Chapter 3

Mobile Radio Propagation

Adapted from class notes by
Prof. Leszek T. Lilien, CS, Western Michigan University
and
Prof. Dharma P. Agrawal & Qing-An Zeng, University of Cincinnati

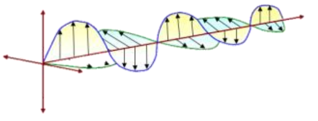
Most slides based on publisher's slides for 1st and 2nd edition of:
Introduction to Wireless and Mobile Systems by Agrawal & Zeng

Outline of Chapter 3

- Introduction
- Types of Waves
  - Speed, Wavelength, Frequency
- 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

3.1. Introduction

- This section covers the distinguishing features of *mobile* radio propagation



- Model of wireless mobile channel
  - Time-varying communication path between 2 terminals
    - Fixed BS and mobile MS
  - Mobility introduces new challenges into radio propagation

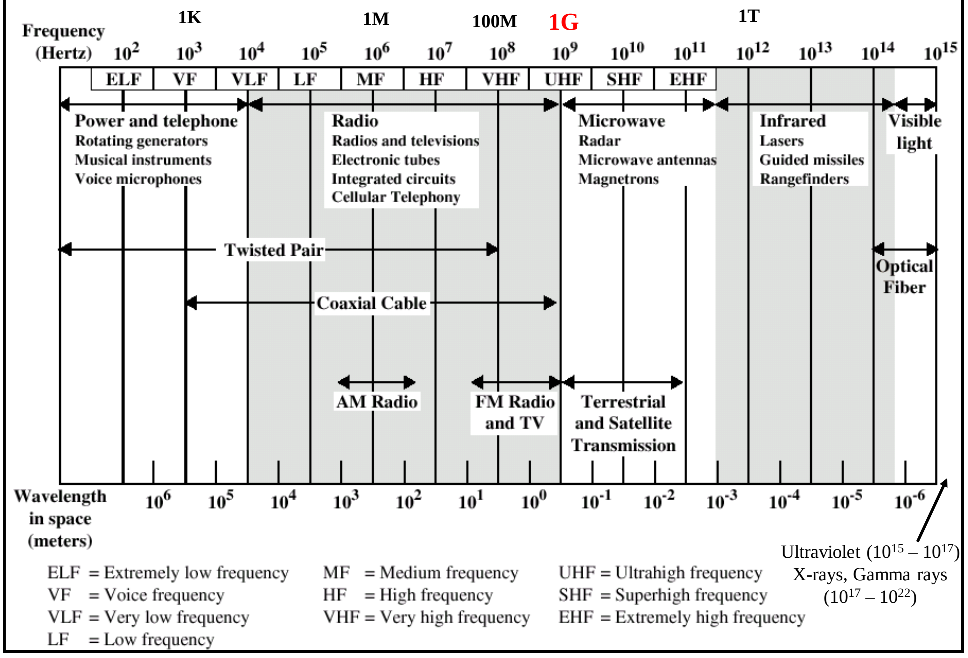
Speed, Wavelength, Frequency

Light speed (*v*) = Wavelength x Frequency
= 2.998 x 10^8 m/s = 3 x 10^8 m/s = 300,000 km/s

System	Frequency (*f*)	Wavelength (λ)
AC current	60 Hz	5,000 km
FM radio	100 MHz (88-99, 100-108)	3 m
Cellular (original)	800 MHz	37.5 cm
Ka band satellite	20 GHz	15 mm
Ultraviolet light	10^{15} Hz	10^{-7} m

$$v = \lambda f$$

Electromagnetic Spectrum for Telecommunication



Metrics

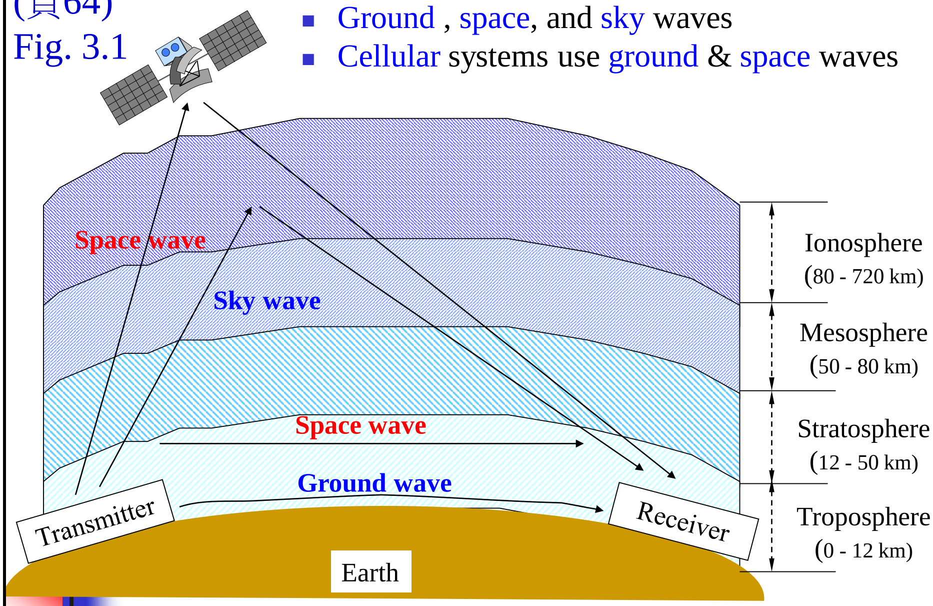
1000^n	10^n	Prefix	Symbol
1000^8	10^{24}	yotta	Y
1000^7	10^{21}	**zetta**	Z
1000^6	10^{18}	exa	E
1000^5	10^{15}	peta	P
1000^4	10^{12}	tera	T
1000^3	10^9	giga	G
1000^2	10^6	mega	M
1000^1	10^3	kilo	k
$1000^{2/3}$	10^2	hecto	h
$1000^{1/3}$	10^1	deca, deka	da

$1000^{-1/3}$	10^{-1}	deci	d
$1000^{-2/3}$	10^{-2}	centi	c
1000^{-1}	10^{-3}	milli	m
1000^{-2}	10^{-6}	micro	µ (u)
1000^{-3}	10^{-9}	nano	n
1000^{-4}	10^{-12}	pico	p
1000^{-5}	10^{-15}	femto	f
1000^{-6}	10^{-18}	atto	a
1000^{-7}	10^{-21}	zepto	z
1000^{-8}	10^{-24}	yocto	y

p. 58
(頁64)
Fig. 3.1

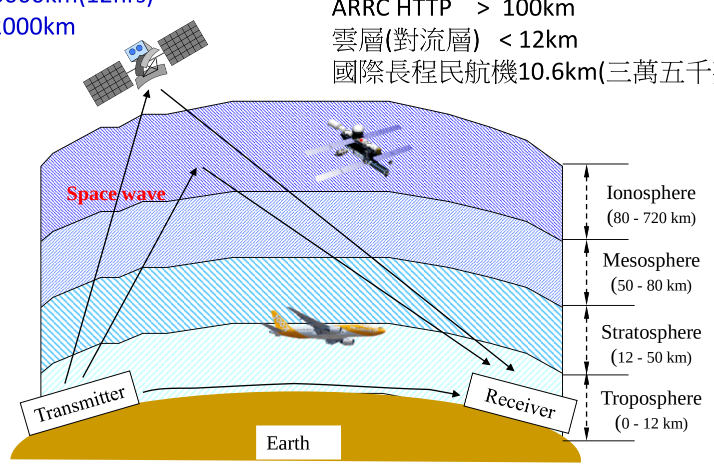
3.2. Types of Radio Waves

- Ground , space, and sky waves
- Cellular systems use ground & space waves

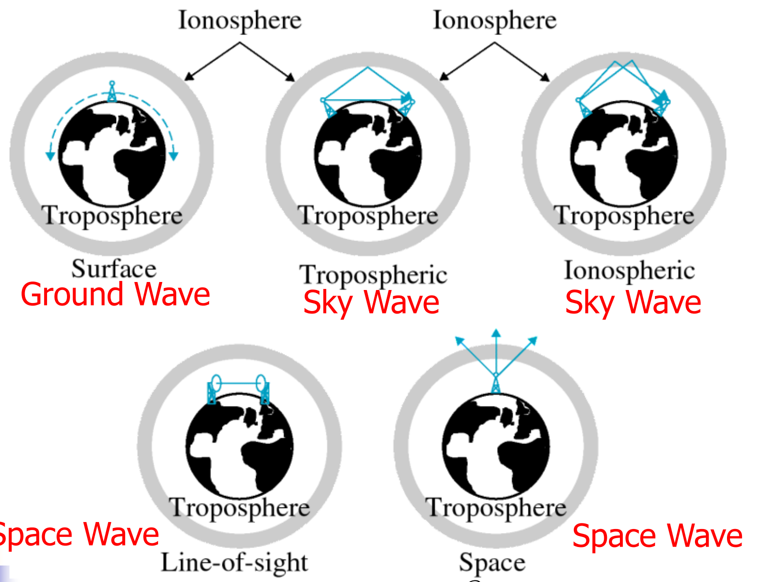


火星 87,000,000km(290光秒; 好奇號253天)
月球近地點357000km
大氣磁層頂 57000km
GEO 35800km(24hrs)
GPS 20000km(12hrs)
LEO < 2000km

太空站 350km
ARRC HTTP > 100km
雲層(對流層) < 12km
國際長程民航機10.6km(三萬五千英呎)

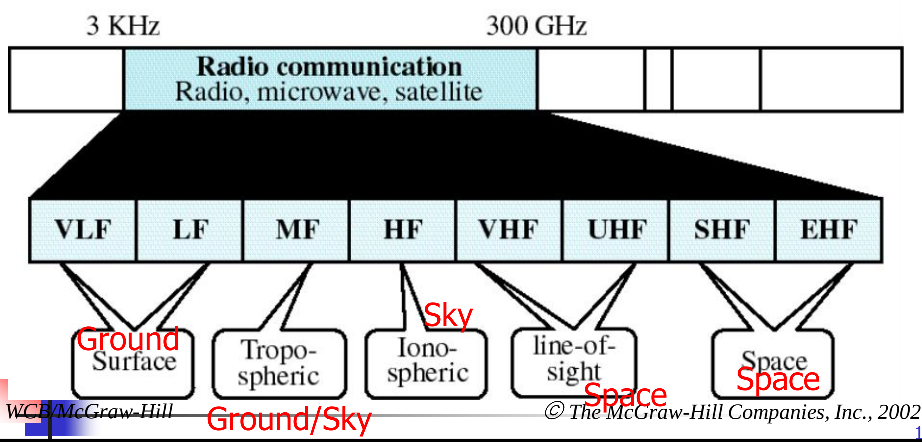


Propagation Types



Radio Communication Band

VLF	Very low frequency	VHF	Very high frequency
LF	Low frequency	UHF	Ultra high frequency
MF	Middle frequency	SHF	Super high frequency
HF	High frequency	EHF	Extremely high frequency



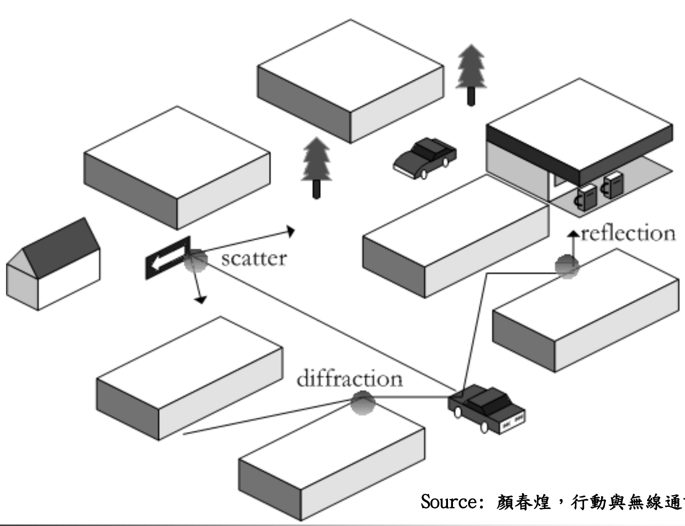
Radio Frequency Bands

p. 58 (頁64) Table 3.1

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		AM long wave
Medium	MF	300 kHz - 3 MHz	Ground/Sky wave	AM med. wave
High	HF	3 MHz - 30 MHz	Sky wave	AM short wave
Very high	VHF	30 MHz - 300 MHz	Space wave	FM, TV
Ultra high	UHF	300 MHz - 3 GHz		TV, cellphones
Super high	SHF	3 GHz - 30 GHz		WLAN
Extremely high	EHF	30 GHz - 300 GHz		
Tremendously high	THF	300 GHz - 3000 GHz		

世界各國家SW短波電台頻率表

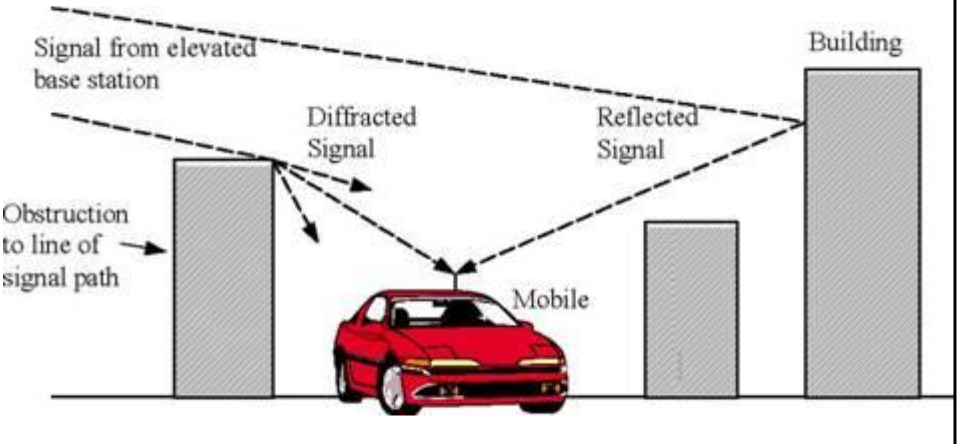
Radio Propagation Effects



Source: 顏春煌，行動與無線通訊，金禾。

3.3. Propagation Mechanisms

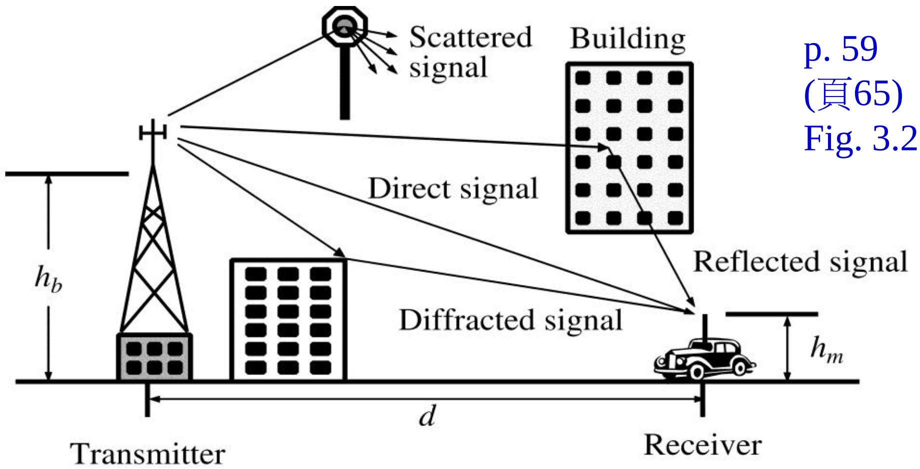
- Ideal propagation in free space (no obstacles)
- Radio signals can penetrate simple walls to some extent
  Large structure, a hill – difficult to pass through
- Propagation effects due to obstacles
  - Reflection (反射)
    - Propagation wave impinges on an object which is large as compared to wavelength
      - E.g., the surface of the Earth, buildings, walls, etc.
  - Diffraction (繞射)
    - 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 (散射)
    - Objects smaller than the wavelength of the propagation wave
      - E.g. foliage, street signs, lamp posts



Source: http://www.ringline.com.tw/support/techpapers/radiodevelop/151-ofdmcdma-.html

Radio Propagation Effects (cont.)

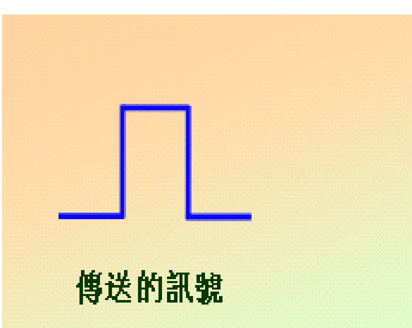
h_b – heights of BS antenna, h_m - heights of MS antenna

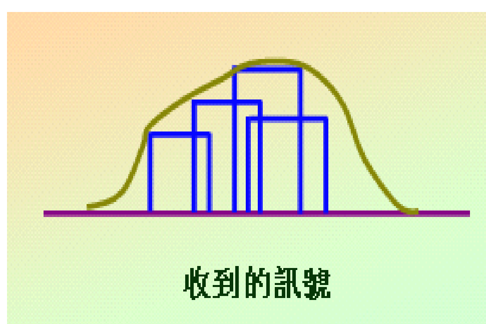


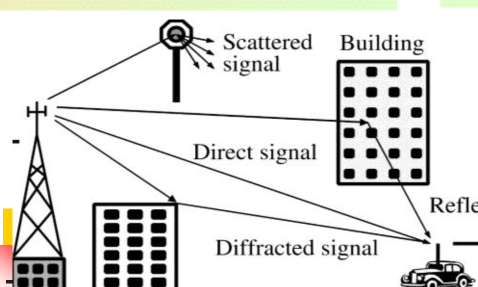
p. 59
(頁65)
Fig. 3.2

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

頻道的散佈特性(dispersive characteristics)

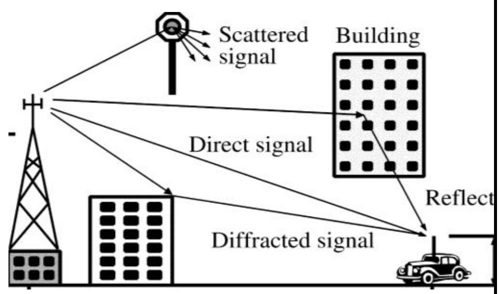






Source: 顏春煌，行動與無線通訊，金禾。

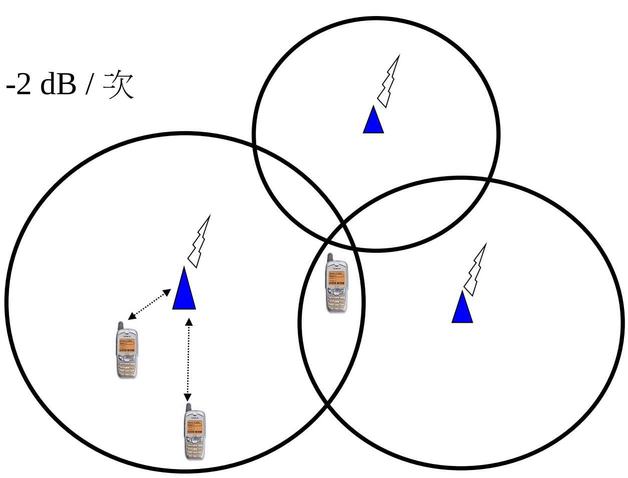
- Quality of signal reaching receiver via different types of radio waves
  - Direct propagation is the best
  - Reflection is 2nd best
  - Diffraction is 3rd best
  - Scattering is 4th best



- If no direct-path waves (LOS waves) can reach receiver mainly by reflection or diffraction

Power Control

-2 dB / 次



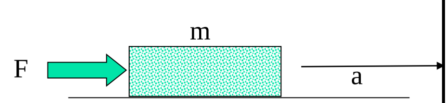
基礎通訊原理

- 訊號(signal)強度?
- Power (功率)?
- Watt (瓦特)?
- dB (分貝) ?
- dBm ?

20

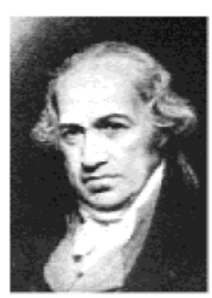
Review

- 力: F = m * a
  1 newton = 1 kg * 1 m/s^2



- 功: J = F * d
  1 joule(焦耳) = 1 newton * 1 m

- 功率(Power): P = J/ t
  表示作功快慢程度的物理量
  1 watt = 1 joule / 1 s = 1 W = 1000 mW



James Watt

21

測量的單位

- 焦耳(Joule)
  國際單位制中功、能量和熱量的計量單位。
  - 1 cal = 4.186 joule
- 功率(Power)
  單位時間內所做的功，或功對於時間的變化率。功率單位“瓦特”(W; Watt)表示在 1秒內完成1焦耳功所需的功率。
- 1 watt也可以指電壓為1伏特(V; volt)的1安培(A, ampere)電流。 **$P=VI=I^2R$**
- 一般的夜燈功率大約是7 watts 。
- FCC規定2.4 GHz點對多點的WLAN所使用的天線功率不能超過4 watts。

Source: 顏春煌，行動與無線通訊，金禾。

釣竿誤觸台鐵高壓電線 婦人皮開肉綻燒傷送醫

日期：2019/01/25

- 苗栗縣1位婦人，拿釣竿在鐵軌旁移動時，不慎碰觸到台鐵高達2萬5千伏特的電車線，送醫急救。

Source: https://tw.appledaily.com/recommend/realtime/20190125/1507485

爬火車頂拍照遭高壓電擊　1:28

Source: https://tw.appledaily.com/headline/daily/20160124/32255502/ ved

雨天拿自拍神器

小心雷擊成「焦」點　　1:30

Source: 東森新聞

- 1000瓦特‧時(1000*60*60焦耳)代表連續作功或耗能量1000 W達一小時。通常1000瓦時又稱一“度”電。每度電價約為2~3元，
- 電器功率：
  - 電燈泡 15 - 100 瓦特
  - 收音機 20 - 100 瓦特
  - 電視機 40 - 200 瓦特
  - 雪櫃 400 - 1000 瓦特
  - 吸塵機 300 - 1000瓦特
  - 電熨斗 400 - 1000瓦特
  - 多士爐 100 - 300瓦特
  - 電風扇 20 - 60瓦特
  - 電飯煲 500 - 2000瓦特
  - 抽濕機 100 - 300瓦特
  - 冷氣機 1000 - 3000瓦特
  - 電暖爐 1000 - 3000瓦特
  - 電熱水爐1500 - 3000瓦特
  - 洗衣機 500 - 3000瓦特
  - 洗碗碟機2000 - 3000瓦特
  - 電爐 1000 - 5000瓦特
  - 手機 ~ 2瓦特

27

基礎通訊原理

- 數學背景
  - $\log_2 = \lg$
  - $\log_e = \ln$
  - $\log_{10} = \log$

    eg. $\log(10) = 1$　　$\log(1) = 0$

    $\log(0.1) = -1$　　$\log(10^2) = 2$
  - 倍數的表示法：dB

    eg. 1000倍 = 30 dB

    算法：$10 \log(1000) = 30$ dB

28

基礎通訊原理(cont.)

- Exercises

  $\log 2 = 0.30103$

  $\log 3 = 0.47712$

  $\log 5 = 0.69897$

  1倍 $= 10\log(1) = 10\,(0) = 0$ dB

  2倍 $= 10\log(2) = 10\,(0.3) = 3$ dB

  20倍 $= 10\log(2*10) = 10\,(\log 2 + \log 10)$

  $= 10\,(0.3 + 1) = 13$ dB

  0.5倍 $= 10\log(5/10) = 10\,(\log 5 - \log 10)$

  $= 10\,(0.7 - 1) = -3$ dB

  50倍 $= 10\log(5*10) = 10\,(\log 5 + \log 10)$

  $= 10\,(0.7 + 1) = 17$ dB

基礎通訊原理(cont.)

- 數學背景
  - 倍數的表示法：dB (Decibel)

    x倍 $= y$ dB　　　$y = 10\log(x)$ dB

    y dB $= x$倍　　　$x = 10^{\frac{y}{10}}$ 倍

    y dBm = 1mW的y dB = 1mW的x倍

    = 1mW的$10^{\frac{y}{10}}$ 倍

    $= 10^{\frac{y}{10}} * 1\text{mW} = 10^{\frac{y}{10}}$ mW

    t mW $= 10\log(t)$ dBm

電波強度(功率)

- 單位：watt(瓦特)
  - 1 watt = 1 W = 1000 mW
- 另一種表示法：dBm
  - 以1mW為基準值，實際功率值對基準值的倍數用dB做表示，記為dBm
  - 1 W = 1000*1mW = 10 log(1000) dBm = 30 dBm
  - 50 W = ? dBm
  - 40 dBm = ? W
  - 功率增強一倍➔即變為兩倍

    10 log(2*P) = 10 log2 + 10 logP = (3 + 10logP) dB

訊號(signal)強度(cont.)

倍數

x倍 = 10 log(x) dB

y dB = $10^{\frac{y}{10}}$ 倍

電波強度(功率)

y dBm = y dB × 1mW = $10^{\frac{y}{10}}$ 倍 × 1mW = $10^{\frac{y}{10}}$ mW

t mW = t × 1mW = t倍 × 1mW

= 10 log(t) dB × 1mW

= 10 log(t) dBm

10 dBm = 10dB × 1 mW = 10倍× 1 mW = 10 mW

20 dBm = 20dB × 1 mW = 100倍× 1 mW = 100 mW

20 mW = 20倍× 1 mW = 13 dB × 1 mW = 13 dBm

3 W = 3000 mW = 3000倍× 1 mW = 34.8 dB × 1 mW

= 34.8 dBm

基礎通訊原理(cont.)

- Exercises

  log 2 = 0.3 log 3 = 0.48 log 5 = 0.7

  30倍 = dB

  150倍 = dB

  30 dB = 倍

  40 dB = 倍

  10 dBm = mW

  20 dBm = mW

  13 dBm = mW

  20 mW = dBm

  3 W = dBm

Power Control (功率控制)

設原始發射功率=0.2512W = 251.2mW= 24 dBm

-2 dB = $10^{-0.2}$ 倍= 0.631倍

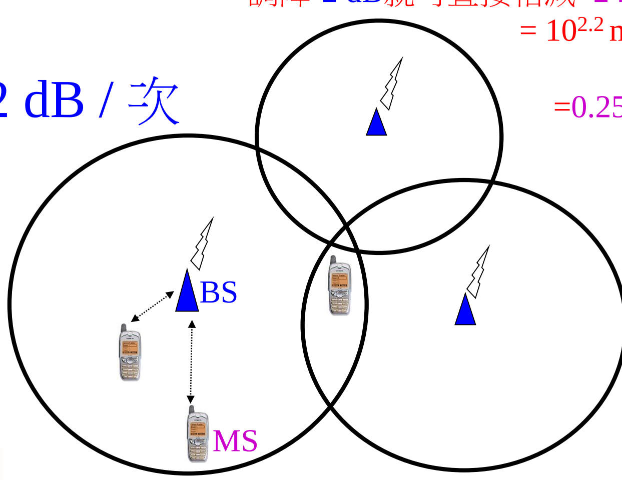
調降-2 dB就可直接相減=24 – 2 = 22 dBm

= $10^{2.2}$ mW=158.5mW

=0.1585W

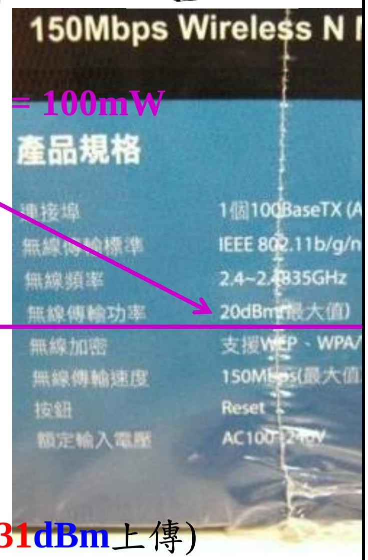
=0.2512Wx0.631倍

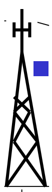
-2 dB / 次



無線網路傳送輸出功率

- WiFi橋接器/AP傳送輸出功率
  - + For 802.11a: 17dBm (typical)
  - + For 802.11b: 20dBm (typical) = 100mW
  - + For 802.11g: 19dBm (typical)
  - + For 802.11n: 17dBm





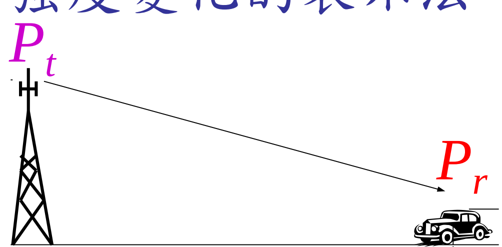
- 行動電話基地台發射功率:
  - 20W(GSM) = 20,000mW
    = 43dBm

- 行動電話手機發射功率:
  - <1W
  - 600~1000mW(GSM, 3G, 4G=31dBm上傳)

http://attach.mobile01.com/attach/201306/mobile01-9b8dd2407d6a4e591cd078c2619ac5dd.jpg

接收訊號(signal) 強度變化的表示法

$$S = \frac{P_r}{P_t} \text{ (倍數)}$$



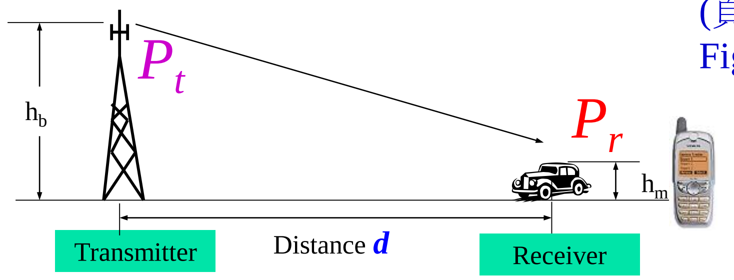
若P_t=2W且P_r =1W, 則S=1/2=0.5倍

$$S_{dB} = 10\log_{10}\frac{P_r}{P_t} = 10*\log(5/10) = 10*(0.7-1) = -3\text{dB}$$

1. **dB**=分貝數(number of decibels)
2. Pt : 傳送的訊號強度
3. Pr : 接收的訊號強度

3.4. Free-space Propagation

p. 63
(頁69)
Fig. 3.5



- The received signal power P_r at distance d: $$P_r = \frac{A_e G_t P_t}{4\pi d^2}$$

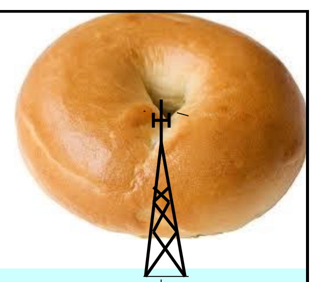
A_e is effective area covered by the transmitter (on the receiver's side - e.g., receiver's antenna)

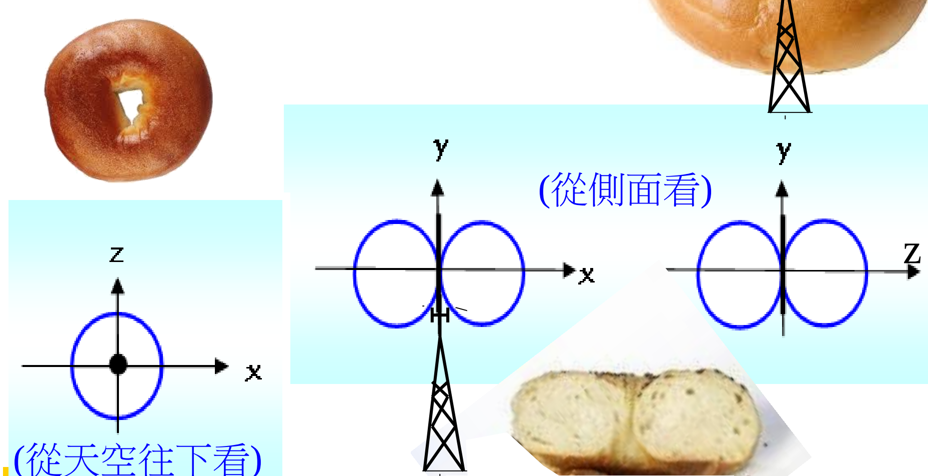
G_t is the transmitting antenna gain (a better antenna has a higher gain)

P_t is transmitting power

(Assuming that the radiated power is uniformly distributed over the surface of the sphere.)

簡易天線(simple dipole)的幅射型式(radiation pattern)

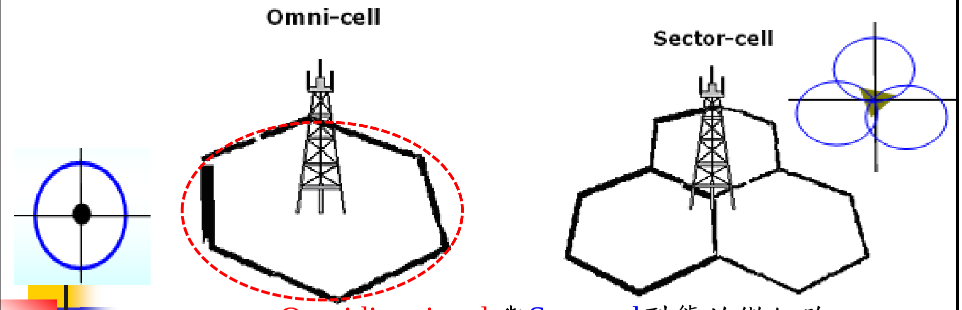




Source: 顏春煌，行動與無線通訊，金禾。

行動通訊系統

- 依天線(antenna)型式可分為:
  - Omnidirectional Cell:全方向性微細胞(基地台的天線向四面八方發射)，常用於鄉村地區。
  - Sectored Cell:基地台天線具備方向性，通常將訊號的發射分為3個方向(角度為120度)，一個基地台的週遭包括三個Sectored微細胞。

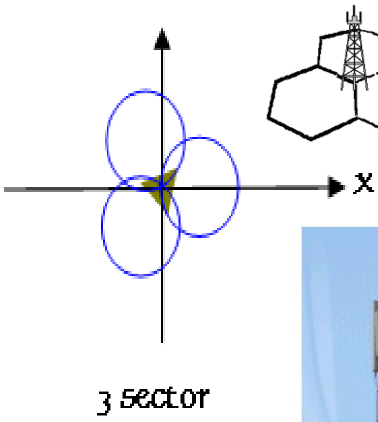


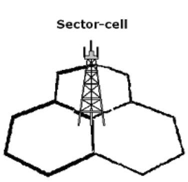
Omnidirectional 與Sectored型態的微細胞

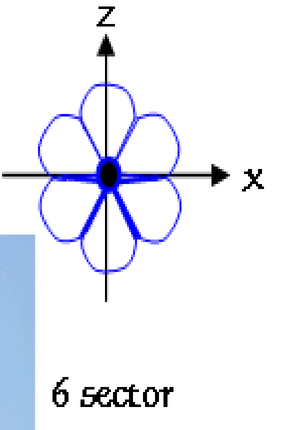
Source: 禹帆，無線通訊網路概論，文魁

39

扇形天線(sectorized antenna)的幅射型式(radiation pattern)



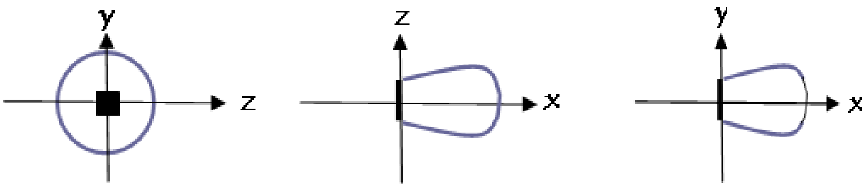


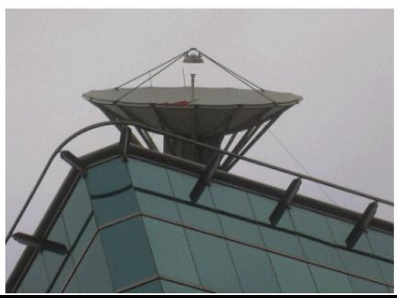


Source:
顏春煌，行動與無線通訊，金禾。

40

有向天線(directed antenna)的幅射型式(radiation pattern)





http://blog.yam.com/munch/article/5693908

Source：顏春煌，行動與無線通訊，金禾。

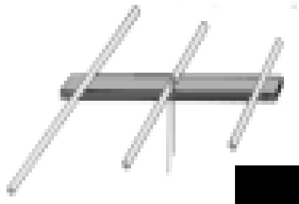
2020新北市平溪天燈節

Source：https://www.marieclaire.com.tw/lifestyle/travel/47128?atcr=a6f60b

Yagi antenna

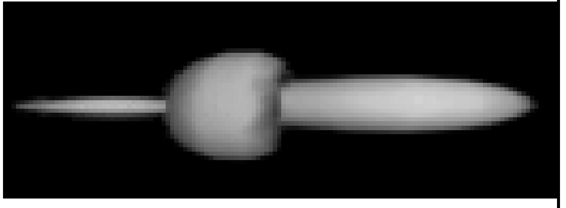
$\lambda/2$

Yagi antenna



https://www.freeway.gov.tw/Publish.aspx?cnid=91&p=32

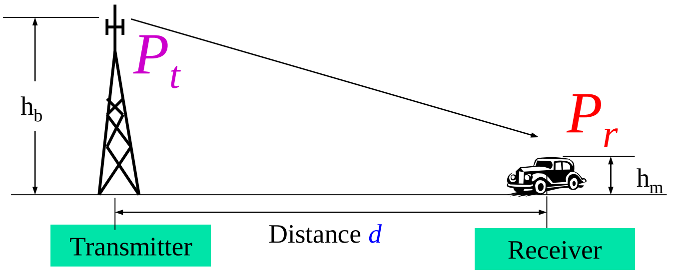
Radiation pattern



Source: 顏春煌，行動與無線通訊，金禾。

3.4. Free-space Propagation

p. 63
(頁69)
Fig. 3.5



- The received signal power P_r at distance d: $$P_r = \frac{A_e G_t P_t}{4\pi d^2}$$

A_e is effective area covered by the transmitter (on the receiver's side - e.g., receiver's antenna)

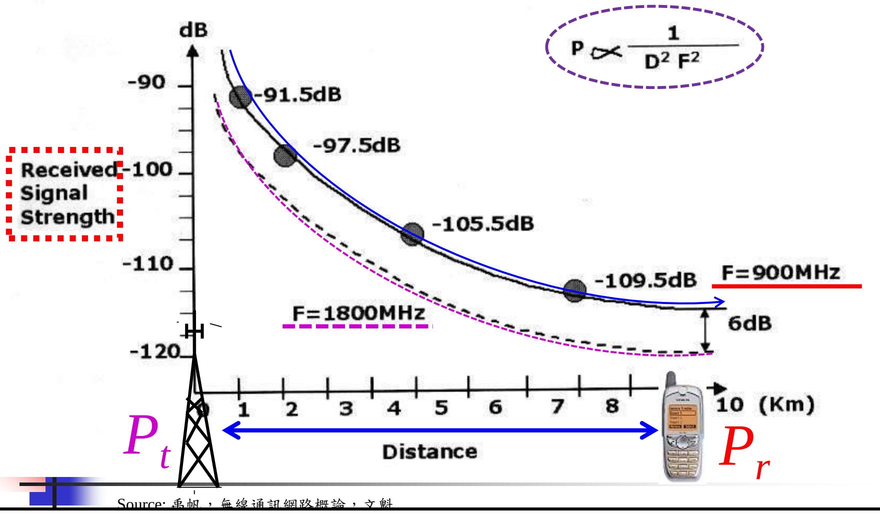
G_t is the transmitting antenna gain (a better antenna has a higher gain)

P_t is transmitting power

(Assuming that the radiated power is uniformly distributed over the surface of the sphere.)

Received Signal Strength $=P_r$

- 當距離增加或是頻率提高時都會使衰減增加



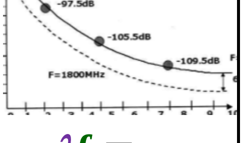
Source: 禹帆，無線通訊網路概論，文魁

The received signal power: $$P_r = \frac{A_e G_t P_t}{4\pi d^2} \quad (3.1)$$

The receiving antenna gain: $$G_r = \frac{4\pi A_e}{\lambda^2} \quad (3.2)$$

$$A_e = \frac{G_r \lambda^2}{4\pi}$$ 代入 (3.1)

The received signal power: $$P_r = \frac{G_r G_t P_t}{(4\pi d/\lambda)^2} \quad (3.3)$$



When $G_t = G_r = 1$, (0 dB) $$P_r = \frac{P_t}{(4\pi d/\lambda)^2}$$

距離 波長

$, \lambda f = c$

頻率

Free-space Path Loss

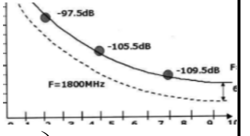
Path Loss vs. Signal Strength $S = \frac{P_r}{P_t}$

$$S_{dB} = 10\log_{10}\frac{P_r}{P_t}$$

- Definition of path loss L_f:

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

  - P_t is transmitted signal power
  - P_r is received signal power



When $G_t = G_r = 1$, $L_f = \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi f_c d}{c}\right)^2$

$$L_f(dB) = 10\log\left(\frac{4\pi f_c d}{c}\right)^2 = 20\log\left(\frac{4\pi f_c d}{c}\right)$$

Path loss in free space (no obstacles):

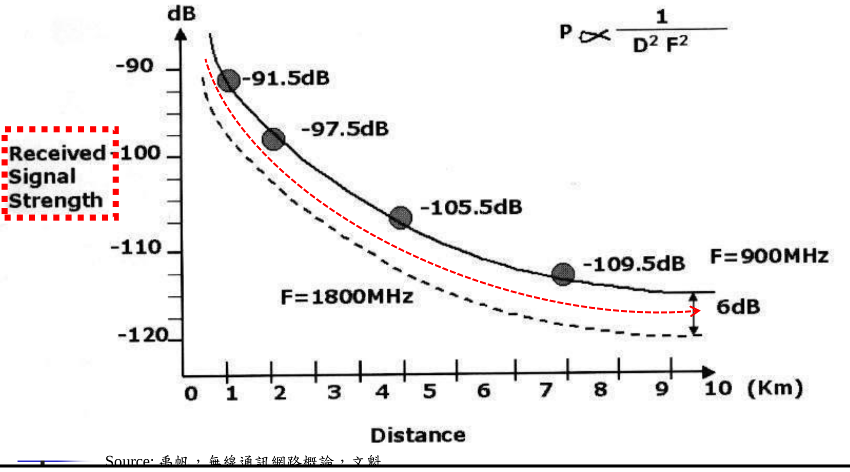
$$L_f(dB) = 32.45 + 20\log_{10} f_c(MHz) + 20\log_{10} d(km),$$

where f_c is the carrier frequency

The greater the f_c, the higher is the loss (see next slide)

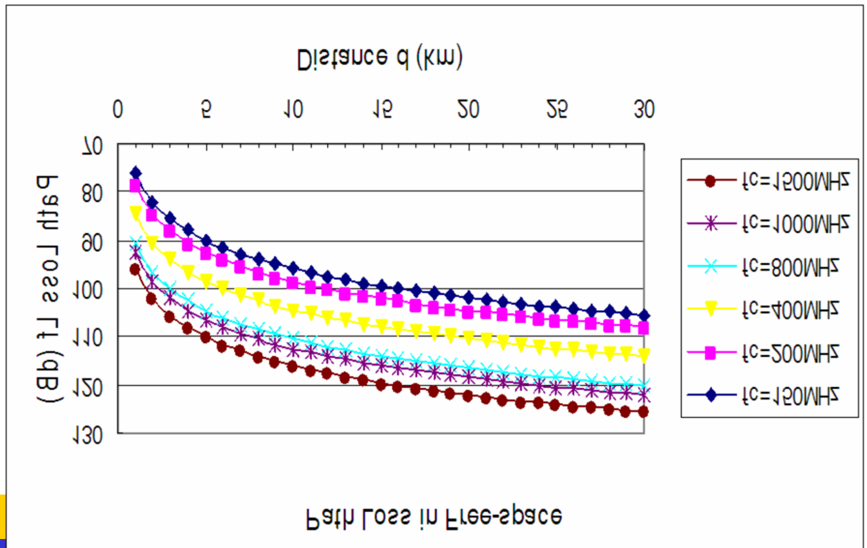
Received Signal Strength

- 接收訊號越來越弱: 訊號衰減(Attenuation)



Source: 禹帆，無線通訊網路概論，文魁

Received Signal Strength (Free-space)



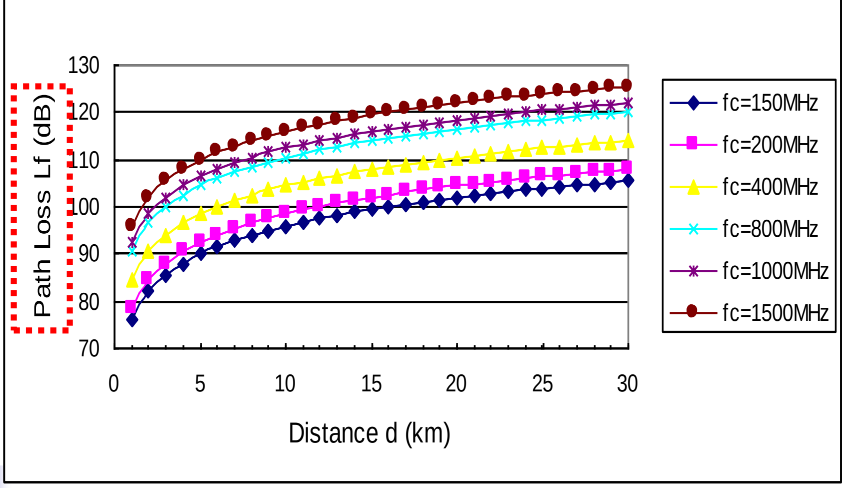
p. 61
(頁67)
Fig. 3.3

Example of Path Loss (Free-space)

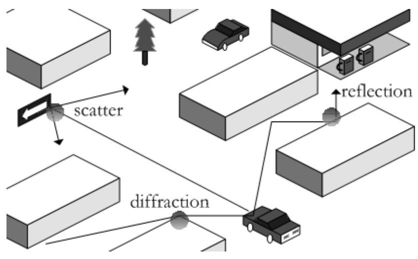
F: MHz
D: km

- Path Loss = 32.4 + 20log F + 20log D (dB)

衰減(Attenuation)



3.5. Land Propagation



- The received signal power:

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

where: G_t is the transmitter antenna gain,

G_r is the receiver antenna gain,

L is the propagation loss in the channel,

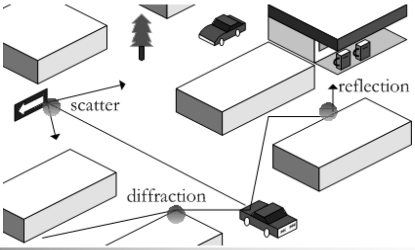
i.e., $L = L_P \, L_S \, L_F$

- L_F: Fast fading (short-term fading)
- L_S: Slow fading (long-term fading)
- L_P: Path loss

Path Loss (for Land Propagation)

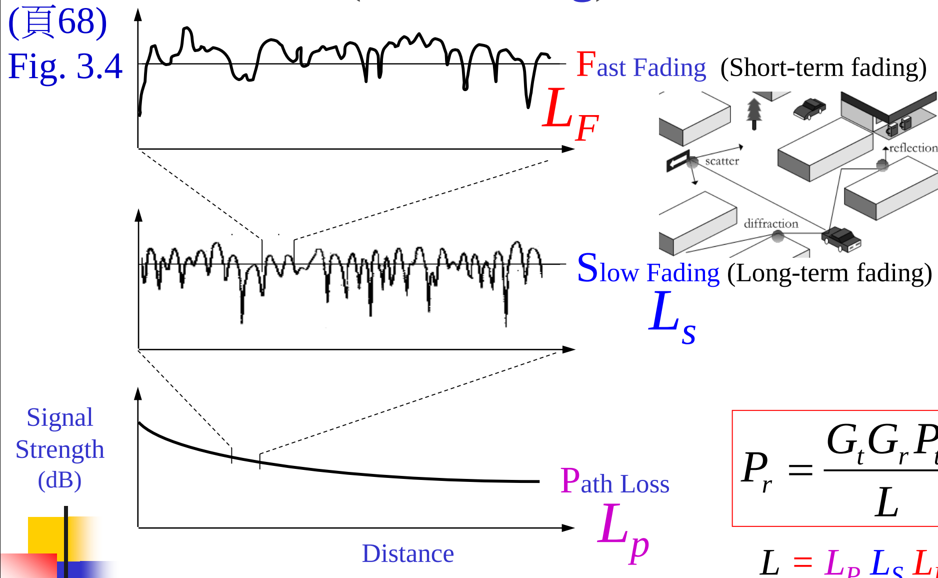
- Path loss in decreasing order:
  - Urban area (large city)
  - Urban area (medium and small city)
  - Suburban area
  - Open area

Path loss



Schematic Diagram of Propagation Loss (and Fading)

p. 62
(頁68)
Fig. 3.4

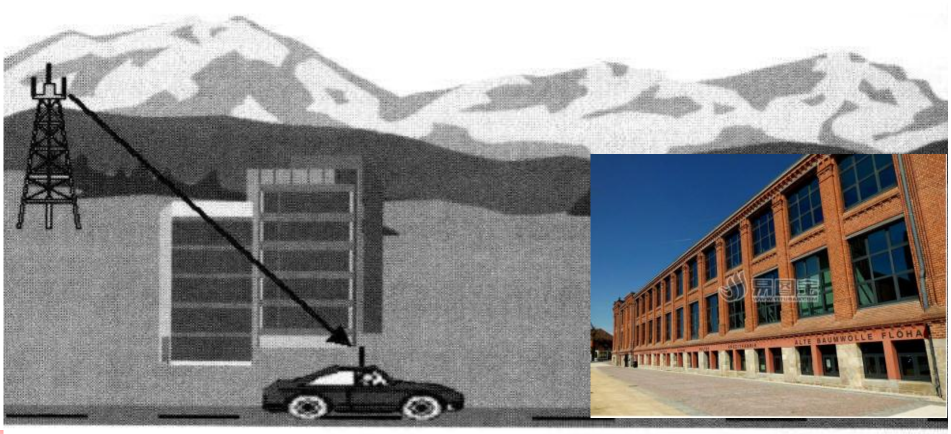


$$P_r = \frac{G_t G_r P_t}{L}$$

$$L = L_P L_S L_F$$

3.7 Shadowing (Slow Fading)

- 屏蔽效應(Shadowing)現象: 高山、樹木、高樓、、、缺少直接傳輸路徑(Line-of-Sight)

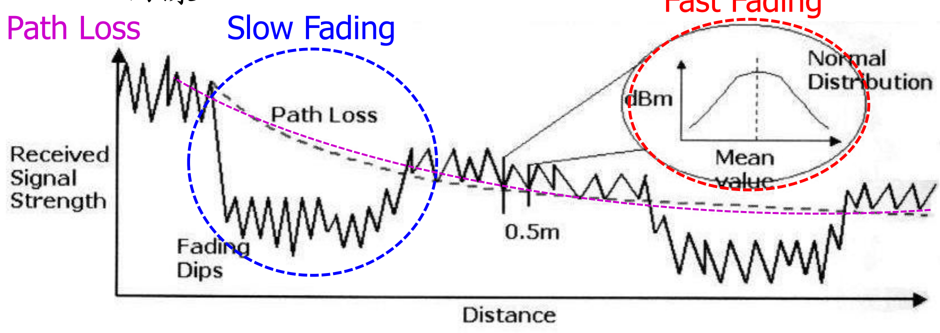


http://www.juimg.com/zhengban/201707/sytukuqita_2246247.html

Source: 禹帆，無線通訊網路概論，文魁

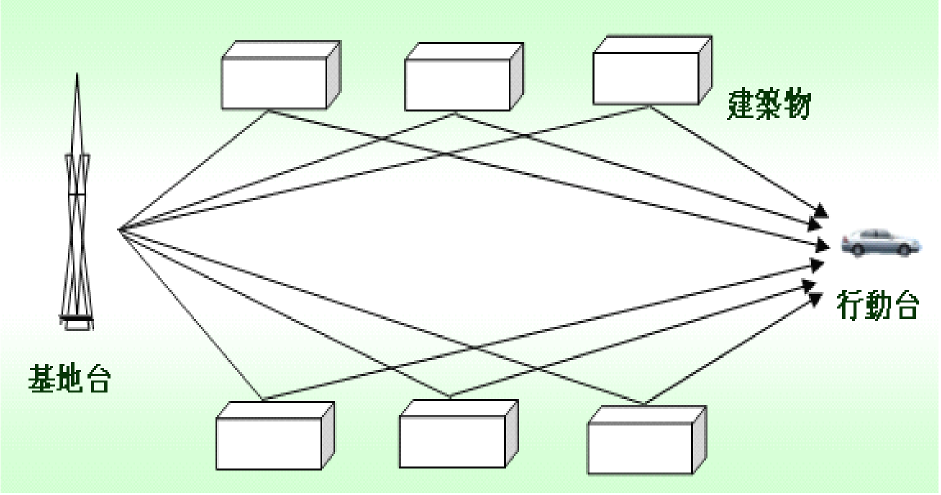
Shadowing (Slow Fading)

- 屏蔽效應(Shadowing)現象時的訊號強度分布曲線



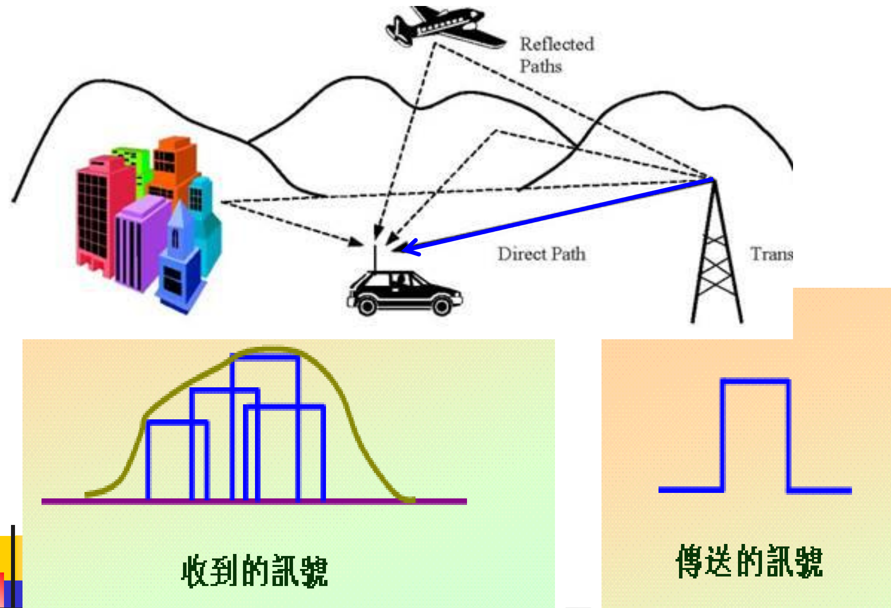
Source: 禹帆，無線通訊網路概論，文魁

3.8 Multi-path Fading (Fast Fading)



Source: 顏春煌，行動與無線通訊，金禾。

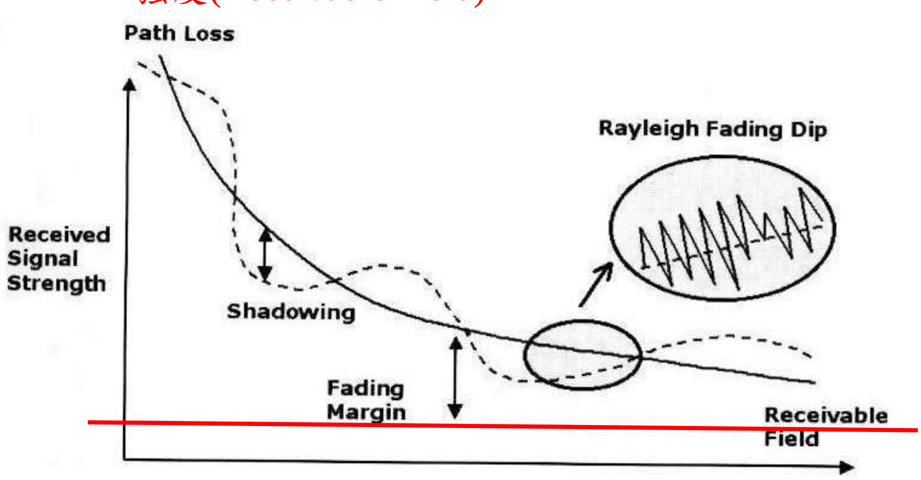
頻道的散佈特性(dispersive characteristics)



Source: 顏春煌，行動與無線通訊，金禾。

Receiver Sensitivity

- 無線電波的通訊訊號必須高於手機的可接收強度(Receivable Field)



Source: 禹帆，無線通訊網路概論，文魁

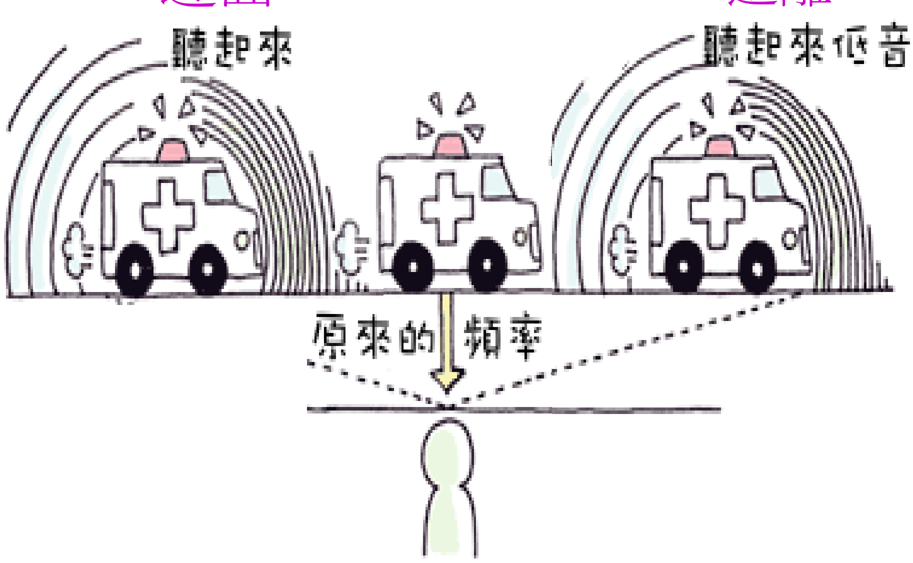
都普勒效應(Doppler effect)

http://blog.xuite.net/osaki99/blog/22358583

http://www.119-999.com.tw/images/0006.jpg

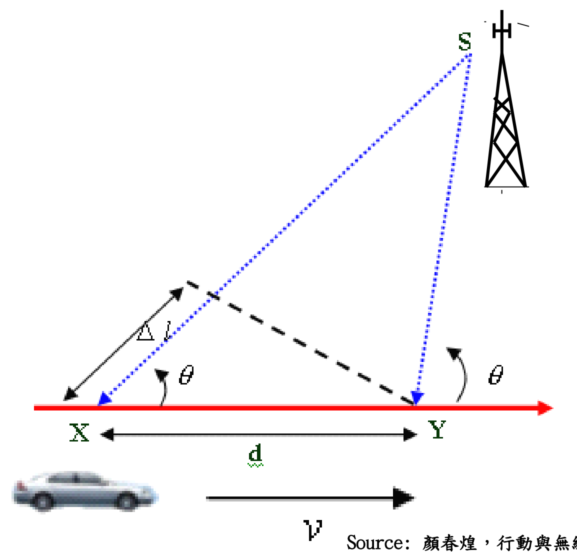
快速迎面而來

快速遠離而去



Source: http://discovery.panasonic.com.tw/science/library/lib05sou/l05014.html

都普勒效應(Doppler effect) (cont.)



Source: 顏春煌，行動與無線通訊，金禾。

3.9. Doppler Effect (Doppler Shift)

- Doppler effect - occurs when a wave source and a receiver are moving towards or away from each other
  - When they are moving toward each other, the frequency of the received signal is higher than the source frequency
  - When they are moving away from each other, the frequency is lower than the source frequency
- Received signal frequency is $f_r = f_c - f_d$

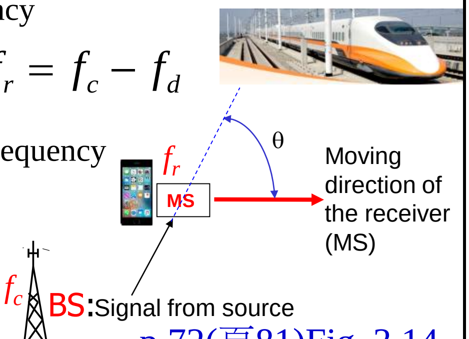
  where: f_c - source frequency ,

  f_d - the Doppler shift in frequency
- Doppler shift is

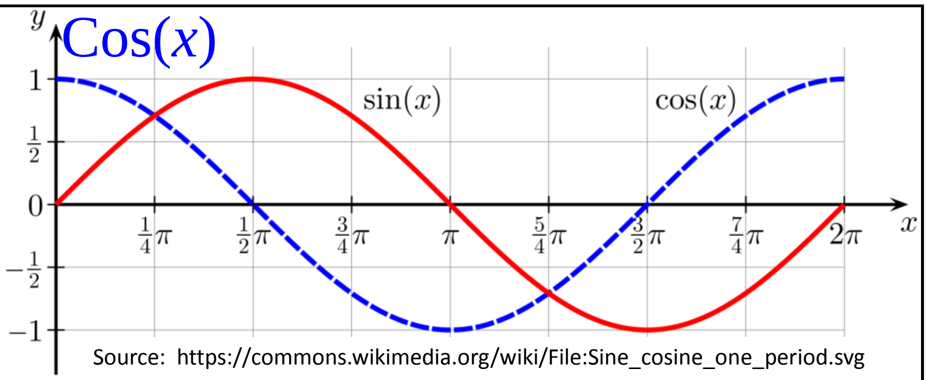
$$f_d = \frac{v}{\lambda}\cos\theta$$

where: v - the moving speed

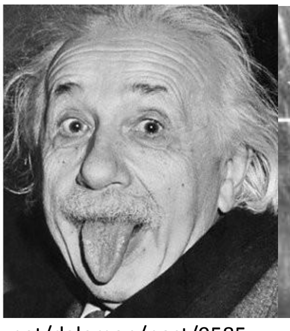
λ - the wavelength of the carrier of the source signal

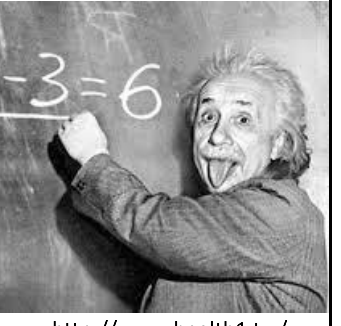


p.72(頁81)Fig. 3.14



Source: https://commons.wikimedia.org/wiki/File:Sine_cosine_one_period.svg





Source: https://www.ettoday.net/dalemon/post/9585 http://www.health1.tw/

For example,

f_c = 300MHz=3x10^{8}Hz(cycle/s)

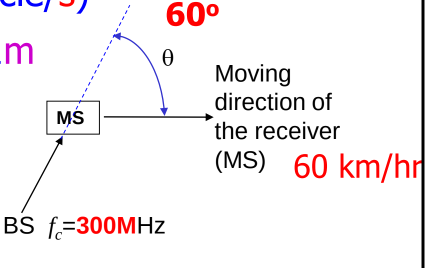
λ = c/f_c = 3x10^8/3x10^8=1m

v = 60km/hr=16.7m/s

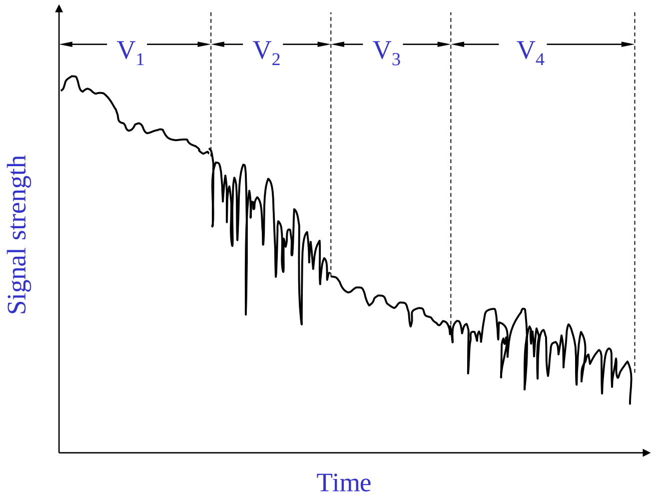
f_d = (v cosθ) / λ
= (16.7 * 0.5)/1
= 8.3 Hz

f_r = f_c - f_d

= 3x10^{8}Hz – 8.3Hz = 299.9999917MHz



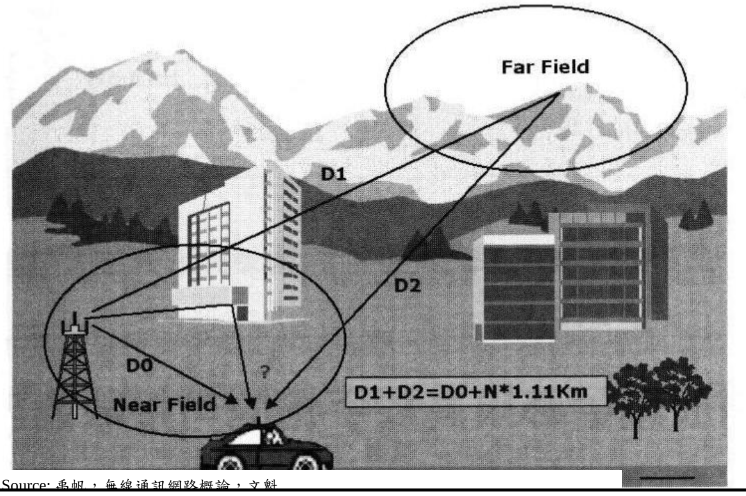
Moving Speed Effect



p. 72 (頁81) Fig. 3.13

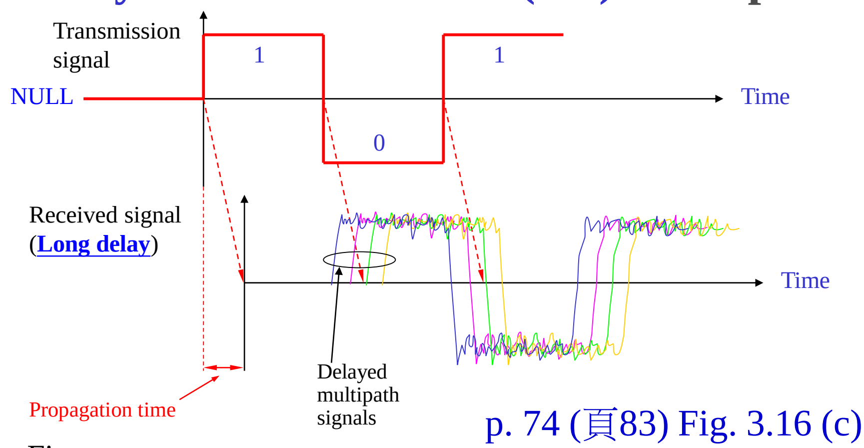
Inter Symbol Interference(ISI)

- 反射電波與正常電波的路徑差恰好是波長的整數倍會發生ISI干擾現象



Source: 禹帆，無線通訊網路概論，文魁

Intersymbol Interference (ISI) Example



p. 74 (頁83) Fig. 3.16 (c)

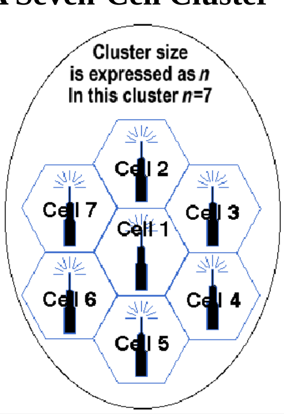
- Figure
  - Transmitter and receiver are synchronized
    - Red broken-line arrows show synchronization
  - "Long delay": only 1 delayed multipath signal showing NULL→1 arrives within duration of its "time slot"
    - 3 delayed multipath signals arrive too late (within the next "time slot")

3.13. Cochannel Interference(CI)

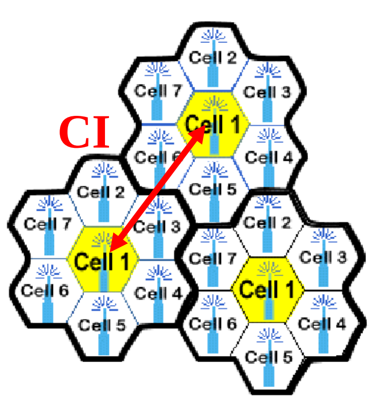
- Cells reuse frequencies
  - Same freq. assigned to different cells

=> cells using the same frequency interfere with each other

A Seven-Cell Cluster



Frequency Reuse



Homework #1 (Due in 2 weeks)-1:

P1.1為何當有線基礎建設已普遍存在,仍需要無線服務?

P1.6無基礎架構網路和蜂巢式網路有何差異?

P1.13在無線網路使用大小不同的細胞有何優缺點?

P1.16手機與衛星電話有何差異?

P3.4發送功率是40W，在自由空間傳播模型下，(a)請問以dbm為單位之發送功率為何? (b)接收端位於1000m遠，請問其接收功率為何?假設載波頻率為*f*(c)=900MHz與G(t)=G(r)=0dB。(c)以分貝表示自由空間路徑衰減。 (free space path loss: $L_f = P_t/P_r$)

105

Homework #1 (Due in 2 weeks)-2:

P3.12請問快速衰落與慢速衰落的差異?

P3.14有一基地台具有900MHz的發送端，以及有一車輛50mph的速度在移動。計算車輛下列移動方向的接收載波頻率。(a)往基地台方向移動 (b)往基地台反方向移動(c)往發送信號呈60度角方向移動。 (mph=mile per hour; 1 mile=**1.6**093 km).

- (前四題每題10分,後三題每題20分)
- Questions?
- Thank you!

End of Chapter 3

106