Mobile Radio Propagation

Wireless Network Characteristics

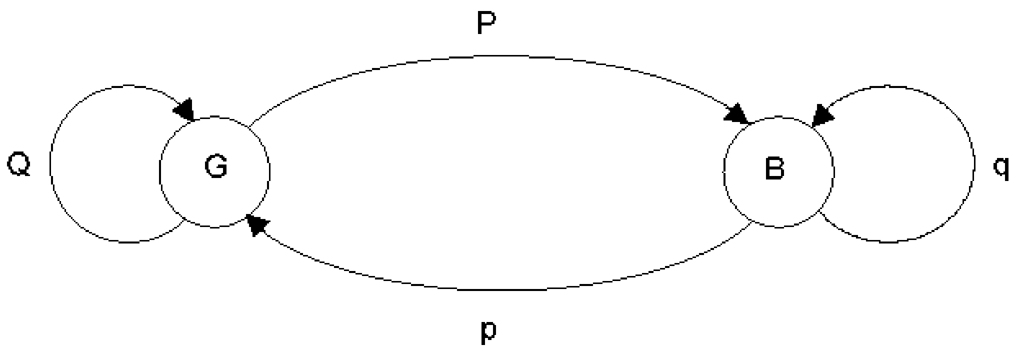
- Increased BER (can be as high as 10^{-3}), compared with wired networks
- Reasons for increased BER: atmospheric noise, multipath propagation, interference, etc
- Need for spectrum licensing to alleviate interference
- Dynamic topologies – hidden terminals, also will result in interference
- Energy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

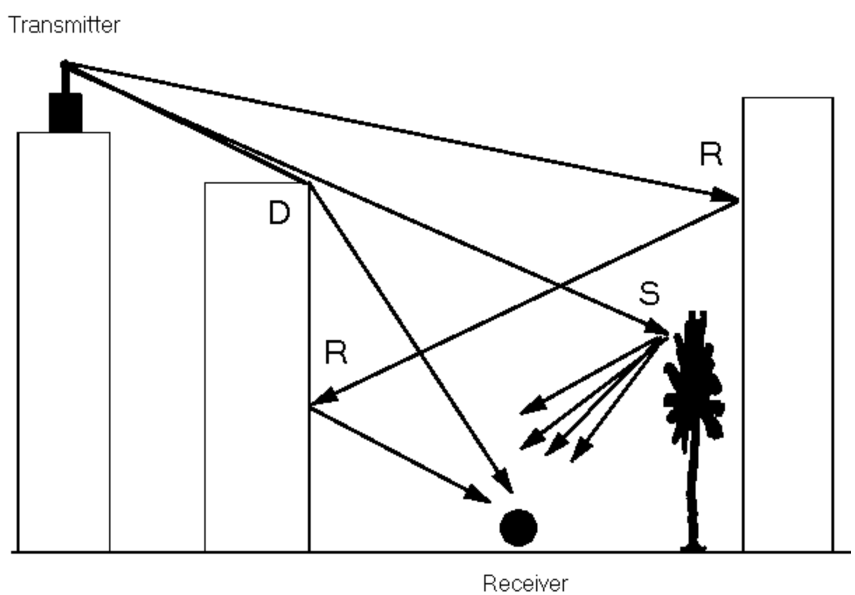
Bit Error Rate (2/2)

- *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 $q=1-p$



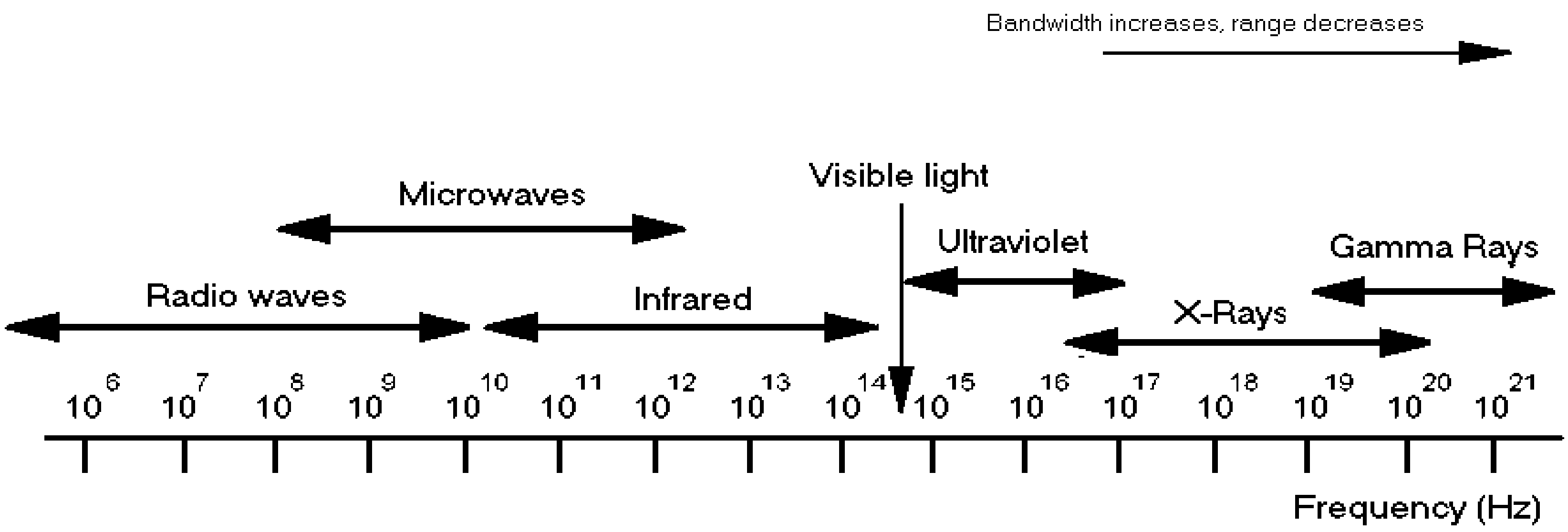
Reasons of Reception Errors

- 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: $$\mathrm{dB} = 10\log_{10}\left(\frac{\mathrm{signal}}{\mathrm{noise}}\right)$$
- dBm: power ratio in dB of the measured power referenced to 1 mW [absolute power measurement]
  - Formula: $$\mathrm{dBm} = 10\log_{10}\left(\frac{\mathrm{power}}{1\mathrm{mW}}\right)$$

dB v.s. dBm (2/2)

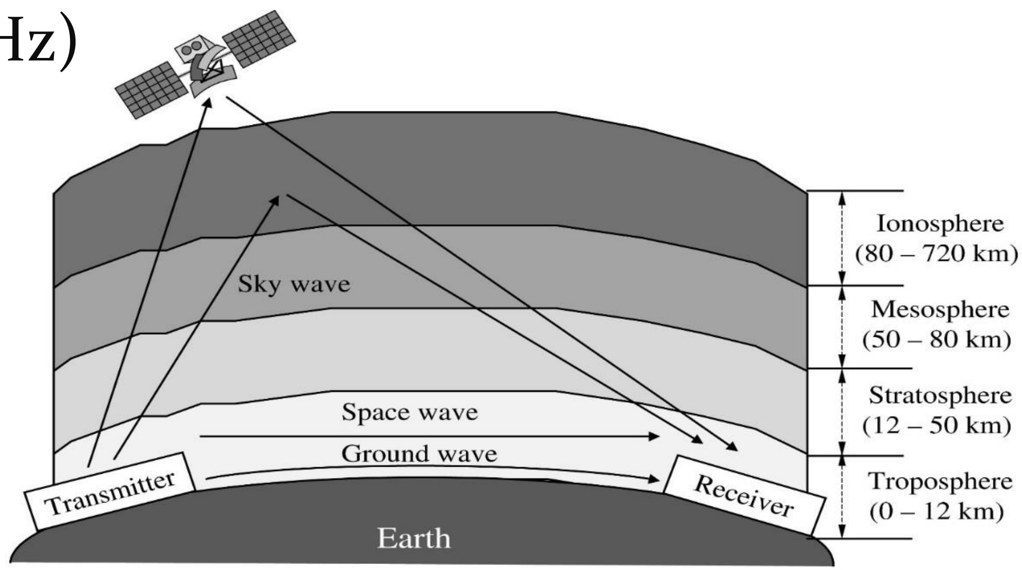
- Log rules
  - $\log_b(mn) = \log_b(m) + \log_b(n)$
  - $\log_b(\frac{m}{n}) = \log_b(m) - \log_b(n)$
  - $\log_b(m^n) = n\log_b(m)$
- What does $(A \text{ dBm} - B \text{ dBm})$ mean?

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

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

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)

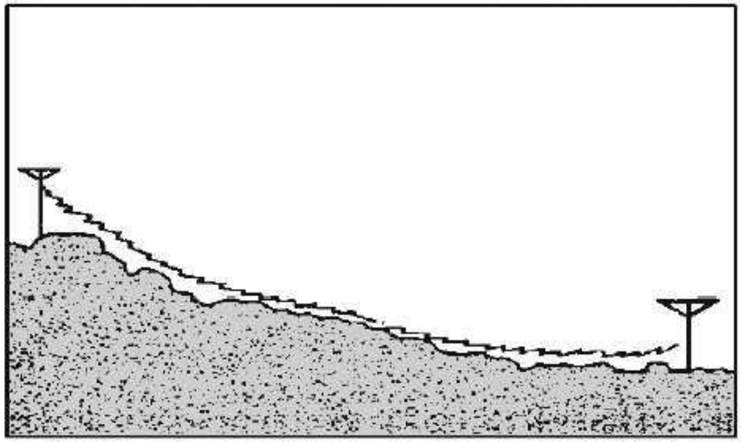


電離層
中間層
平流層
對流層

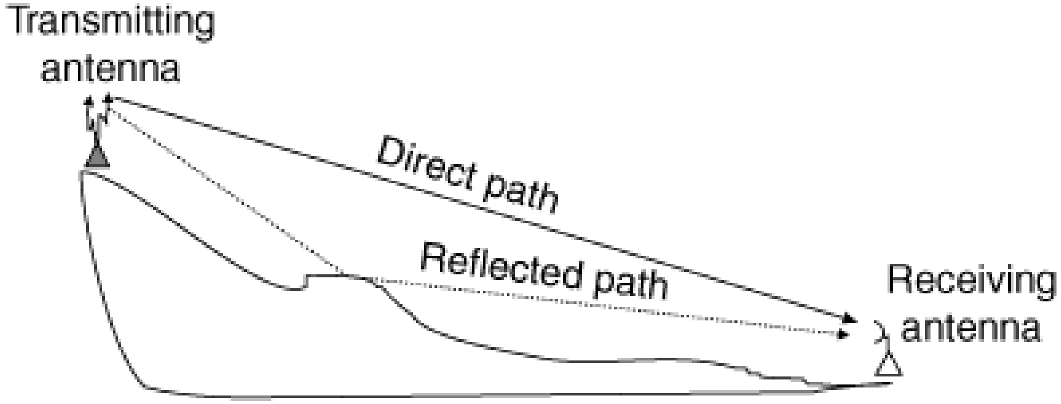
Figure 3.1 Propagation of different types of radio waves.

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)

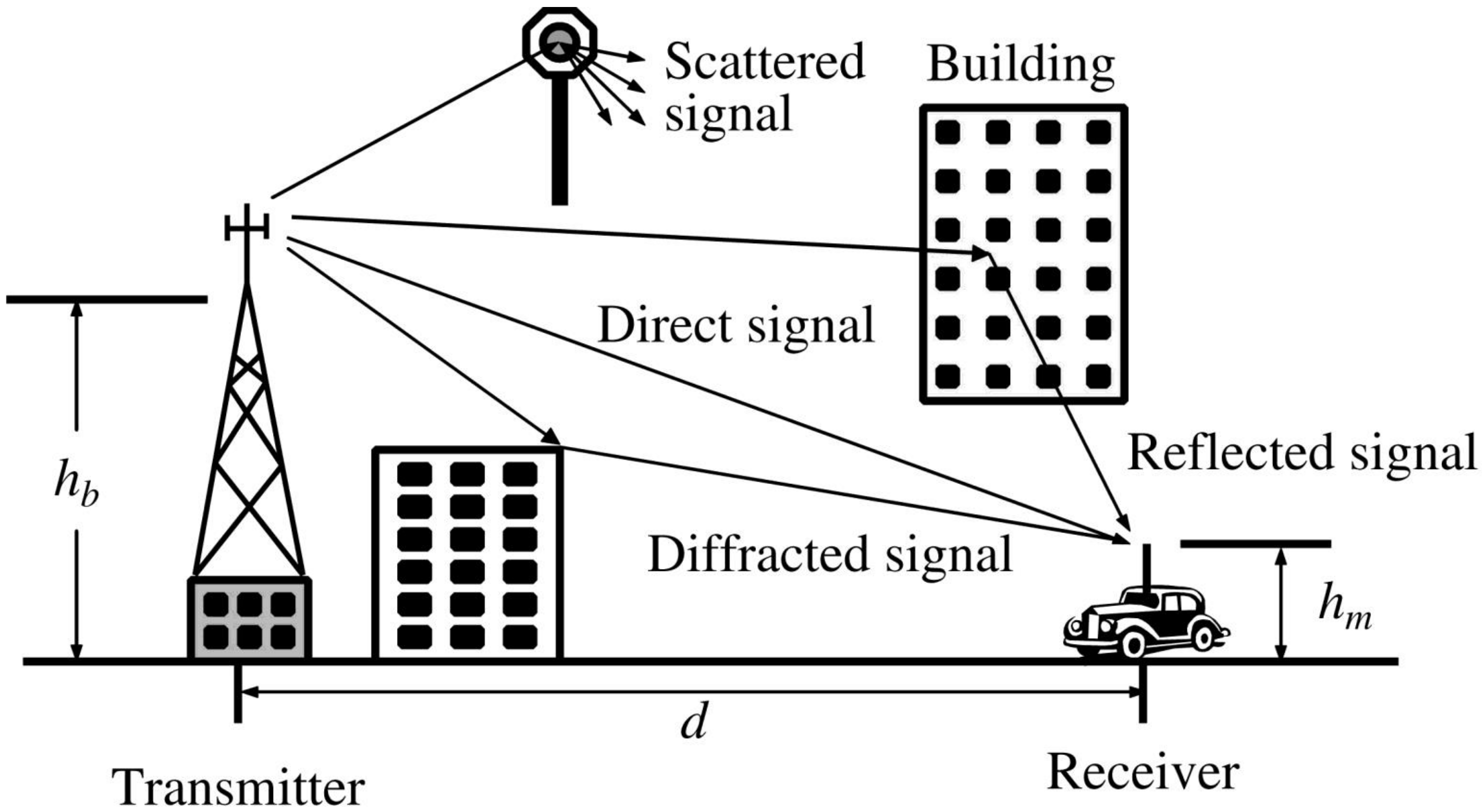


Figure 3.2 Reflection, diffraction, and scattering of radio signals.

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

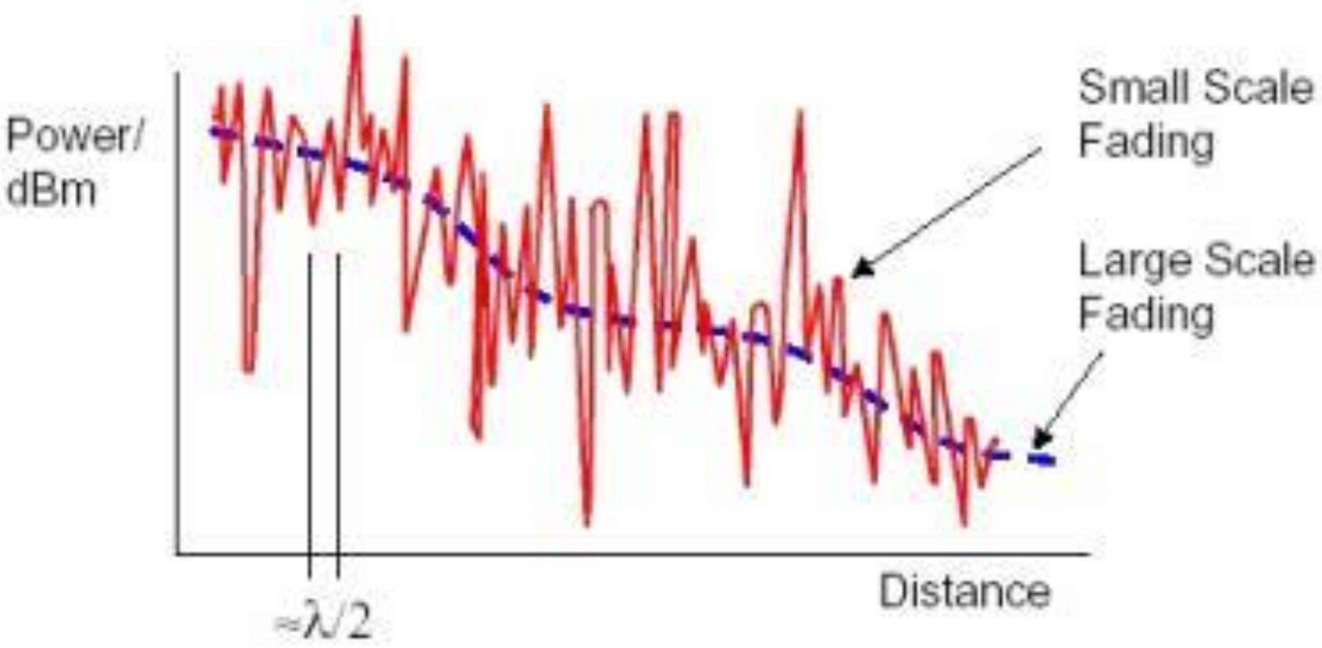
Propagation Mechanisms (4/5)

- 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

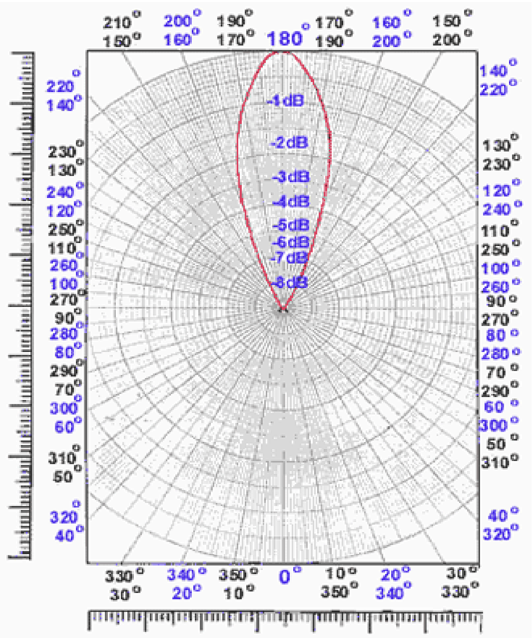


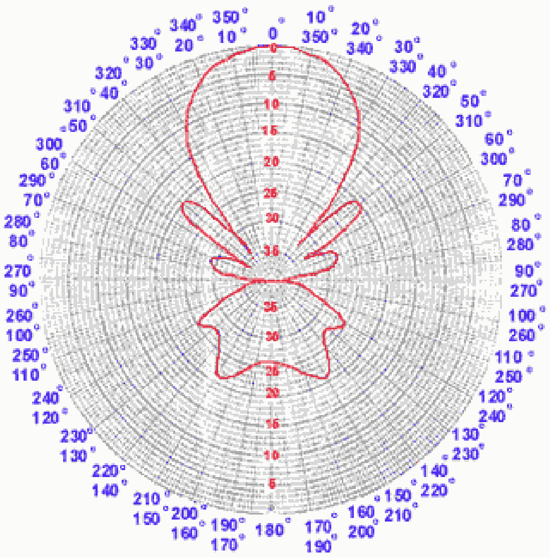
Free Space Propagation (1/3)

- Receiving signal power: $P_r = \frac{A_e G_t P_t}{4\pi d^2} = \frac{G_r G_t P_t}{(\frac{4\pi d}{\lambda})^2}$
  - 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: $L_f = \frac{P_t}{P_r} = \frac{1}{G_r G_t}(\frac{4\pi d}{\lambda})^2$
- 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
  - $G_t = G_r = 1$
  - $c = 2.998 \times 10^8$ m/s
  - f_c is carrier frequency

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

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

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

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

  - $L_{\mathrm{PU}}(\mathrm{dB}) = 10\log_{10} L_{\mathrm{PU}}$
  - 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

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

– Medium and small cities

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

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

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

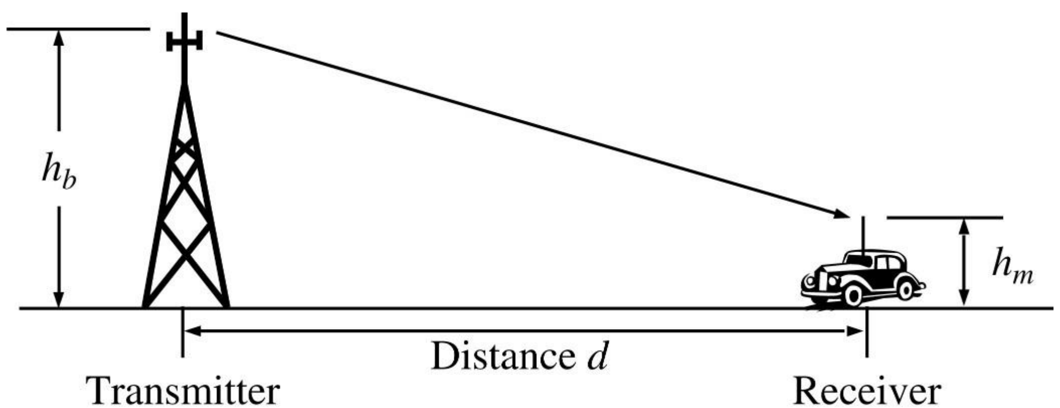


Figure 3.5 Radio propagation.

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)

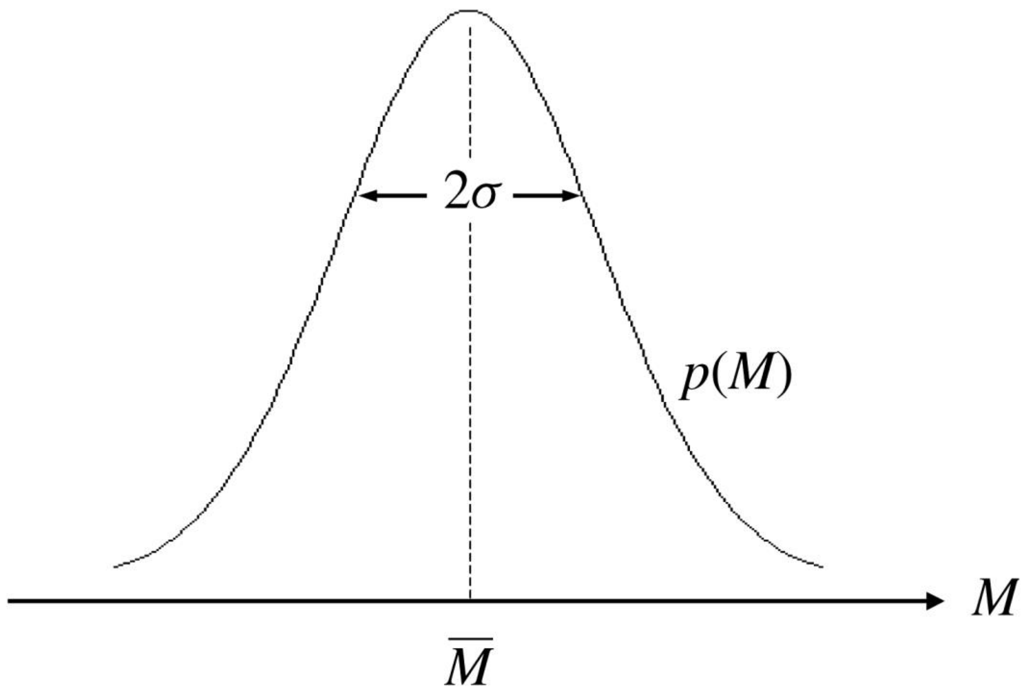


Figure 3.10 The pdf of log-normal distribution.

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:

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

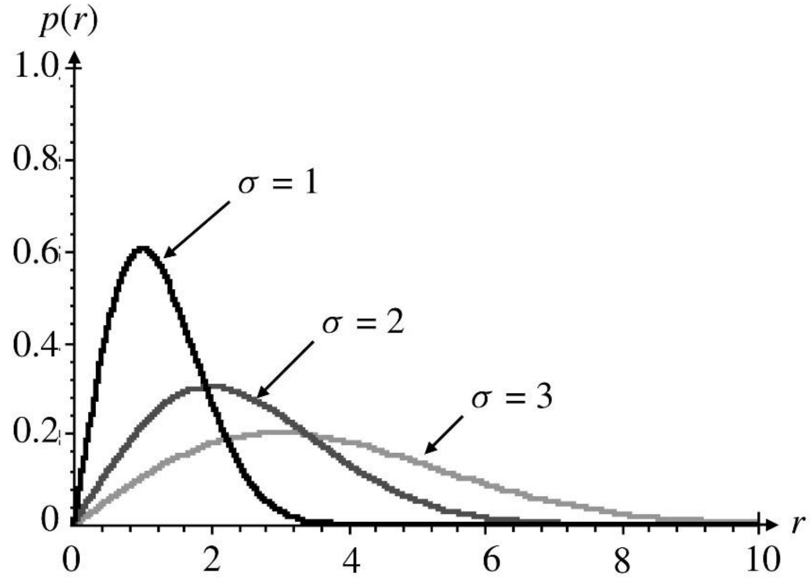


Figure 3.11 The pdf of Rayleigh distribution when σ = 1, 2, and 3.

Fast Fading (2/3)

- Receiver close to the transmitter: Rician (Ricean) model
  - LOS
  - Distribution:

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

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

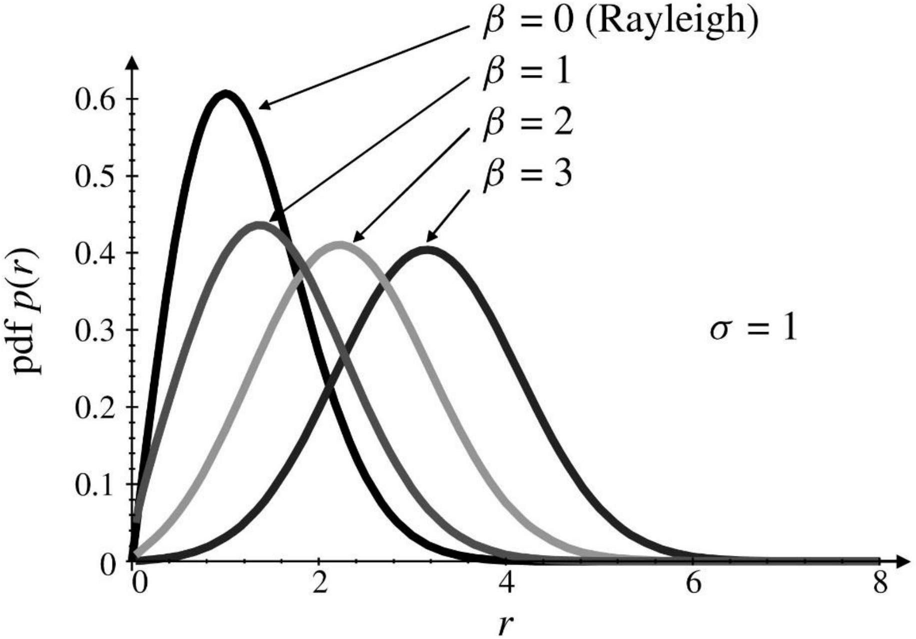


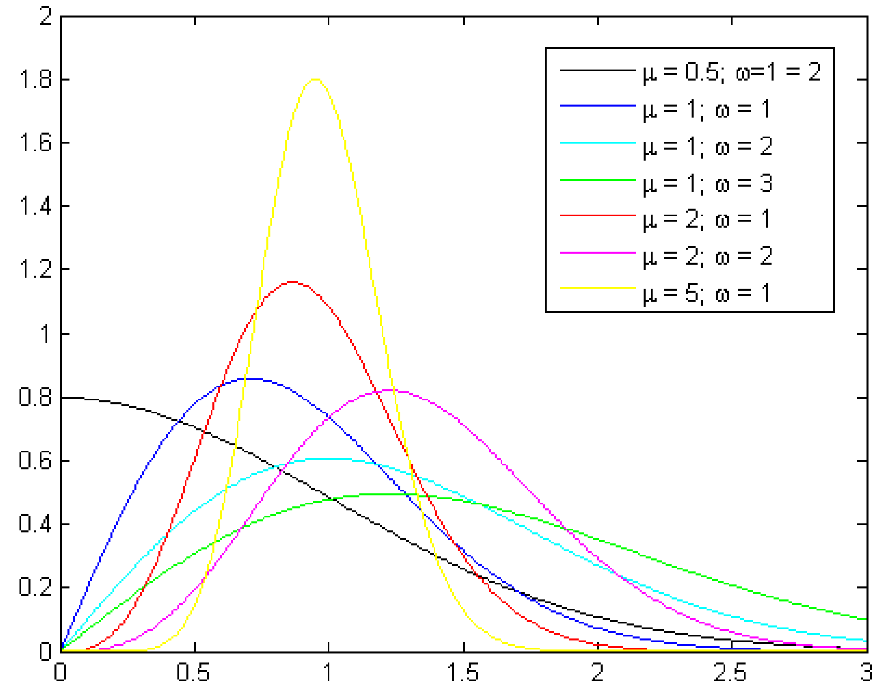
Figure 3.12 The pdf of the envelope of composite signals according to Rician distribution.

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

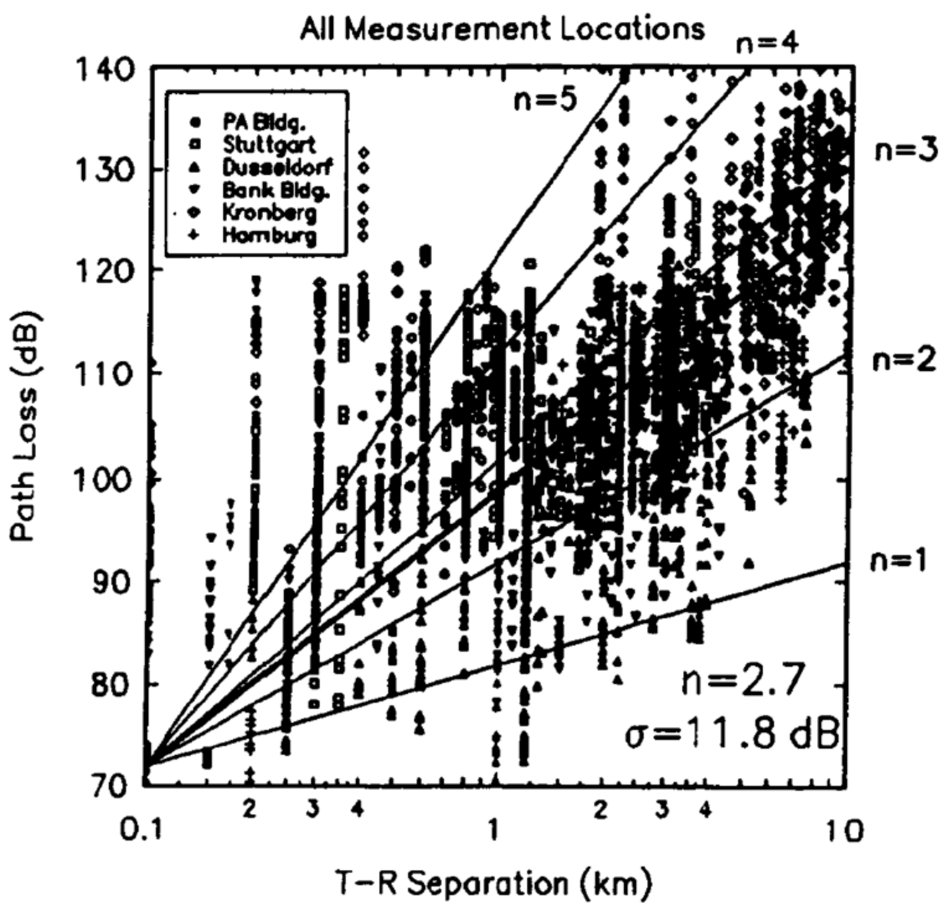
$$\overline{\mathrm{PL}}(\mathrm{dB}) = \overline{\mathrm{PL}}(d_0) + 10n\log_{10}\left(\frac{d}{d_0}\right)$$

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
    - $f_d = \frac{\mathrm{v}}{\lambda}\cos\theta$

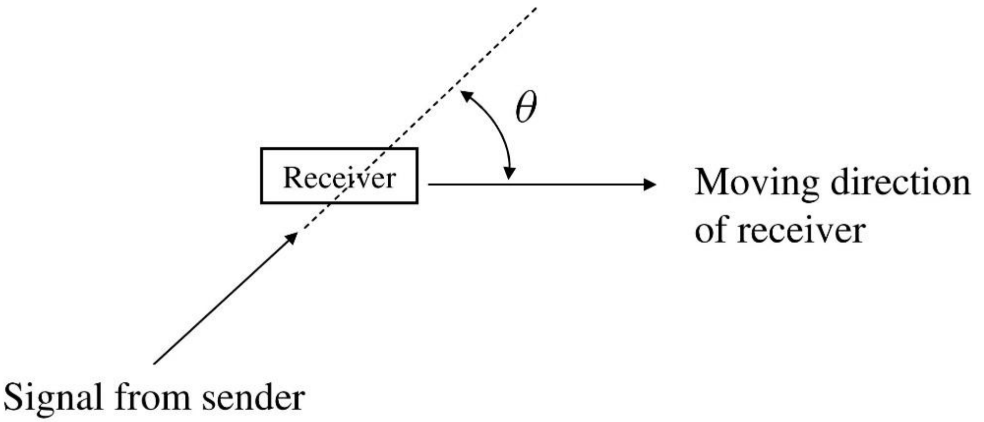


Figure 3.14 Relation of moving speed and moving direction.

Doppler Effect (2/3)

- Observer vs. source

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

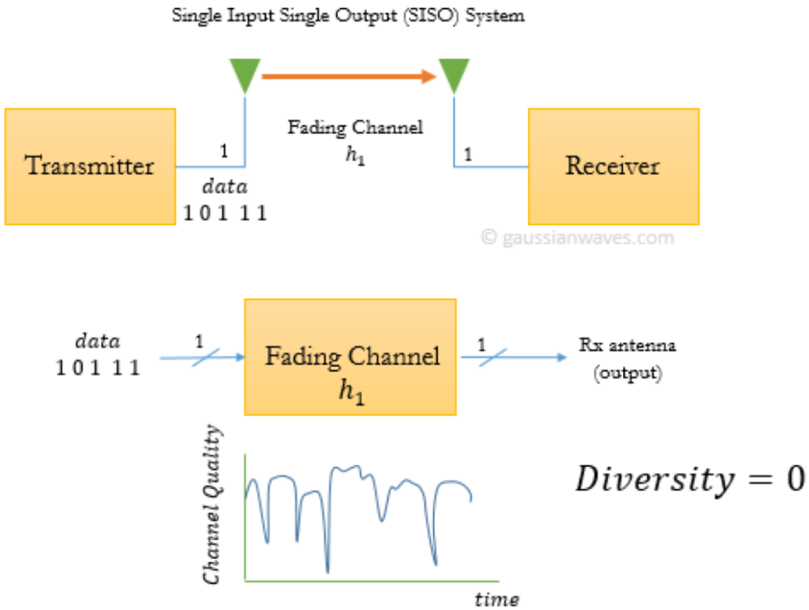
  - f': observed frequency
  - f: transmitted frequency
  - v: wave speed
  - v_o: observer's speed
  - v_s: transmitter's speed
  - For v_o, + means moving close to the transmitter; - means moving away from the transmitter
  - For v_s, + means moving away from the receiver, - means moving close to the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

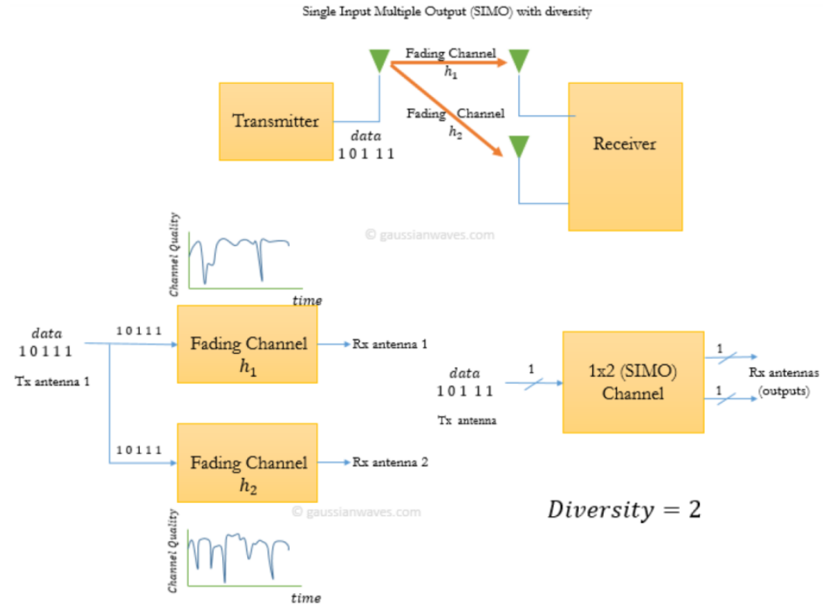
Doppler Effect (3/3)

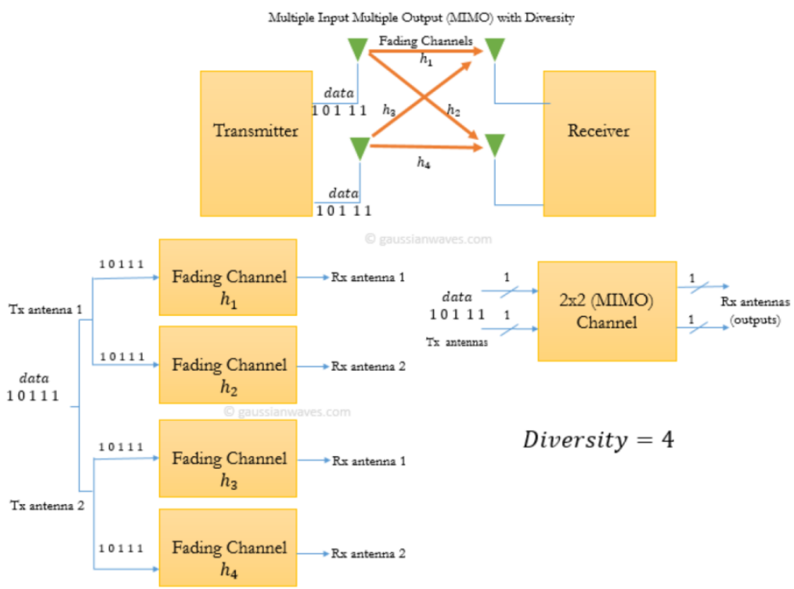
- Signals travelling along different paths can have different Doppler shifts, corresponding to different rates of change in phase
- The difference in Doppler shifts between different signal components contributing to a single fading channel tap is known as the Doppler spread

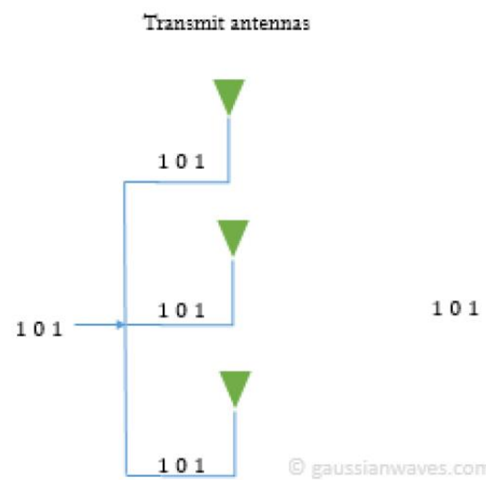
MIMO Classification v.s. Antenna Configuration

- 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

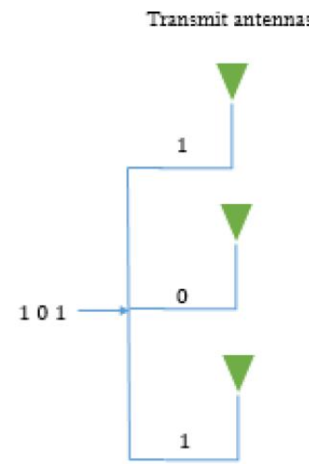








MIMO with Diversity
(Transmit diversity)
Improves reliability



MIMO with
Spatial Multiplexing
Increases data rate

Delay Spread (1/4)

- Reason: multipath fading
  - Resolvable (可解析)
  - Unresolvable (不可解析)

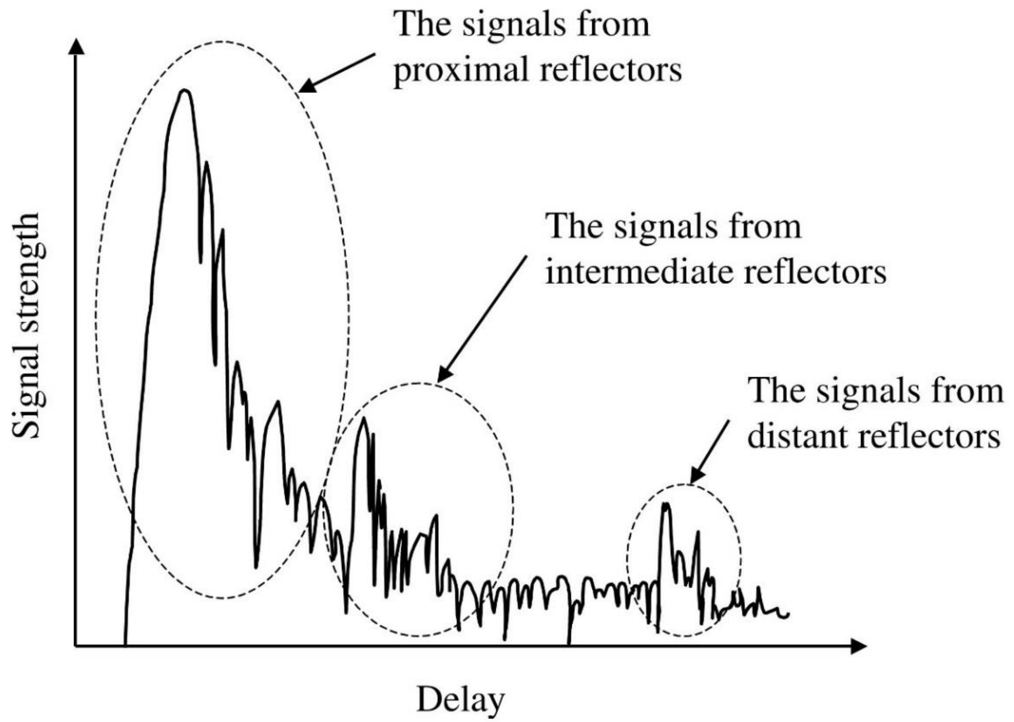


Figure 3.15 The delay spread of a signal.

Delay Spread (2/4)

- Assume the pdf of the delay t is $p(t)$
  - The average delay spread

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

  - 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 μs	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)

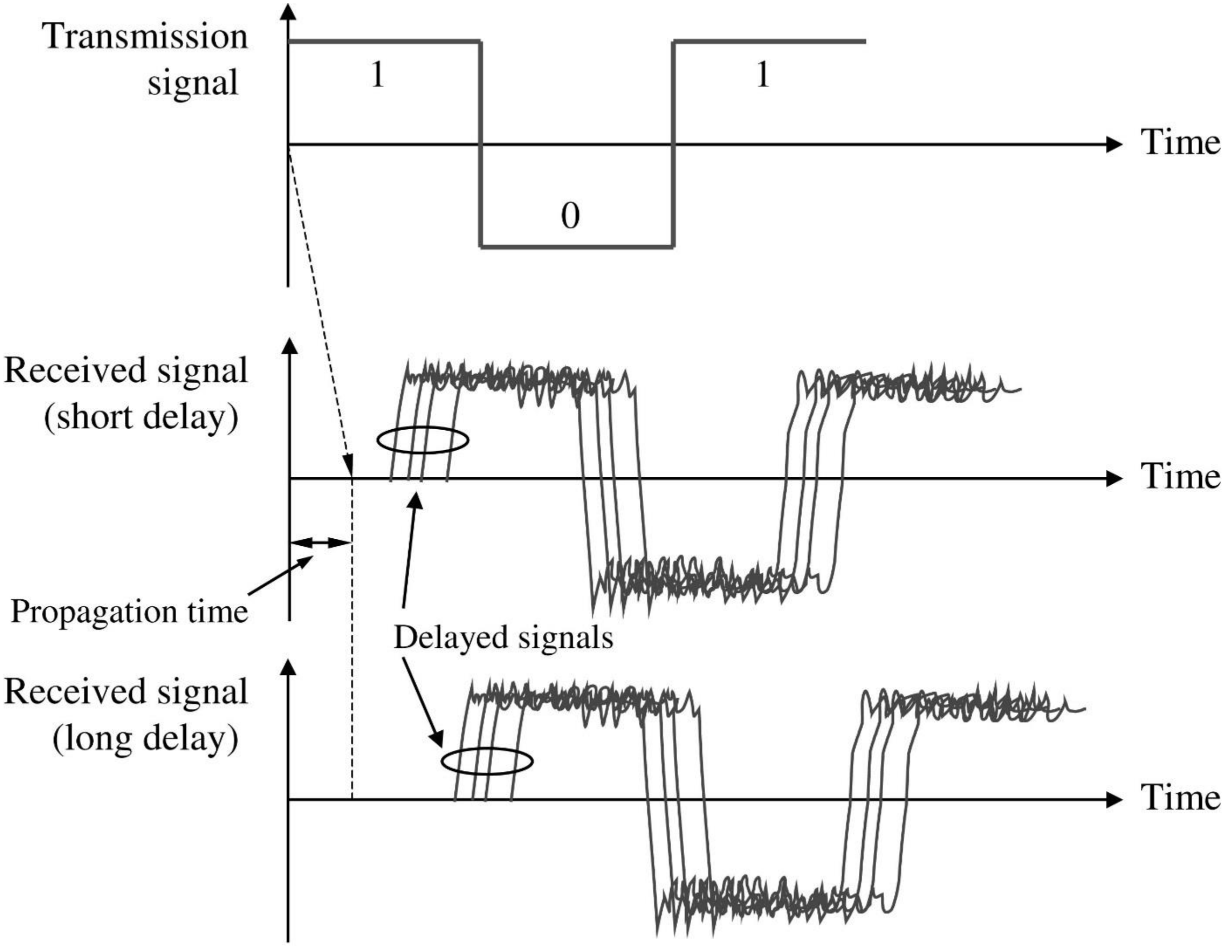


Figure 3.16 ISI caused by multipath signals.

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 envelops at frequencies f_1 and f_2 is a function of delay spread, that is, coherence bandwidth ~ 1/(delay spread)
- When the correlation coefficient for two fading signal envelops 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 $\Delta f = |f_1 - f_2| > B_c = \dfrac{1}{2\pi\tau_d}$
- Coherence bandwidth for two random phases of two received signals is $\Delta f = |f_1 - f_2| < E[B_c] = \dfrac{1}{4\pi\tau_d}$

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

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

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

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

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 $T_c = t_2 - t_1$
  - Clarkes' 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