wavelength of the electromagnetic wave.
By substituting A_e of the equation (2) into (1), we obtain

$$P_r = \frac{G_r G_t P_t}{\left(\frac{4\pi d}{\lambda}\right)^2} \qquad (3)$$

3.4 Free Space Propagation

- **Free space path loss L_f** is defined as

$$L_f = \frac{P_t}{P_r} = \frac{1}{G_r G_t}\left(\frac{4\pi d}{\lambda}\right)^2 \quad (4)$$

  - L_f: the amount of power lost in the space.
  - A larger loss implies the use of higher transmitting power level, as the received signal strength must be at some minimal power level for correct reception at the receiver.

- When $G_t = G_r = 1$, free space path loss is given by

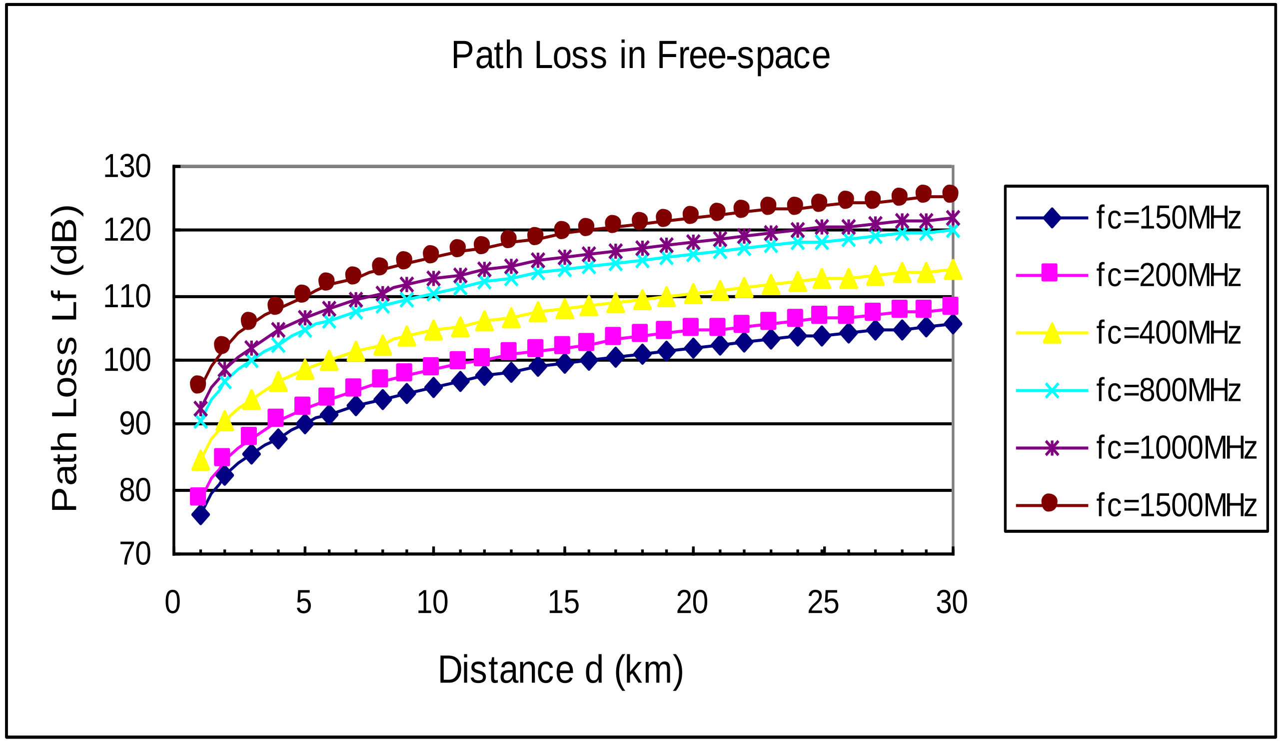
$$\boxed{L_f = \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi \boldsymbol{f_c d}}{c}\right)^{\mathbf{2}}} \quad (5)$$

where c is the speed of light (=2.998 x 10^8 m/s), and
f_c is carrier frequency.

- Free space path loss L_f in decibels (dB)

$$L_f(dB) = 32.45 + 20\log_{10} f_c\ (\text{MHz}) + 20\log_{10} d\ (\text{km}) \qquad (3.6)$$

⇒ This shows greater the f_c and d, more is the loss.



3.5 Land Propagation

- The received signal power P_r

$$P_r = \frac{G_t G_r P_t}{L} \qquad (3.6)$$

where G_r is the receiver antenna gain,

L is the propagation loss in the channel, i.e.,

$L = L_P \, L_S \, L_F$

Fast fading

Slow fading

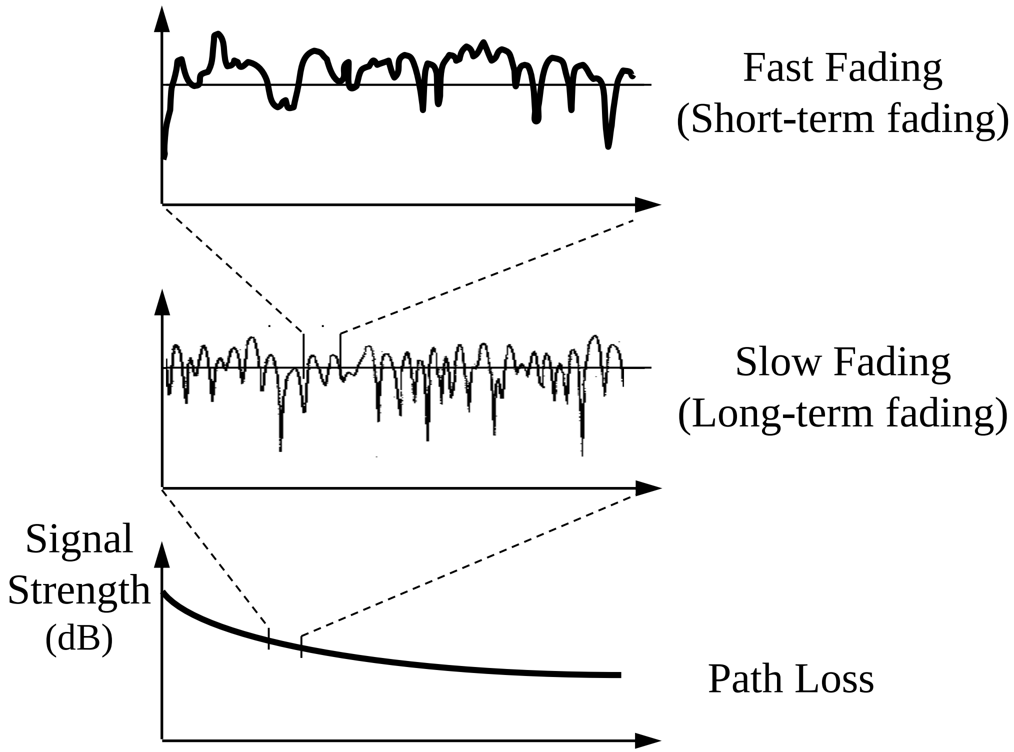
Path loss

3.5 Land Propagation

- Mathematically, **fading** is usually modeled as a time-varying random change in the amplitude and phase of the transmitted signal.
- The **path loss L_P** ⇒ the average propagation loss over a wide area
  - Determined by the macroscopic parameters such as:
    - the distance between the Tx. and Rx.
    - the carrier frequency
    - the land profile
- The **slow fading Loss L_S** ⇒ variation of the propagation loss in a local area (several tens of meters)
  - Caused by the variation in propagation conditions due to buildings, road, and other obstacles in a relatively small area.
  - Slow fading is an overall average fading over some distances traveled by a MS.

3.5 Land Propagation

- The **fast fading Loss L_F** ⇒ microscopic aspect of the channel
  - Due to the motion of the MS that consists of many diffracted waves.
  - Fast fading is a fast-changing fading. (e.g., every step taken by a moving MS)



3.6 Path Loss

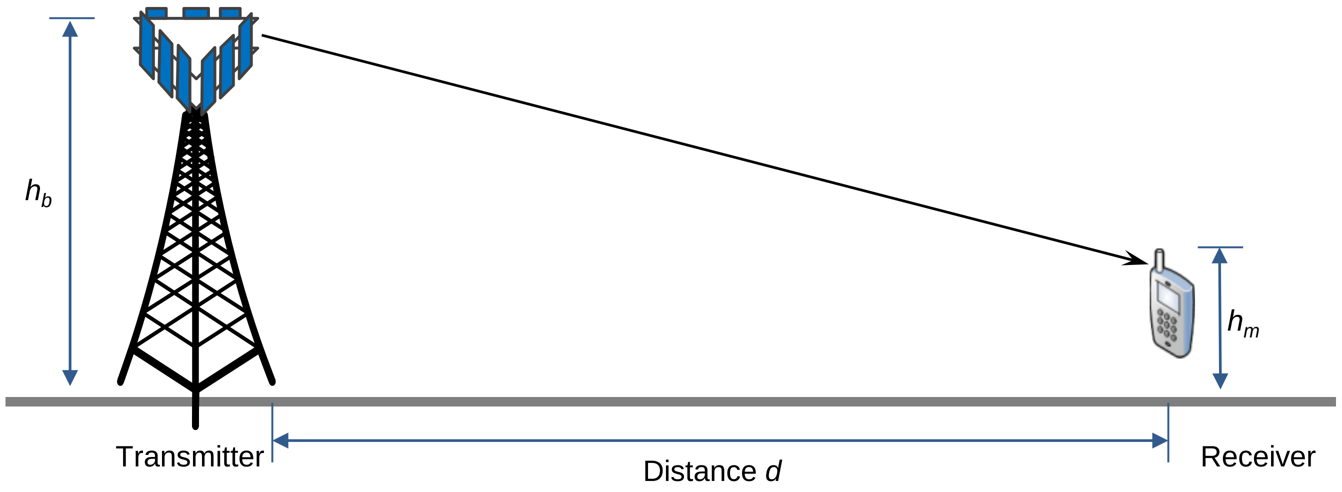
- The simplest formula for path loss of land propagation is

$$L_P = Ad^{\alpha}$$

where A and α are propagation constant,

d : distance between Tx and Rx.

  - $\alpha = 2$ for free space
  - $\alpha = 3 \sim 4$ for typical urban area



3.6 Path Loss

- Hata Model (based on Okumura model)
  - Urban Area

$$L_{PU}(dB) = 69.55 + 26.16\log_{10} f_c(MHz) - 13.82\log_{10} h_b(m) - \alpha\left[h_m(m)\right]$$
$$+\left[44.9 - 6.55\log_{10} h_b(m)\right]\log_{10} d(km)$$

where $L_{PU}(dB) = 10\log_{10} L_{PU}$,

f_c is carrier frequency (150~1500 MHz),

h_b is the effective BS antenna height (30~200m),

h_m is the MS antenna height (1~10m),

$\alpha[h_m]$ is a correction factor for the mobile antenna height.

$$\alpha\left[h_m(m)\right] = \begin{cases} \left[1.1\log_{10} f_c(MHz) - 0.7\right]h_m(m) - \left[1.56\log_{10} f_c(MHz) - 0.8\right], & \text{for large city} \\ \left.\begin{array}{l} 8.29\left[\log_{10} 1.54 h_m(m)\right]^2 - 1.1, \quad for \quad f_c \le 300MHz \\ 3.2\left[\log_{10} 11.75 h_m(m)\right]^2 - 4.97, \quad for \quad f_c \ge 300MHz \end{array}\right\}, & \text{for small \& medium city} \end{cases}$$

3.6 Path Loss

- Hata Model (based on Okumura model) (Cont'd)
  - Suburban Area

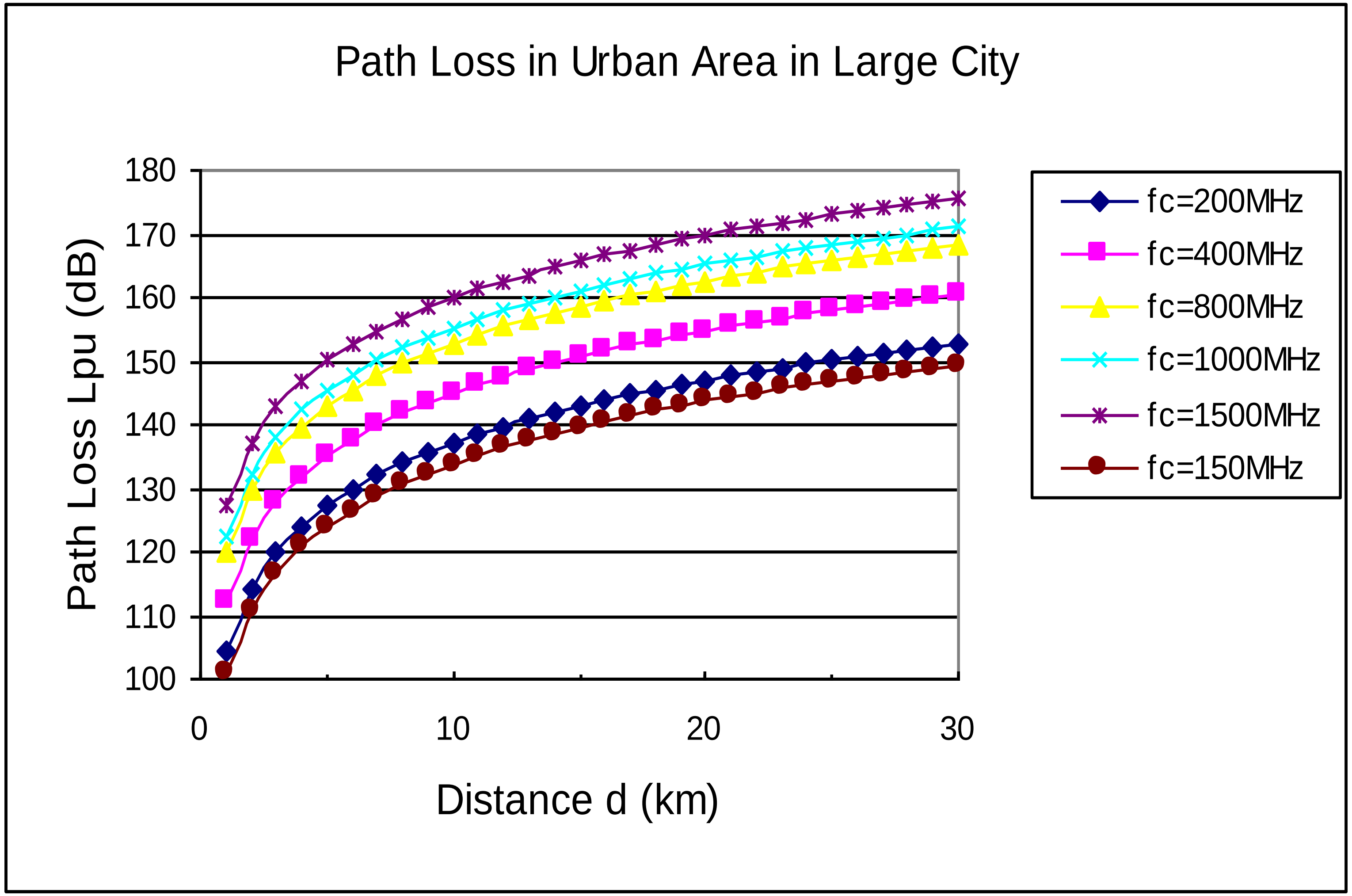
$$L_{PS}(dB) = L_{PU}(dB) - 2\left[\log_{10}\frac{f_c(MHz)}{28}\right]^2 - 5.4$$

  - Open Area

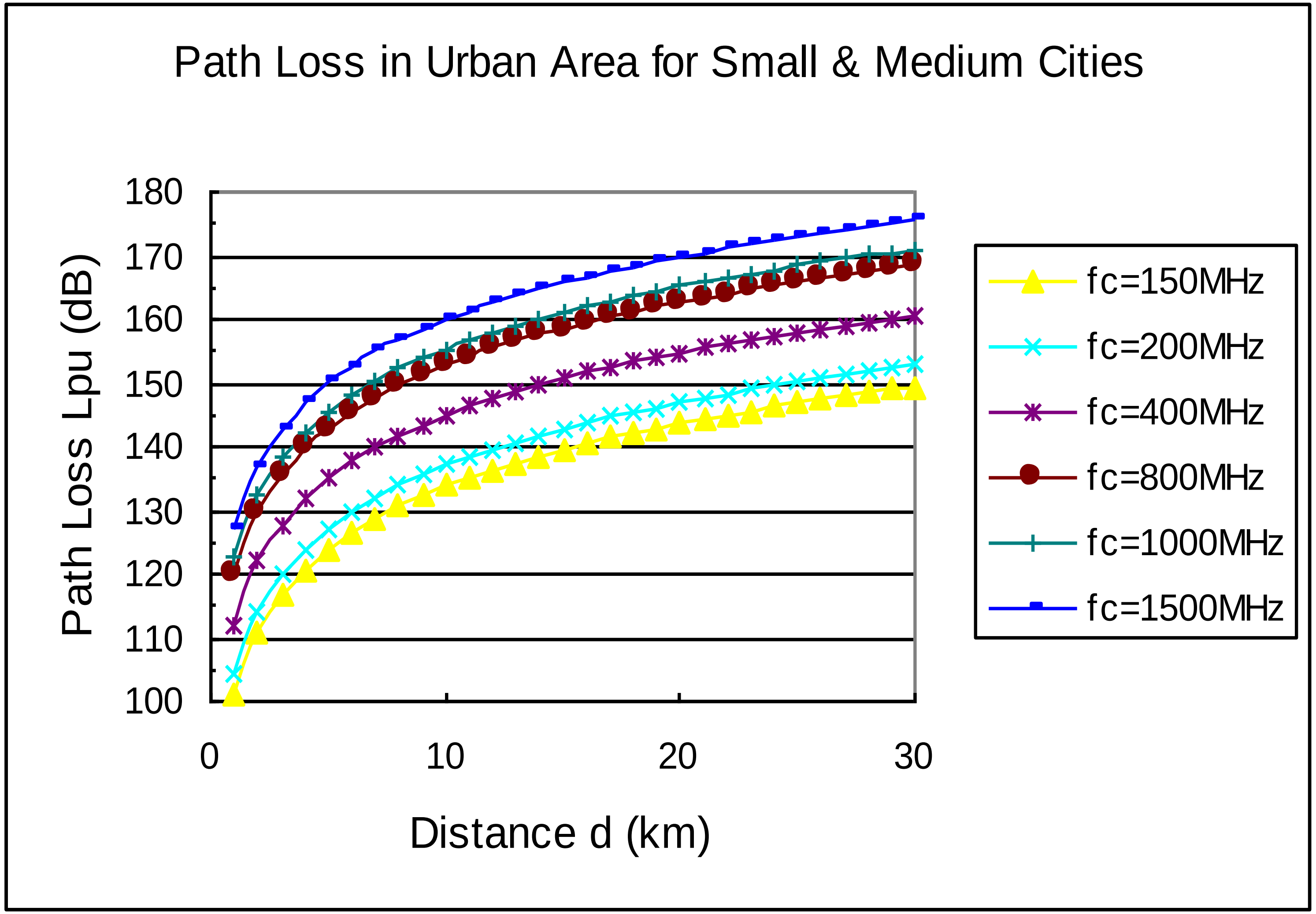
$$L_{PO}(dB) = L_{PU}(dB) - 4.78\left[\log_{10} f_c(MHz)\right]^2 + 18.33\log_{10} f_c(MHz) - 40.94$$

- Path loss in decreasing order
  - Urban area (large city)
  - Urban area (medium and small city)
  - Suburban area
  - Open area

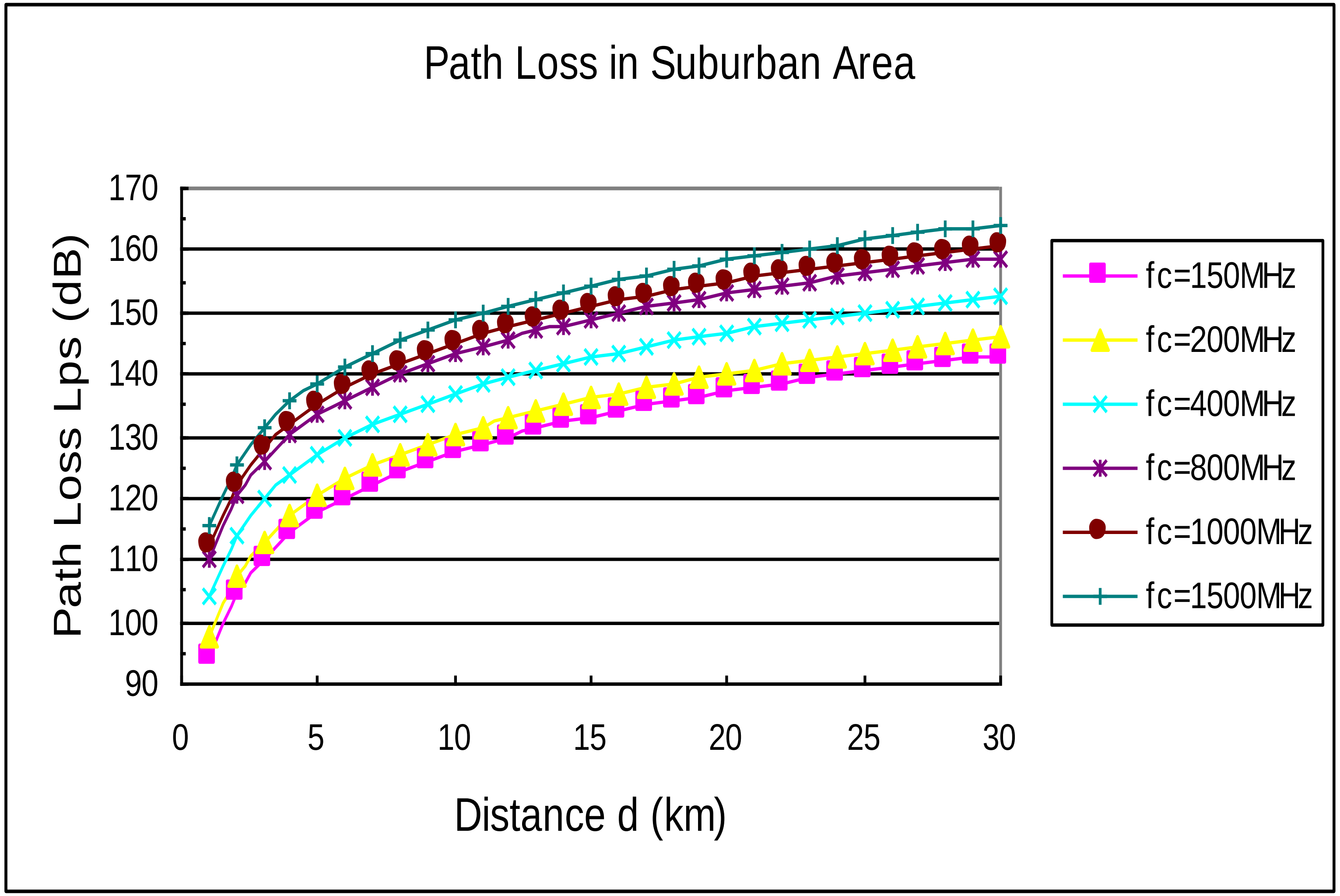
Path Loss Example for Urban: large city



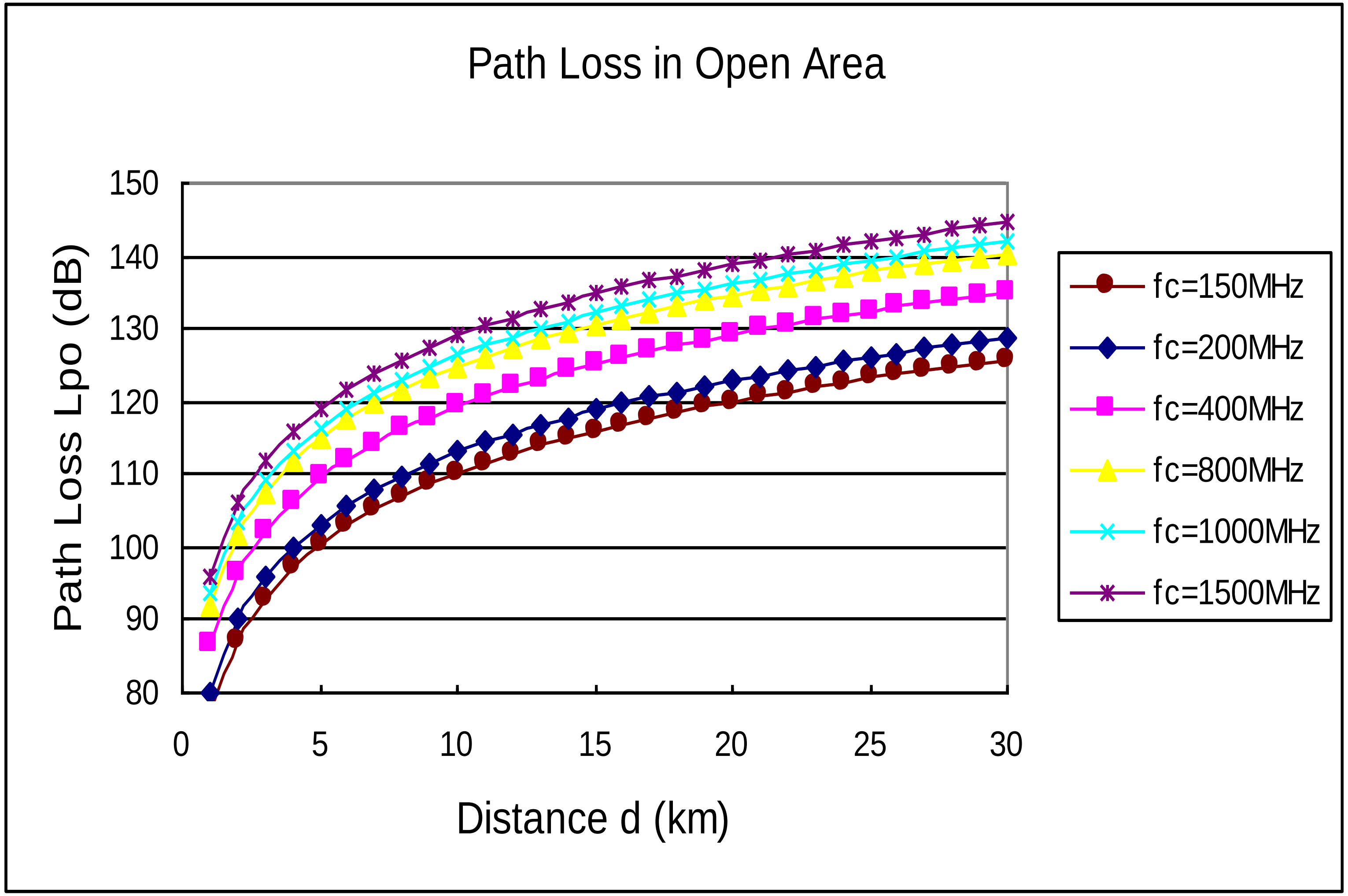
3.6 Path Loss
Path Loss Example for Urban: Small & Medium city



3.6 Path Loss
Path Loss Example for Suburban



3.6 Path Loss
Path Loss Example for Open Area



3.7 Slow Fading

- **Slow fading** is caused by the **long term** spatial and temporal variations over distances large enough to produce gross variations in the overall path between transmitter and receiver.
  - The long-term variation in the mean level is known as slow fading.
  - Also called **shadowing** or **log-normal fading**, because its amplitude has a log-normal pdf.

- In slow fading, the local mean value $r_m(d)$ at location d is defined as follows:

$$r_m(d) = \frac{1}{2d_w} \int_{d-d_w}^{d+d_w} r(x)dx,$$

where $r(x)$ is the received signal at position x and d_w is window size.

3.7 Slow Fading

- Slow fading obeys **log-normal distribution**.
  - The pdf of the received signal level is given in decibels by

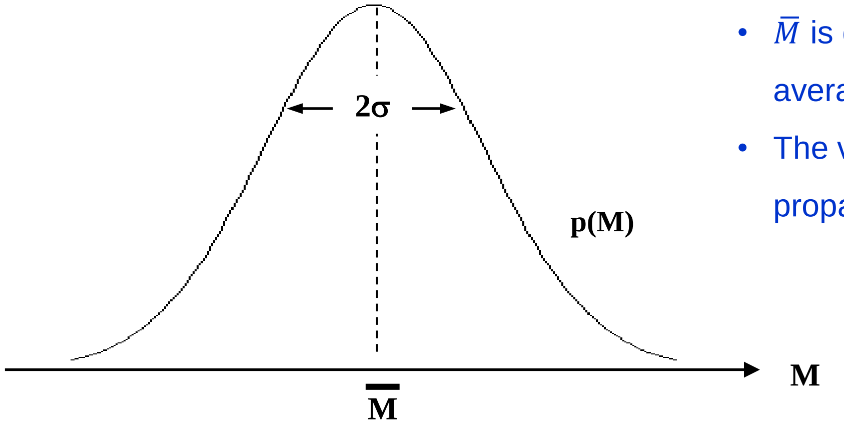
$$p(M) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(M-\bar{M})^2}{2\sigma^2}}$$

where

M : the received signal level m in decibels (dB), (i.e., $M = 10\log_{10} m$),

$\bar{M}$: the area average signal level (i.e., the mean of M), and

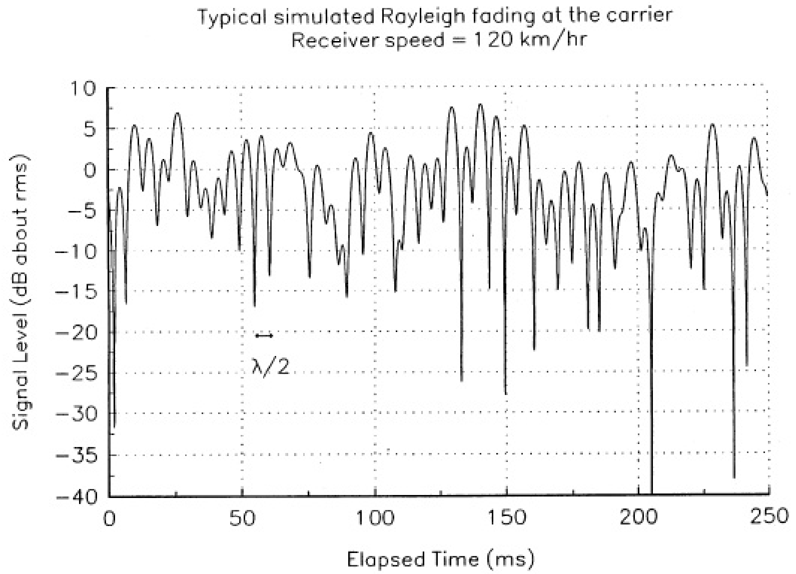
σ : the standard deviation in decibels.



- $\bar{M}$ is defined over a distance that is long enough for average microscopic variation (several wavelengths)
- The variance takes values of 4~12dB depending on the propagation environment.

3.8.1 Statistical Characteristics of Envelope

- Fast fading
  - Fast fading is due to **scattering** of the signal by object near transmitter.
  - The signal from the transmitter may be reflected from objects such as hills, buildings, or vehicles. ⇒ **multipath** fading
  - The rapid fluctuations in the spatial and temporal characteristics caused by local multipath ⇒ fast fading
  - Distances of about half wavelength result in fast fading.



3.8.1 Statistical Characteristics of Envelope

- Receiver Far from the transmitter ⇒ Rayleigh fading
  - Assume that
    - No direct radio waves between Tx. and Rx.
    - Pdf of signal amplitude of every path is a Gaussian distribution.
    - Their phase distribution is uniform within $(0, 2\pi)$ radians.

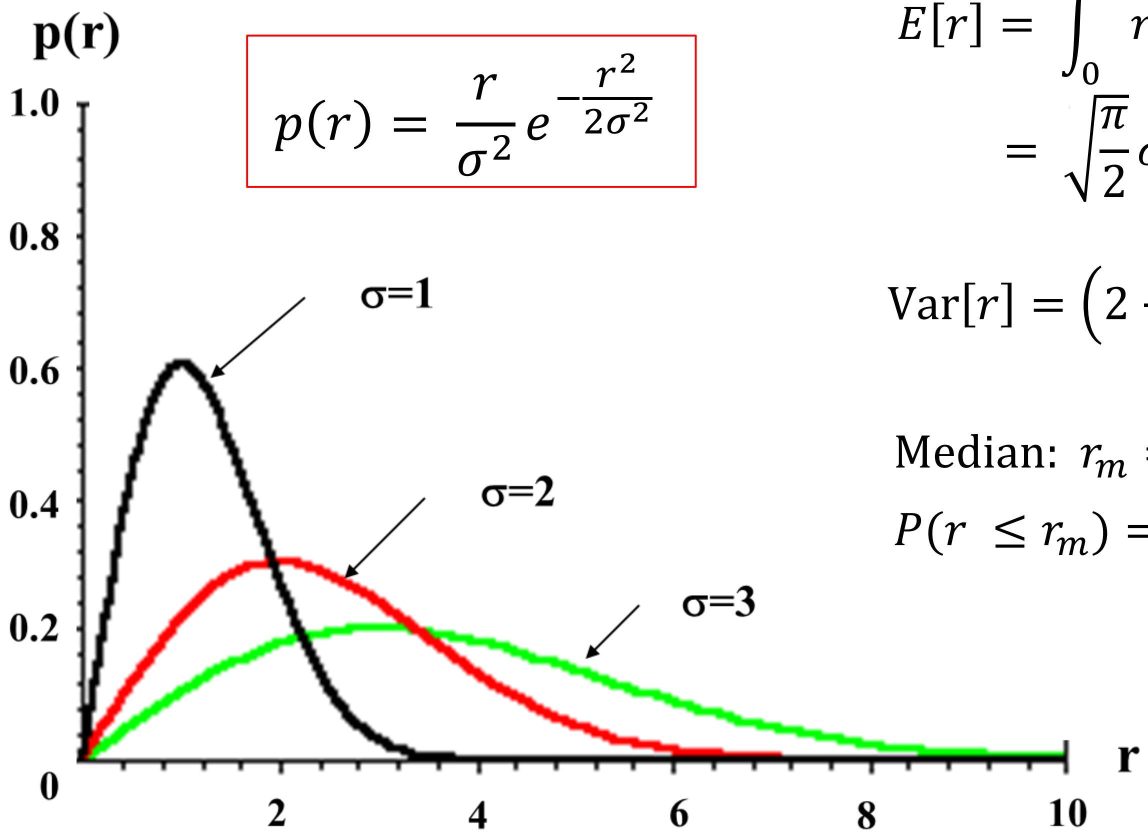
  - Pdf of the envelope for the composite signals ⇒ **Rayleigh distribution**
    - $R \sim \text{Rayleigh}(\sigma), R = \sqrt{X^2 + Y^2}$ where $X \sim N(0, \sigma^2)$, $Y \sim N(0, \sigma^2)$ are independent.
    - Pdf of Rayleigh distribution

$$p(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}}, \qquad r > 0$$

where r : envelope of the fading signal
σ : standard deviation.

3.8.1 Statistical Characteristics of Envelope

- Pdf of Rayleigh distribution



$$p(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}}$$

$$E[r] = \int_0^\infty r p(r) dr$$
$$= \sqrt{\frac{\pi}{2}}\sigma \approx 1.25\sigma$$

$$\mathrm{Var}[r] = \left(2 - \frac{\pi}{2}\right)\sigma^2 \approx 0.429\sigma^2$$

Median: $r_m = 1.777\sigma$

$P(r \le r_m) = 0.5$

3.8.1 Statistical Characteristics of Envelope

- Receiver close to the transmitter ⇒ Rician fading
  - Assume that
    - Direct radio wave is stronger compared to other waves between Tx. and Rx.
    - Pdf of signal amplitude of every path is a Gaussian distribution.
    - Their phase distribution is uniform within $(0, 2\pi)$ radians.
    - Stronger or direct component
  - Pdf of the envelope for the composite signals ⇒ **Rician distribution**
    - $R \sim \text{Rician}(\beta, \sigma), R = \sqrt{X^2 + Y^2}$ where $X \sim N(\beta\cos\theta, \sigma^2)$, $Y \sim N(\beta\sin\theta, \sigma^2)$ are independent.
    - Pdf of Rician distribution

$$p(r) = \frac{r}{\sigma^2} e^{-\frac{(r^2+\beta^2)}{2\sigma^2}} I_0\left(\frac{\beta r}{\sigma^2}\right), \qquad r > 0$$

where r : envelope of the fading signal, σ : standard deviation,

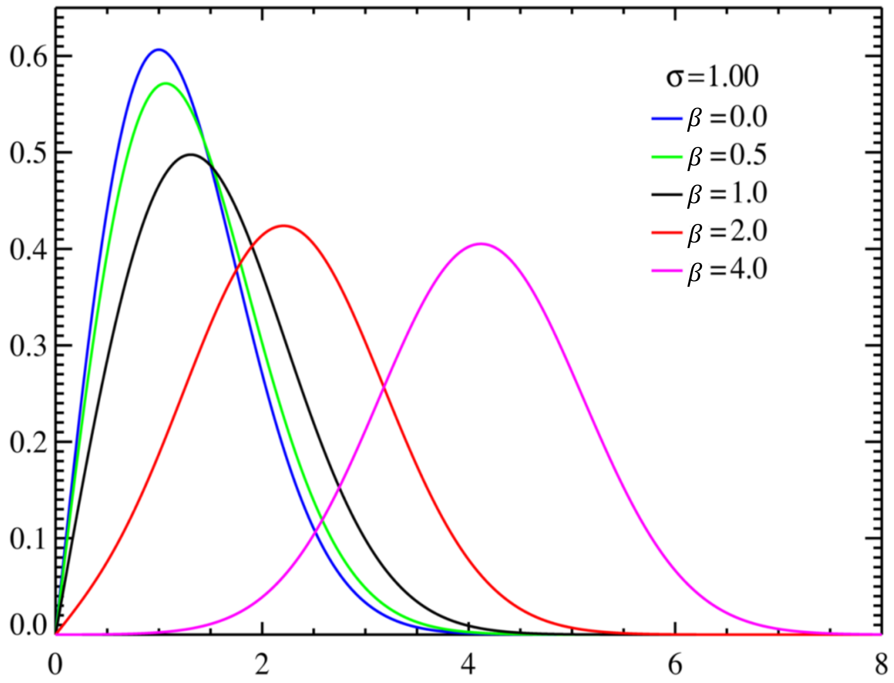
β: the amplitude of direct signal,

$I_0(x)$: zero-order modified Bessel function of the first kind

$$I_0(x) = \frac{1}{2\pi}\int_0^{2\pi} e^{x\cos\theta} d\theta \approx \frac{e^x}{\sqrt{2\pi x}}$$

3.8.1 Statistical Characteristics of Envelope

- Pdf of Rician distribution
  - When the direct signal is very strong ($\beta \gg 1$)
    → can be approximated by a **Gaussian distribution**
  - When the direct signal is very small ($\beta \approx 0$)
    → can be approximated by a **Rayleigh distribution**



3.8.1 Statistical Characteristics of Envelope

- Generalized Model ⇒ Nakagami (or Nakagami-m) distribution
  - Pdf of the envelope for the received signals

$$p(r) = \frac{2r^{2m-1}}{\Gamma(m)}\left(\frac{m}{\Omega}\right)^m e^{-\frac{mr^2}{\Omega}}, \qquad r \geq 0$$

where $\Gamma(m)$: Gamma function,

$\Omega = E[r^2]$: the average power

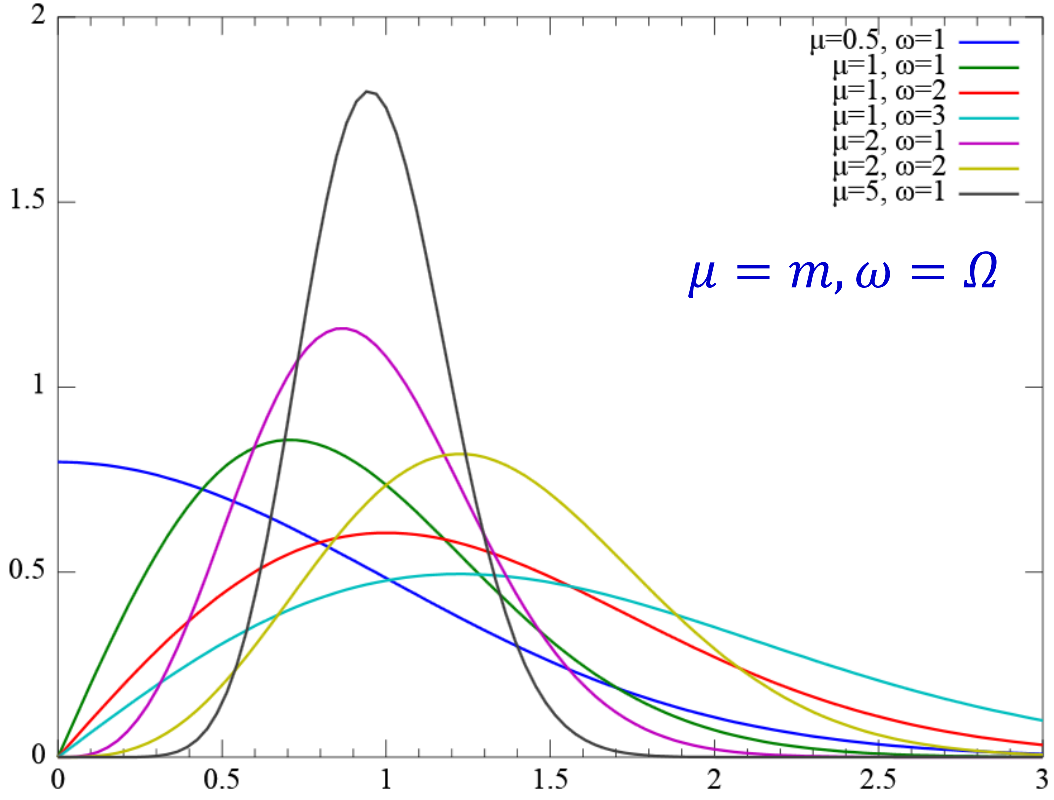
m: fading factor with $m \geq 0.5$, $m = 1$ → Rayleigh distribution.

  - Easier to use than the Rician distribution with Bessel function
  - Indoor and outdoor channel can be often better modeled by Nakagami distribution than Rician distribution.
  - Modeling wireless channel with No LOS → Rayleigh distribution

3.8.1 Statistical Characteristics of Envelope

- Pdf of Nakagami (or Nakagami-*m*) distribution

$$p(r) = \frac{2r^{2m-1}}{\Gamma(m)}\left(\frac{m}{\Omega}\right)^m e^{-\frac{mr^2}{\Omega}}, \qquad r \geq 0$$



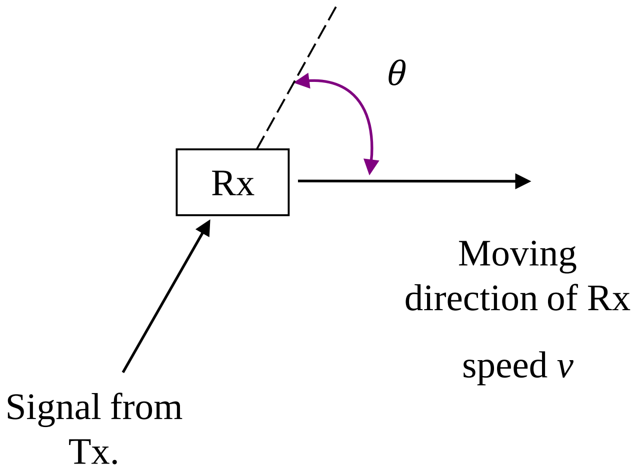
3.8.2 Characteristics of Instantaneous Amplitude

- Level Crossing Rate:
  - Average number of times per second that the signal envelope crosses the level (called threshold) in positive going direction.
- Fading Rate:
  - Number of times signal envelope crosses middle value in positive going direction per unit time.
- Depth of Fading:
  - Ratio of the mean square value and the minimum value of fading signal.
- Fading Duration:
  - Duration for which signal is below given threshold.

3.9 Doppler Effect

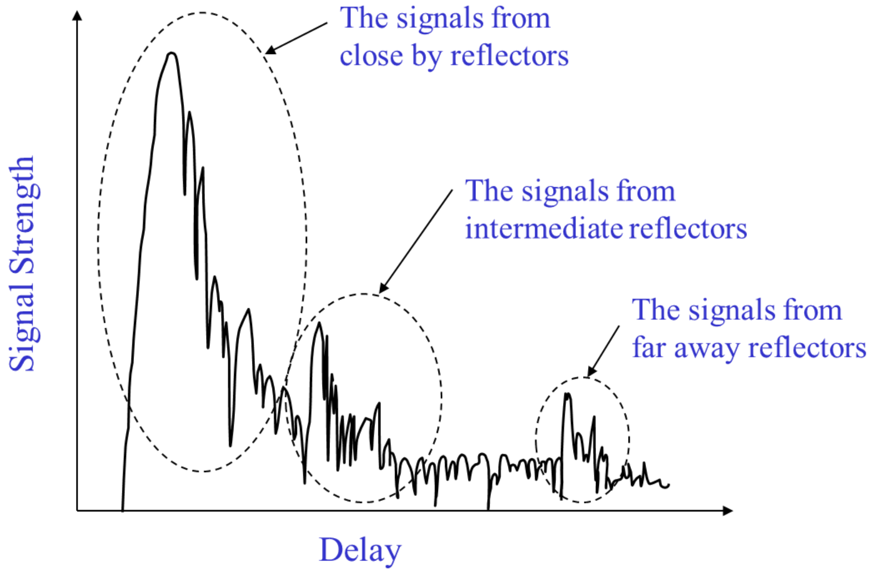
- When a wave source and a receiver are moving towards each other, the frequency of the received signal will not be the same as the source.
  - When they are moving toward each other,
    $\Rightarrow$ the frequency of the received signal is higher than the source.
  - When they are opposing each other,
    $\Rightarrow$ the frequency decreases.

- The freq. f_r of the received signal: $f_r = f_c - f_d$
  - f_c : the frequency of source carrier
  - f_d : the Doppler frequency or Doppler shift
    - $f_d = \frac{v}{\lambda} \cos\theta$
      where v : the moving speed (velocity),
      λ: wavelength



3.10 Delay Spread

- When a signal propagates from a transmitter to a receiver, signal suffers one or more reflections.
  - This forces signal to follow different paths.
  - Each path has different path length, so the time of arrival for each path is different.
  - This effect which spreads out the signal is called **"Delay Spread"**.
- Delay spread can cause **ISI (Inter-Symbol Interference)**.



The average delay

$$\tau_m = \int_0^\infty t p(t) dt$$

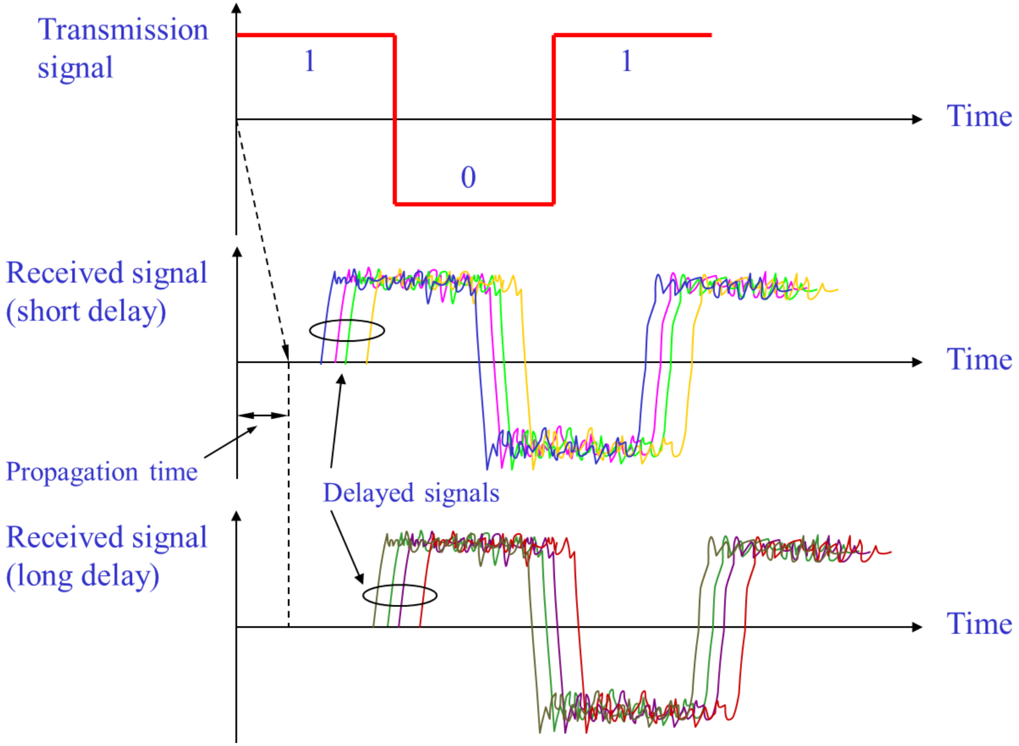
$p(t)$: pdf of the delay t

The delay spread is defined as

$$\tau_d = \sqrt{\int_0^\infty (t - \tau_m)^2 p(t) dt}$$

3.11 InterSymbol Interference (ISI)

- ISI is caused by time delayed multipath signals ⇒ impacts on burst error rate
- Second multipath is delayed and is received during next symbol
- For low bit-error-rate (BER): transmission rate $R < \frac{1}{2\tau_d}$



3.12 Coherence Bandwidth

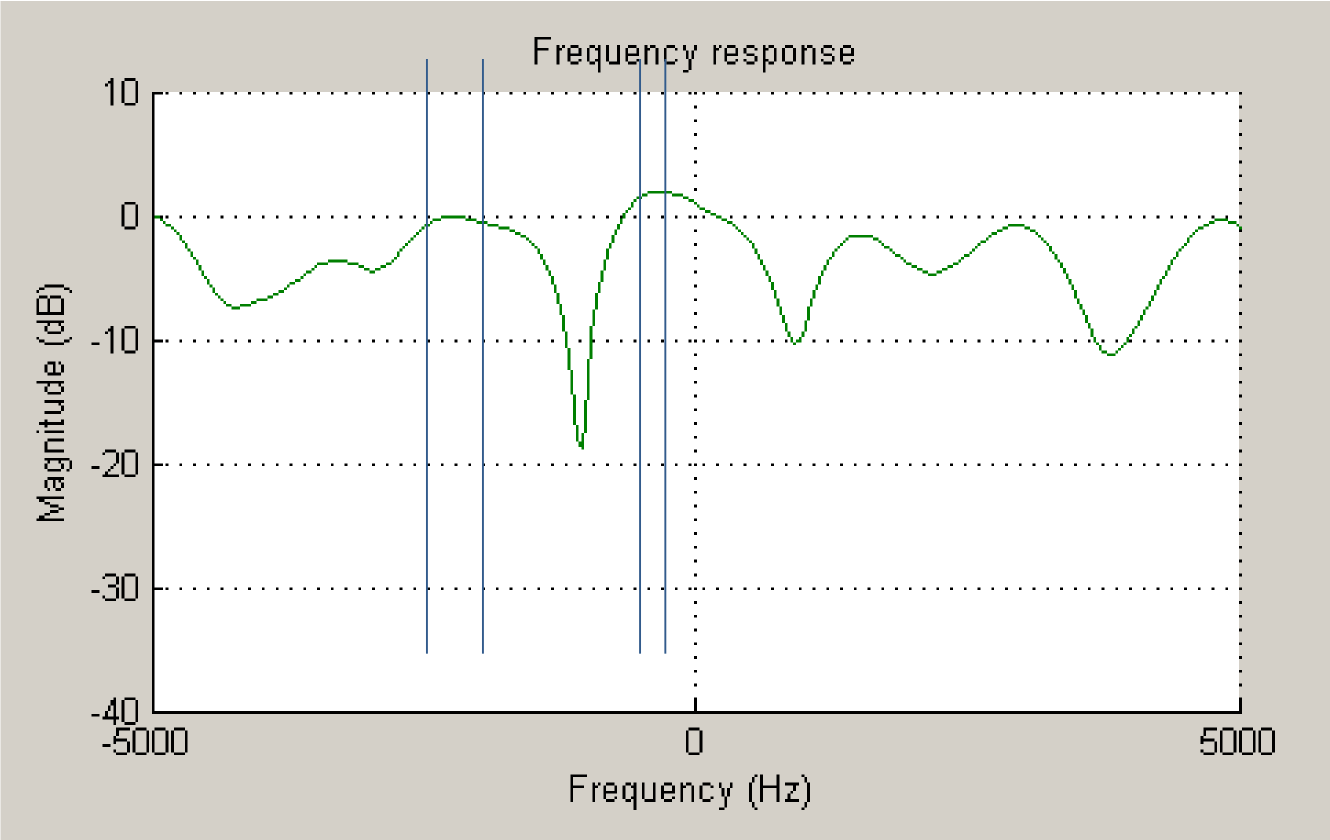
- Coherence Bandwidth B_c
  - The range of frequencies over which the channel can be considered "flat".
    (i.e., a channel which passes all spectral components with approximately equal gain and linear phase)
  - Represents correlation between two fading signal envelopes at frequencies f1 and f2.
  - Coherence bandwidth is a function of delay spread τ_d.

$$B_c \approx \frac{1}{2\pi\tau_d}$$

  - Two frequencies that are larger than coherence bandwidth fade independently. ⇒ useful in diversity reception
    - Multiple copies of same message are sent using different frequencies.

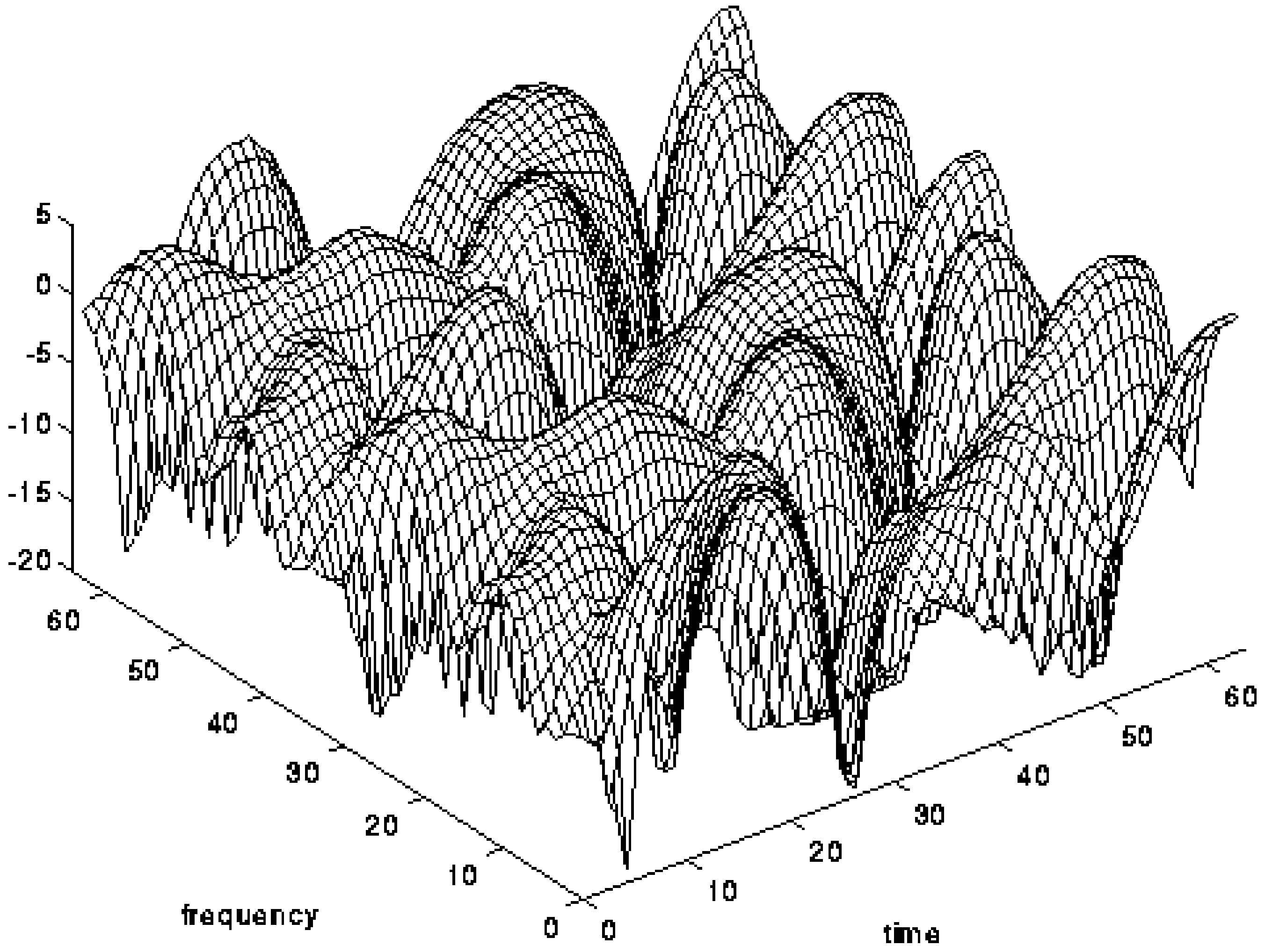
3.12 Coherence Bandwidth

- Coherence Bandwidth B_c



3.12 Coherence Bandwidth

- Wireless channel



3.12 Coherence Bandwidth

- Frequency nonselective fading (Flat fading)
  - If the bandwidth of Tx signal is smaller than the coherent bandwidth,

    $\Rightarrow$ only the gain and phase of the signal are changed

    $\Rightarrow$ No nonlinear transformation.

- Frequency-selective fading
  - If the bandwidth of Tx signal is larger than the coherent bandwidth,

    $\Rightarrow$ part of the Tx signal is truncated

    $\Rightarrow$ Nonlinear transformation can occur

3.13 Co-channel Interference

- Cells having the same frequency interfere with each other.
- P_{co}: the prob. of co-channel interference between cells using the same frequency is less than a given value.
- $P_{co} = P(r_d \le \beta r_u)$
  - r_d : the desired signal level
  - β : the protection ratio
  - r_u : the undesired signal level

Greek Alphabet

대문자	소문자	명칭	대응 영문자	일반적으로 사용되고 있는 표시 사항
A	α	알파(alpha)	A	제1종오류,각도,면적,계수,감쇠상수,흡수율,베이스접지전류이득
B	β	베타(beta)	B	제2종오류,각도,플럭스밀도,위상상수,에미터접지전류이득
Γ	γ	감마(gamma)	G	확률분포형태,각도,도전율,비중
Δ	δ	델타(delta)	D	밀도,각도,변분(變分)
E	ε	엡실론(espsilon)	E	오차,자연대수의밑수,전계강도
Z	ζ	제타(zeta)	Z	임피던스(대문자),계수
H	η	에타(eta)	H	척도모수,히스테리시스계수,효율,표면전하밀도
Θ	θ	시타<테타>(theta)	Q	온도,위상각,시상수,리액턴스,각도
I	ι	이오타<아이오타>(iota)	I	단위벡터
K	κ	카파(kappa)	K	유전계수,서셉티빌리티
Λ	λ	람다(lambda)	L	멱급수,파장,감쇠상수
M	μ	뮤(mu)	M	모평균,마이크로,증폭율,투자율
N	ν	뉴(nu)	N	리럭티비티
Ξ	ξ	크시<크사이>(xi)	X	좌표
O	o	오미크론(omicron)	O	
Π	π	파이<피>(pi)	P	원주율,누적곱
P	ρ	로(rho)	R	상관계수,저항율,좌표
Σ	σ	시그마(sigma)	S	표준편차,도합(대문자),전기도전도,누설계수,표면전하밀도,복소수,전파(電播)상수
T	τ	타우(tau)	T	시상수,시간,위상변위밀도,전송율
Y	υ	윕실론(upsilon)	U	
Φ	ϕ	파이<피>(phi)	F	각도,자속,스칼라전위(대문자)
X	χ	카이(chi)	C	분포형태,각도,전기서셉티빌리티
Ψ	ψ	프시<사이>(psi)	Y	유전속,위상차,좌표,각도
Ω	ω	오메가(omega)	W	각속도,저항(대문자),입체각(대문자)

Thank You !