

Mobile Radio Propagation

Wireless Network Characteristics

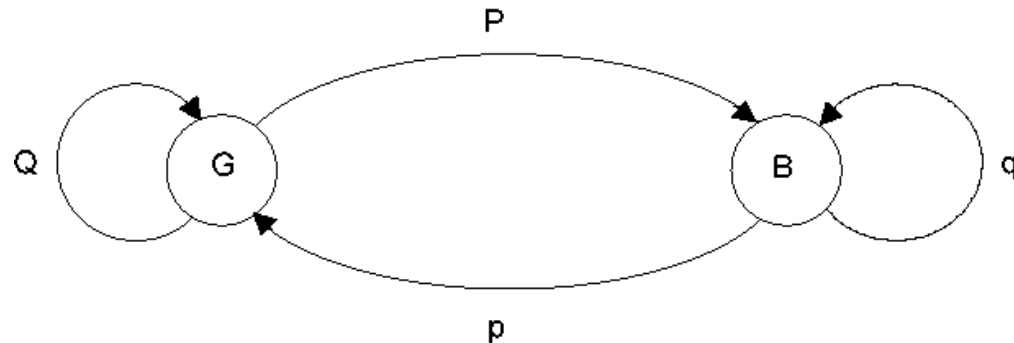
- ✿ Increased BER (can be as high as 10^{-3}), compared with wired networks
- ✿ Reasons for increased BER: atmospheric noise, multipath propagation, interference, etc
- ✿ Need for spectrum licensing to alleviate interference
- ✿ Dynamic topologies – hidden terminals, also will result in interference
- ✿ Energy limitation is another interference control mechanism

Bit Error Rate (1/2)

- ✿ Bit errors over wireless channels occur in bursts
- ✿ Markov chain model approximations have been shown to be adequate for wireless channel bit error modeling
- ✿ Such models comprise two states, a Good (G) and a Bad (B) one, and parameters that define the transition procedure between the two states
- ✿ Future states are independent of past states and depend only on the present state. In other words the model is memoryless

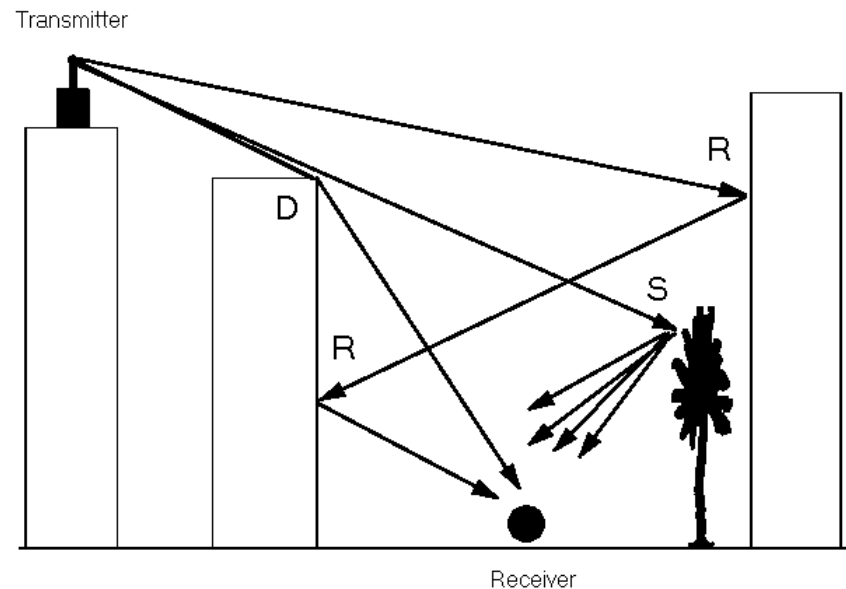
Bit Error Rate (2/2)

- ✿ P is the probability of the channel state transiting from state G to state B
- ✿ p defines the probability of transition from state B to state G
- ✿ Q and q the probabilities of the channel remaining in states G and B respectively
- ✿ Obviously $Q=1-P$ and $q=1-p$



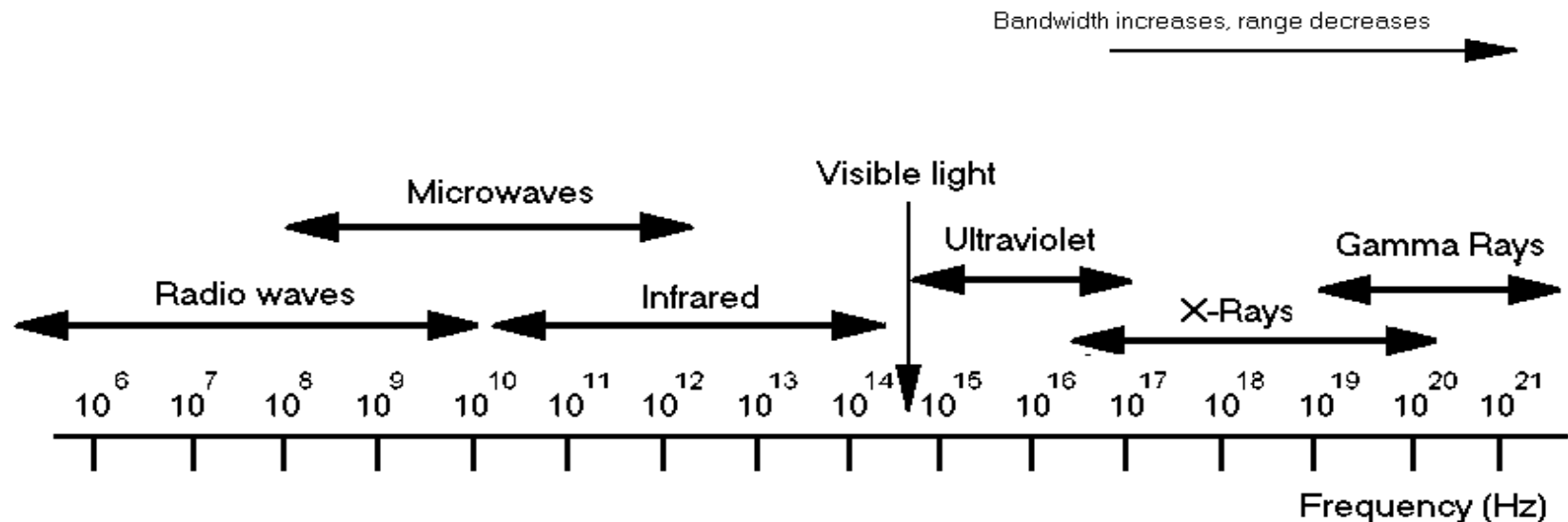
Reasons of Reception Errors

- ✿ Free space path loss
- ✿ Doppler shift: caused by station mobility
- ✿ Propagation mechanisms (reflection, diffraction, scattering) make signals travel over many different paths
=> Multipath propagation



Electromagnetic Spectrum (1/2)

- ✿ Different spectrum bands have different properties
- ✿ Higher bands: less coverage, more energy
- ✿ Lower bands: higher coverage, less energy



Electromagnetic Spectrum (2/2)

Spectrum allocation

Table 3.1: ►
Radio Frequency
Bands

Classification Band	Initials	Frequency Range	Propagation Mode
Extremely low	ELF	<300 Hz ~3 kHz	Ground wave
Infra low	ILF	300 Hz ~3 kHz	Ground wave
Very low	VLF	3 kHz ~30 kHz	Ground wave
Low	LF	30 kHz ~300 kHz	Ground wave
Medium	MF	300 kHz ~3 MHz	Ground/sky 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	Space wave
Super high	SHF	3 GHz ~30 GHz	Space wave
Extremely high	EHF	30 GHz ~300 GHz	Space wave
Tremendously high	THF	300GHz ~3000 GHz	Space wave

Shannon's Formula

- ✿ C : upper bound on the bit rate
- ✿ B : channel bandwidth in Hz
- ✿ δ : signal to noise ratio
- ✿ The formula is $C = B \log_2(1 + \delta)$

dB v.s. dBm (1/2)

✿ dB (decibel): used for quantifying the ratio of two values, such as signal-to-noise ratio [dimensionless measurement]

– **Formula:**

$$\text{dB} = 10 \log_{10} \left(\frac{\text{signal}}{\text{noise}} \right)$$

✿ dBm: power ratio in dB of the measured power referenced to 1 mW [absolute power measurement]

– **Formula:**

$$\text{dBm} = 10 \log_{10} \left(\frac{\text{power}}{1\text{mW}} \right)$$

dB v.s. dBm (2/2)

Log rules

- $\log_b(mn) = \log_b(m) + \log_b(n)$

- $\log_b\left(\frac{m}{n}\right) = \log_b(m) - \log_b(n)$

- $\log_b(m^n) = n \log_b(m)$

What does $(A \text{ dBm} - B \text{ dBm})$ mean?

$$(A \text{ dBm} - B \text{ dBm}) = 10 \log_{10} \left(\frac{P_1}{1\text{mW}} \right) - 10 \log_{10} \left(\frac{P_2}{1\text{mW}} \right)$$

$$= 10 \log_{10} \left(\frac{\frac{P_1}{1\text{mW}}}{\frac{P_2}{1\text{mW}}} \right) = 10 \log_{10} \frac{P_1}{P_2} \quad [\text{in dB}]$$

Types of Radio Waves (1/2)

- ✿ Ground: follow the curvature of the earth, and is used for long range navigation (below 2MHz)
- ✿ Space: only travel in straight lines (line of sight) and are used for mobile phones, two-way radio and radar (30 MHz– 3000 GHz)
- ✿ Sky: reflected off the ionosphere and are used for amateur radio and long distance aircraft and ship communication (2 – 30 MHz)

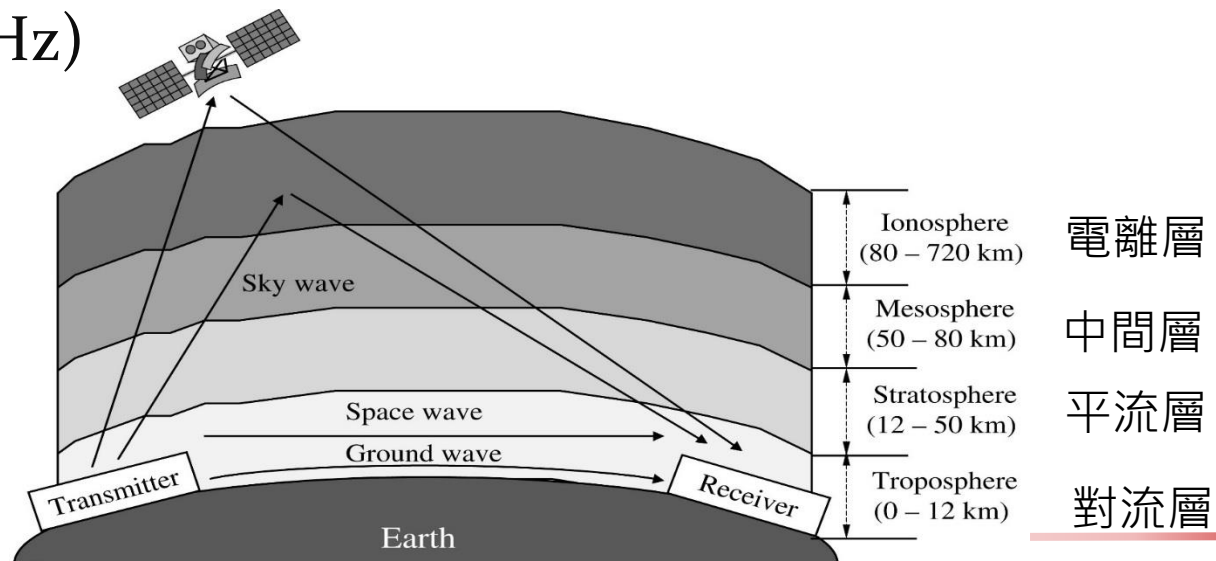
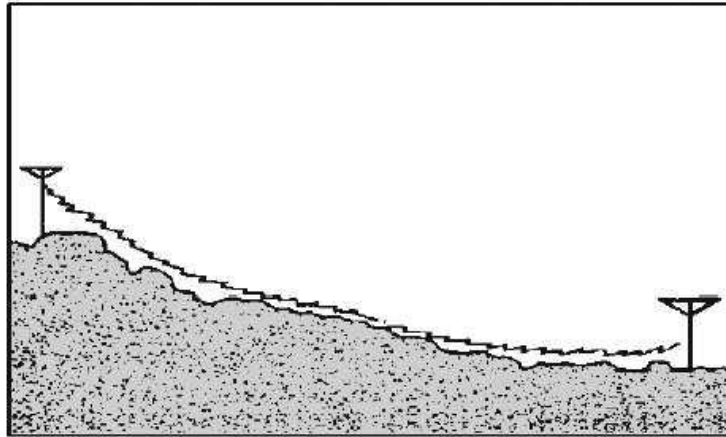


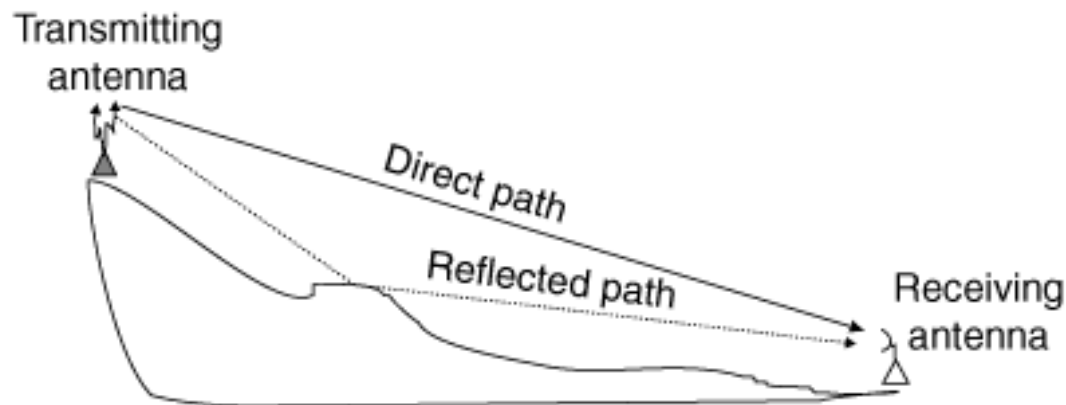
Figure 3.1 Propagation of different types of radio waves.

Types of Radio Waves (2/2)

🌾 Ground wave



🌾 Space wave



Propagation Mechanisms (1/5)



Propagation effect

- Reflection: occur when an electromagnetic wave falls on an object with dimensions very large compared to the wave's wavelength
- Scattering: occur when the signal is obstructed by objects with dimensions in the order of the wavelength of the electromagnetic wave. The energy of the signal is transmitted over different directions
- Diffraction: occur when an electromagnetic wave falls on an impenetrable object. Secondary waves are formed behind the obstructing body
 - Also known as shadowing
 - Low frequency signals diffract more than high frequency signals
 - Shadowed areas are often large, resulting in the rate of change of the signal power being slow, thus shadowing is also referred to as slow fading

Propagation Mechanisms (2/5)

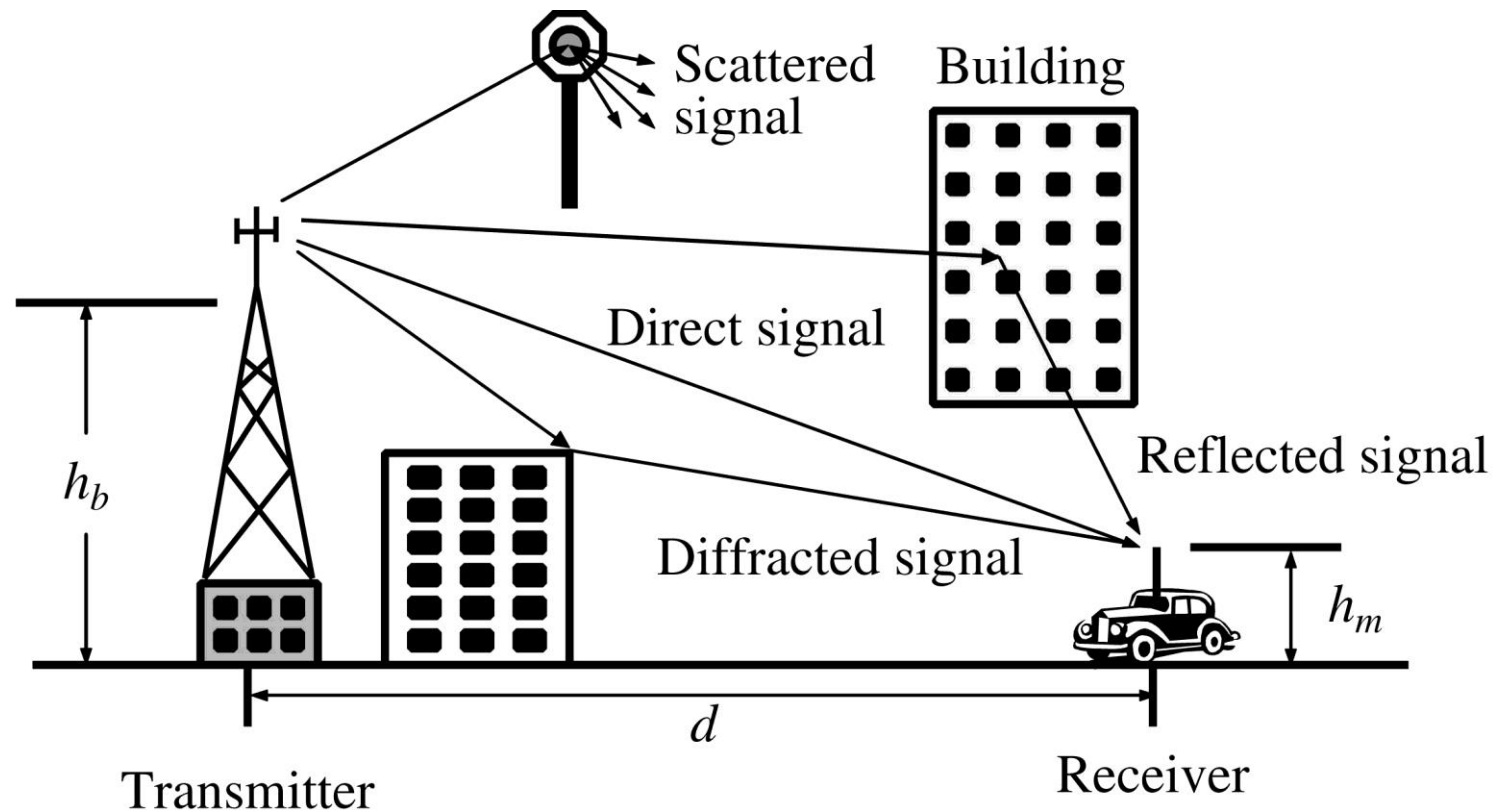


Figure 3.2 Reflection, diffraction, and scattering of radio signals.

Propagation Mechanisms (3/5)

Free space path loss

- Signal attenuation is due to distance between the transmitter and the receiver
- The received power is proportional to r^{-2} , where r is the distance between the transmitter and the receiver

Multipath propagation

- Signals from the transmitter may be reflected from objects resulting in signal propagating over different paths with different path lengths
- Original reception signal distortion (small-scale fluctuations)
- The time duration between the reception of the first signal and the reception of the last echo is named channel's delay spread

Propagation Mechanisms (4/5)

- Because these small-scale fluctuations are experienced over very short distances, multipath fading is also referred to either as fast fading or small-scale fading
- When a LOS exists between the receiver and the transmitter, this kind of fading is known as Rician fading
- When a LOS does not exist, it is known as Rayleigh fading

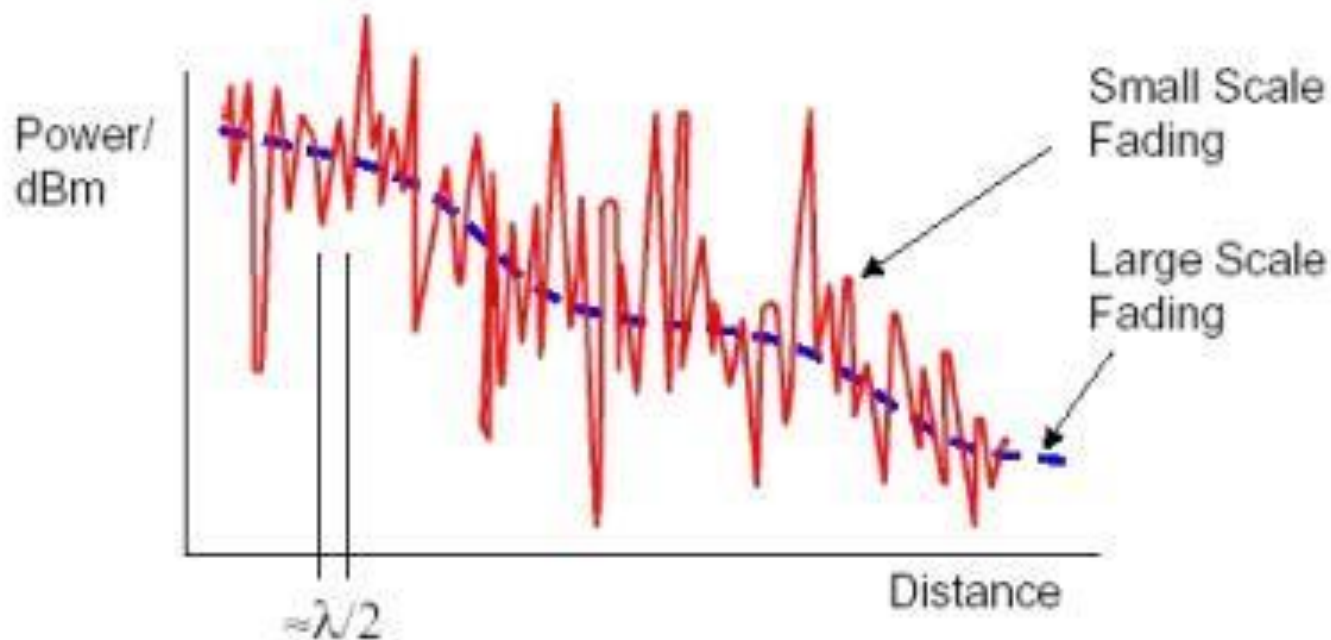


Large-scale propagation model

- Path loss
- Free space propagation model
- Propagation mechanism
- Indoor propagation model
- Outdoor propagation model

Propagation Mechanisms (5/5)

- ✿ Small-scale propagation: signal variation in small spatial and temporal in amplitude, phase, and frequency
 - Multipath: time dispersion
 - Doppler: frequency dispersion



Free Space Propagation (1/3)

✿ Receiving signal power:
$$P_r = \frac{A_e G_t P_t}{4\pi d^2} = \frac{G_r G_t P_t}{\left(\frac{4\pi d}{\lambda}\right)^2}$$

- d : distance between the transmitter and receiver
- A_e : effective area covered by the transmitter
- G_t : transmitting antenna gain

✿ Receiving antenna gain:
$$G_r = \frac{4\pi A_e}{\lambda^2}$$

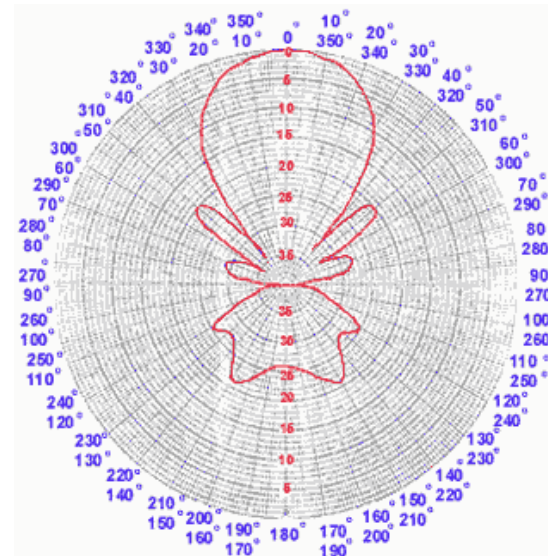
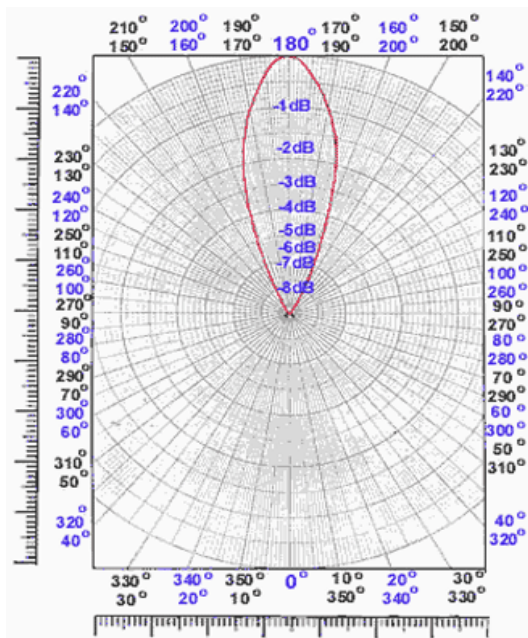
✿ Free space path loss L_f :
$$L_f = \frac{P_t}{P_r} = \frac{1}{G_r G_t} \left(\frac{4\pi d}{\lambda}\right)^2$$

✿ A.k.a **Friis** free space propagation model

Free Space Propagation (2/3)

🌿 Antenna gain

- As a transmitting antenna, the figure describes how well the antenna converts input power into radio waves headed in a specified direction
- As a receiving antenna, the figure describes how well the antenna converts radio waves arriving from a specified direction into electrical power



Free Space Propagation (3/3)

🌾 An example

- $G_t = G_r = 1$
- $c = 2.998 \times 10^8 \text{ m/s}$
- f_c is carrier frequency

$$L_f = \left(\frac{4\pi d}{\lambda} \right)^2 = \left(\frac{4\pi f_c d}{c} \right)^2$$

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

Land Propagation

- ✿ Communications from/to a fixed station to/from a MS
- ✿ Multipath propagation channel with fading
- ✿ Receiving signal power: $P_r = \frac{G_t G_r P_t}{L}$
 - L : propagation loss
 - Three aspects of loss
 - Path loss (L_P)
 - Slow fading (shadowing) (L_S)
 - Fast fading (L_F)
 - $L = L_P L_S L_F$

Path Loss (1/4)

- ✿ This is about Hata Model
- ✿ Average propagation loss over a wide area
- ✿ Determined by distance, carrier frequency, and land profile
- ✿ Simplest formula: $L_P = Ad^\alpha$
 - A & α : propagation constants
 - α : 3~4
 - d : distance between the transmitter and receiver

Path Loss (2/4)

Urban area

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

- $L_{\text{PU}}(\text{dB}) = 10 \log_{10} L_{\text{PU}}$
- f_c : carrier frequency (150MHz~1500MHz)
- h_b : effective BS antenna height (30m~200m)
- h_m : effective MS antenna height (1m~10m)
- d : distance (1m~20km)
- $\alpha(h_m)$: correction factor for the mobile antenna height

Path Loss (3/4)

- Large cities

$$\alpha[h_m(m)] = [1.1 \log_{10} f_c (\text{MHz}) - 0.7] h_m(m) - [1.56 \log_{10} f_c (\text{MHz}) - 0.8]$$

- Medium and small cities

$$\alpha[h_m(m)] = \begin{cases} 8.29 [\log_{10} 1.54 h_m(m)]^2 - 1.1, & f_c < 300 \text{ MHz} \\ 3.2 [\log_{10} 11.75 h_m(m)]^2 - 4.97, & f_c > 300 \text{ MHz} \end{cases}$$

Path Loss (4/4)

🌾 Suburban area

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

🌾 Open area

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

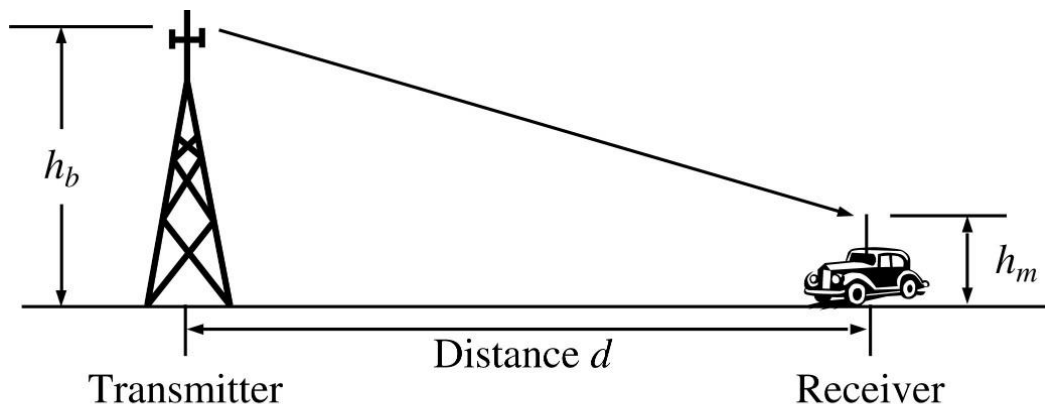


Figure 3.5 Radio propagation.

Slow Fading (1/3)

- ✿ Same T-R distance usually have different path loss
 - Surrounding environment is different
- ✿ Reality: simplified path-loss model represents an “average”
- ✿ How to represent the difference between the average the actual path loss?
- ✿ Measurements have shown that
 - It is random (and so is a random variable)
 - Log-normal distributed

Slow Fading (2/3)

- ✿ A.k.a. log-normal fading or shadowing
- ✿ Long-term spatial and temporal variations over large distances
- ✿ Related to propagation conditions due to buildings, roads and other obstacles in a relative small area
 - M : received signal level m in dB
 - m : received signal level in mW
 - σ : standard deviation in dB

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

$$M = 10\log_{10}m$$

$$p(M) = \frac{1}{\sqrt{2\pi}m\sigma_0} e^{-\frac{\left(\log_{10}\frac{m}{\overline{m}}\right)^2}{2\sigma_0^2}}$$

$$\sigma_0 = \frac{10\log_{10}\sigma}{10}$$

Slow Fading (3/3)

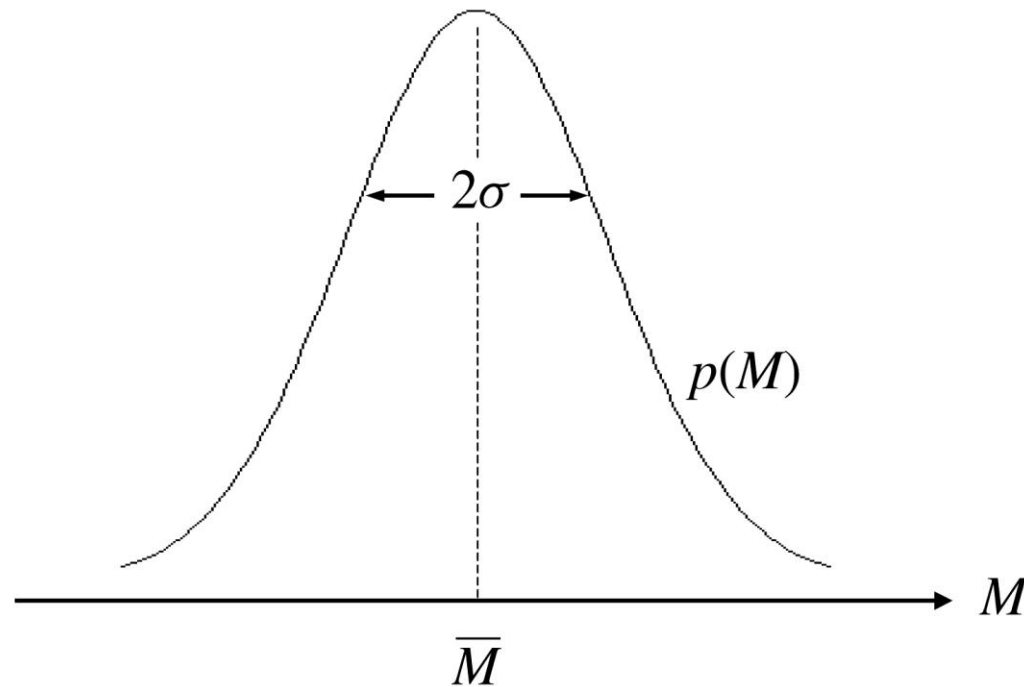


Figure 3.10 The pdf of log-normal distribution.

Fast Fading (1/3)

- ✿ A.k.a. multipath fading or small-scale fading
- ✿ Reflection + diffraction + scattering
- ✿ Receiver far from the transmitter: Rayleigh model
 - NLOS
 - Distribution:

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

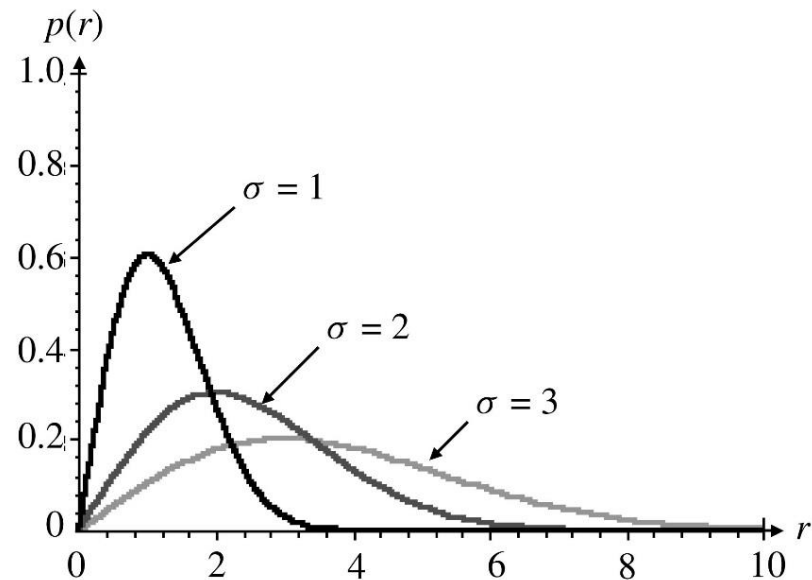


Figure 3.11 The pdf of Rayleigh distribution when $\sigma = 1$, 2, and 3.

Fast Fading (2/3)

🌾 Receiver close to the transmitter: Rician (Ricean) model

- LOS
- Distribution:

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

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

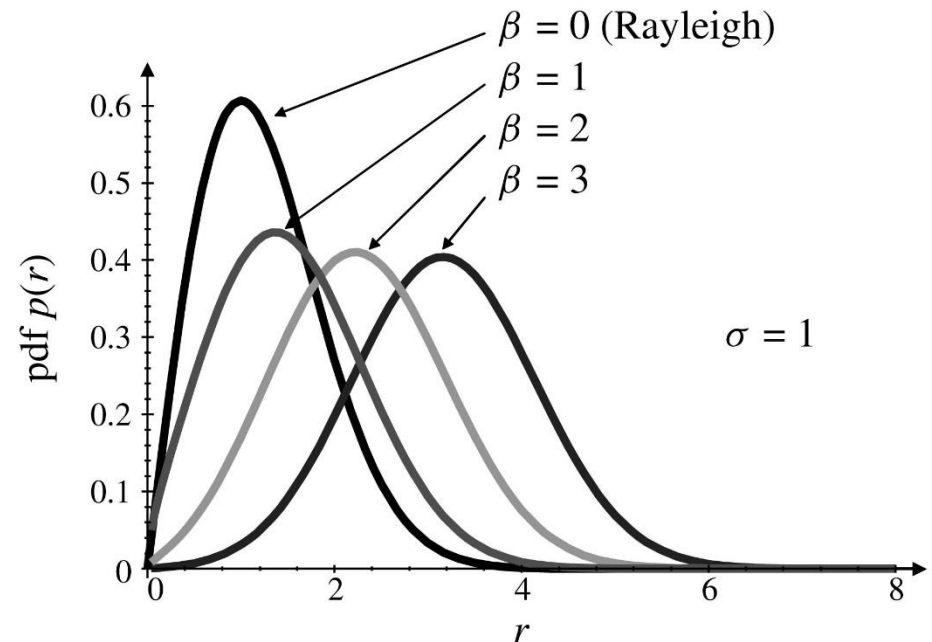


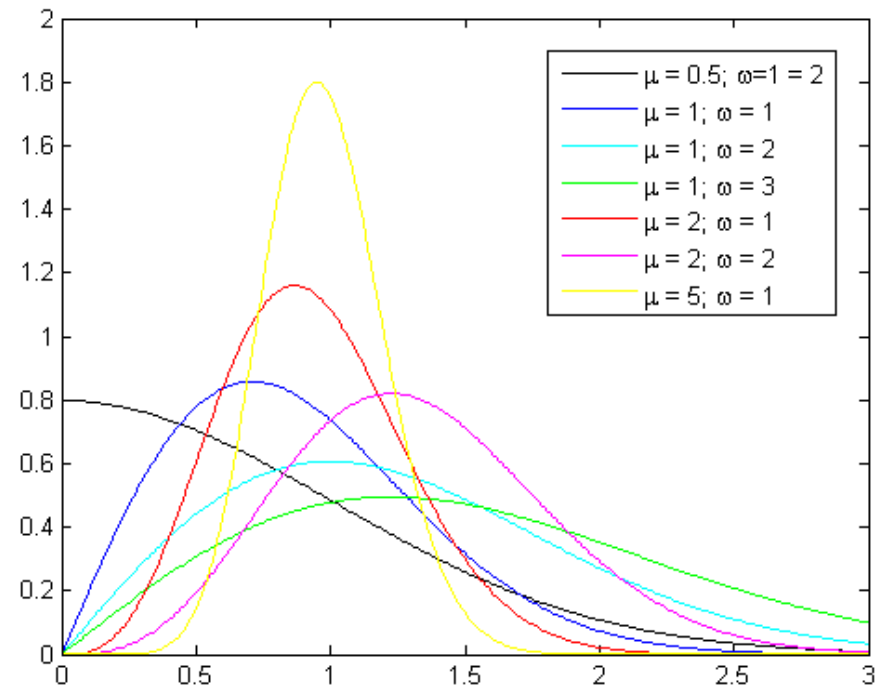
Figure 3.12 The pdf of the envelope of composite signals according to Rician distribution.

Fast Fading (3/3)

🌾 Generalized model: Nakagami-m distribution

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

$$m = \frac{(K+1)^2}{2K+1}$$



Wireless Channel Models--Summary

- ✿ Propagation path loss model
 - Free space propagation model
 - Log-distance path loss model
 - Hata model
- ✿ Large-scale propagation model
 - Log-normal distribution (log-normal shadowing)
- ✿ Small-scale propagation model
 - Multi-path effect
 - Doppler effect
- ✿ If focusing on channel capacity analysis, handoff, coverage range analysis, propagation path loss model and large-scale propagation model are considered
- ✿ If focusing on baseband symbol processing, small-scale propagation model is mainly considered

Log-Distance Path Loss Model

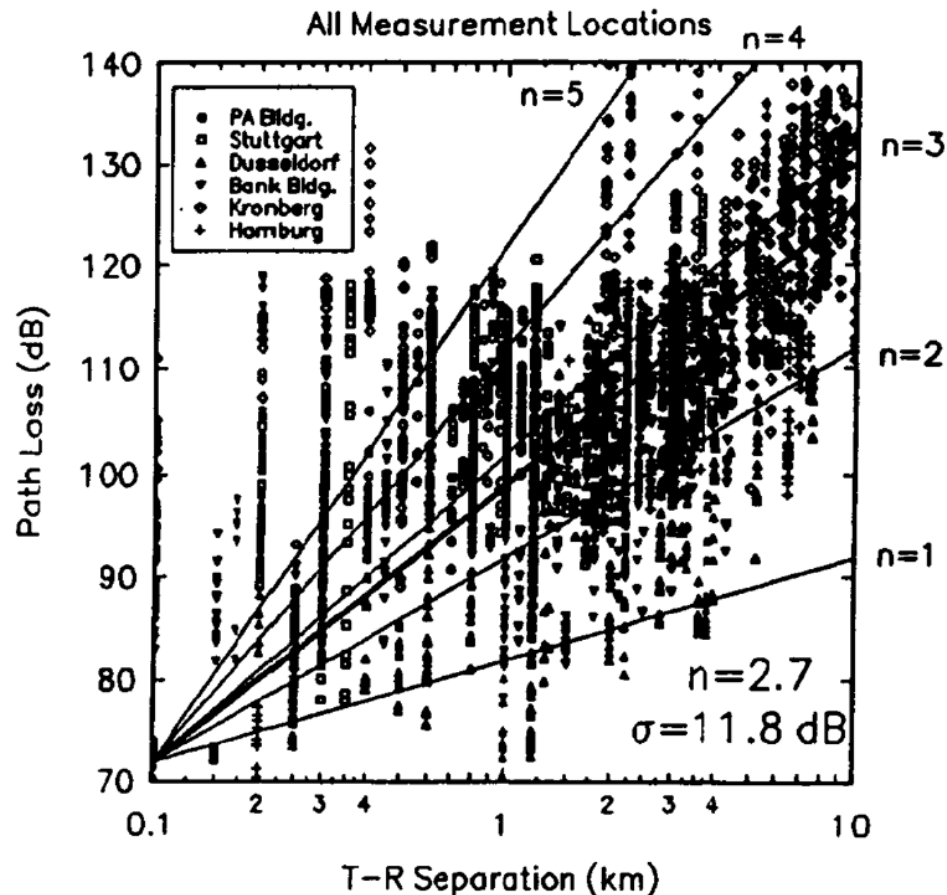
$$\overline{PL}(\text{dB}) = \overline{PL}(d_0) + 10n\log_{10}\left(\frac{d}{d_0}\right)$$

表 6.1：各種環境中的 n 值

環境	路徑散逸指數 n
暢通空間	2
都會地區的無線電	2.7 至 3.5
有遮蔽效應的都會地區無線電	3 至 5
在建築物內視線所及之區域	1.6 至 1.8
在建築物內有遮蔽之區域	4 至 6
在工廠內有遮蔽之區域	2 至 3

Some empirical results

Measurements in Germany Cities



Environment	Path-loss Exponent
Free-space	2
Urban area cellular radio	2.7-3.5
Shadowed urban cellular radio	3-5
In building LOS	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

Doppler Effect (1/3)

🌾 Mobility impact

- Moving toward each other: higher received signal frequency
- Moving away from each other: lower received signal frequency
- The frequency of received signal is $f_r = f_c - f_d$
 - f_d : Doppler frequency/Doppler shift
 - v : moving speed
 - λ : wavelength of carrier
 - $f_d = \frac{v}{\lambda} \cos \theta$

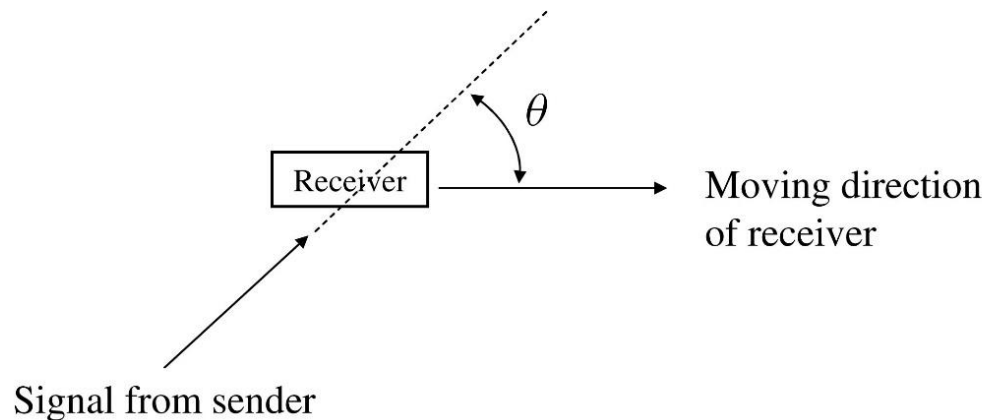


Figure 3.14 Relation of moving speed and moving direction.

Doppler Effect (2/3)

Observer vs. source

$$f' = \left(\frac{v \pm v_o}{v \mp v_s} \right) f$$

- f' : observed frequency
- f : transmitted frequency
- v : wave speed
- v_o : observer's speed
- v_s : transmitter's speed
- For v_o , + means moving close to the transmitter; - means moving away from the transmitter
- For v_s , + means moving away from the receiver, - means moving close to the receiver

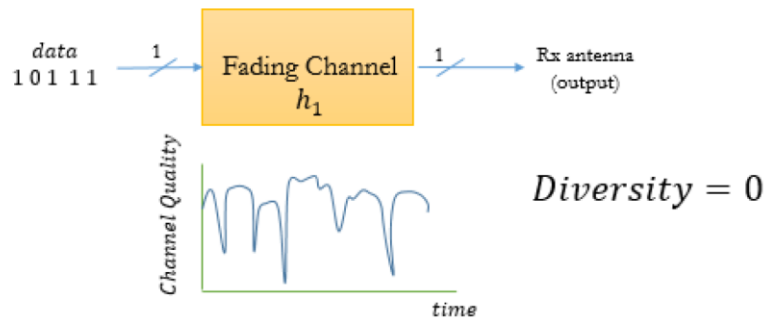
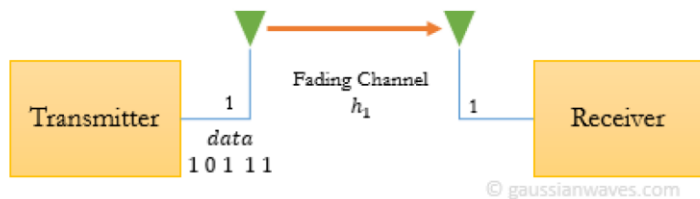
Doppler Effect (3/3)

- ✿ Signals travelling along different paths can have different Doppler shifts, corresponding to different rates of change in phase
- ✿ The difference in Doppler shifts between different signal components contributing to a single fading channel tap is known as the Doppler spread

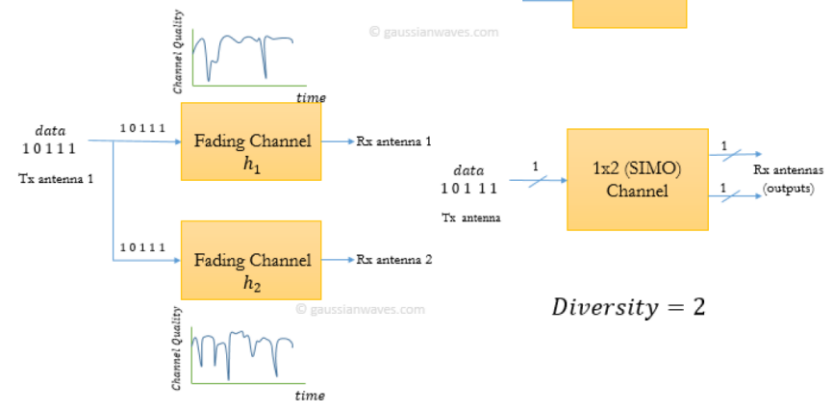
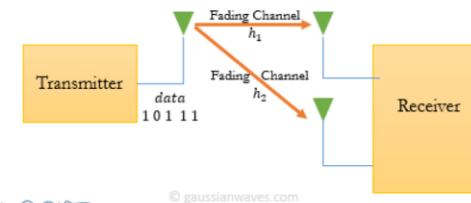
MIMO Classification v.s. Antenna Configuration

- 🌾 Single Input Single Output (SISO)
- 🌾 Single Input Multiple Output (SIMO)
- 🌾 Multiple Input Single Output (MISO)
- 🌾 Multiple Input Multiple Output (MIMO)
- 🌾 Spatial diversity v.s. spatial multiplexing

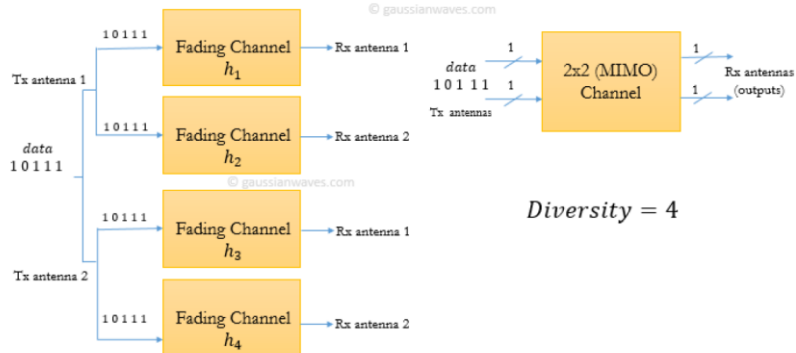
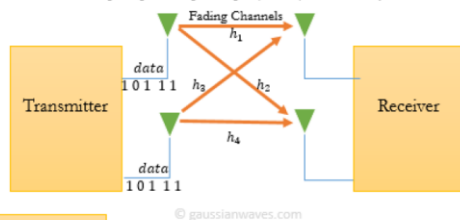
Single Input Single Output (SISO) System



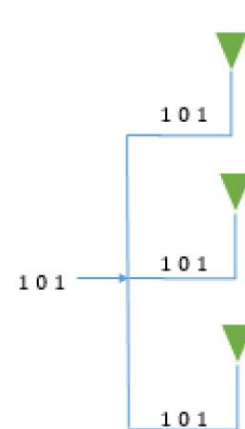
Single Input Multiple Output (SIMO) with diversity



Multiple Input Multiple Output (MIMO) with Diversity

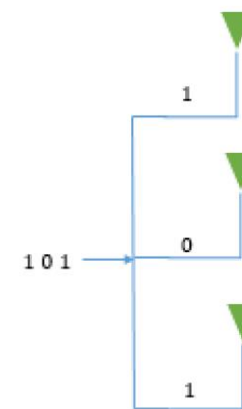


Transmit antennas



MIMO with Diversity
(Transmit diversity)
Improves reliability

Transmit antennas



MIMO with
Spatial Multiplexing
Increases data rate

Delay Spread (1/4)

Reason: multipath fading

- Resolvable (可解析)
- Unresolvable (不可解析)

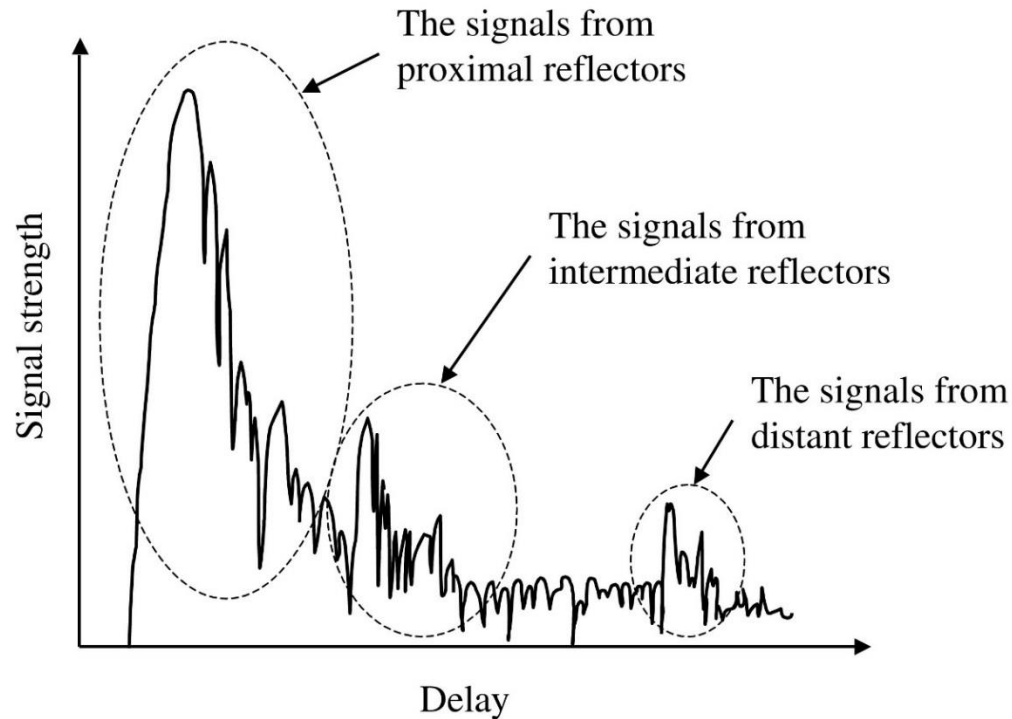


Figure 3.15 The delay spread of a signal.

Delay Spread (2/4)

✿ Assume the pdf of the delay t is $p(t)$

- The average delay spread

$$\tau_m = \int_0^{\infty} tp(t)dt$$

- The delay spread is defined as

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

✿ Delay spread is around 3 μs for a city area, and up to 10 μs in hilly terrains

Delay Spread (3/4)

🌾 Well-known representative delay functions

- Exponential

$$p(t) = \frac{1}{\tau_m} e^{-\frac{t}{\tau_m}}$$

- Uniform

$$p(t) = \begin{cases} \frac{1}{2\tau_m} & 0 \leq t \leq 2\tau_m \\ 0 & \text{elsewhere} \end{cases}$$

Delay Spread (4/4)

表 6.2 各種環境中的方均根延遲擴展

環境	頻率(MHz)	方均根延遲擴展	備註
都會區(urban)	910	1300 ns avg. 600 ns st. dev. 3500 ns max.	紐約市
都會區(urban)	892	10-25 μ s	舊金山
郊區(suburban)	910	200-310 ns	一般狀況
郊區(suburban)	910	1960-2110 ns	最差狀況
室內(indoor)	1500	10-50 ns 25 ns median	辦公大樓
室內(indoor)	850	270 ns max	辦公大樓
室內(indoor)	1900	70-94 ns avg. 1470 ns max.	舊金山辦公大樓

Intersymbol Interference (ISI) (1/2)

- ✿ Caused by time-delayed multipath signals
- ✿ Impact on the burst error rate of the channel
- ✿ Transmission rate R for a digital transmission is limited by the delay spread $R < \frac{1}{2\pi_d}$
- ✿ In a real situation, R is determined based on the required BER, which may be limited by the delay spread

Intersymbol Interference (ISI) (2/2)

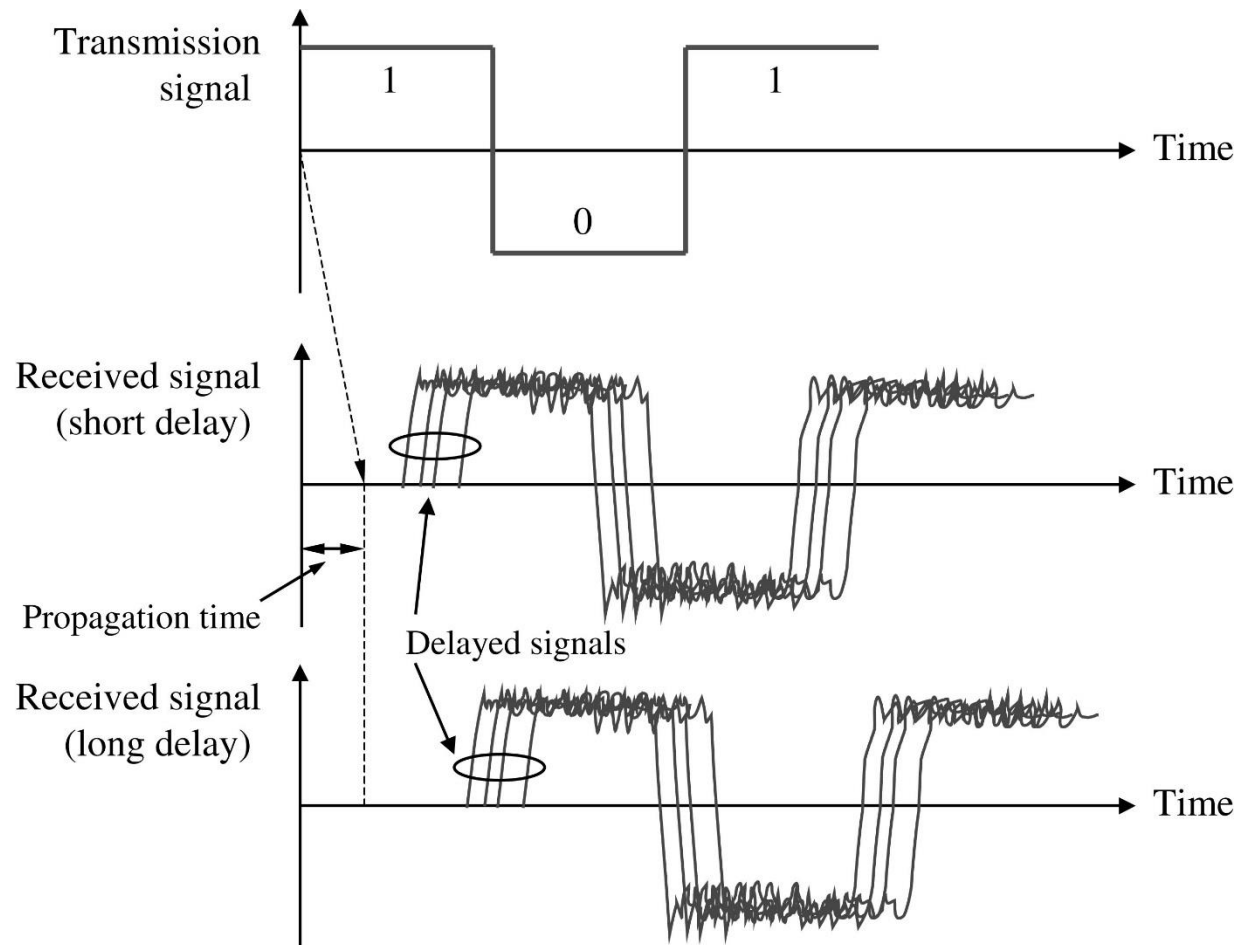


Figure 3.16 ISI caused by multipath signals.

Coherence Bandwidth (1/2)

- ✿ The coherence bandwidth measures the separation in frequency after which two signals will experience uncorrelated fading
- ✿ A statistical measure of the range of frequencies over which the channel can be considered “flat”
- ✿ Coherence bandwidth represents the correlation between two fading signal envelopes at frequencies f_1 and f_2 is a function of delay spread, that is, coherence bandwidth $\sim 1/(\text{delay spread})$
- ✿ When the correlation coefficient for two fading signal envelopes at frequencies f_1 and f_2 is equal to 0.5, the coherence bandwidth is approximated by $B_c \approx \frac{1}{2\pi\tau_d}$

Coherence Bandwidth (2/2)

- ✿ Signal bandwidth > coherence bandwidth (wideband):
frequency-selected fading
- ✿ Signal bandwidth < coherence bandwidth (narrowband):
flat fading
- ✿ Coherence bandwidth for two fading amplitudes of two received signals is $\Delta f = |f_1 - f_2| > B_c = \frac{1}{2\pi\tau_d}$
- ✿ Coherence bandwidth for two random phases of two received signals is $\Delta f = |f_1 - f_2| < E[B_c] = \frac{1}{4\pi\tau_d}$

Co-channel Interference

- ✿ Frequency reuse: same frequency is assigned to different cells
- ✿ Guideline
 - The probability of co-channel interference between cells using the same frequency is less than a given value
 - The probability that the desired signal level r_d drops below a value proportional to the interfering undesired signal r_u
- ✿ Assume that desired and undesired interfering signals are independent of each other

$$P_{co} = P(r_d \leq \beta r_u)$$

$$P_{co} = \int_0^{\infty} P(r_1 = x) P(r_2 \geq \frac{x}{\beta}) dx$$

$$= \int_0^{\infty} p_1(r_1) \int_{\frac{r_1}{\beta}}^{\infty} p_2(r_2) dr_2 dr_1$$

Coherence Time (1/2)

- ✿ In communication systems, a communication channel may change with time
- ✿ Coherence time is the time duration over which the channel impulse response is considered to be not varying
- ✿ Such channel variation is much more significant in wireless communications systems, due to Doppler effects

Coherence Time (2/2)

Simple example

$$y_{t_1}(t) = x(t - t_1) \times h_{t_1}(t)$$

$$y_{t_2}(t) = x(t - t_2) \times h_{t_2}(t)$$

- If $h_{t_1}(t) - h_{t_2}(t)$ is relative small, the channel may be considered constant within the interval t_1 to t_2
- Coherence time T_c is given by $T_c = t_2 - t_1$
- ~~Clarke's~~ model: maximum Doppler frequency f_d

$$T_c = \frac{0.423}{f_d}$$

Wideband Communication v.s. Narrowband Communication

- ✿ In radio communication, wideband and narrowband mean the utilized bandwidth are larger and smaller, respectively, than the coherence bandwidth
- ✿ In data network, wideband and narrowband mean high and low data rates, respectively

