Chapter 3

Mobile Radio Propagation

Outline

- Speed, Wavelength, Frequency
- Types of Waves
- Radio Frequency Bands
- Propagation Mechanisms
- Radio Propagation Effects
- Free-Space Propagation
- Land Propagation
- Path Loss
- Fading: Slow Fading / Fast Fading
- Delay Spread
- Doppler Shift
- Co-Channel Interference
- The Near-Far Problem
- Digital Wireless Communication System
- Analog and Digital Signals
- Modulation Techniques

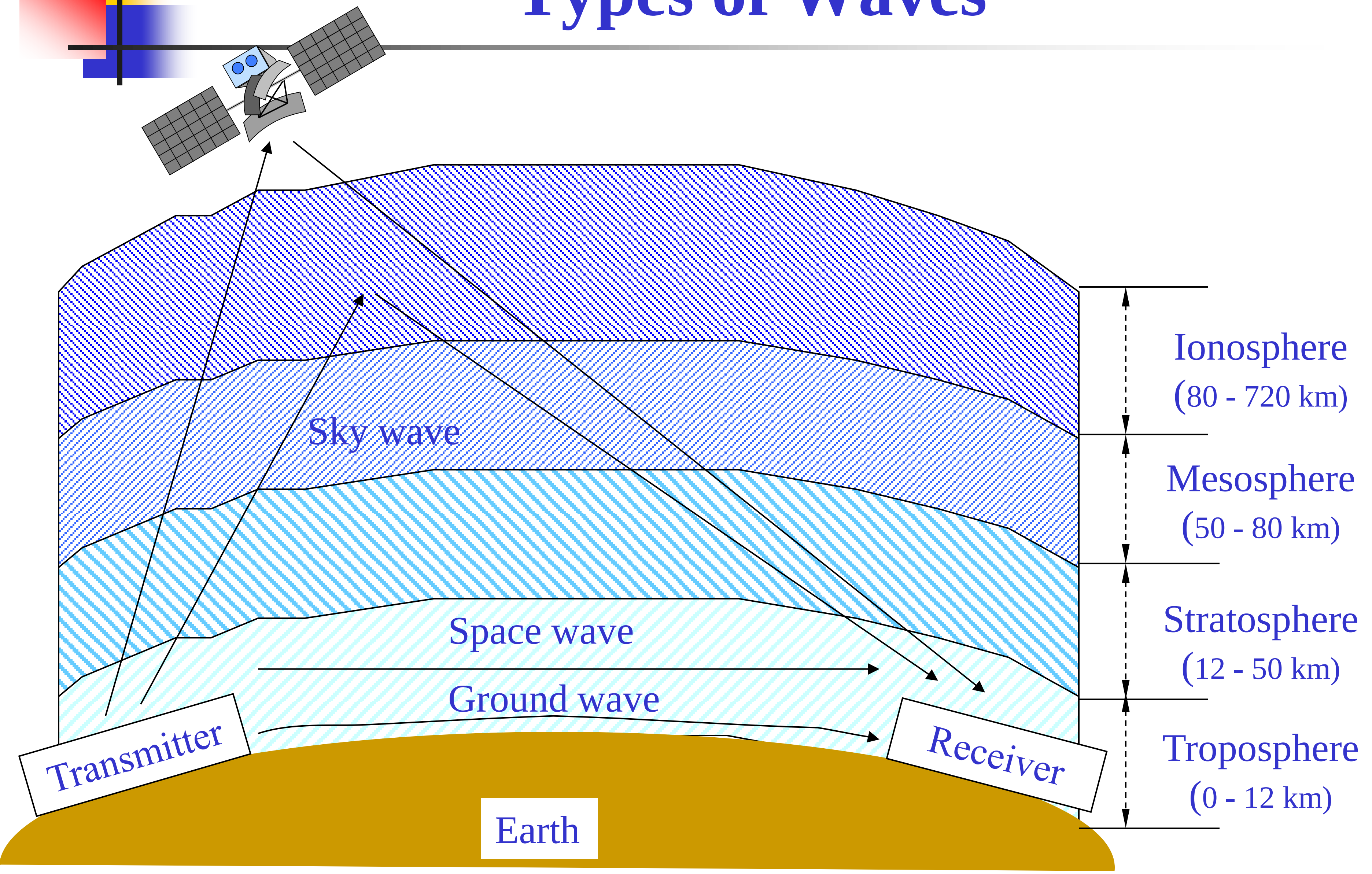
Speed, Wavelength, Frequency

Light speed = Wavelength x Frequency

$= 3 \times 10^8$ m/s = 300,000 km/s

System	Frequency	Wavelength
AC current	60 Hz	5,000 km
FM radio	100 MHz	3 m
Cellular	800 MHz	37.5 cm
Ka band satellite	20 GHz	15 mm
Ultraviolet light	10^{15} Hz	10^{-7} m

Types of Waves



Radio Frequency Bands

Classification Band	Initials	Frequency Range	Characteristics
Extremely low	ELF	< 300 Hz	Ground wave
Infra low	ILF	300 Hz - 3 kHz	
Very low	VLF	3 kHz - 30 kHz	
Low	LF	30 kHz - 300 kHz	
Medium	MF	300 kHz - 3 MHz	Ground/Shy wave
High	HF	3 MHz - 30 MHz	Sky wave
Very high	VHF	30 MHz - 300 MHz	Space wave
Ultra high	UHF	300 MHz - 3 GHz	
Super high	SHF	3 GHz - 30 GHz	
Extremely high	EHF	30 GHz - 300 GHz	
Tremendously high	THF	300 GHz - 3000 GHz	

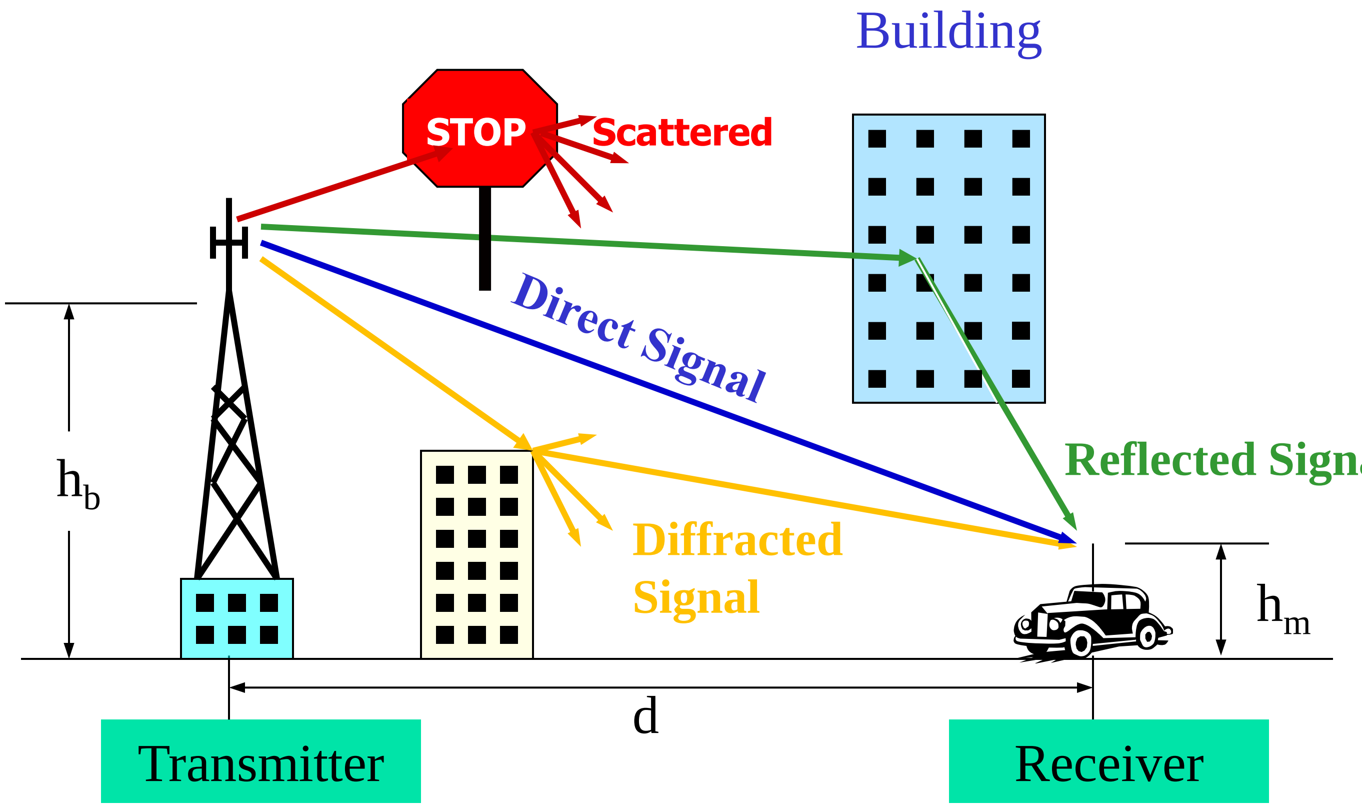
Propagation Mechanisms

- Reflection
  - Propagation wave impinges on an object which is large as compared to wavelength

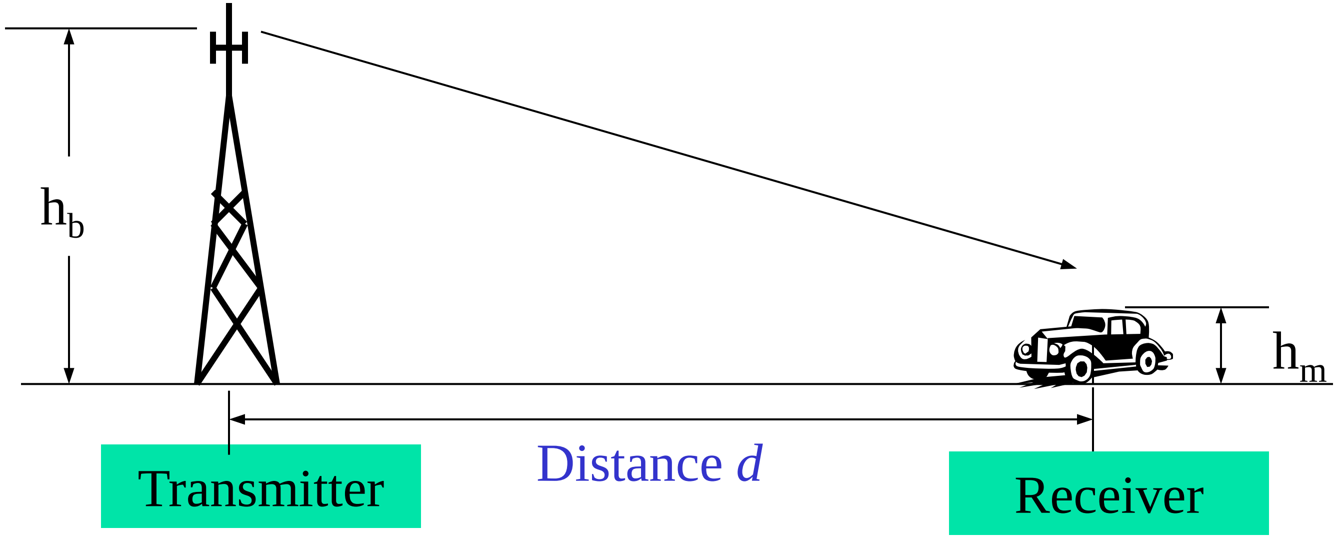
    - e.g., the surface of the Earth, buildings, walls, etc.
- Diffraction
  - Radio path between transmitter and receiver obstructed by surface with sharp irregular edges
  - Waves bend around the obstacle, even when LOS (line of sight) does not exist
- Scattering
  - Objects smaller than the wavelength of the propagation wave

    - e.g. foliage, street signs, lamp posts

Radio Propagation Effects



Free-space Propagation



- The received signal power at distance *d*:

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

where P_t is transmitting power, A_e is effective area, and G_t is the transmitting antenna gain. Assuming that the radiated power is uniformly distributed over the surface of the sphere.

Antenna Gain

- For a circular reflector antenna

  Gain $G = \eta\, (\pi D / \lambda)^2$

  η = net efficiency (depends on the electric field distribution over the antenna aperture, losses, ohmic heating, typically 0.55)

  D = diameter

- Thus, $G = \eta\, (\pi D f / c)^2$, $c = \lambda f$ (c is speed of light= 299,792,458m/s= 186,000miles per second)

Example:

- Antenna with diameter= 2 m, frequency= 6 GHz, wavelength= 0.05 m

  G= 39.4 dB

- Frequency= 14 GHz, same diameter, wavelength= 0.021 m

  G= 46.9 dB

* Higher the frequency, higher will be the gain for the same size antenna

Land Propagation

- The received signal power:

$$P_r = \frac{G_t G_r P_t}{L}$$

where P_r is the received power,

P_t is the transmitting power,

G_r is the receiver antenna gain,

G_t is the transmitter 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

Example about Gain

- **Example 3.1**: In a free-space propagation environment, if the transmission power of a transmitter is 60 watts, a receiver is in a distance of 2 km from the transmitter, the carrier frequency is 1000 MHz and the transmitter and receiver antennas gains are the same—that is, $G_t=G_r=0$dm, find received power at the receiver site and the path loss?

$$P_r = \frac{A_e G_t P_t}{4\pi d^2} = \frac{G_r G_t P_t}{\left[\frac{4\pi f_c d}{c}\right]}$$

where $G_t=G_r=0$db, $P_t=60$W, $f_c=1000$MHz, d=2000m, and $c=2.998X10^8$ m/s

- The received power can be calculated by

$$P_r = \frac{A_e G_t P_t}{4\pi d^2} = \frac{G_r G_t P_t}{\left[\frac{4\pi f_c d}{c}\right]^2} = \left[\frac{1X1X60}{\frac{4\pi X1000X10^6 X2000}{2.998X10^8}}\right] = 0.85X10^8 W$$

- From Equation (3.6), the free-space path loss is

$$L_f(\mathrm{dB}) = 32.45 + 20\log_{10} f_c\,(\mathrm{MHz}) + 20\log_{10} d\,(\mathrm{km})$$
$$= 32.45 + 20\log_{10}(1000) + 20\log_{10}(2) = 98.45\ \mathrm{dB}$$

Path Loss (Free-space)

- <u>Path Loss</u>: The signal strength decays exponentially with distance d between transmitter and receiver;

  The loss could be proportional to somewhere between d^2 and d^4 depending on the environment.

- Definition of path loss L_P :

$$L_P = \frac{P_t}{P_r},$$

Path Loss in Free-space:

$$L_{PF}(dB) = 32.45 + 20\log_{10} f_c(MHz) + 20\log_{10} d(km),$$

where f_c is the carrier frequency

➔This shows greater the f_c, more is the loss

Path Loss (Land Propagation)

- Simplest Formula:

$$L_p = A\, d^{\alpha}$$

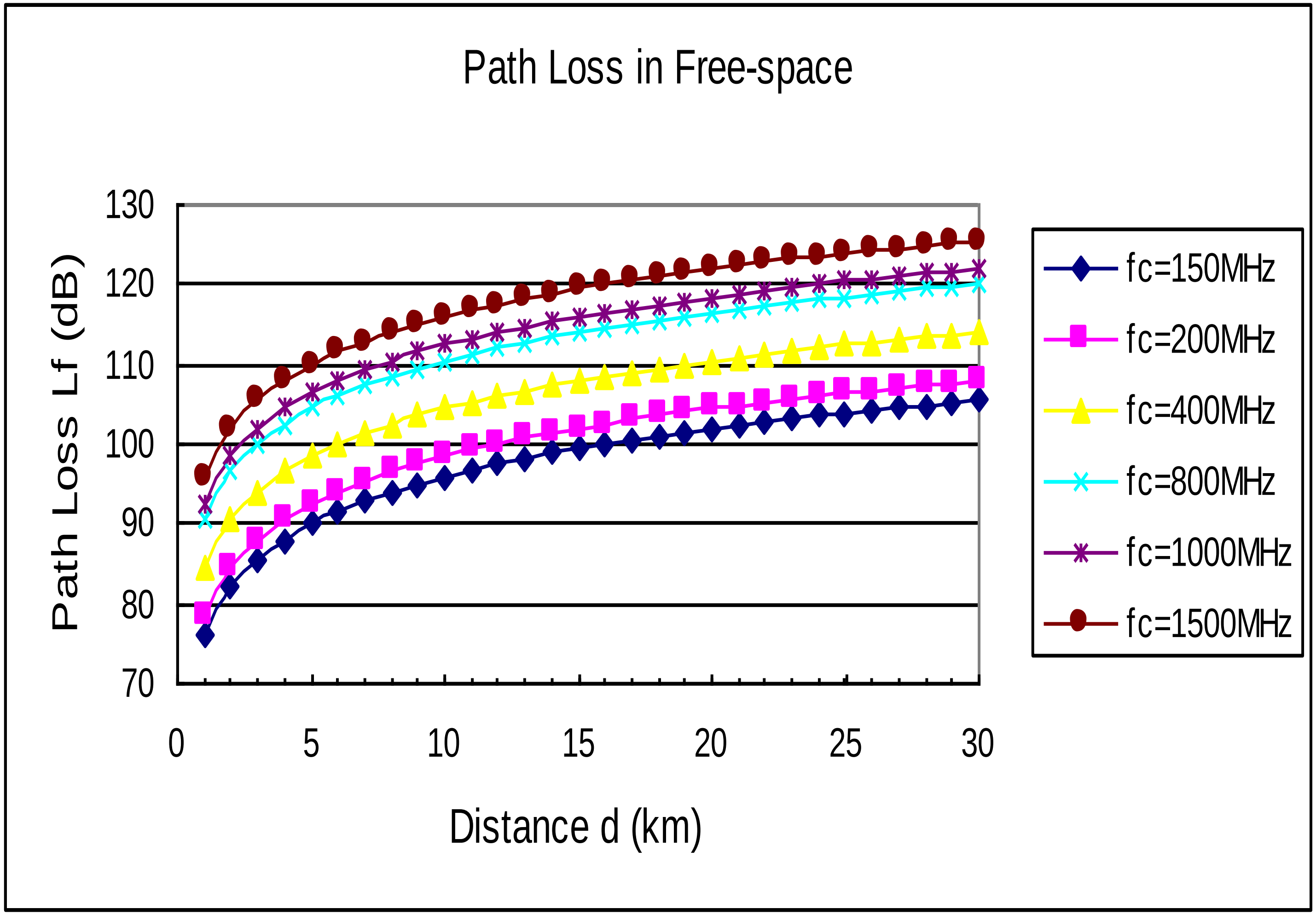
where

A and α: propagation constants

d : distance between transmitter and receiver

α : value of 3 ~ 4 in typical urban area

Example of Path Loss (Free-space)



Path Loss

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

Path Loss (Urban, Suburban and Open areas)

- Empirical results
- 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

$$\alpha\left[h_m(m)\right] = \begin{cases} \left[1.1\log_{10} f_c(MHz) - 0.7\right]h_m(m) - \left[1.56\log_{10} f_c(MHz) - 0.8\right], & for\ l\arg e\ city \\ \left.\begin{matrix} 8.29\left[\log_{10} 1.54 h_m(m)\right]^2 - 1.1, & for \quad f_c \le 200MHz \\ 3.2\left[\log_{10} 11.75 h_m(m)\right]^2 - 4.97, & for \quad f_c \ge 400MHz \end{matrix}\right\}, & for\ small\ \&\ medium\ city \end{cases}$$

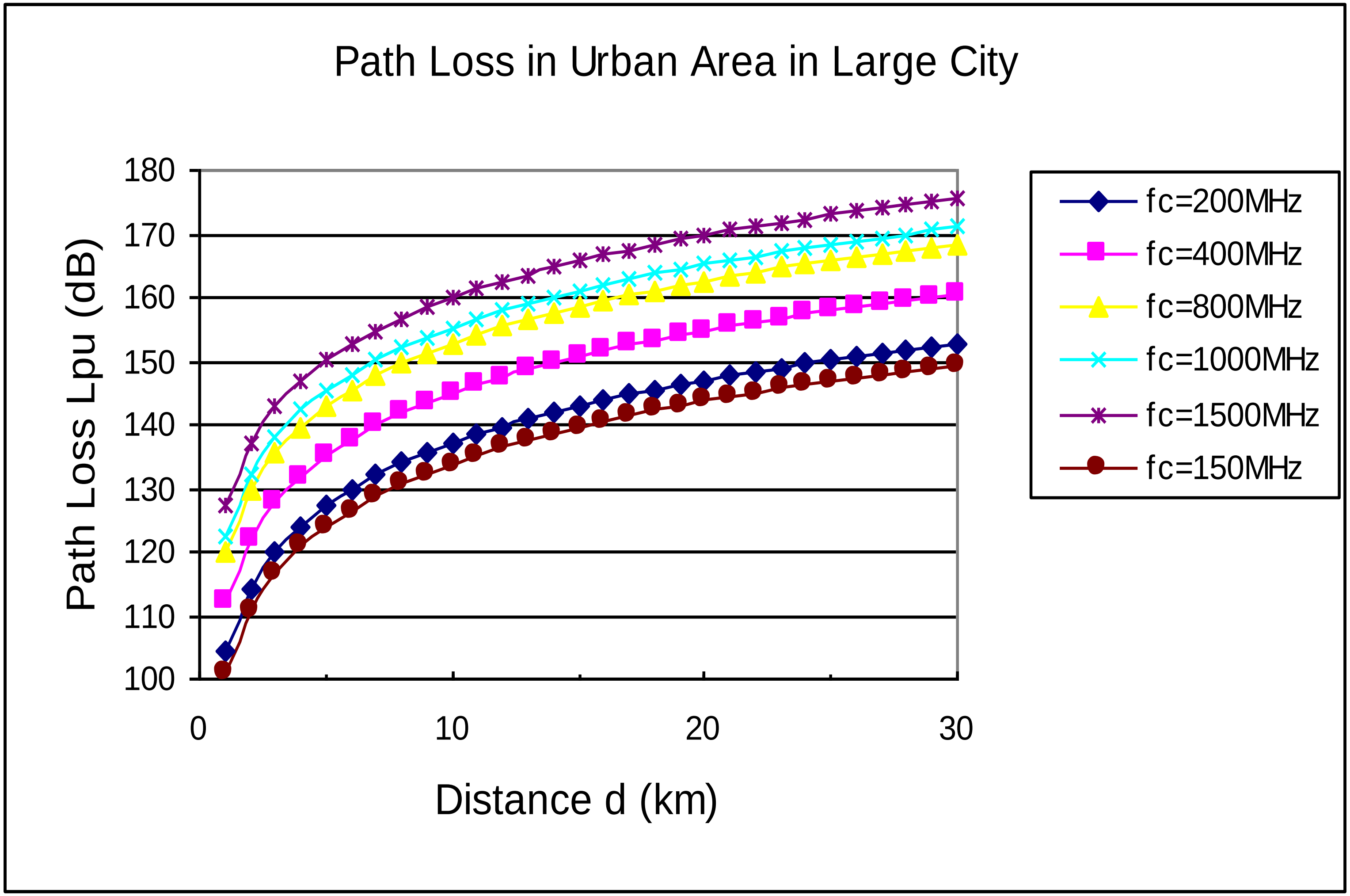
- Suburban area:

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

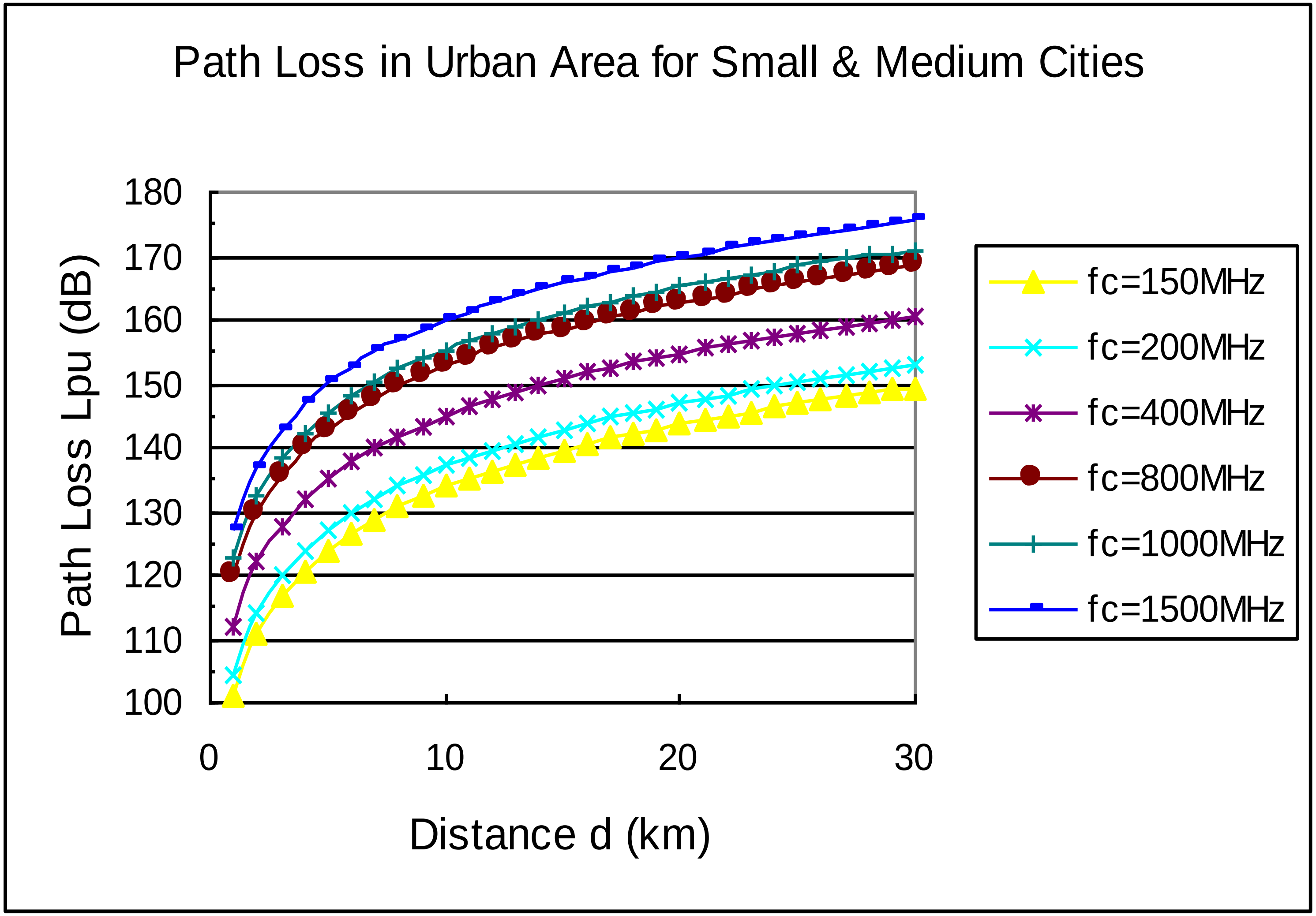
- Open area:

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

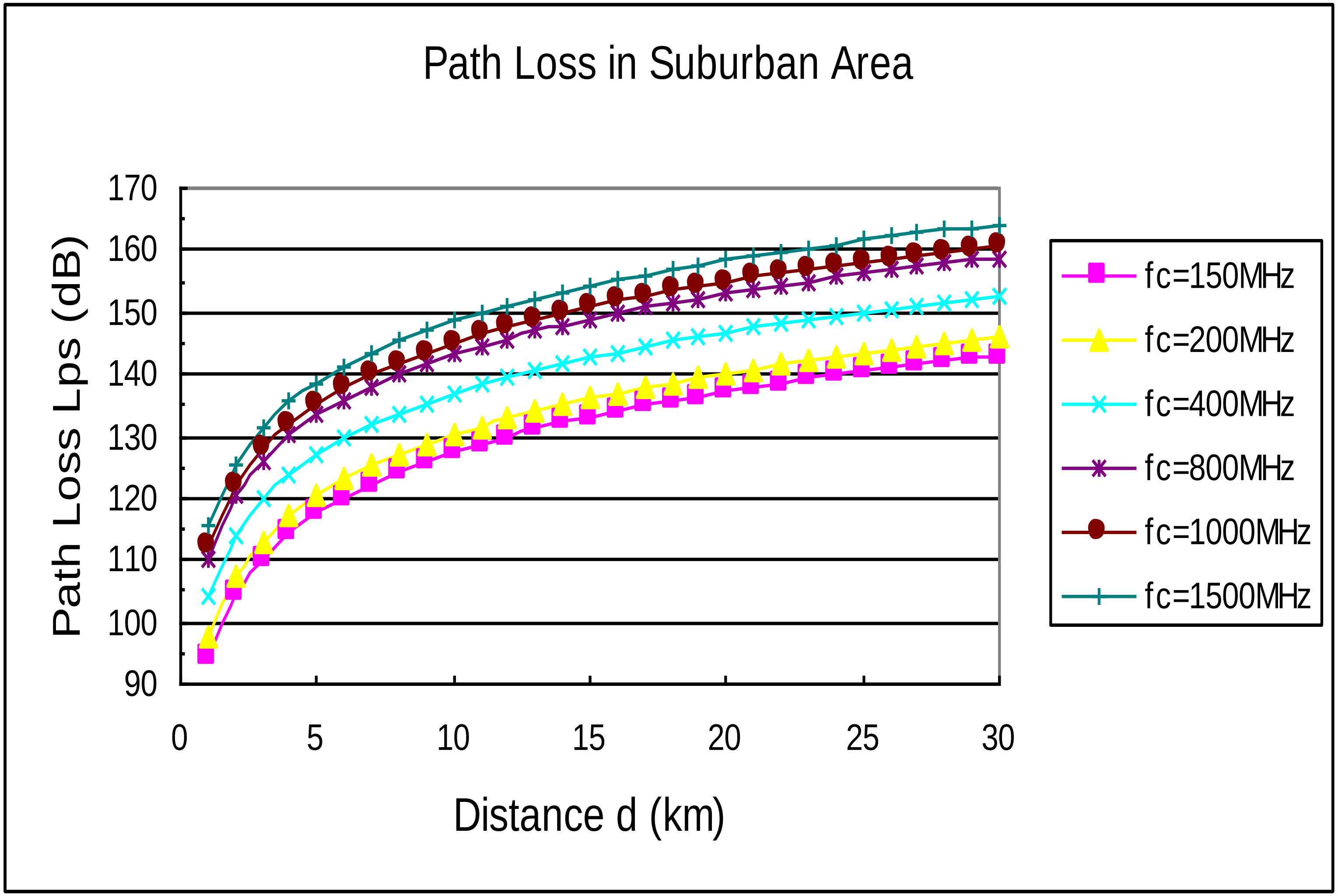
Example of Path Loss (Urban Area: Large City)



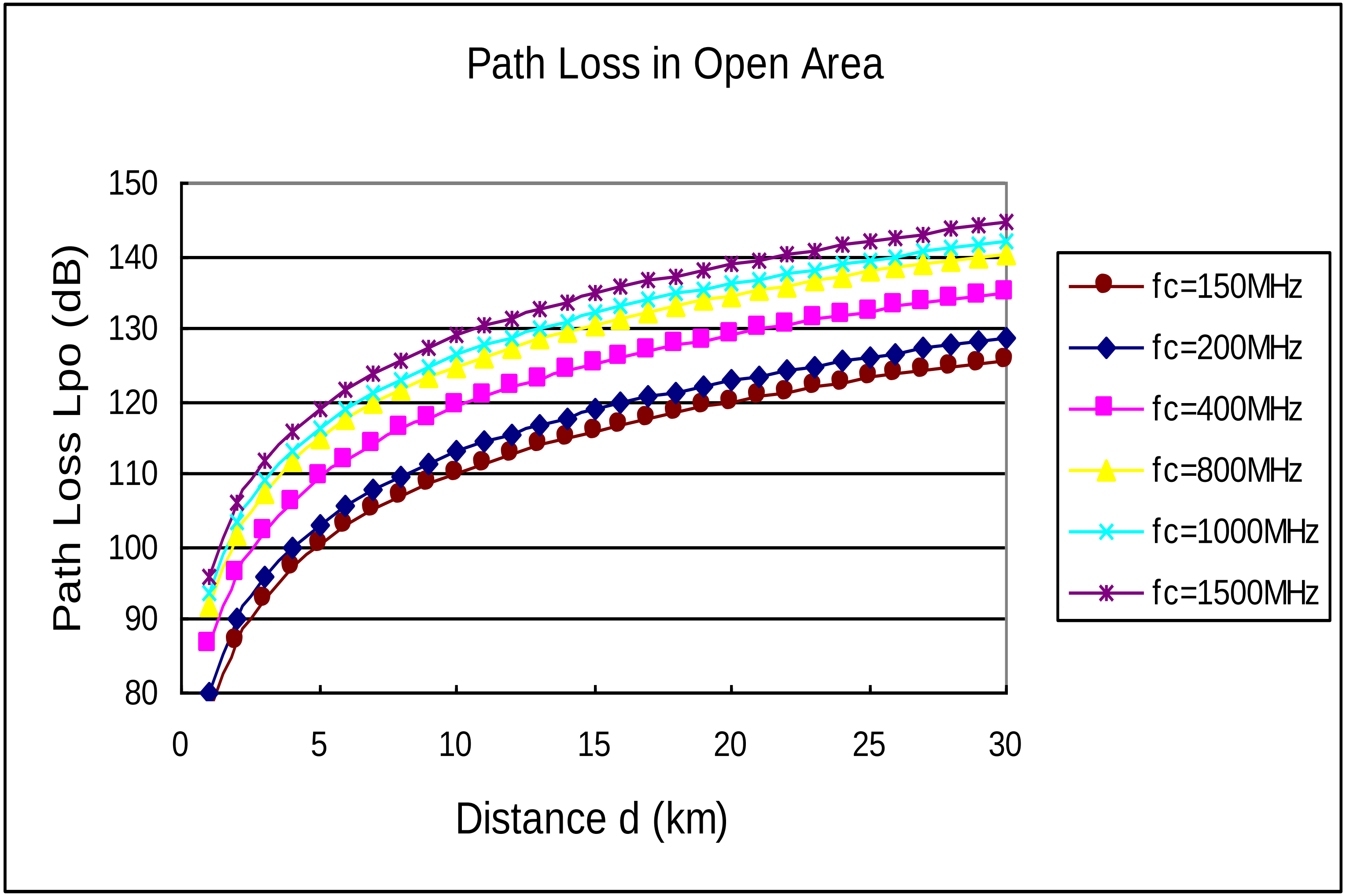
Example of Path Loss
(Urban Area: Medium and Small Cities)



Example of Path Loss (Suburban Area)



Example of Path Loss (Open Area)

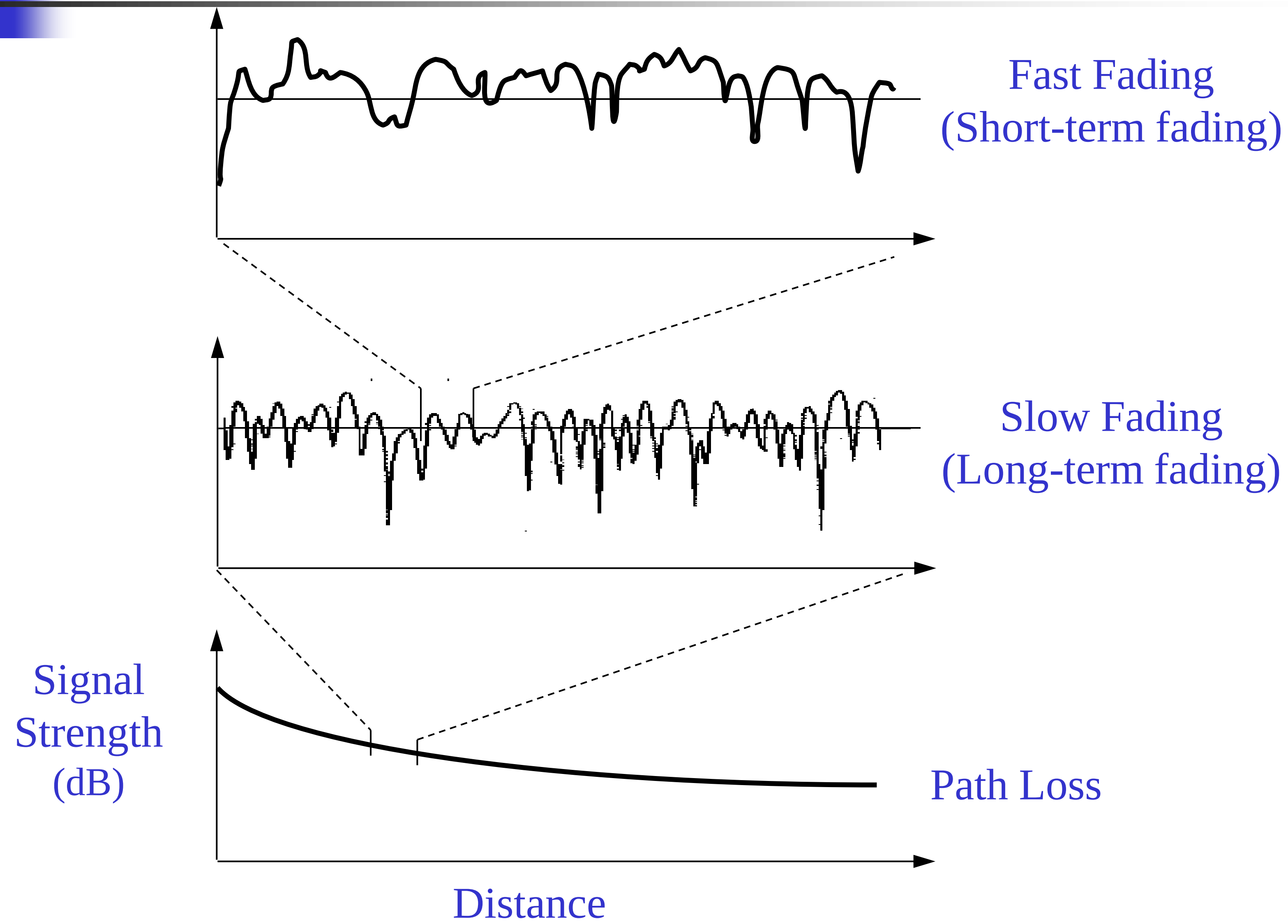


Example of Path Loss (Open Area)

Example 3.2: A base station has a 900 MHz transmitter and its antenna is 40 meters high from the ground. A mobile station with an antenna height of 2 m from the ground is located at a distance of 15 km from the base station. Compute the path loss in an Urban Area (neglect the correction factor for the mobile antenna height)

From Equation(3.10), the path loss in Urban Area can be calculated as:
Loss in Power in Urban Area(dB)= $69.55+26.16\log_{10} f_c\,(\text{MHz})-13.82\log_{10}h_b(\text{m})-\alpha[h_m(\text{m})]+[44.9-6.55\log_{10}h_b(\text{m})]\log_{10}d(\text{km})$
$=69.55+26.16\log_{10}(900)-13.82\log_{10}(40)+[44.9-6.55\log_{10}(40)]\log_{10}(15)=164.86$ dB

Fading


Fast Fading
(Short-term fading)
Slow Fading
(Long-term fading)
Signal
Strength
(dB)
Path Loss
Distance

Slow Fading

- Slow fading is caused by movement 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 (shadowing or log-normal fading). This fading caused by shadowing

Shadowing

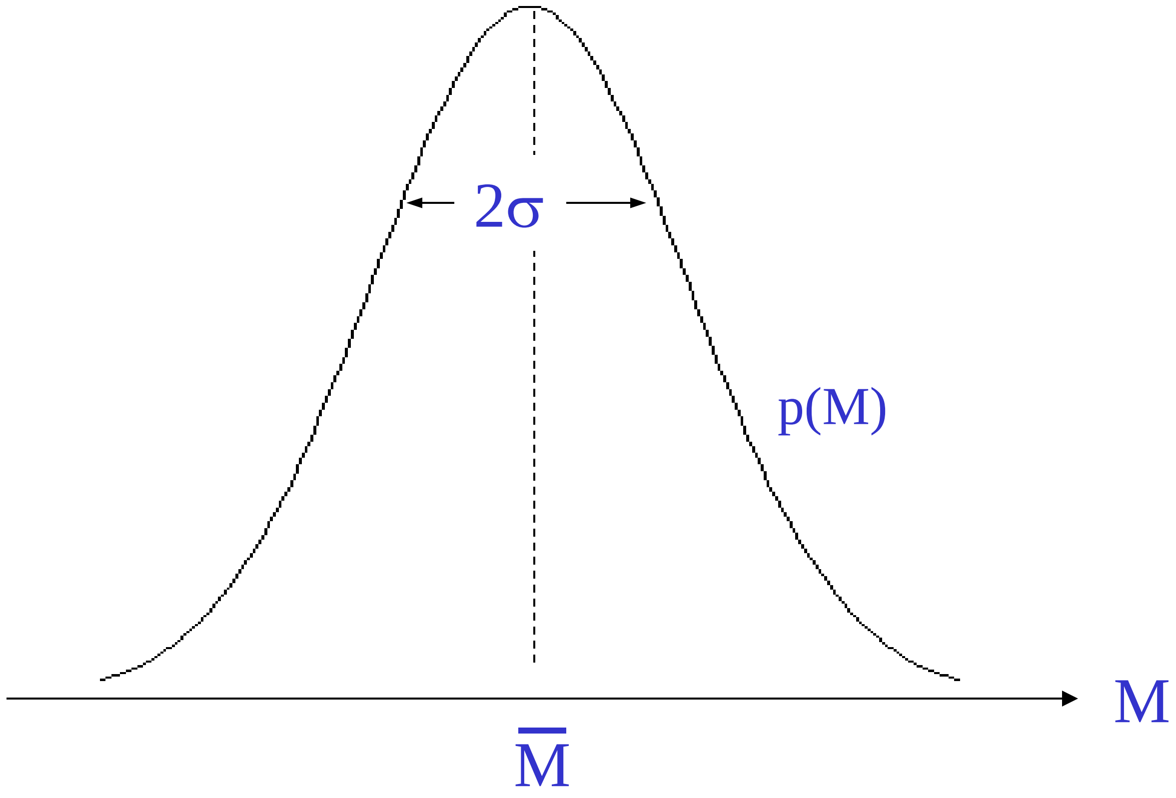
- **Shadowing**: Often there are millions of tiny obstructions in the channel, such as water droplets if it is raining or the individual leaves of trees. Because it is too cumbersome to take into account all the obstructions in the channel, these effects are typically lumped together into a random power loss

- **Log-normal distribution:**
  - The pdf of the received signal level is given in decibels by

$$p(M) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{\left(M-\overline{M}\right)^2}{2\sigma^2}},$$

where $\overline{M}$ is the true received signal level m in decibels, i.e., $10\log_{10}m$,
M is the area average signal level, i.e., the mean of M,
σ is the standard deviation in decibels

Log-normal Distribution



The pdf of the received signal level

Fast Fading

- The signal from the transmitter may be reflected from objects such as hills, buildings, or vehicles. Fast fading is due to scattering of the signal by object near transmitter.
  - When MS far from BS, the envelope distribution of received signal is Rayleigh distribution with β=0. The pdf is

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

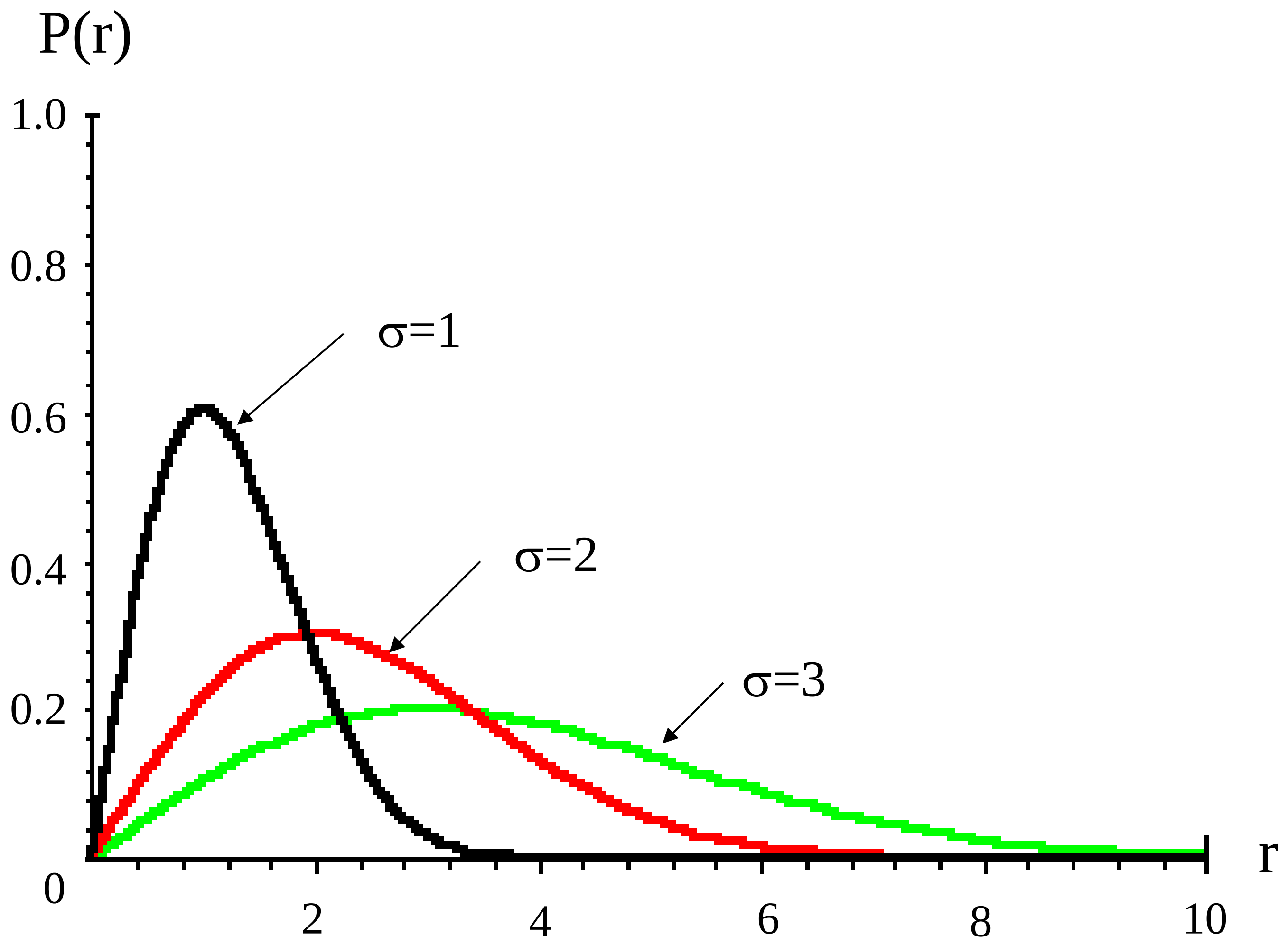
where σ is the standard deviation, r is the envelope of fading signal, β is the amplitude of direct signal, and I_0 is the zero order Basel Function.

  - Middle value r_m of envelope signal within sample range to be satisfied by

$$P(r \le r_m) = 0.5.$$

  - We have $r_m = 1.777$♦

Rayleigh Distribution



The pdf of the envelope variation

Fast Fading (Continued)

- When MS is far from BS, the envelope distribution of received signal is called a <u>Rician</u> distribution. The pdf is

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

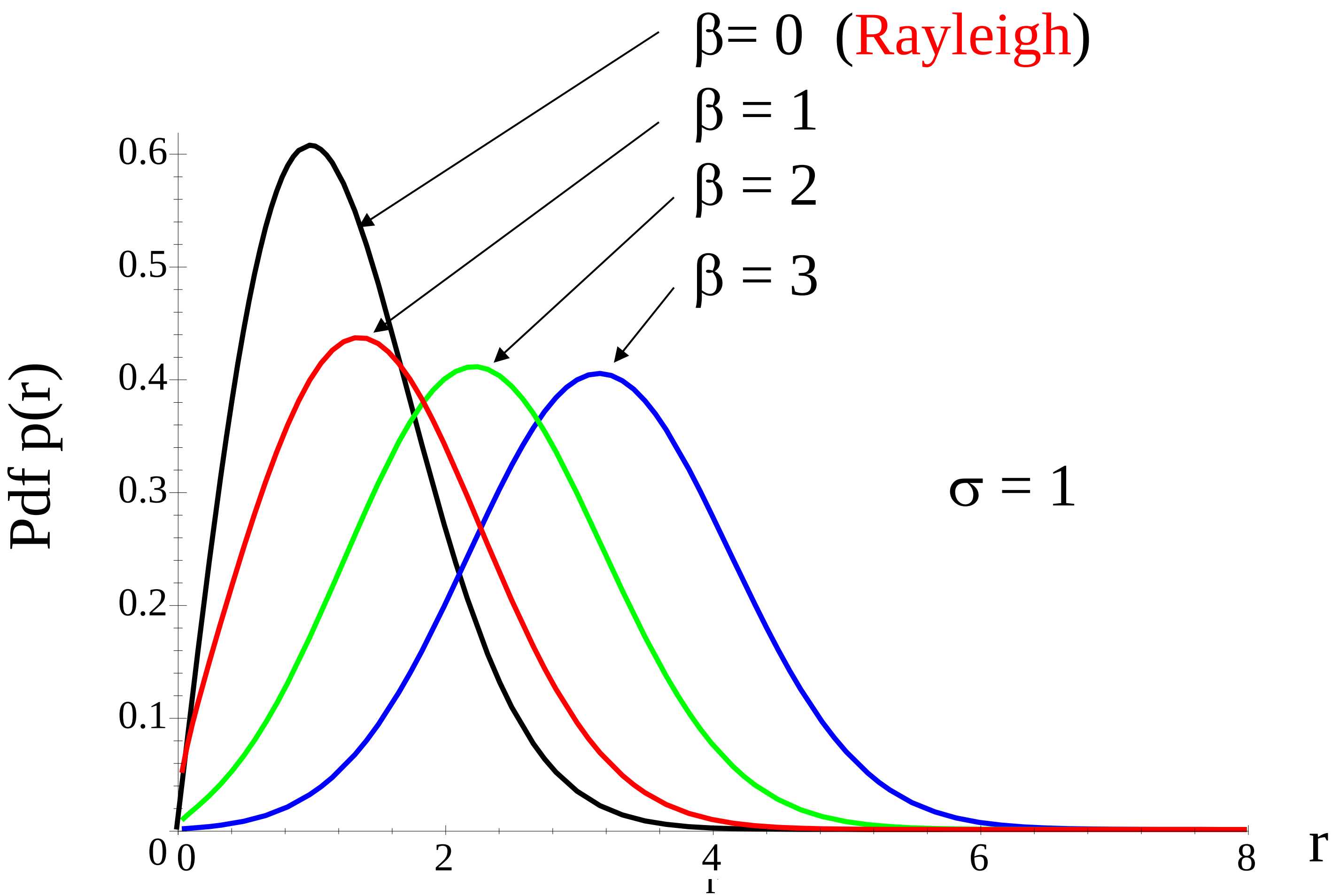
where

σ is the standard deviation,

$I_0(x)$ is the zero-order Bessel function of the first kind,

α is the amplitude of the direct signal

Rician Distribution



The pdf of the envelope variation

Characteristics of Instantaneous Amplitude

- Level Crossing Rate:
  - Average number of times per second that the signal envelope crosses the level 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 mean square value and minimum value of fading signal
- Fading Duration:
  - Time for which signal is below given threshold

Doppler Shift

- **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, the frequency of the received signal is higher than the source.
  - When they are opposing each other, the frequency decreases.

Thus, the frequency of the received signal is

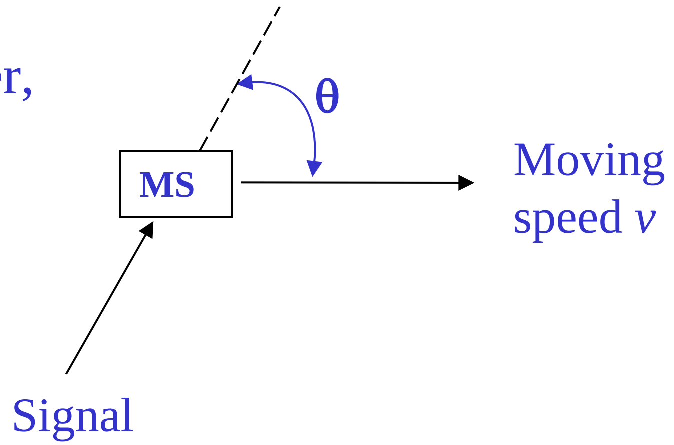
$$f_R = f_C - f_D$$

where f_C is the frequency of source carrier,
f_D is the Doppler frequency.

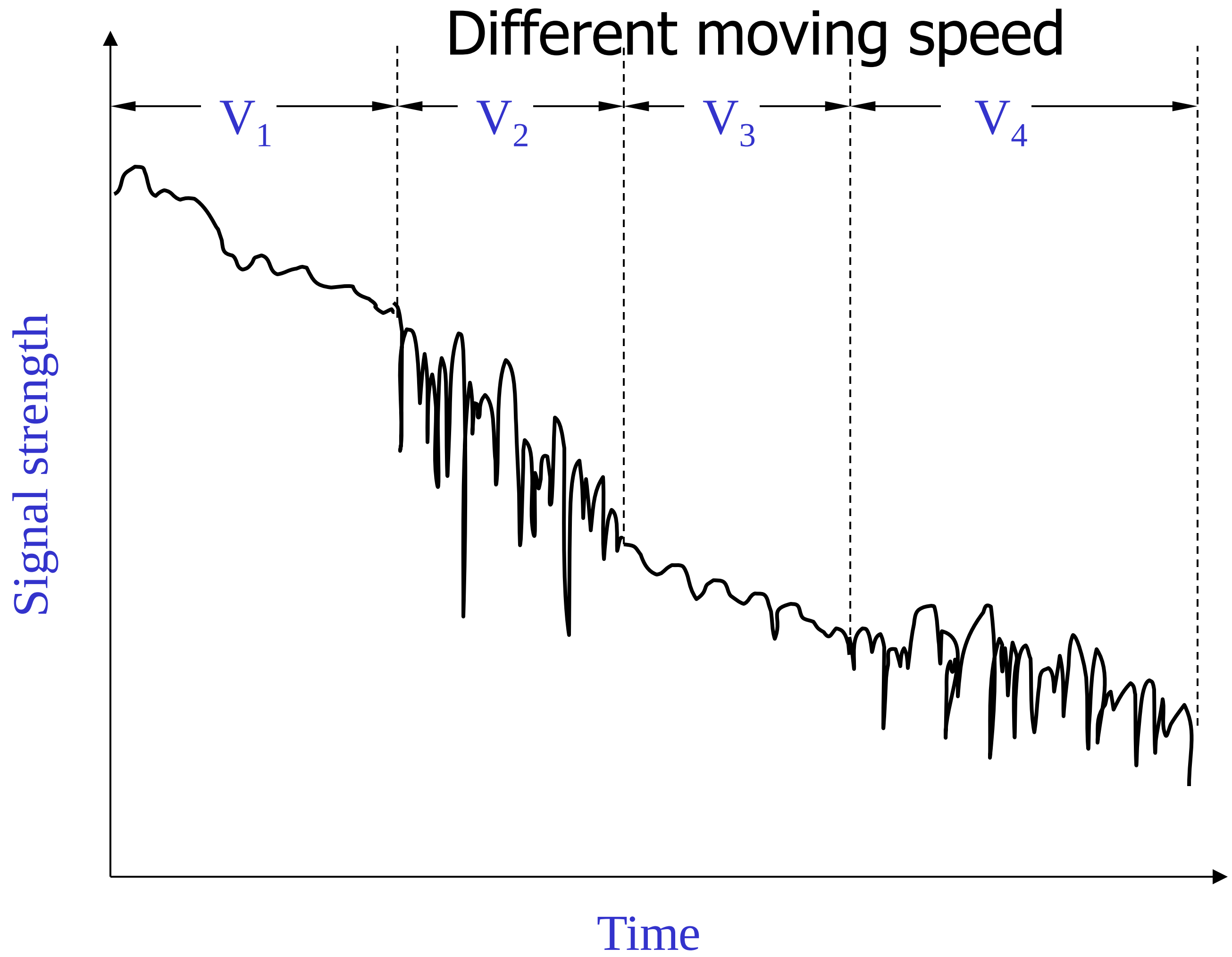
- **Doppler Shift** in frequency:

$$f_D = \frac{v}{\lambda} \cos\theta$$

where v is the moving speed,
λ is the wavelength of carrier.



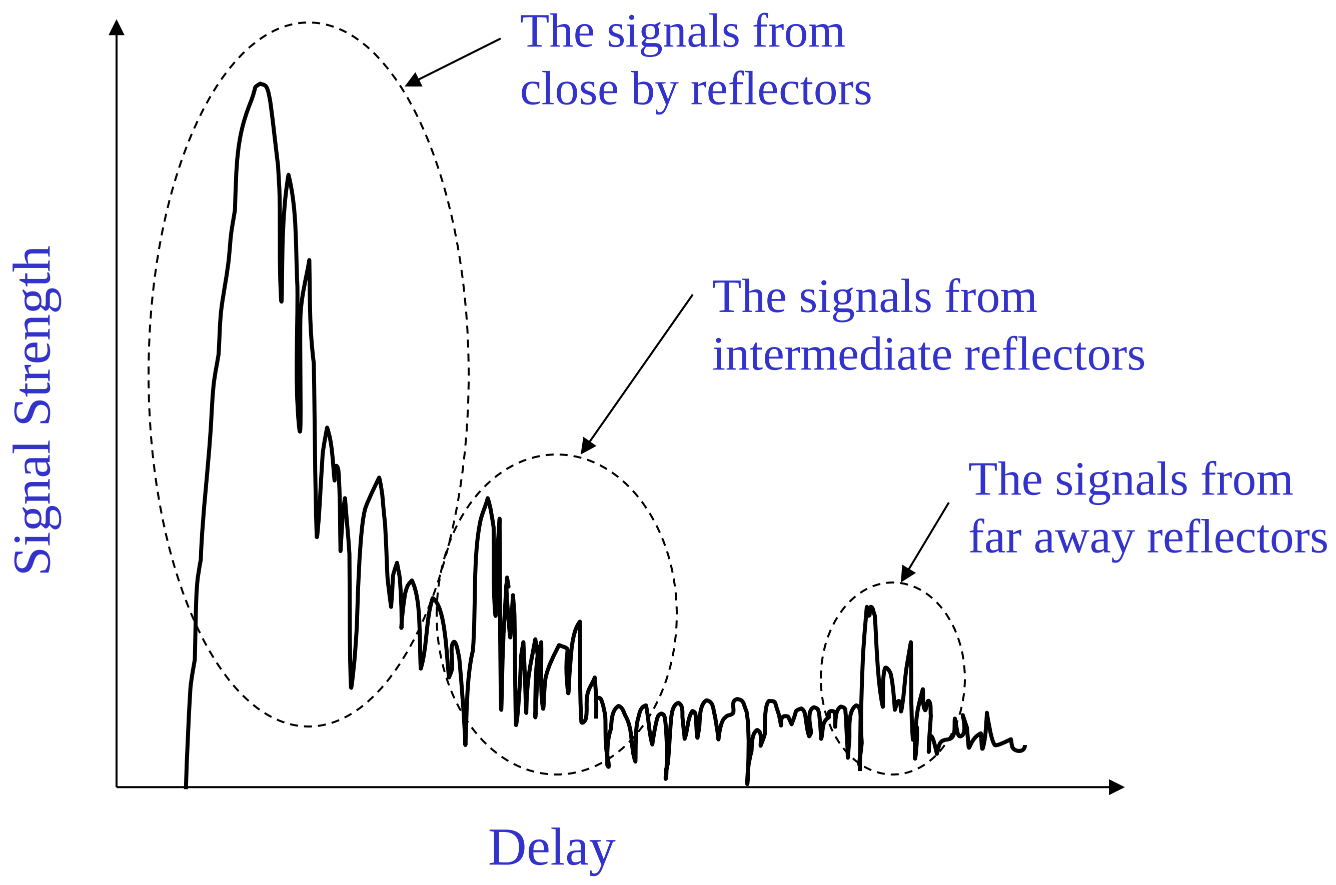
Moving Speed Effect



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



Mobile User

- **Example 3.3**: A vehicle is moving directly away from the BS with a moving speed of 60 km/h. The BS has a 900 MHz transmitter. If the ratio ρ between specified level and the rms amplitude of the fading envelope is 0.2 and the travel speed of light c=3X10^{8}m/s, compute the fading rate?

Based on Equation (3.34), the level crossing rate can be calculated as

$$N(r_m) = \frac{2v}{\lambda} = \frac{2vf_c}{c} = \frac{2\chi\frac{60X10^3}{3600}\chi 900\chi 10^6}{3\chi 10^8} = 100Hz$$

- What is the fading duration?

From Equation (3.33), the maximum Doppler frequency can be computed by

$$f_m = \frac{v}{\lambda} = \frac{vf_c}{c} = 50Hz$$

- What is the level crossing rate?

Using Equation (3.36), the fading duration is given by

$$\tau(R_s) = \frac{e^{p^2} - 1}{\sqrt{2\pi} f_m \rho} = \frac{e^{2^2} - 1}{\sqrt{2\pi} x 50 x 0.2} = 1.6x10^3 s$$

Mobile User

- **Example 3.4**: If a vehicle is moving at a speed of 60 mph and a BS has a 1500 MHz transmitter, find the received carrier frequency under following different situations.
- If the vehicle is moving directly toward the BS.

Equation (3.37) defines that the received carrier frequency for a moving receiver and Equation (3.38) is the Doppler frequency. Since *v* = 60 mph = 26.82 m/s, the travel speed of light $c=2.998x10^8 m/s$ and original carrier frequency f_c=1500MHz, the Doppler frequency f_d can be calculated by Equation (3.38) as follows:

$$f_d = \frac{v}{\lambda}\cos\theta = \frac{26.82x1500x10^6}{2.998x10^8} x\cos\theta\ Hz = 134.1x\cos\theta\ Hz$$

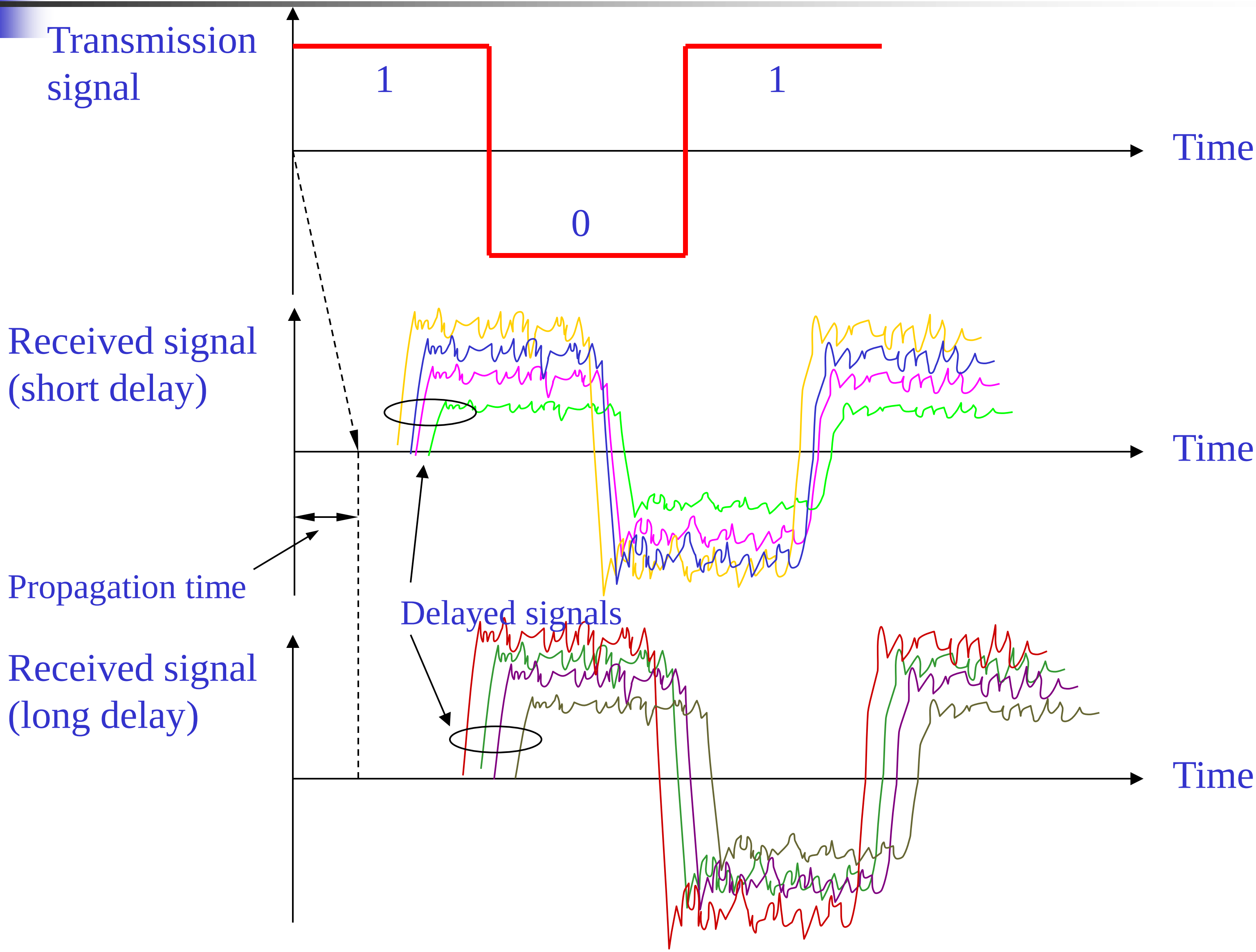
- If the vehicle is moving directly away from the BS.

When the vehicle is moving directly away from the BS – that is, $\theta=180^0$, the frequency of received signal is $f_Y=f_c-f_d=1500x10^6+134.1x\cos(180^0)=1500.000134$ MHz

- When the vehicle is moving directly toward the BS – that is, $\theta=0^0$, the frequency of received signal is $f_Y=f_c-f_d=1500x10^6+134.1x\cos(0^0)=1499.999866$ MHz.
- When the moving direction of vehicle is 90 degree with the direction of received signal – that is, $\theta=90^0$, the frequency of received signal is

$f_Y=f_c-f_d=1500x10^6+134.1x\cos(90^0)=1500$ MHz

Inter-Symbol Interference (ISI)



Inter-Symbol Interference (ISI)

- Caused by time delayed multipath signals
- Has impact on the burst error rate of channel
- Second multipath is delayed and is received during next symbol
- For low bit-error-rate (BER)

$$R < \frac{1}{2\tau_d}$$

- R (digital transmission rate) limited by delay spread τ_d.

Coherence Bandwidth

- Coherence bandwidth B_c
  - Represents correlation between two fading signal envelopes at frequencies f_1 and f_2
  - Is a function of delay spread
  - Two frequencies that are larger than coherence bandwidth fade independently
  - Concept useful in diversity reception
    - Multiple copies of the same message are sent using different frequencies

Cochannel Interference

- Cells having the same frequency interfere with each other.
- r_d is the desired signal
- r_u is the interfering undesired signal
- β is the protection ratio for which $r_d \leq \beta r_u$ (so that the signals interfere the least)
- If $P(r_d \leq \beta r_u)$ is the probability that $r_d \leq \beta r_u$, <u>Cochannel probability</u> $P_{co} = P(r_d \leq \beta r_u)$