無線通訊系統
(Wireless Communications Systems)

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課程要求

- Required Prior Knowledge: **Signals & Systems; Probability; Communication Systems**
- Homework: 20%
- Project: 20%
- Midterm Exam: 30%
- Final Exam: 30%
- Web Site: (140.114.26.93) http://nyquist.ee.nthu.edu.tw/
  - Password: 2021COM5170WCS0913
- Textbook: Gordon L. Stüber, Principles of Mobile Communication, **Second/Third/Fourth** Edition
- 助教：TWNTHUCOM5170@gmail.com

Contents

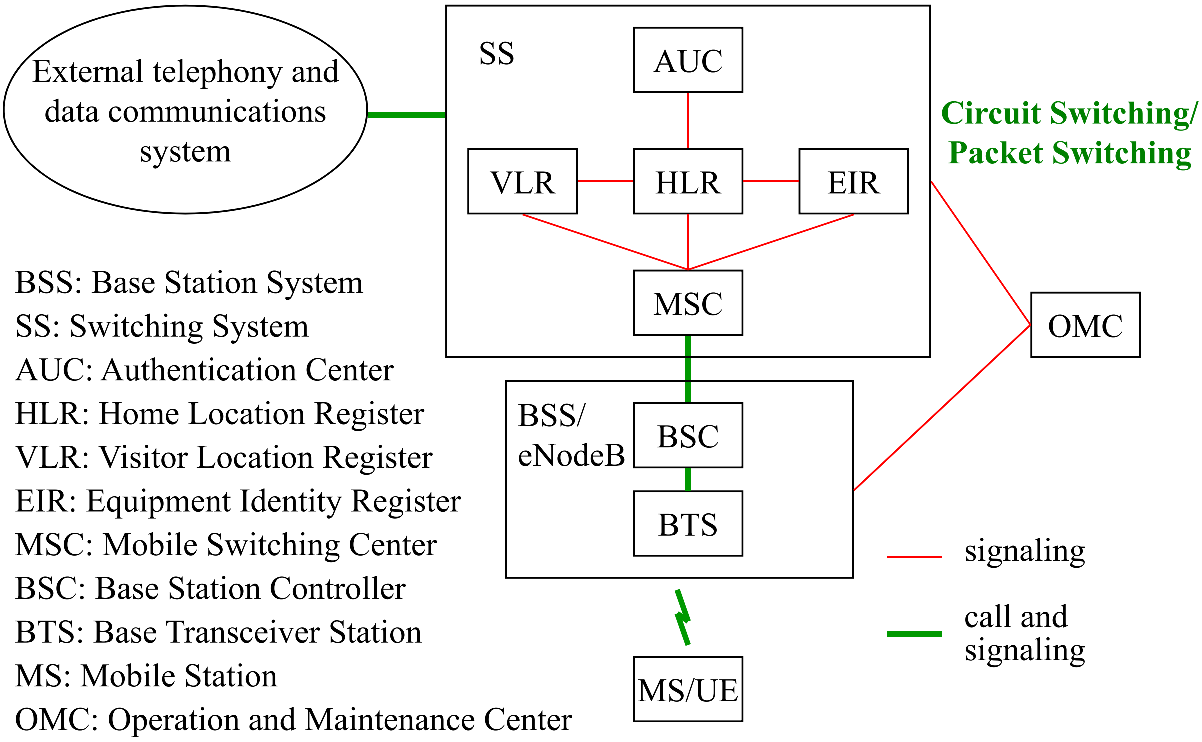
Chapter 1
Introduction

Mobile Cellular Systems

Mobile Communications Systems

- First generation (1G): analog systems
  - AMPS – US, NMT – North Europe, TACS – Europe, JTACS – Japan
- 2G: digital systems
  - High-tier systems: IS-136, IS-95 – US, GSM – Europe, PDC – Japan
  - Low-tier systems: PACS – US, DECT – Europe, PHS – Japan
- 3G: wideband transmission systems
  - W-CDMA (3GPP) – Europe, cdma2000 (3GPP2) – US
- 4G:
  - Evolve from datacom standards: OFDM – WiMAX
  - Evolve from telecom standards: OFDM – LET (3GPP Long-Term Evolution)
- 5G:
  - OFDM, DFT-Spread OFDM

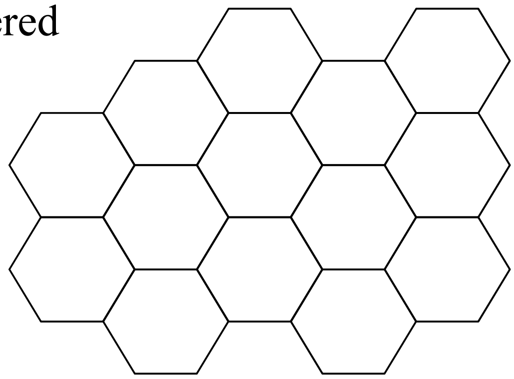
Mobile Communications Systems Architecture



BSS: Base Station System
SS: Switching System
AUC: Authentication Center
HLR: Home Location Register
VLR: Visitor Location Register
EIR: Equipment Identity Register
MSC: Mobile Switching Center
BSC: Base Station Controller
BTS: Base Transceiver Station
MS: Mobile Station
OMC: Operation and Maintenance Center

Mobile Cellular Communications Systems

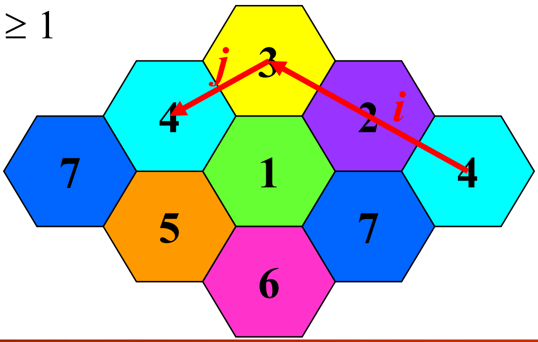
- The advantages of cellular systems:
  - High spectral efficiency
  - Large system capacity
  - Limited cell coverage ⇒ reduce the transmission power
  - Flexibility
- The radio coverage, traffic distribution, and users behavior should be considered



Frequency Reuse

- **Frequency assignment** is the major issue in cellular systems
- For **fixed** frequency/channel assignment:
  - All channels are divided into several groups
- **Frequency Reuse Factor:** the number of channel groups
  - Both the number of channels per cell and the co-channel interference are **fixed**
  - Theoretically, $\boldsymbol{N = i^2 + i \times j + j^2}$, i and j are non-negative integers $i \geq 0, j \geq 0, i + j \geq 1$

$\boldsymbol{N = 7}$



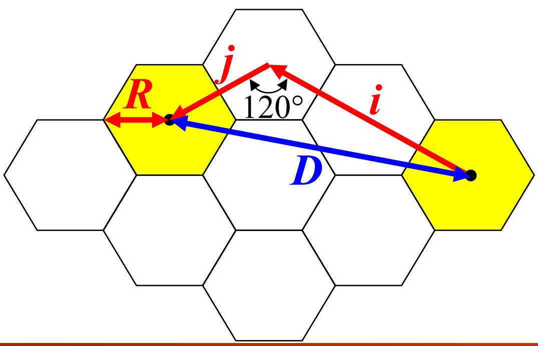
Frequency Reuse (Cont.)

- **Co-channel reuse distance:** the minimum distance between any two co-channel base station (BS)
  - **Co-channel BS**: The BSs use the same frequency allocation
- For regular hexagonal cells, the co-channel reuse distance is

$$D = \sqrt{3N}R$$

  - R is the cell radius
  - Based on the **cosine rule** $a^2 = b^2 + c^2 - 2bc \times \cos\alpha$

$\boldsymbol{N = 7}$



Frequency Reuse (Cont.)

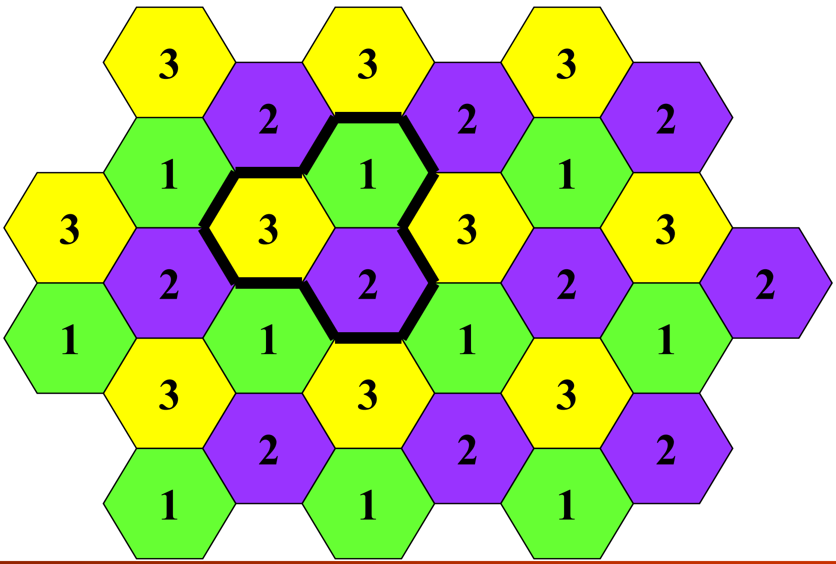
- Some possible theoretical frequency reuse factors

(*i*, *j*) pair	Frequency Reuse Factor
(1, 0)、(0, 1)	**1**
(1, 1)	**3**
(2, 0)、(0, 2)	**4**
(2, 1)、(1, 2)	**7**
(2, 2)	12
(3, 0)、(0, 3)	9
(3, 1)、(1, 3)	13
(3, 2)、(2, 3)	19
(3, 3)	27

- In practice, the BSs may not be regularly distributed
  - The frequency reuse factor is chosen based on the acceptable co-channel interference

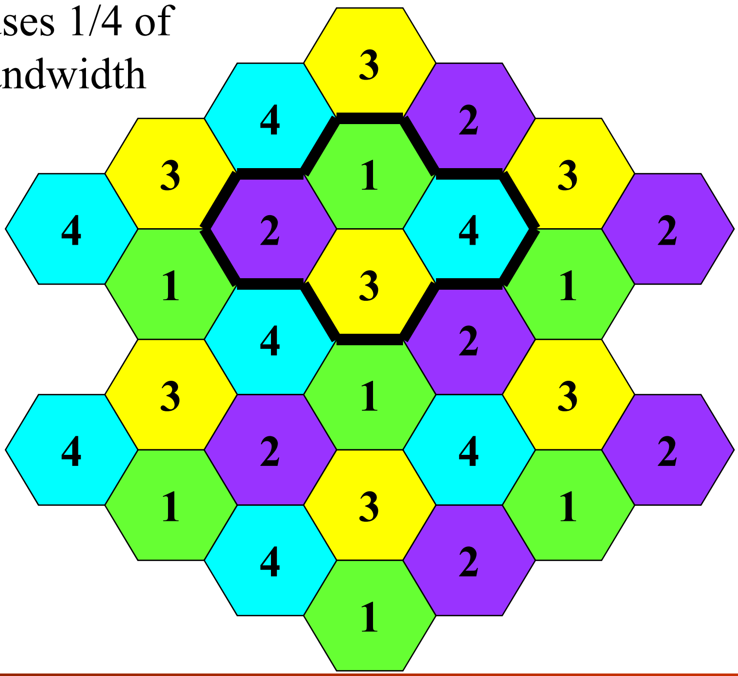
Frequency Reuse (Cont.)

- Frequency reuse factor $N = 3$
- Each cell uses 1/3 of the total bandwidth
  - All channels are divided into 3 groups



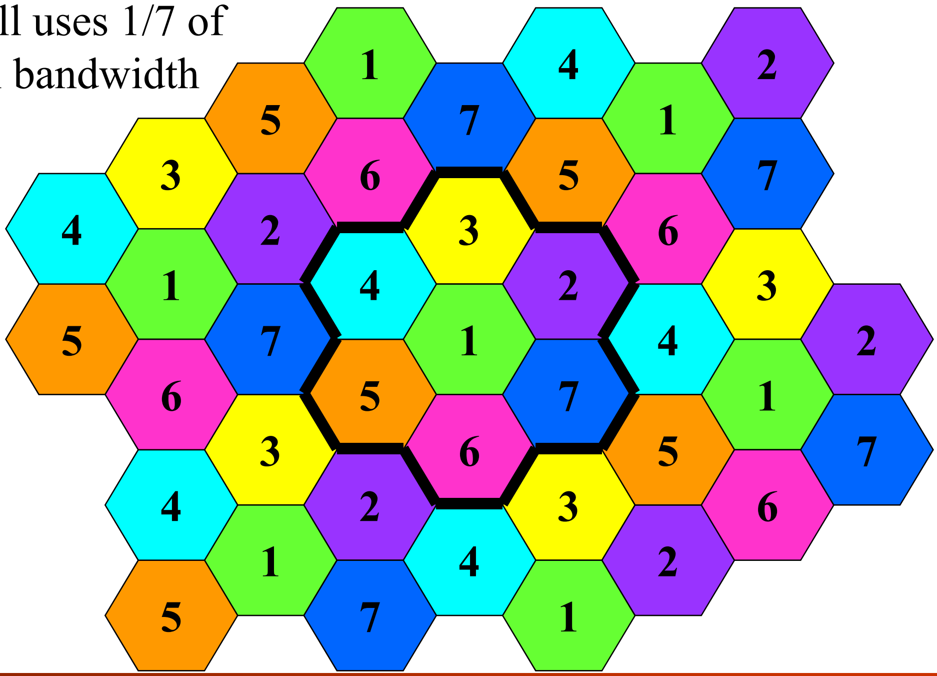
Frequency Reuse (Cont.)

- Frequency reuse factor $N = 4$
- Each cell uses 1/4 of the total bandwidth



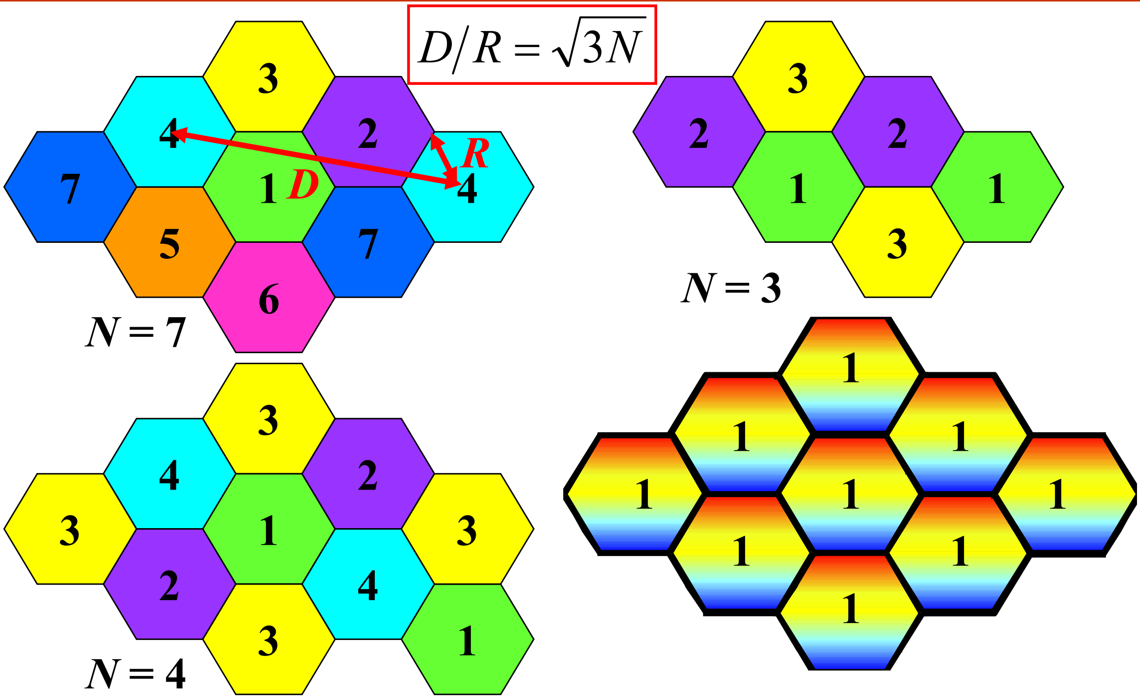
Frequency Reuse (Cont.)

- Frequency reuse factor $N = 7$
- Each cell uses 1/7 of the total bandwidth



Frequency Reuse (Cont.)

$$D/R = \sqrt{3N}$$



FDMA Reuse

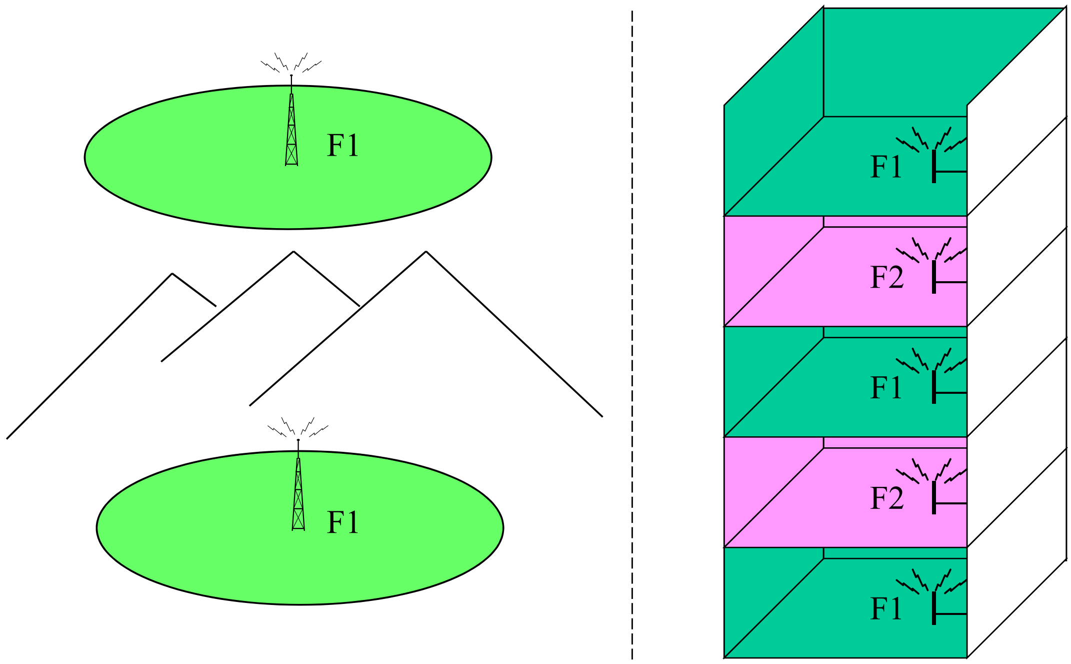
CDMA Reuse

Frequency Reuse (Cont.)

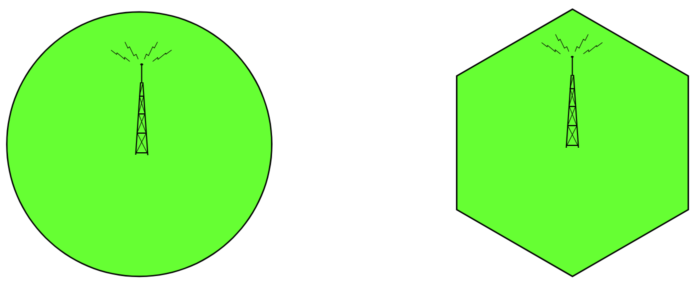
- Assume that the total available bandwidth is divided into multiple channels, with the channel numbering 1, 2, 3, …
- For $N = 3$, each cell uses one of the following channel sets:
  - **Channel set 1**: 1, 4, 7, …
  - **Channel set 2**: 2, 5, 8, …
  - **Channel set 3**: 3, 6, 9, …
- For $N = 4$, each cell uses one of the following channel sets:
  - **Channel set 1**: 1, 5, 9, …
  - **Channel set 2**: 2, 6, 10, …
  - **Channel set 3**: 3, 7, 11, …
  - **Channel set 4**: 4, 8, 12, …
- For $N > 1$, adjacent channels are not used in the same cell

Frequency Reuse (Cont.)

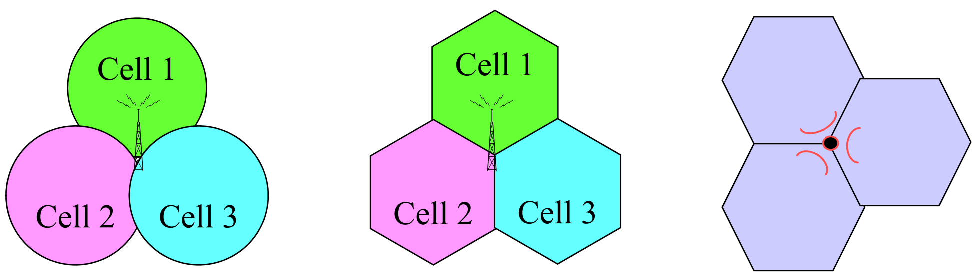
- Frequency assignment also depends on the environments



Omni-Directional and Sectored Cells

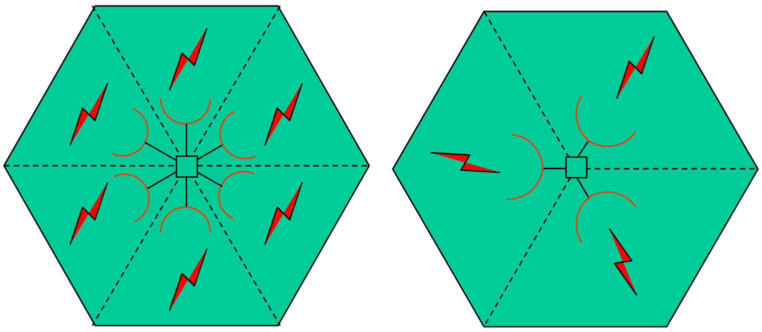


Omni-Directional Cell (360°×1)



3-Sector Cell (120°×3)

Omni-Directional and Sectored Cells (Cont.)



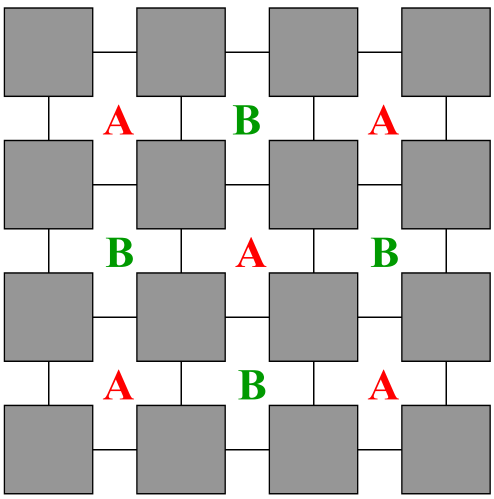
6-Sector Cell
(60° directional Antenna)

3-Sector Cell
(120° directional Antenna)

2-Sector Cell
(180° directional Antenna)

Manhattan Microcell Frequency Reuse

- In an area with urban canyons:
  - The buildings act as waveguides to channel the signal energy along the street corridors
  - Co-channel interference can be significantly reduced
  - Signals are blocked by buildings

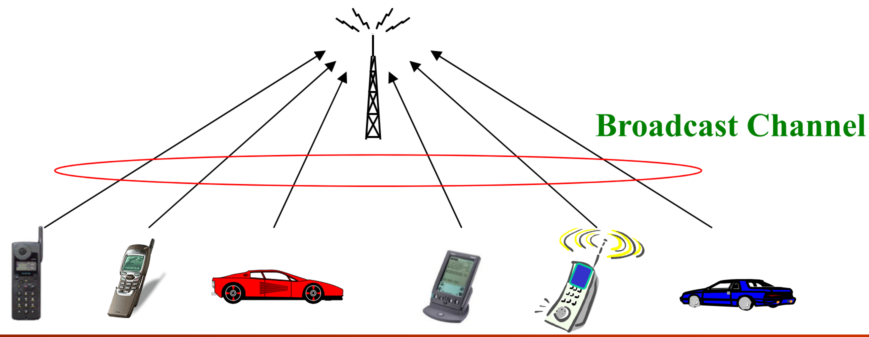


Manhattan microcell deployment

Multiple Access & Duplex

Multiple Access

- In a **broadcast channel** (such as a wireless channel), one of the key issues is to determine who gets the right of using the channel when there is **competition** for it.
- In a **synchronous** system (with a **central controller**), the **controlled-access** (**multiple access**) **techniques** can be applied to prevent/reduce **signal collision** or **mutual interference**.
- In an **asynchronous** system, **random access techniques** should be used.

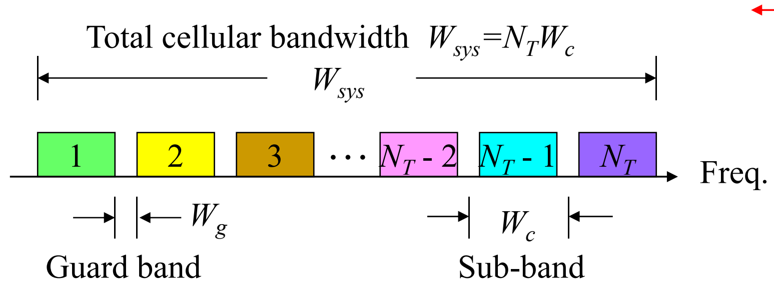


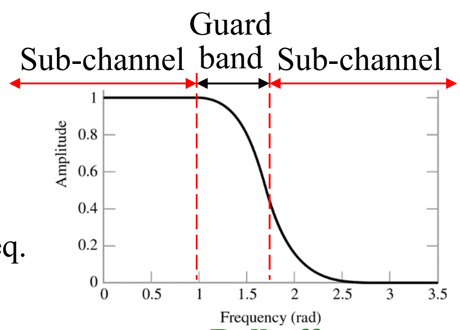
Multiple Access Techniques

- **FDMA:** Frequency Division Multiple Access
  - Divide a frequency band into multiple sub-bands
  - Generally, a **guard band** between two contiguous sub-bands is required
  - Generally, no **self-interference** is introduced
- **TDMA:** Time Division Multiple Access
  - Divide a time interval (frame) into multiple time-slots
  - A **guard time** between two contiguous time-slots is required
  - Generally, no **self-interference** is introduced
- **CDMA:** Code Division Multiple Access
  - Divide the spectral resource in the **code domain**
  - A set of low **cross-correlation** codes is needed
  - **Self-interference** is introduced among different signals

FDMA & TDMA

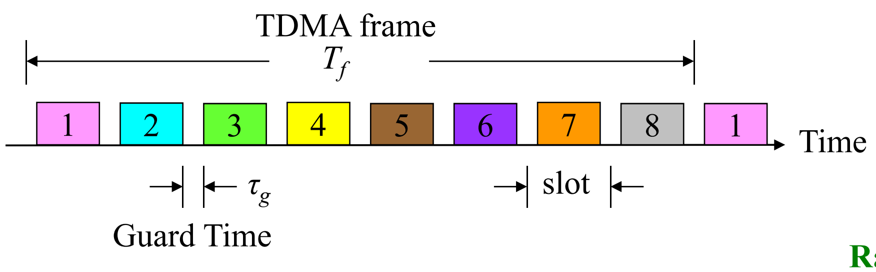
- FDMA: AMPS

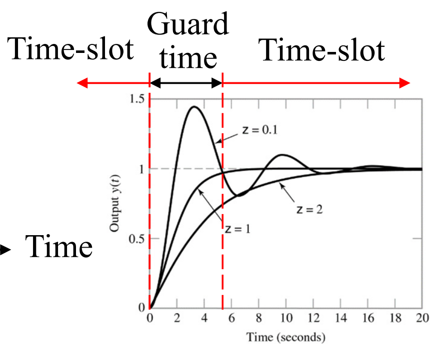




Roll-off

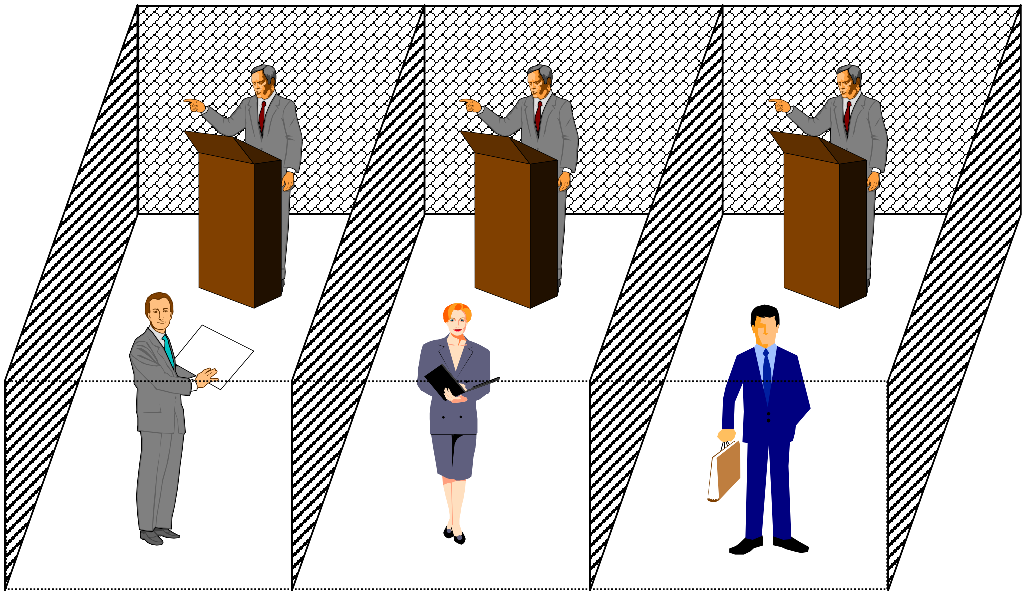
- TDMA: GSM, IS-136, PDC



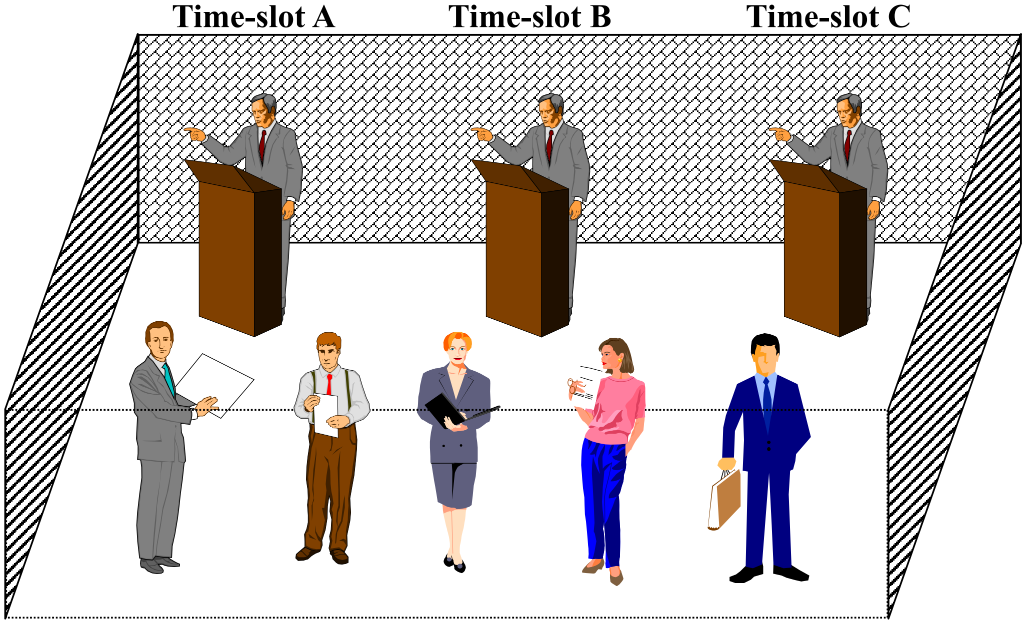


Ramp-up & Ramp-down

Frequency Division Multiple Access

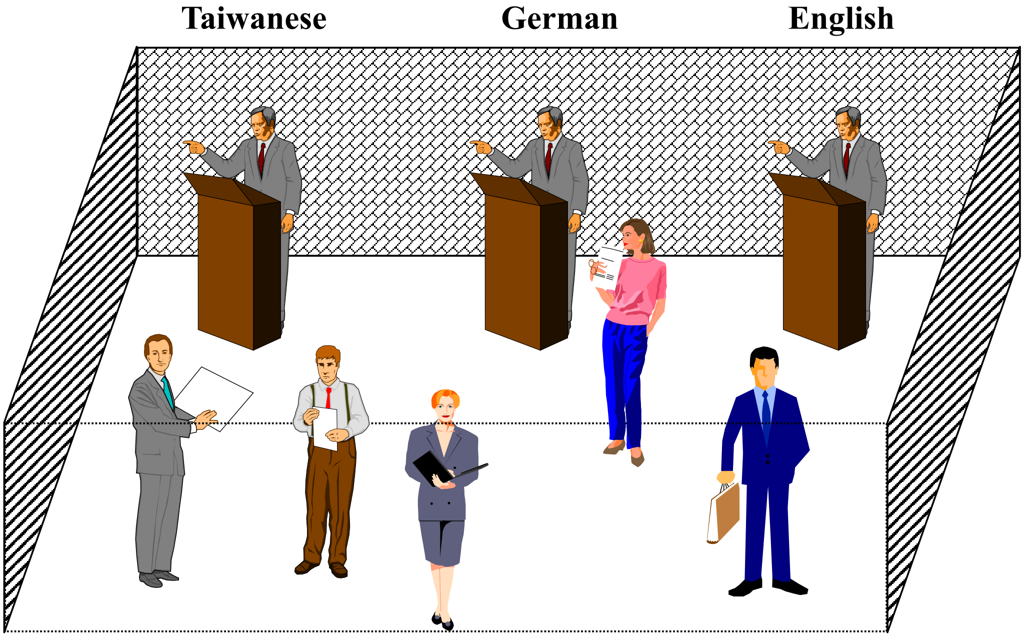


Time Division Multiple Access

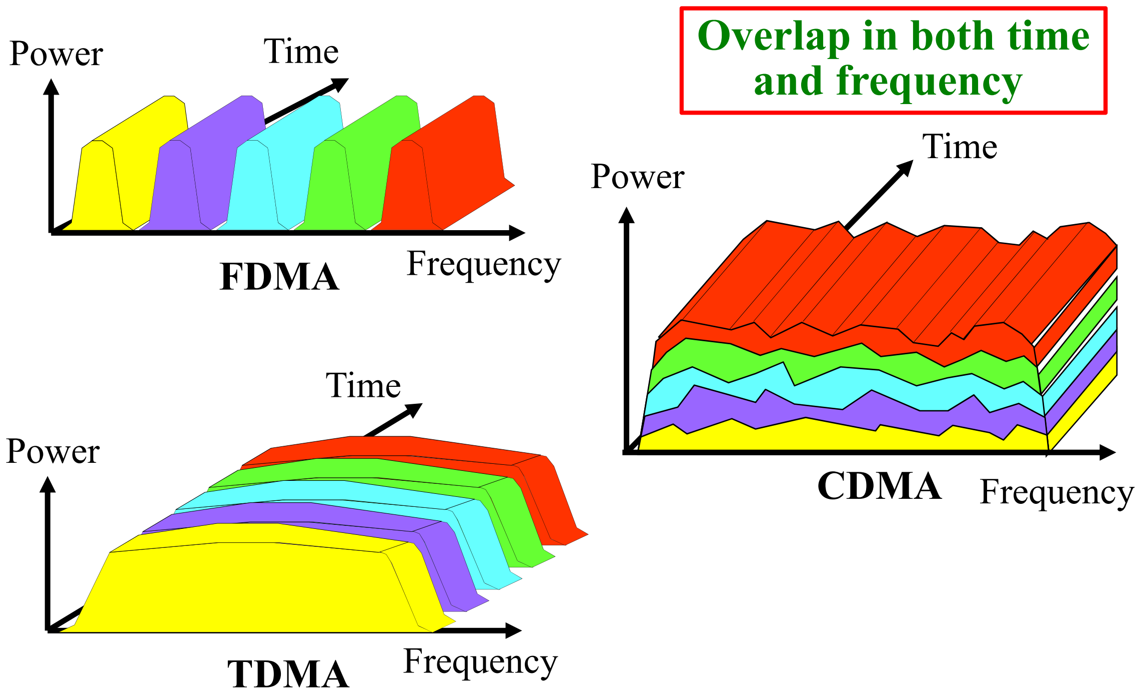


Code Division Multiple Access

- Based on the **spread spectrum** technologies

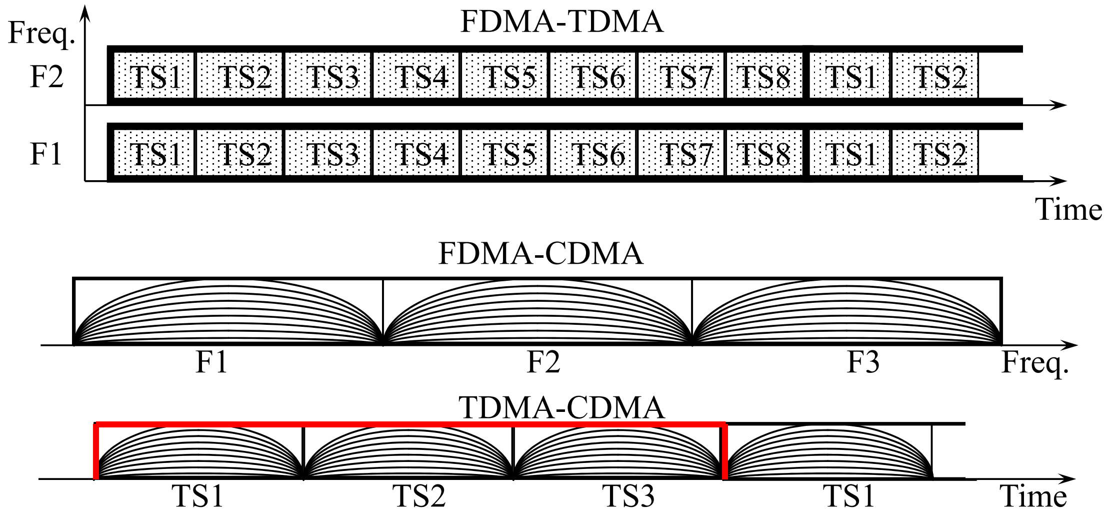


Multiple Access – Resource Allocation



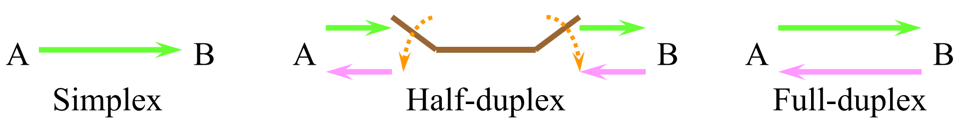
Hybrid Multiple Access Schemes

- Hybrid Multiple Access schemes
  - FDMA-TDMA
  - FDMA-CDMA
  - TDMA-CDMA



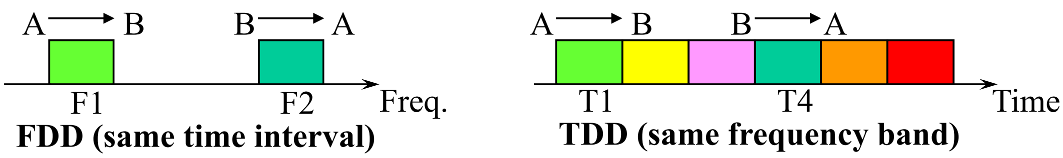
Duplex

- **Duplex** is a description of the communication capabilities between two connected devices that can communicate with each another in **both directions**.
- Conventionally, the transmissions of different signals must use **separate radio resources** to prevent mutual interference.
- **Simplex:** one-way communications
  - Paging system (Historically, two-way paging system is available)
- **Half-duplex:** two-way comm. (One-way at any time instant)
  - Dispatch communications system
- **Full-duplex:** two-way communications (at any time instant)



Duplex (Cont.)

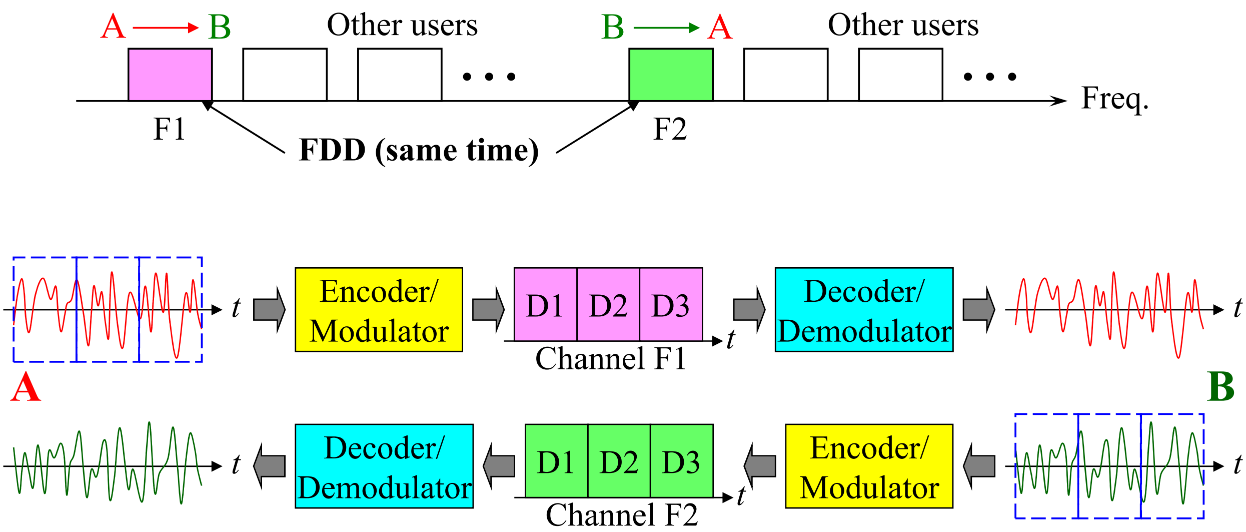
- There are two common approaches for supporting duplex transmissions
  - **FDD:** Frequency Division Duplex (use different frequency bands)
  - **TDD:** Time Division Duplex (use different time-slots)



- Nowadays, in the discussion on 4G/5G technologies, **full-duplex** transmission is referred to as a transmission approach that can **support two-way transmissions using the same frequency band at the same time**
  - Use the **same** radio resources to improve **bandwidth efficiency**
  - An effective **interference cancellation** mechanism is required

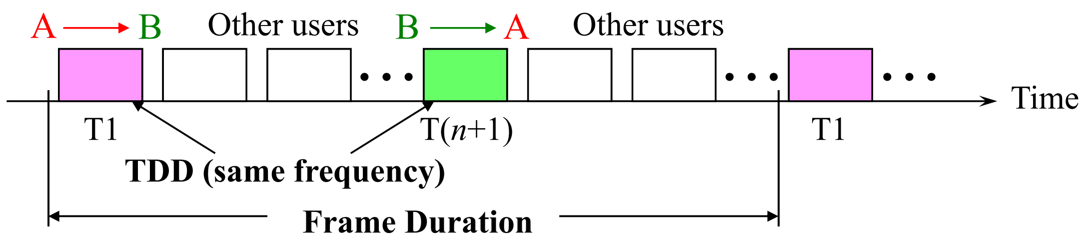
Duplex – FDD

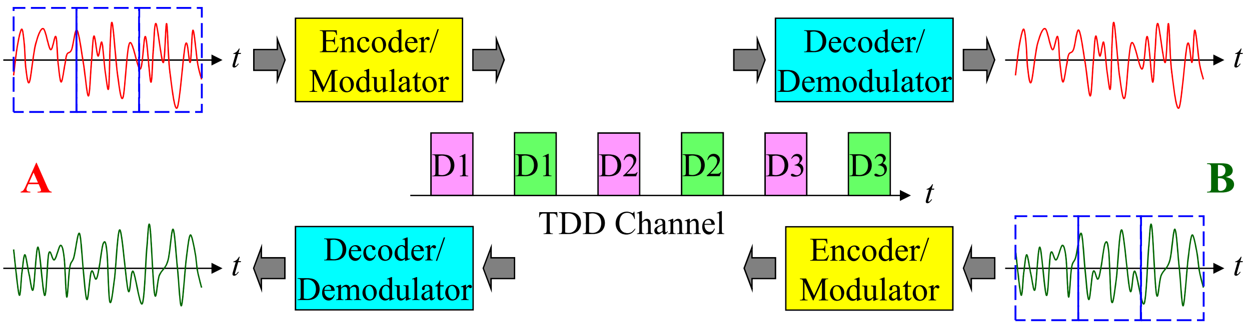
- **FDD:** Frequency Division Duplex



Duplex – TDD

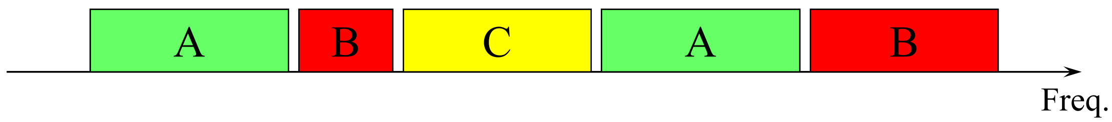
- **TDD:** Time Division Duplex





Question

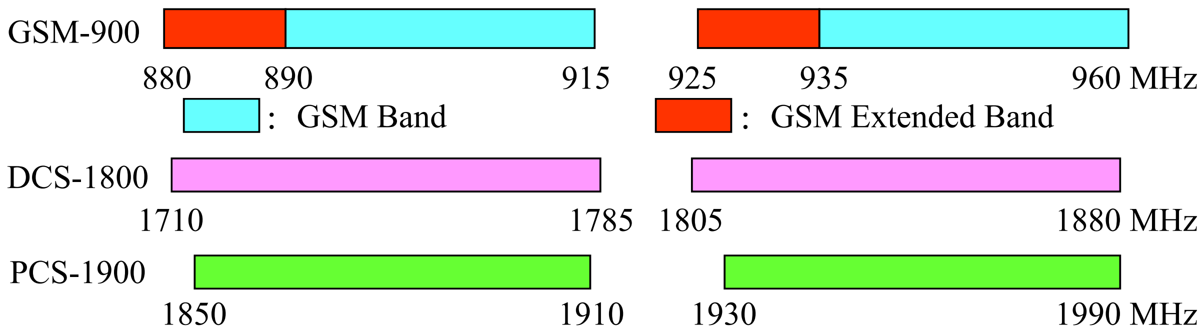
- Assume that we have the frequency allocations for three systems A, B, C shown as follows:



- **Questions:**
  - Is "A"("B" or "C") an FDD or TDD system?
  - Is it possible that "A" is a TDD system?
  - Is it possible that "C" is an FDD system?

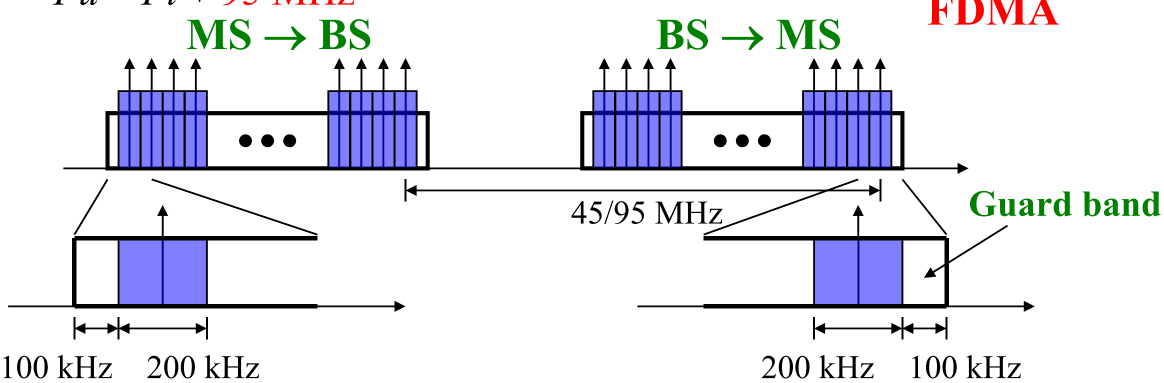
GSM Frequency Bands

- Three major frequency bands are available for GSM standards.
- **Duplex distance:** The frequency separation between a pair of FDD channels. It is essential for preventing interference.
  - GSM-900: 45 MHz
  - DCS-1800: 95 MHz
  - PCS-1900: 80 MHz
- GSM carrier frequency spacing: 200 kHz



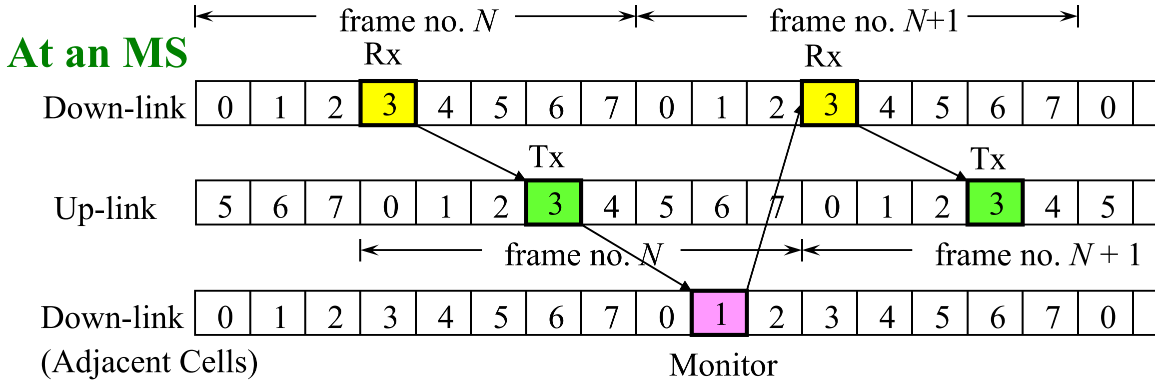
GSM Carrier Frequency Assignment

- GSM:
  - $Fl = 890 + n \times 0.2$ MHz, $0 \le n \le 124$
  - $Fl = 890 + (n - 1024) \times 0.2$ MHz, $975 \le n \le 1023$
  - $Fu = Fl +$ 45 MHz
- DCS-1800:
  - $Fl = 1710.2 + (n - 512) \times 0.2$ MHz, $512 \le n \le 885$
  - $Fu = Fl +$ 95 MHz



GSM Time Slot Assignment and Duplex

- In GSM systems, each time frame of **a carrier** is divided into 8 slots to support **8** users
  - TDMA (a hybrid **FDMA-TDMA** scheme)
- For supporting FDD duplex transmission, the transmissions of uplink and downlink are allocated **the same time slot number**
  - A **timing offset** is introduced to prevent **simultaneous transmission/reception** at mobile equipment

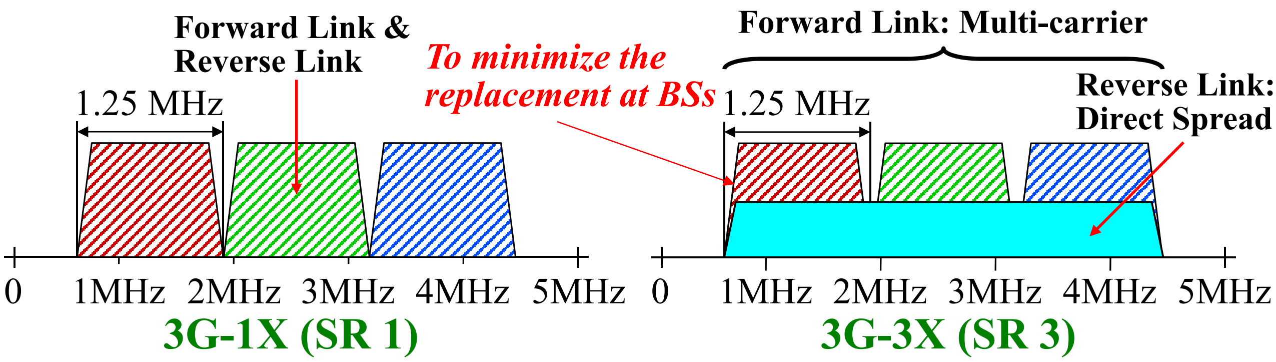


GSM Time Slot Assignment and Duplex (Cont.)

- Simultaneous transmission/reception at a node requires a high-order filter (**duplexer**) for preventing the interference from the transmitter to the receiver (because the same antenna is used)
  - Greatly increase the **implementation complexity**
  - The **timing offset** reduces the hardware complexity at mobile equipment
- By using TDMA, there are some free slots available for an MS to perform **signal measurement** (reception only)
  - In the **handoff procedure**, the signal strength of neighboring cells is essential information

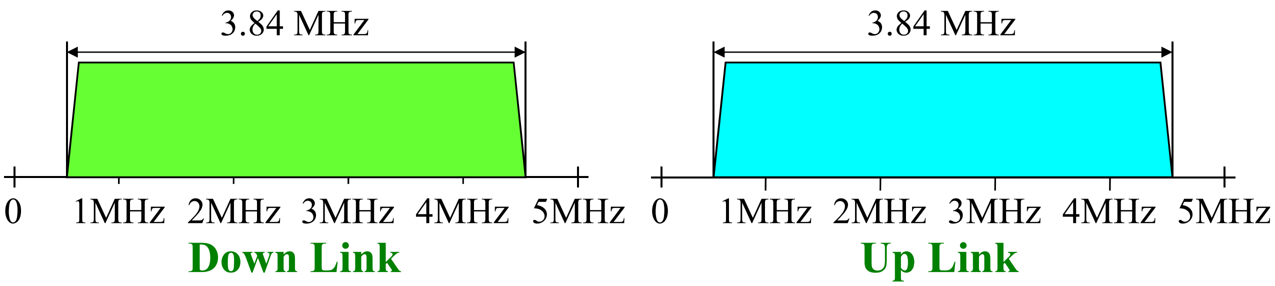
3G cdma2000 Systems

- **cdma2000** systems support SR (Spreading Rate) 1 and SR 3 modes
  - SR 1: the conventional IS-95 system with bandwidth 1.25 MHz
  - SR 3: the **MC (Multi-Carrier)** mode with three times bandwidth
- The whole band is divided into multiple sub-bands ⇒ **FDMA**
- Each sub-band supports multiple users via **DS** spread spectrum
  - CDMA (a hybrid **FDMA-CDMA** scheme)



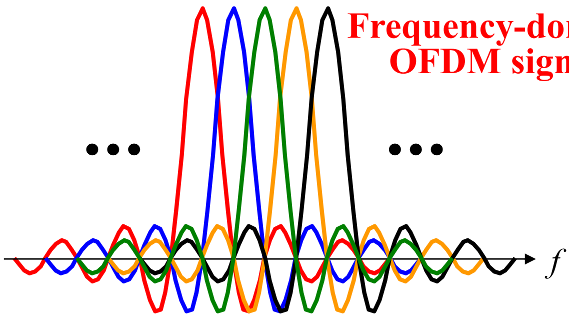
3G WCDMA Systems

- **WCDMA** is a new standard without the issue of **backward compatibility**
- Only **DS (Direct Spreading) mode** is supported
  - It is not MC (Multi-Carrier) mode
  - It supports only one spreading rate – **3.84 Mchips/s** (with the bandwidth claimed to be 5 MHz)



4G/5G OFDM/OFDMA Systems

- 4G/5G systems use the **orthogonal frequency division multiplexing (OFDM)** technique
  - The whole band is divided into multiple **sub-carriers**
- Multiple data streams for different users can be simultaneously carried in the same band via allocating **different sets of sub-carriers** for transmission (OFD multiple access, **OFDMA)**
  - It can be regarded as a **frequency-division multiplexing (FDM)** scheme or an **FDMA** scheme



dB Representation

Decibel (dB)

- The **decibel** (**dB**) is a relative unit used to express the **ratio** of one value to another on a **logarithmic scale**.
- It can be used to express an **absolute value**. In this case, it expresses the ratio of a value to a **fixed reference value**.
  - A **suffix** indicating the reference value is appended after dB
  - e.g., dBW, dBm, dBV
- The definition of dB is $X_{(\text{dB})} = 10 \times \log_{10}(X)$
- The representation of dB can be used to expression a very large value or a very small (closed to 0) value
  - 100 dB = 10000000000
  - −100 dB = 0.0000000001
  - 2 = 3dB; 3 = 4.771dB; 5 = 7dB

Decibel (dB) (Cont.)

- Someone may question that there seems to be another expression of dB defined as

$$X_{(\text{dB})} = 20 \times \log_{10}(X)$$

  - **No!** There is only one expression of dB:

$$X_{(\text{dB})} = 10 \times \log_{10}(X)$$

- In electrical circuits, power dissipation is proportional to the square of voltage or current when the impedance is constant.
  - The power gain level (in dB) is expressed as

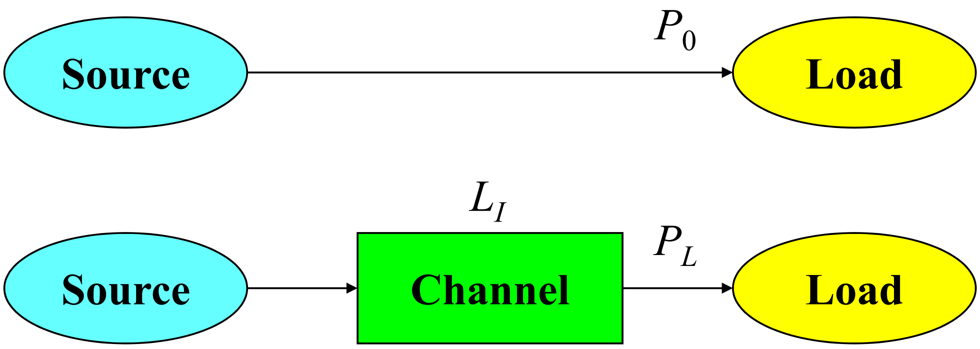
$$G_{(\text{dB})} = 20 \times \log_{10}(V_{\text{out}} / V_{\text{in}})$$

- However, the expression is due to

$$G_{(\text{dB})} = 10 \times \log_{10}(V_{\text{out}}^2 / V_{\text{in}}^2) = 10 \times \log_{10}(V_{\text{out}} / V_{\text{in}})^2$$
$$= 20 \times \log_{10}(V_{\text{out}} / V_{\text{in}})$$

Insertion Loss (Path Loss)

- P_0: the power delivered to a load when it is connected directly to the source (linear scale, W, mW, …)
- P_L: the power delivered to a load from a source via a **channel**
- Insertion loss $L_I = 10 \log_{10} (P_0 / P_L)$ **dB**
- $x \leftrightarrow y$ dB $\Rightarrow y = 10 \log_{10} x$, e.g., 20 = 13 dB



Insertion Loss (Path Loss) (Cont.)

- For example, if the transmit power is $P_{(\text{dB})} = 0$ dBW (i.e., 1W), the channel bandwidth is $B = 100$ KHz, and the noise power spectral density is $N_0/2$ with $N_0 = -110$ dBW/Hz.
- If the propagation loss of the channel is $L = 40$ dB, the received signal power is

$$P_{\text{r(dB)}} = 10 \times \log_{10}\left(P/L\right) = P_{(\text{dB})} - L_{(\text{dB})} = -40 \text{ dBW}$$

- The symbol energy is

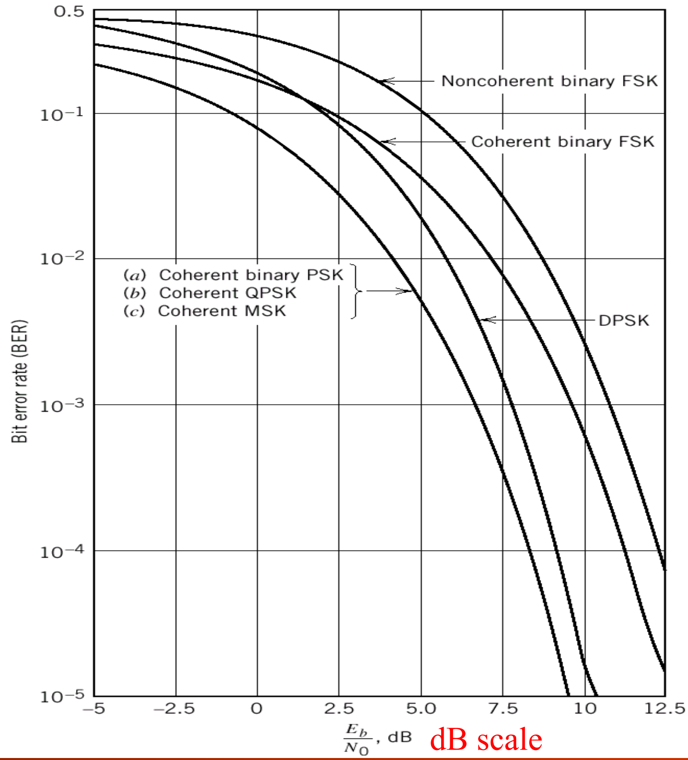
$$\begin{aligned} E_{(\text{dB})} &= 10 \times \log_{10}\left(P_{\text{r}} \times T\right) = 10 \times \log_{10}\left(P_{\text{r}}/B\right) \\ &= P_{\text{r(dB)}} - B_{(\text{dB})} = -40 - 50 = -90 \text{ dB Joules (W/Hz)} \end{aligned}$$

- The received signal SNR is

$$\left(E/N_0\right)_{(\text{dB})} = E_{(\text{dB})} - N_{0(\text{dB})} = -90 - \left(-110\right) = 20 \text{ dB}$$

Representation of Probability of Error

dB scale



dB scale

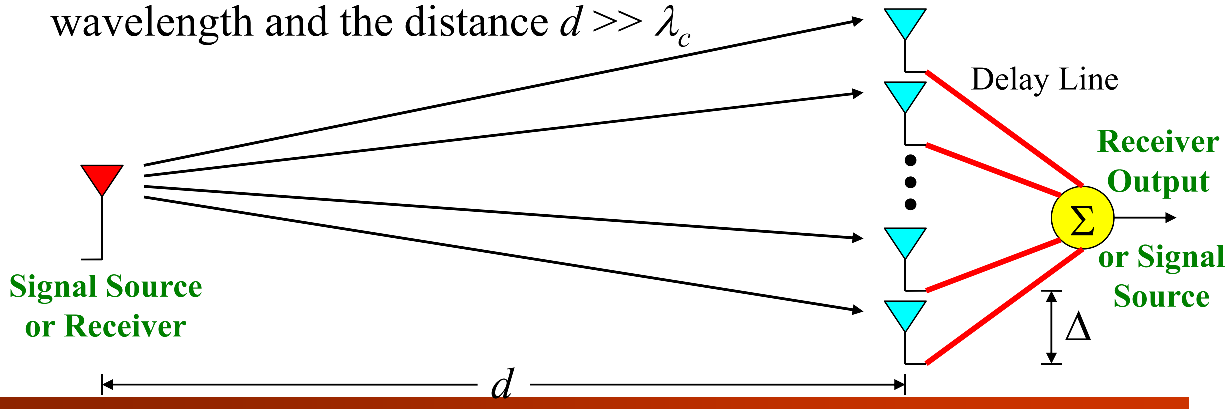
Antenna

Antenna

- An antenna system is used to **transmit and receive** the modulated carrier signal for wireless communications.
  - It may contain a single antenna (one antenna element or multiple antenna elements) or multiple antennas.
- The fundamental characteristics of an antenna are
  - **Gain:** The ratio of the maximum radiated power to the input power
  - **Half power beamwidth:** The angular separation between the half power points
  - Both can be described by the **antenna radiation pattern**
- The transmitting and receiving patterns of an antenna are **identical** at a given wavelength (the reciprocity theorem)

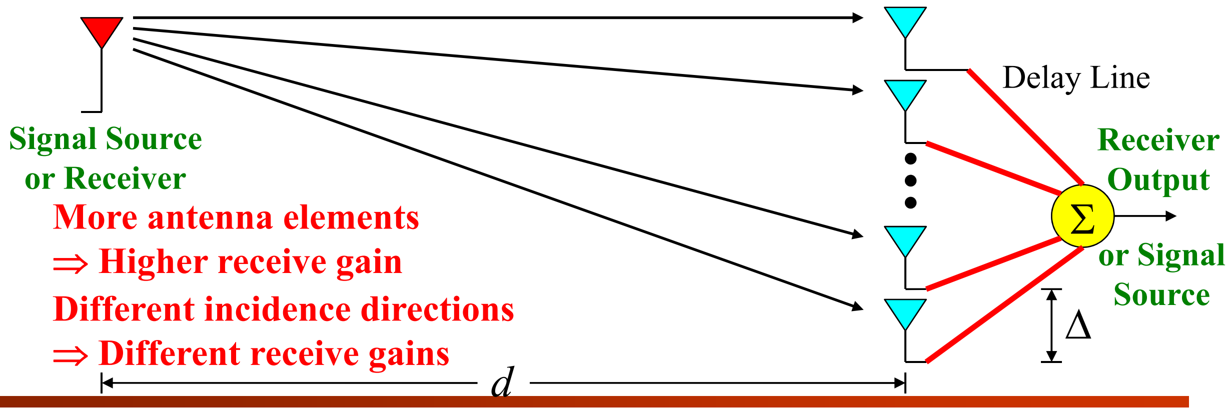
Antenna (Cont.)

- Consider a **uniform linear antenna (ULA) arrays**, where multiple antenna elements are **evenly spaced** on a straight line.
- We also consider a free space propagation environment (no reflectors or scatterers), where only a direct signal path between the signal source and each receive antenna.
- The antenna separation is $\Delta < \lambda_c$ (in general $\Delta = \lambda_c/2$), λ_c is the wavelength and the distance $d >> \lambda_c$



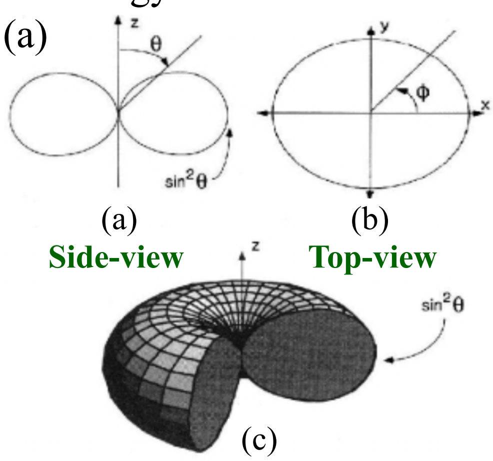
Antenna (Cont.)

- For a specific incidence direction, the receiver can **coherently combine** all the signals received on different antenna elements
  - Greatly enlarge the received signal strength⇒ a **high** antenna gain
- If the source signal comes from other direction, all the received signals **cannot** be coherently combined, resulting a degradation in the receive signal strength → a **small** antenna gain



Antenna Radiation Pattern

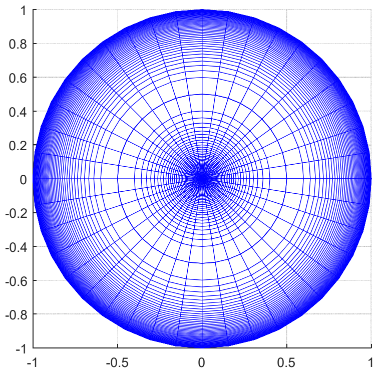
- An antenna **radiation pattern** is a 3-D plot of its radiation far from the source.
  - It is defined by the **incidence direction** (θ and ϕ).
- Antenna radiation patterns usually take two forms:
  - The **elevation pattern** is a graph of the energy radiated from the antenna **looking at it from the side** (a)
  - The **azimuth pattern** is a graph of the energy radiated from the antenna **looking at it from directly above the antenna** (b)
- When you combine the two graphs, you have a 3-D representation of the antenna radiation pattern (c)

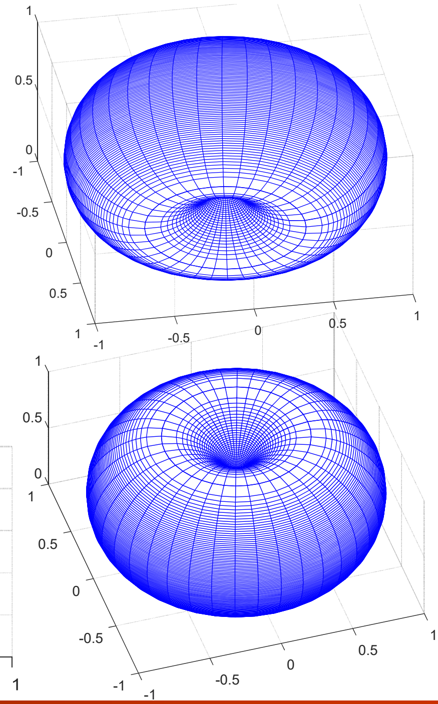


Antenna Radiation Pattern (Cont.)

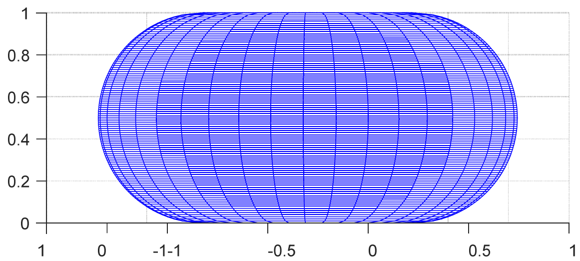
- The **radiation pattern** of a dipole antenna

Top-view



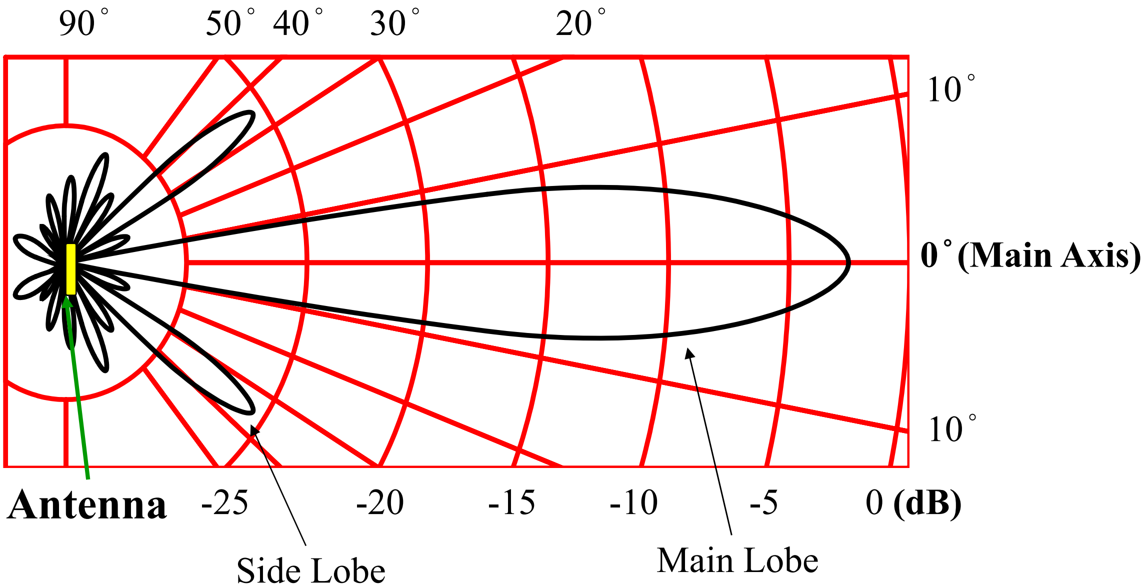


Side-view

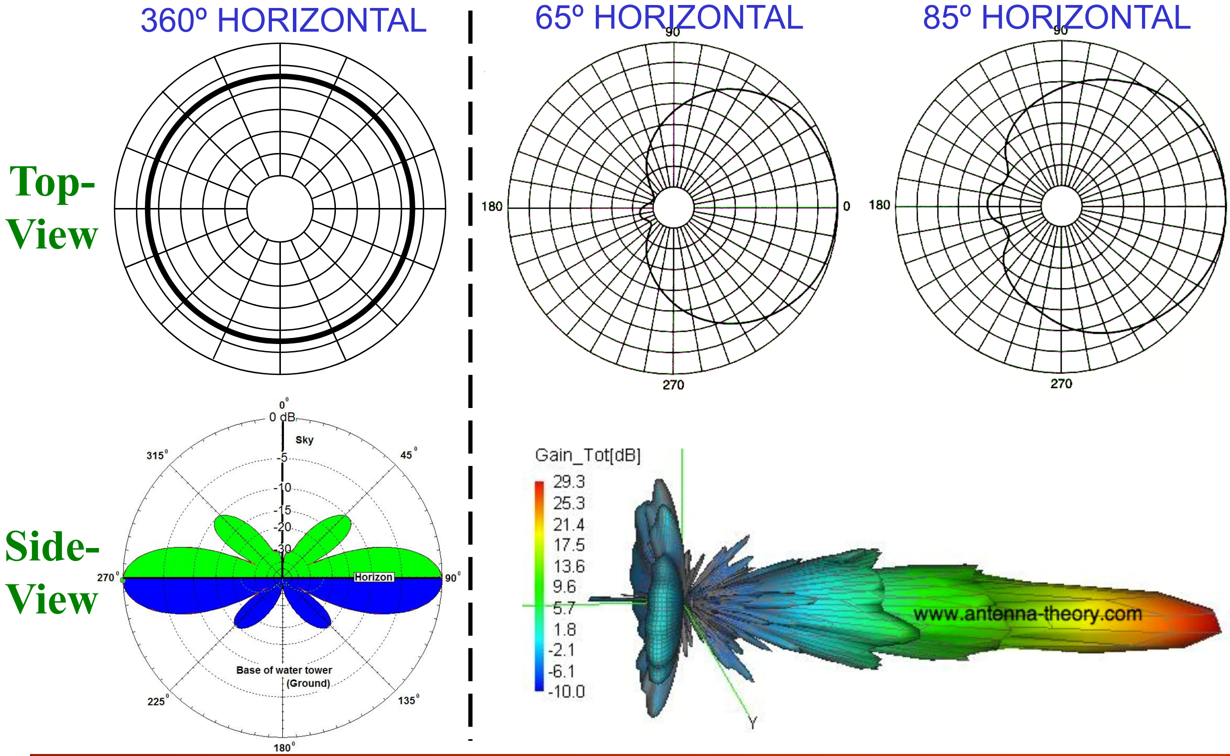


Vertical (Elevation) Antenna Radiation Pattern

Side-View



Horizontal (Azimuth) Antenna Radiation Pattern

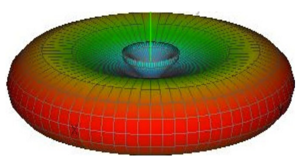


Antenna Gain

- **Antenna gain** is a measure of how much of the input power is concentrated in a particular direction
  - **dBi:** Expressed with respect to an **isotropic antenna**, which radiates equally in **all directions** (not physically realizable)
    - Isotropic antenna gain: 1 (0 dB)
  - **dBd:** Expressed with respect to a **half-wave dipole antenna**
    - Half-wave dipole antenna gain: **1.64 (2.15 dB)**

$G \propto \frac{4\pi A_e}{\lambda_c^2}$, A_e is related to the physical size of the antenna

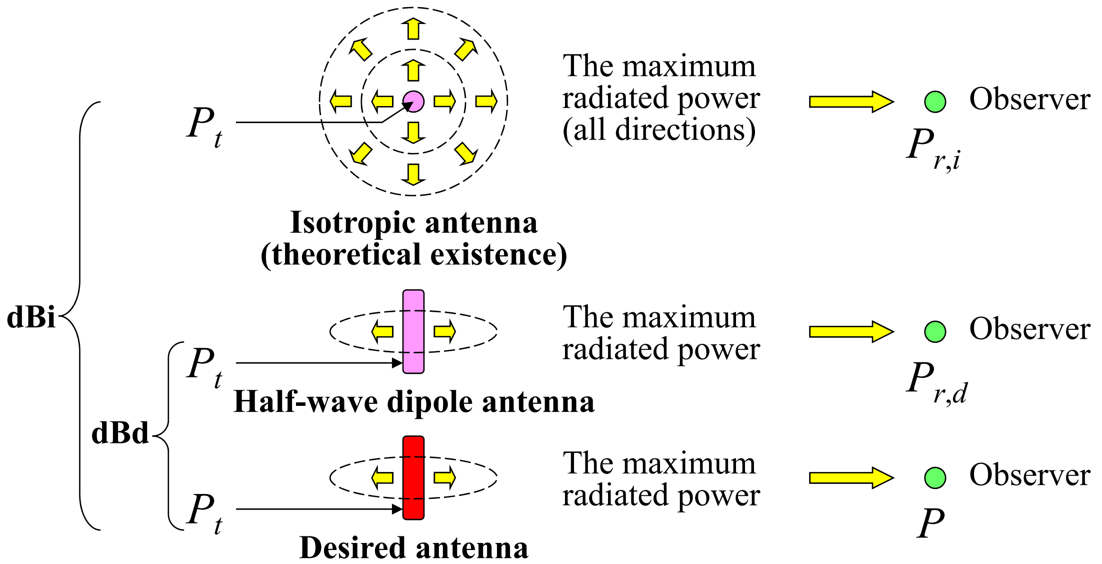
- Antenna **directivity**:
  - **Omni-directional antenna:** omni-directional in the **azimuth pattern**
  - **Directional antenna:** directional in the **azimuth pattern**



Antenna Gain (Cont.)

- The antenna gain can be expressed in dBi or dBd

$$G = 10\log_{10}\frac{P}{P_{r,i}}\ \text{(dBi)} \quad \text{or} \quad G = 10\log_{10}\frac{P}{P_{r,d}}\ \text{(dBd)}$$



EIRP & ERP

- **Effective isotropic radiated power (EIRP):** (dBm or dBW)

$$EIRP = P_t - L_c + G_i$$

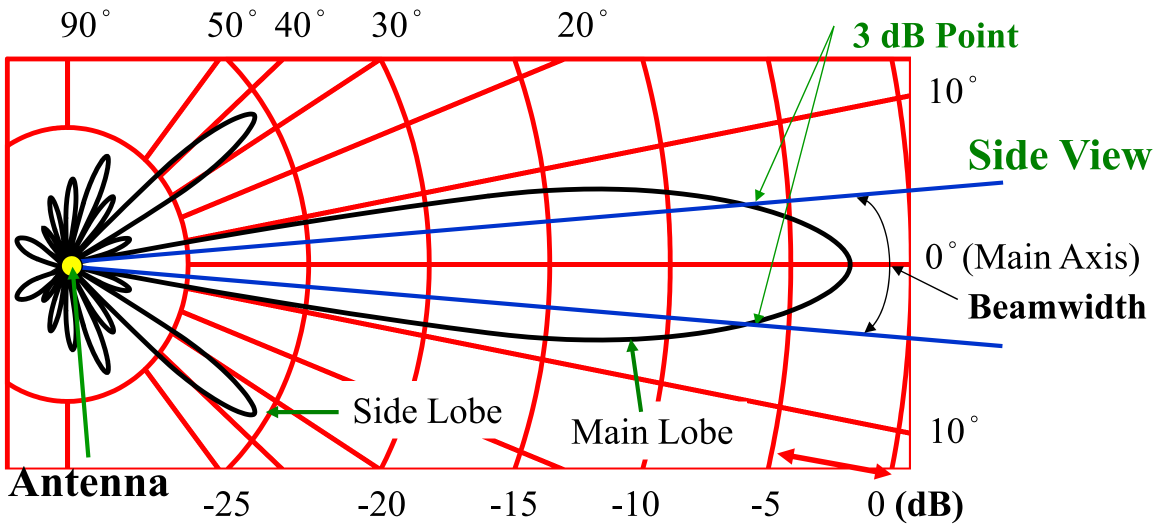
  - where P_t is the transmission power in dBm or dBW, L_c is the cable loss in dB, and G_i is the antenna gain expressed in **dBi**
  - The maximum radiated power available from a transmitter in the direction with the maximum antenna gain
  - Compared to **an isotropic antenna**
- **Effective radiated power (ERP):** (dBm or dBW)

$$ERP = P_t - L_c + G_d$$

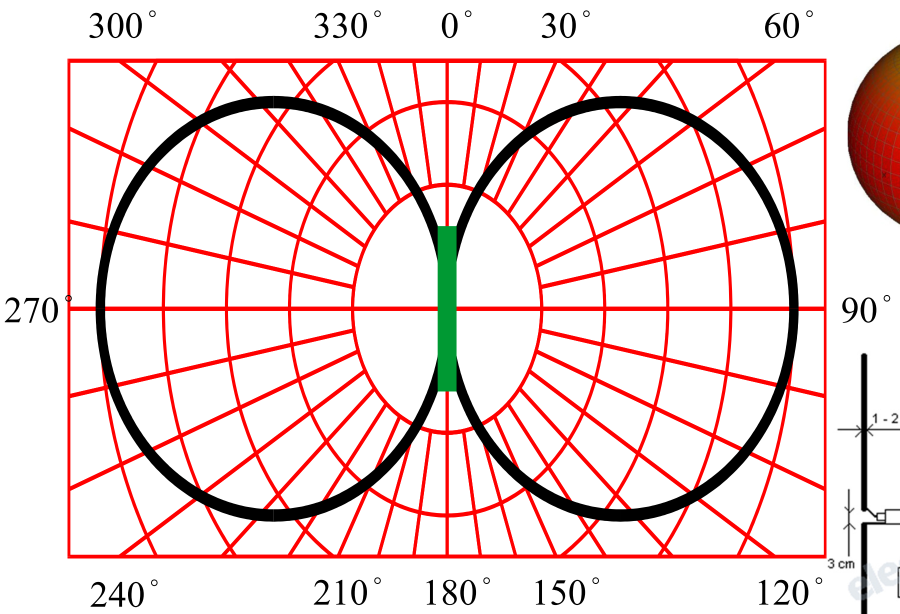
  - where P_t is the transmission power in dBm or dBW, L_c is the cable loss in dB, and G_d is the antenna gain expressed in **dBd**
  - Compared to **a half-wave dipole antenna**

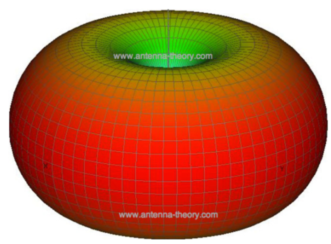
Half Power Beamwidth

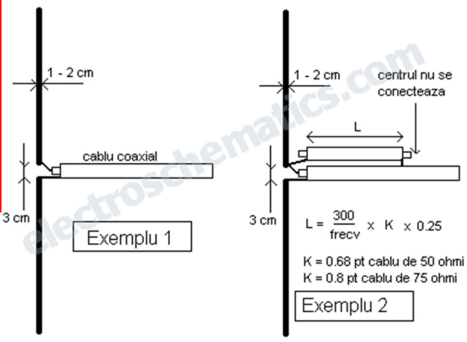
- The half-power beamwidth is
  - The **angular separation** between the half power points on the antenna radiation pattern
  - The half power points: the gain is one half of the maximum value



Half-Wave Dipole Antenna

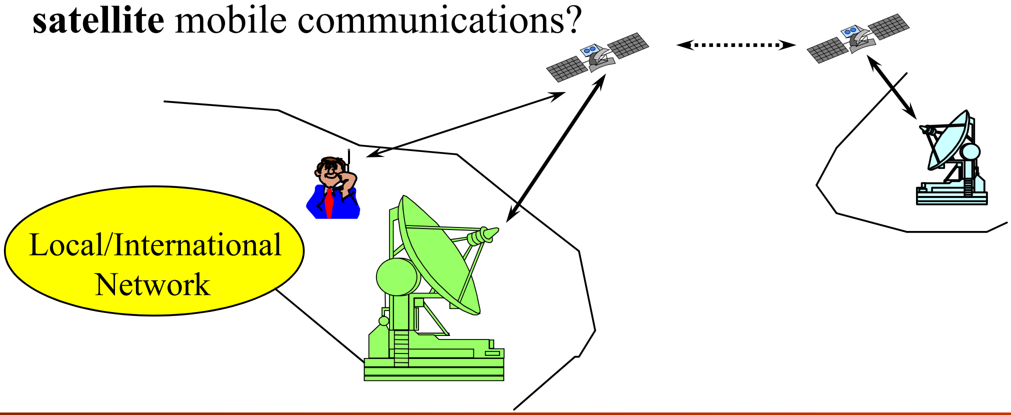






Question

- **Question:**
  - Why a directional (in vertical plane) antenna is generally used in the BS side?
  - Why an omni-directional antenna (such as the dipole antenna) is generally used in the MS side?
  - Can you imagine the antenna radiation pattern required for **satellite** mobile communications?

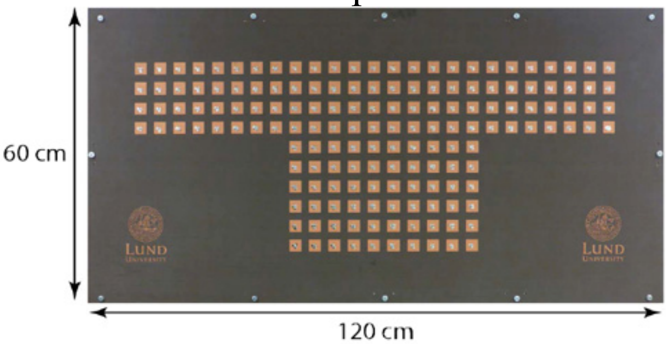


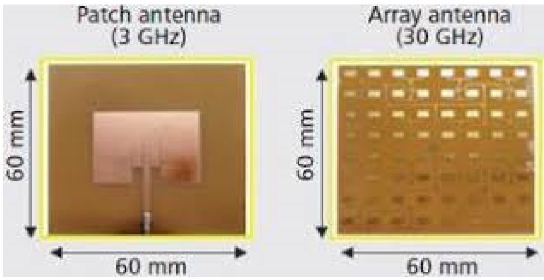
Question (Cont.)

- Handsets for satellite mobile communications

Massive MIMO Antennas

- Multiple-antenna (MIMO) technology is becoming mature for wireless communications.
- Basically, the more antennas the transmitter/receiver is equipped with, the better performance can be obtained.
- **Massive MIMO Antennas** use a very large number of service antennas that are operated fully coherently and adaptively.
  - Feasible for operations in the **millimeter-wave** (mm-wave) bands

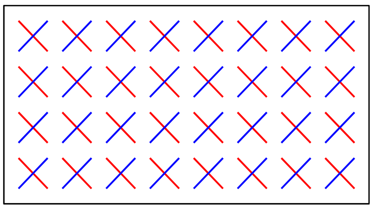




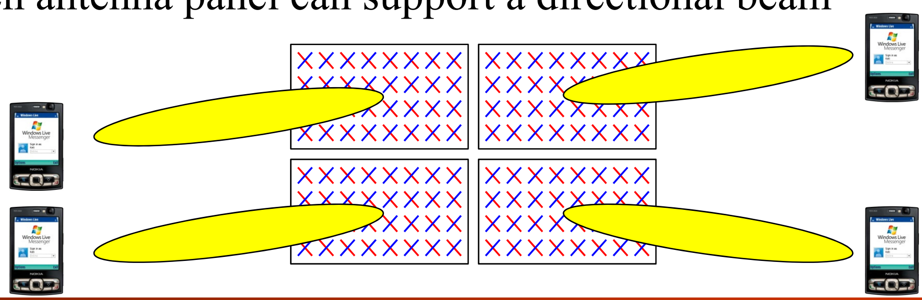
Massive MIMO Antennas (Cont.)

- In 5G systems, the massive MIMO antennas are configured to support beamforming transmission with multiple antenna panels
- Each antenna panel is denoted as $(M \times N \times P)$
  - M: number of antenna rows
  - N: number of antenna columns
  - P: number of different polarizations
  - For example, $(4 \times 8 \times 2)$ array

64 elements $(4 \times 8 \times 2)$



- Each antenna panel can support a directional beam



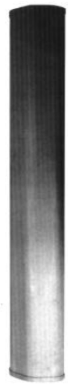
Antenna Catalog

- In the following, we show the catalog of some commercial antennas

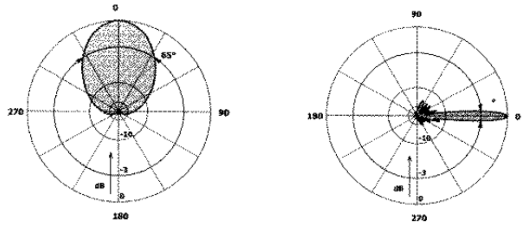
Model No. GSMA065-18-0

Frequency	870-960MHz
Gain	16.5 ±0.5dBi (14.4 ±0.5dBd)
Input Impedance	50 ohms
VSWR	1.4: 1 maximum
Polarisation	Vertical
Electrical downtilt	0°
Azimuth beamwidth	65° ±3°
Elevation beamwidth	8.9° ±0.6°
1st Upper sidelobe	*-20dB typical, -15dB maximum*
1st Null	*First minimum below main beam >-21dB*
Front/Back ratio	>30dB
Intermodulation	<-153dBc for 2 x 20W carriers
Input Power	500W at 40°C (continuous rating)
Input Connector	7/16-DIN
Mounting Interface	Wall or pole 2 - 4.5 in dia. (48 - 115mm), c/w pan and tilt
Survival wind speed	56m/s (125 mi/h)
Temperature	140° (60°C) at full rated power
Dimensions	1800 x 360 x 173mm
Weight	Antenna 16.4kg Mountings 5.6kg

Mounting bracket required : XSL51204



Radiation Pattern File available from Website.



Azimuth Pattern Elevation Pattern

Antenna Catalog (Cont.)

- **Model No. GSMA065-18-0**

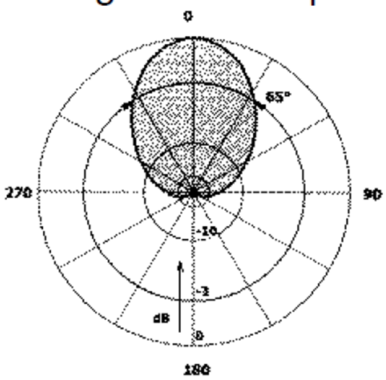
Frequency	870-960MHz
Gain	16.5 ±0.5dBi (14.4 ±0.5dBd)
Input Impedance	50 ohms
VSWR	1.4: 1 maximum
Polarisation	Vertical
Electrical downtilt	0°
Azimuth beamwidth	65° ±3°
Elevation beamwidth	8.9° ±0.6°
1st Upper sidelobe	*-20dB typical, -15dB maximum*
1st Null	*First minimum below main beam >-21dB*
Front/Back ratio	>30dB
Intermodulation	<-153dBc for 2 x 20W carriers
Input Power	500W at 40°C (continuous rating)
Input Connector	7/16-DIN
Mounting Interface	Wall or pole 2 - 4.5 in dia. (48 - 115mm), c/w pan and tilt

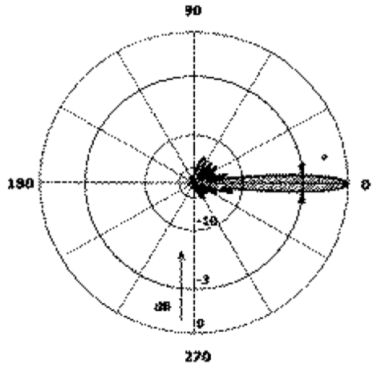
Antenna Catalog (Cont.)

- **Model No. GSMA065-18-0**

Survival wind speed	56m/s (125 mi/h)
Temperature	140° (60°C) at full rated power
Dimensions	1800 x 360 x 173mm
Weight	Antenna 16.4kg Mountings 5.6kg

Mounting bracket required : XSL51204





Antenna Catalog (Cont.)

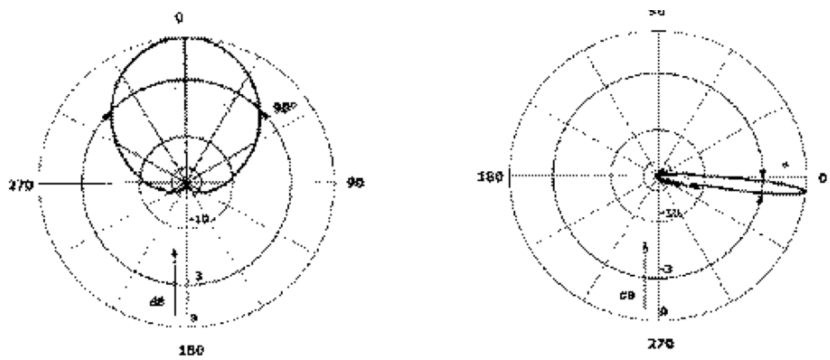
- **Model No. GSMA090-12-6**

Frequency	870 - 960MHz
Gain	14.6 ±0.5dBi (12.5 ±0.5dBd)
Input Impedance	50 ohms
VSWR	1.4: 1 maximum
Polarisation	Vertical
Electrical downtilt	6°
Azimuth beamwidth	90° ±5°
Elevation beamwidth	15.1° ±1°
1st Upper sidelobe	*<-16dB*
1st Null	*First null below elevation peak >-20dB*
Front/Back ratio	≥ 25dB
Intermodulation	<-153dBc for 2 x 20W carriers
Input Power	50w AT 40°c (continuous rating)
Input Connector	7/16-DIN
Mounting Interface	Wall or pole 2 - 4.5in diameter (48 -115mm), c/w pan and tilt

Antenna Catalog (Cont.)

- **Model No. GSMA090-12-6**

Survival wind speed	56m/s (125 mi/h)
Temperature	-40°F (-40°C) to 140°F (60°C)
Dimensions	1176 x 310 x 18 mm
Weight	Antenna 9.7kg Mountings 5.6kg



Antenna Catalog (Cont.)

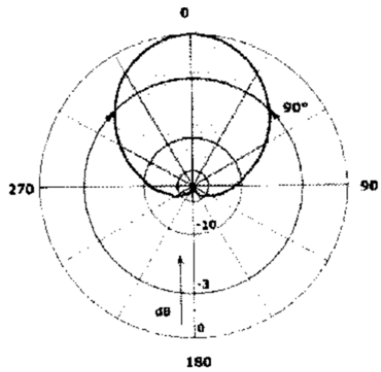
- **Model No. GSMA090-25-***

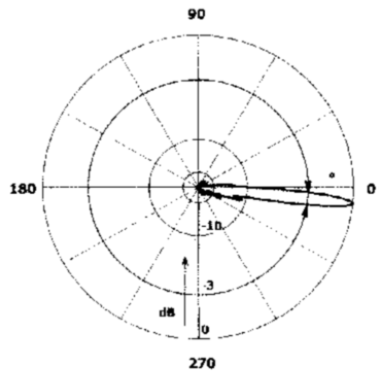
Frequency		870 - 960MHz
Gain		16.8 ±0.5dBi (14.7 ±0.5dBd)
Input Impedance		50ohms
VSWR		1.4: 1 maximum
Polarisation		Vertical
Electrical downtilt	*	0°, 6°
Azimuth beamwidth		90° ±5°
Elevation beamwidth		7.2° ±0.7°
1st Upper sidelobe		*<-19dB (except for 8° beamtilt model which is <-17dB)*
1st Null		*First minimum below main beam >-25dB*
Front/Back ratio		≥ 30dB
Intermodulation		<-153dBc for 2 x 20W carriers
Input Power		500W at 40°C (continuous rating)
Input Connector		7/16-DIN
Mounting Interface		Wall or pole 2 - 4.5in diameter (48 -115mm), c/w pan and tilt

Antenna Catalog (Cont.)

- **Model No. GSMA090-25-***

Survival wind speed	56m/s (125 mi/h)
Temperature	-40°F (-40°C) to 140°F (60°C)
Dimensions	2485 x 310 x 180mm
Weight	Antenna 18.7kg
	Mountings 5.6kg

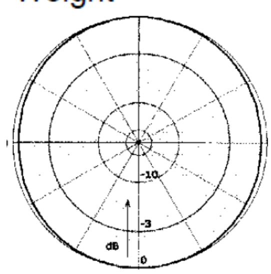


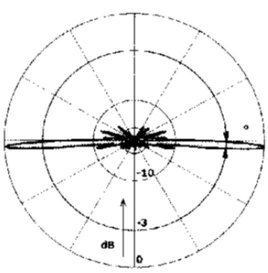


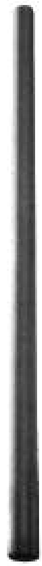
Antenna Catalog (Cont.)

- **Model No. PCNC360-25-***

Frequency		1710 - 1880 MHz
Gain		11 dBi
Input Impedance		50 ohms
VSWR		1.4: 1 (1.5 : 1 for 0 ° model)
Polarisation		Vertical
Electrical downtilt	*	0, 2 or 4 °
Azimuth radiation pattern		Omnidirectional ±1.5dB
Elevation beamwidth		4.5° ± 0.25 °
Input Power		150 W at 60° C (Continuous rating)
Intermodulation products		< - 153dBc for 2 x 20W carriers
Dimensions		70 x 2465mm
Weight		Antenna 18.7kg
		Mount 7kg



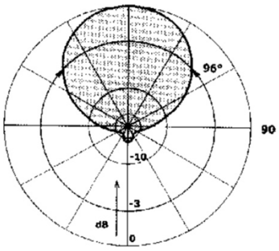


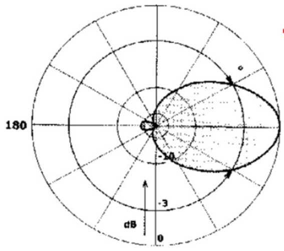


Antenna Catalog (Cont.)

- **Model No. GSMM096-02-0**

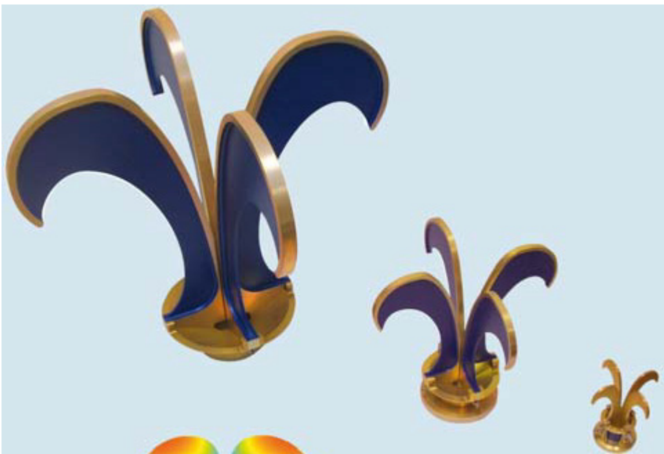
Frequency	870 - 960MHz
Gain	8 dBi nominal
Input Impedance	50 ohms
VSWR	<1.5 : 1
Polarisation	Vertical
Electrical downtilt	0°
Azimuth beamwidth	95° nominal
Elevation beamwidth	60° nominal
Input Connector	TNC female
Dimensions	70 x 2465mm
Weight	Antenna 18.7kg Mount 7kg

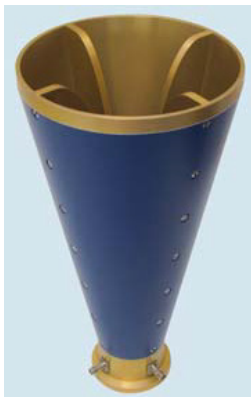


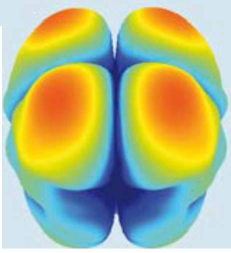


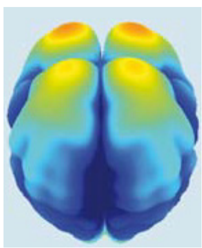
Antenna Catalog (Cont.)

- Open boundary wideband quad ridge horns





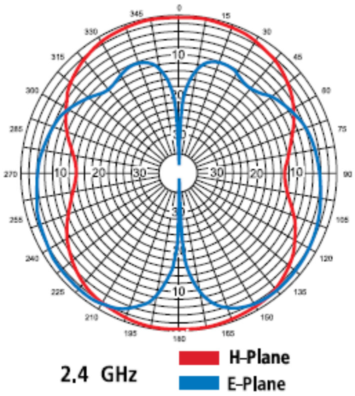


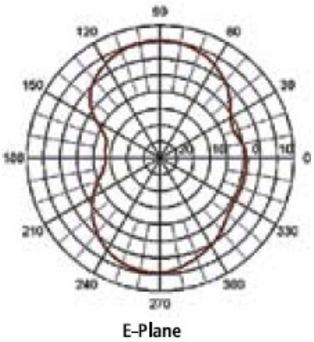


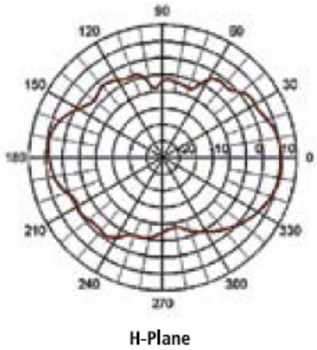
Antenna Catalog (Cont.)

- Dual-directional antennas



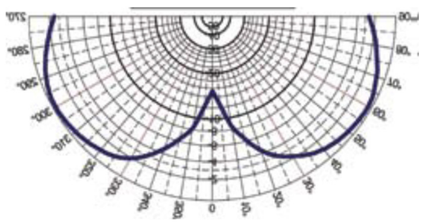




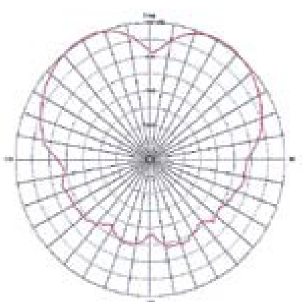


Antenna Catalog (Cont.)

- 2.4 GHz 3 dBi mobile antenna

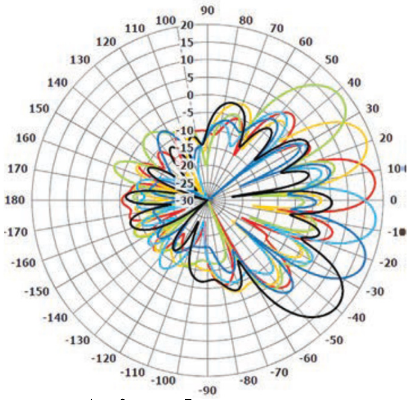
- 5 GHz 5 dBi Omni in-building antenna

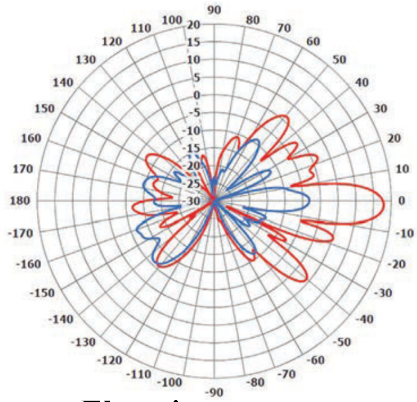
Antenna Catalog (Cont.)

- **Multi-Beam** Hub Base Station antenna

Multiple Inputs/Outputs



Azimuth patterns

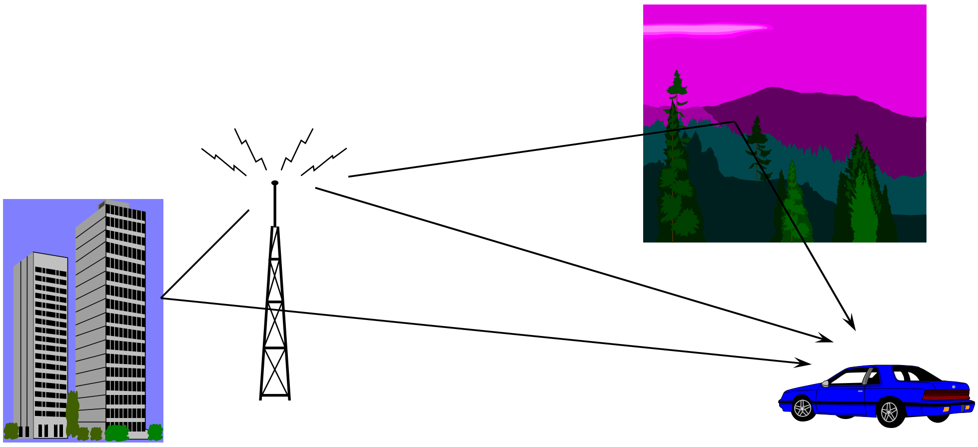


Elevation patterns

Introduction to Wireless Propagation

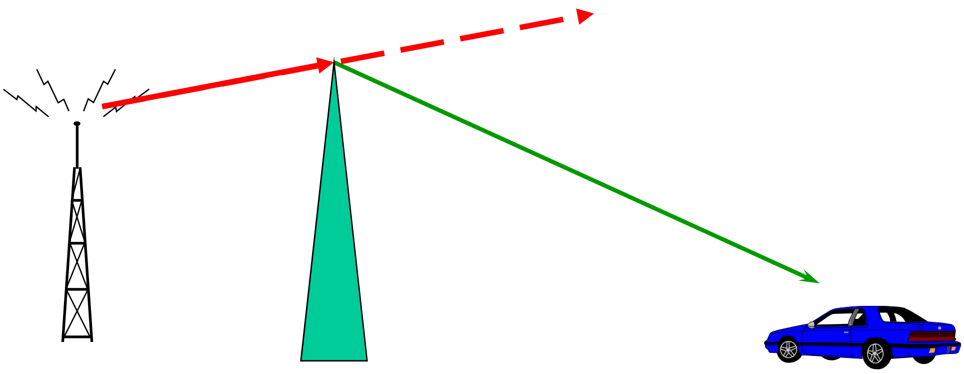
Propagation Mechanisms

- There are three major mechanisms in wireless propagation
- **Reflection**
  - Propagating wave impinges on an object which is **large** compared to its wavelength
  - e.g., the surface of the Earth, buildings, walls, etc.



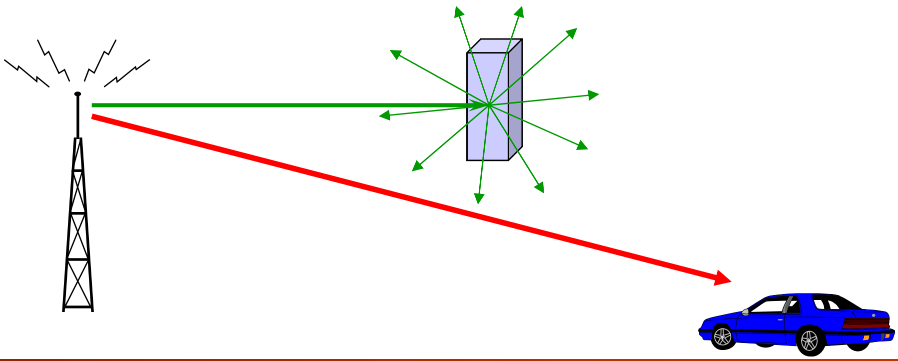
Propagation Mechanisms (Cont.)

- **Diffraction**
  - Radio path between the transmitter and the receiver obstructed by a surface with **sharp irregular edges**
  - Waves bend around the obstacle, even when **line-of-sight** (LOS) propagation does not exist



Propagation Mechanisms (Cont.)

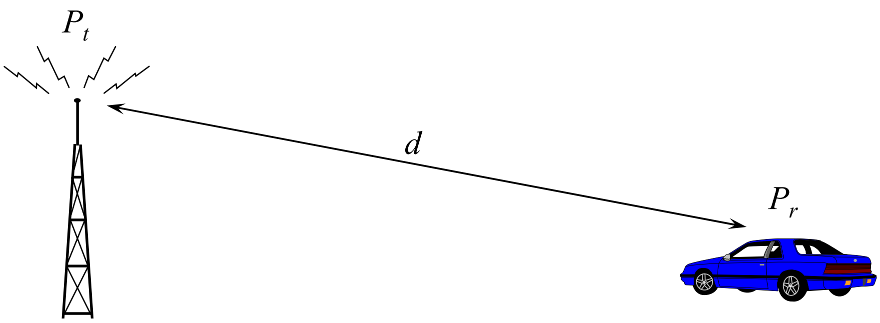
- **Scattering**
  - The radio wave impinges on a rough surface and the reflected energy is **spread out in all directions**
  - Objects **smaller** than the wavelength of the propagating wave (Objects larger than the wavelength may be modeled as reflection)
  - e.g., street tree, street signs, lamp posts, etc.

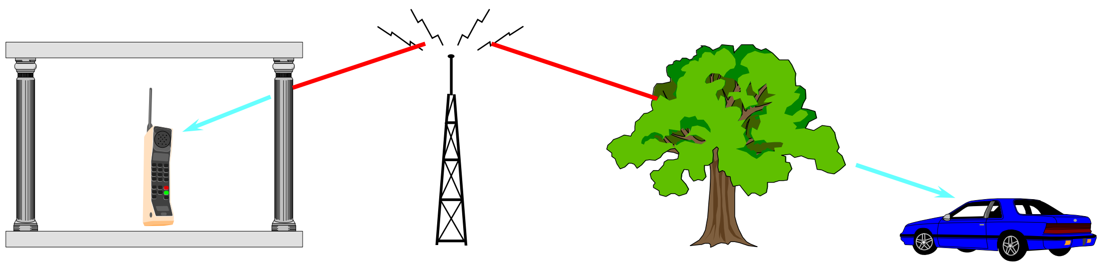


Radio Propagation

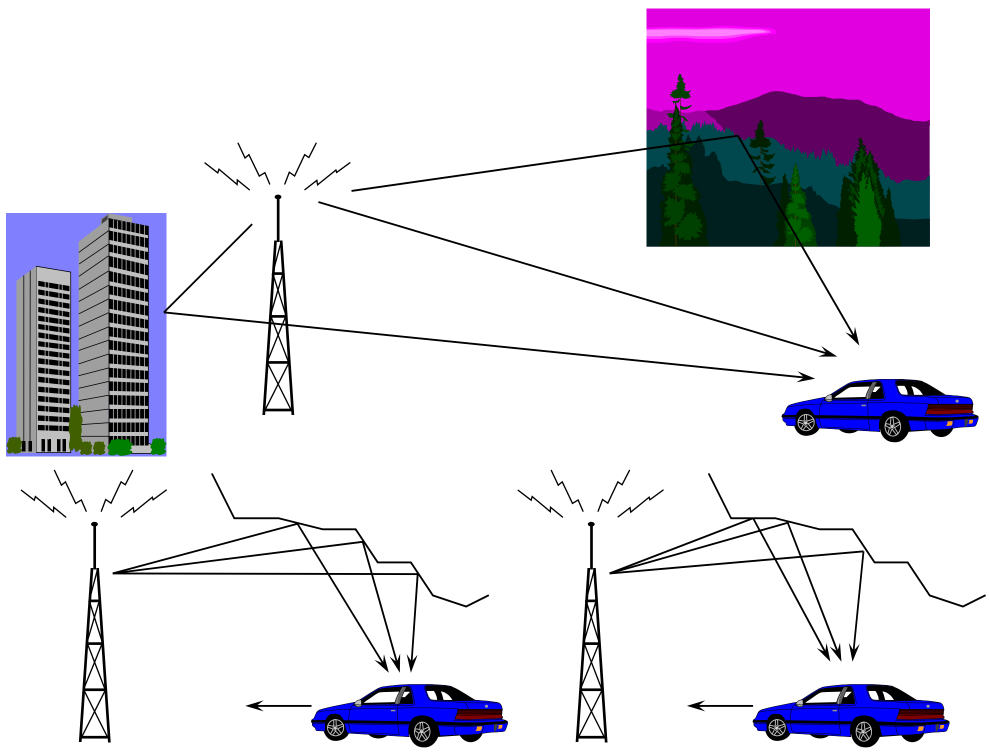
- The propagation effects in **macrocellular** radio propagation can be classified into 3 terms:
  - **Large-scale fading**
    - **Path loss:**
      - Proportional to the propagation distance
    - **Shadowing:** Slow fading
      - Depending on the local environment
  - **Small-scale fading**
    - **Fast multipath fading:** Fast fading
      - Fast fluctuation of the received signal envelope
      - Received envelope can vary 30 dB to 40 dB
      - Causing time dispersion: need equalization in TDMA systems and RAKE reception in CDMA systems

Path Loss and Shadowing



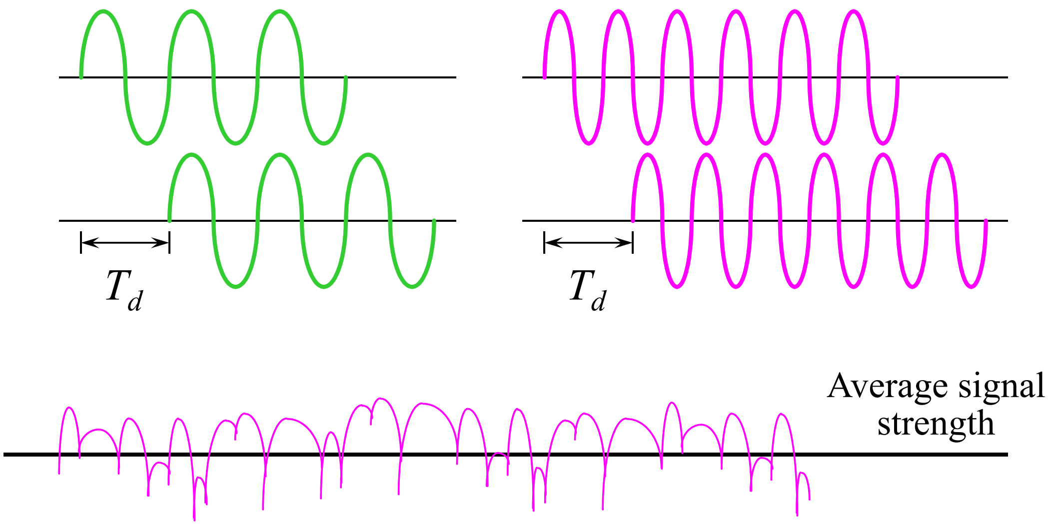


Multipath Propagation

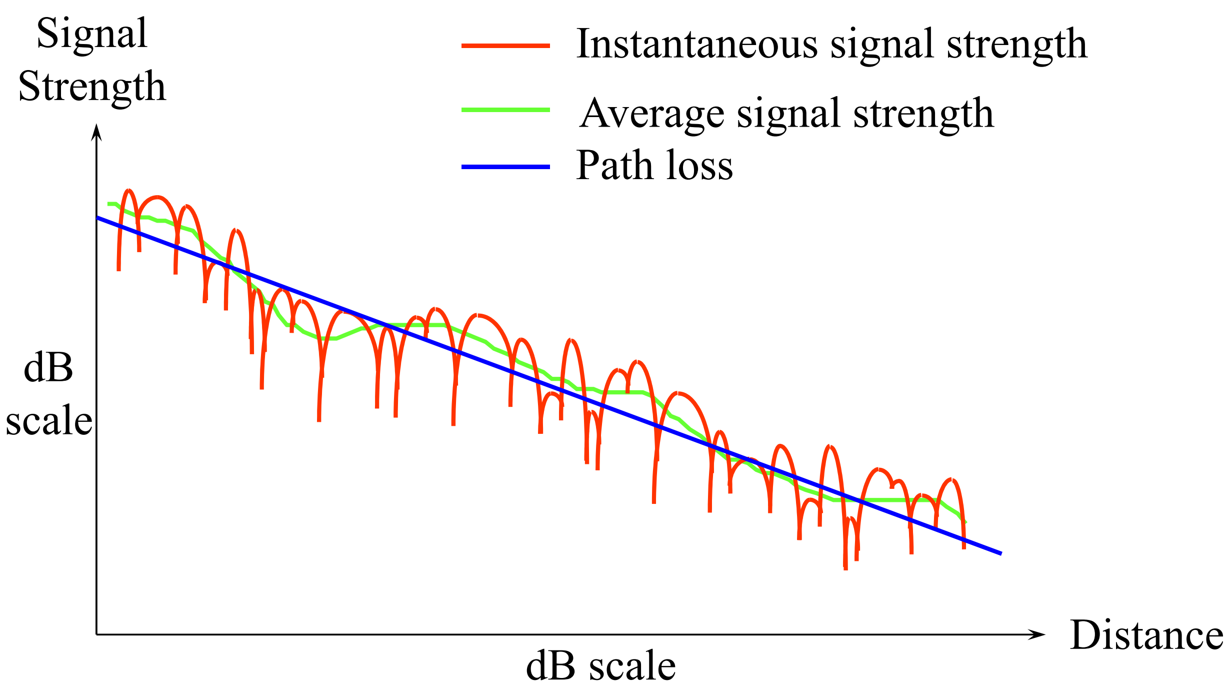


Fast Multipath Fading

- Different signal components may be accumulated constructively or destructively
- The fast multipath fading effect is **frequency dependent**



Overall Propagation Effects



Path Loss & Shadowing

- In **free space** propagation, the received signal power is

$$\Omega(d) = P\left(\lambda_c / 4\pi d\right)^2$$

$$\Omega_{(\mathrm{dB})}(d) = 10\log_{10}\left(P/16\pi^2\right) + 20\log_{10}\lambda_c - 20\log_{10} d$$

  - P: the transmitted power
  - λ_c: the wavelength
  - d: propagation distance

$$\boxed{\begin{aligned} L_p(d) &= P/\Omega(d) \\ &= P_{(\mathrm{dB})} - \Omega_{(\mathrm{dB})}(d) \end{aligned}}$$

- In **mobile radio environments**, path loss depends on:
  - Distance
  - Wavelength (frequency)
  - Antenna heights of MS and BS
  - Local terrain characteristics: buildings and hills

Path Loss & Shadowing

- The **simplest** path loss model:

$d > d_0$ to ensure that the term is positive

$$\Omega_{(\mathrm{dB})}(d) = \underline{\Omega_{(\mathrm{dB})}(d_0)} - 10\beta\log_{10}(d/d_0) + \varepsilon_{(\mathrm{dB})} \text{ dBm}$$

Tx power, antenna height, frequency, …

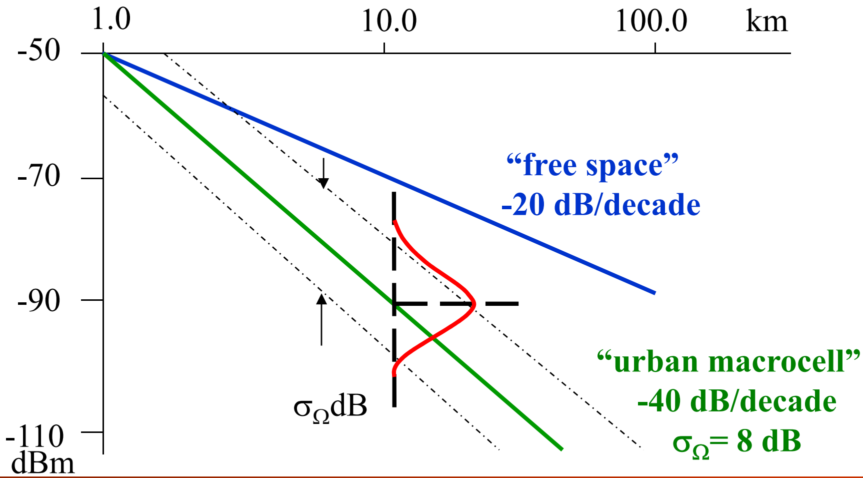
  - Path loss model is feasible only for the receivers **in the far field**
    - How about the receivers **in the near field**?
  - $\Omega_{(\mathrm{dB})}(d_0)$: the received signal power (in dBm) at a known reference distance (in the far field of the signal transmission)
  - d_0: 1 km for macrocells, 100 m for outdoor microcells, and 1 m for indoor picocells
  - The path loss exponent β: **3 ~ 4** for urban macrocellular environments.
  - ε (dB): caused by **shadowing**; it's a zero-mean Gaussian random variable with $\sigma_\Omega = 8$ dB (5~12 dB).

Path Loss & Shadowing

- The probability density function of $\Omega_{(\text{dB})}$ is

$$p_{\Omega_{(\text{dB})}}(x) = \frac{1}{\sqrt{2\pi}\sigma_\Omega} \exp\left[-\frac{(x-\mu_\Omega)^2}{2\sigma_\Omega^2} \right]$$

$$\mu_\Omega(d) = \Omega_{(\text{dB})}(d_0) - 10\beta \log_{10}(d/d_0)$$



Question

- For receivers **in the far field**, we have $d >> d_0$
  - $\Omega(d)$ is surely smaller than the transmission power

$$\Omega_{(\text{dB})}(d) = \Omega_{(\text{dB})}(d_0) - 10\beta \log_{10}(d/d_0) + \varepsilon_{(\text{dB})} \text{ dBm}$$

- **Question:** How about the receivers **in the near field**?
  - For receivers **in the near field**, we have $d << d_0$
    - If $d << d_0$, $d/d_0 << 1$ and $\Omega(d) >> \Omega(d_0)$
  - It is possible that $\Omega(d)$ is larger than the transmission power for a very small d. However, this is **impossible!**
    - The received power must be upper bounded by the transmission power
  - Another path loss model with a much smaller reference distance shall be used that makes the receivers **in the far field** of the new model

Question

- The path loss exponent for urban macrocellular environments is $\beta = 3\sim4$
- **Question:**
  - Is the signal power decay in urban macrocellular environments faster or slower than that in the free space propagation?
  - Is the path loss exponent in urban macrocellular environments favorable or unfavorable for cellular systems?
- The signal power decay is faster.
- It is favorable for some aspects, and is unfavorable for others
  - Favorable: system capacity, CCI (signal quality)
  - Unfavorable: power consumption, coverage

System Performance

Interference and Noise

- Frequency reuse introduces two kinds of interference
  - **Co-channel interference** (Major)
  - Adjacent channel interference (Minor)
- Threshold effect: the link quality is acceptable if
  - Average received carrier-to-**noise** ratio $\Gamma > \Gamma_{th}$
  - Average received carrier-to-**interference** ratio $\Lambda > \Lambda_{th}$
- From system aspect, the probability of link failures is the major concern $\Rightarrow$ Outage probability
  - For thermal noise (**TN**): $O = \Pr(\Gamma < \Gamma_{th})$
  - For co-channel interference (**CCI**): $O = \Pr(\Lambda < \Lambda_{th})$
- TN: Link budget (**coverage** limitation)
  - Required transmission power (sensitivity)
- CCI: Capacity (**capacity** limitation)
  - Frequency reuse factor $D/R = \sqrt{3N}$

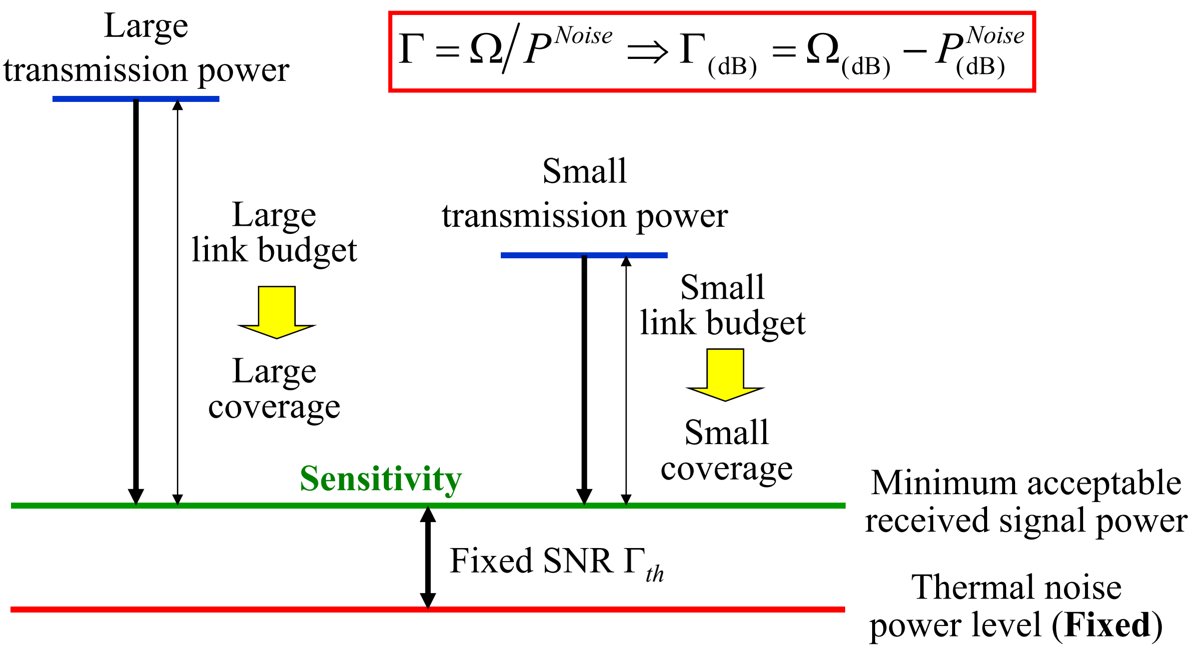
$\Gamma < \Lambda$: only need to consider Γ

$\Gamma > \Lambda$: only need to consider Λ

Minimum Required Transmit Power

- For thermal noise (TN): $O = \Pr(\Gamma < \Gamma_{th})$

$$\boxed{\Gamma = \Omega / P^{Noise} \Rightarrow \Gamma_{(\mathrm{dB})} = \Omega_{(\mathrm{dB})} - P^{Noise}_{(\mathrm{dB})}}$$



Minimum Required Transmit Power (Cont.)

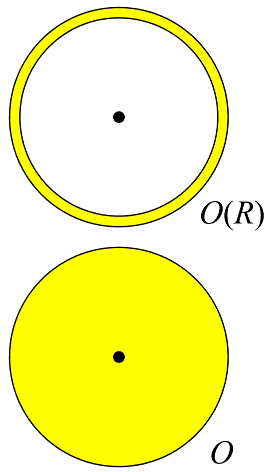
- Specify the outage probability of TN:
  - $O(R)$: outage probability **at cell edge**
  - O: area **average** outage probability
- The outage probability for thermal noise on cell fringe:

$$\Gamma = \Omega / P^{Noise}\,;\; \mu_{\Gamma(\mathrm{dB})} = \mu_{\Omega(\mathrm{dB})} - P^{Noise}_{(\mathrm{dB})}\,;\; (\text{i.e., } \mu_\Omega / P^{Noise})$$

$$O(R) = \Pr(\Gamma(R) < \Gamma_{th})$$

$$= \int_{-\infty}^{\Gamma_{th(\mathrm{dB})}} \frac{1}{\sqrt{2\pi}\sigma_\Omega} \exp\left[-\frac{\left(x - \mu_\Gamma(R)\right)^2}{2\sigma_\Omega^2} \right] dx$$

$$= Q\left(\frac{\mu_\Gamma(R) - \Gamma_{th(\mathrm{dB})}}{\sigma_\Omega} \right)$$



Minimum Required Transmit Power (Cont.)

- Assuming a uniform spatial density, the area averaged outage probability for thermal noise is

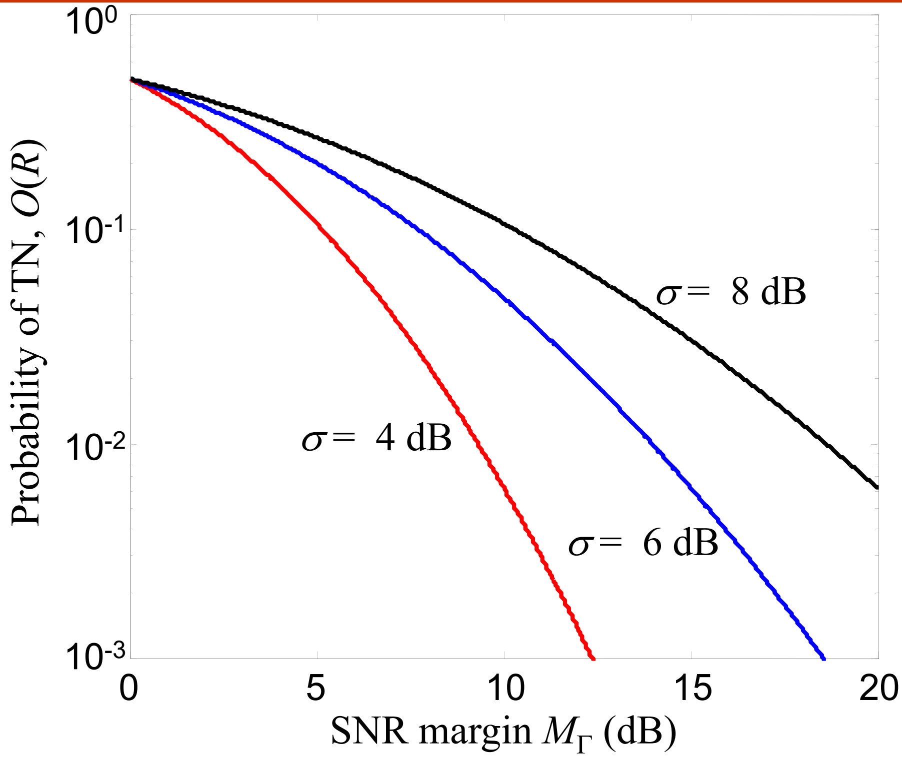
$$O = \frac{1}{\pi R^2} \int_0^R O(r) 2\pi r\, dr$$

$$= Q(X) - \exp\left[XY + Y^2/2 \right] Q(X + Y)$$

$$X = \frac{\mu_{\Gamma(R)} - \Gamma_{th(\mathrm{dB})}}{\sigma_\Omega}, \quad Y = \frac{2\sigma_\Omega}{\beta\xi}$$

  - where $\xi = 10/\ln 10$
- Solve $M_\Gamma(R) = \mu_\Gamma(R) - \Gamma_{th}$ (in dB) for a specified $O(R)$ or O
  - $M_\Gamma(R)$ is the minimum carrier-to-noise ratio **margin** required on cell fringe

Minimum Required Transmit Power (Cont.)



Minimum Required Transmit Power (Cont.)

- Determine Γ_{th}: It can be obtained from theory, experiments, or simulation, and depends on equipment (**sensitivity**)
  - Depending on the required SNR
- According to the desired service quality, we can derive the desired SNR mean value at cell edge $\mu_\Gamma(R)$
  - It depends on the outage performance: $O(R)$ or O
- According to the system (path loss) model, we can derive the minimum required transmitted power
  - We should determine the path loss, antenna gains and received noise power

$$\mu_{\Gamma(\mathrm{dB})} = \mu_{\Omega(\mathrm{dB})} - P_{(\mathrm{dB})}^{Noise}$$

$$\mu_{\Omega(\mathrm{dB})}(d) = \Omega(d_0) - 10\beta \log_{10}(d/d_0)$$

Example

- Assume that the desired outage probability is $O(R) = 0.01$ and the desired SNR is $\Gamma_{th} = 7$dB.
- $Q(2.3) \approx 0.01$

$$\boxed{O(R) = Q\left(\left(\mu_\Gamma(R) - \Gamma_{th(\text{dB})}\right)/\sigma_\Omega\right)}$$

$$\frac{\mu_{\Gamma(R)} - \Gamma_{th(\text{dB})}}{\sigma_\Omega} = \frac{\mu_{\Gamma(R)} - 7}{8} = 2.3 \Rightarrow \mu_{\Gamma(R)} = 25.4 \text{ dB}$$

- If the received noise power is $P^{Noise}_{(\text{dB})} = -100$ dBW, the coverage shall be R = 10km and the path loss model for the transmission power **1W** is

$$\mu_\Omega(d) = -50 - 10 \times 4 \times \log_{10}(d/1\text{km})$$

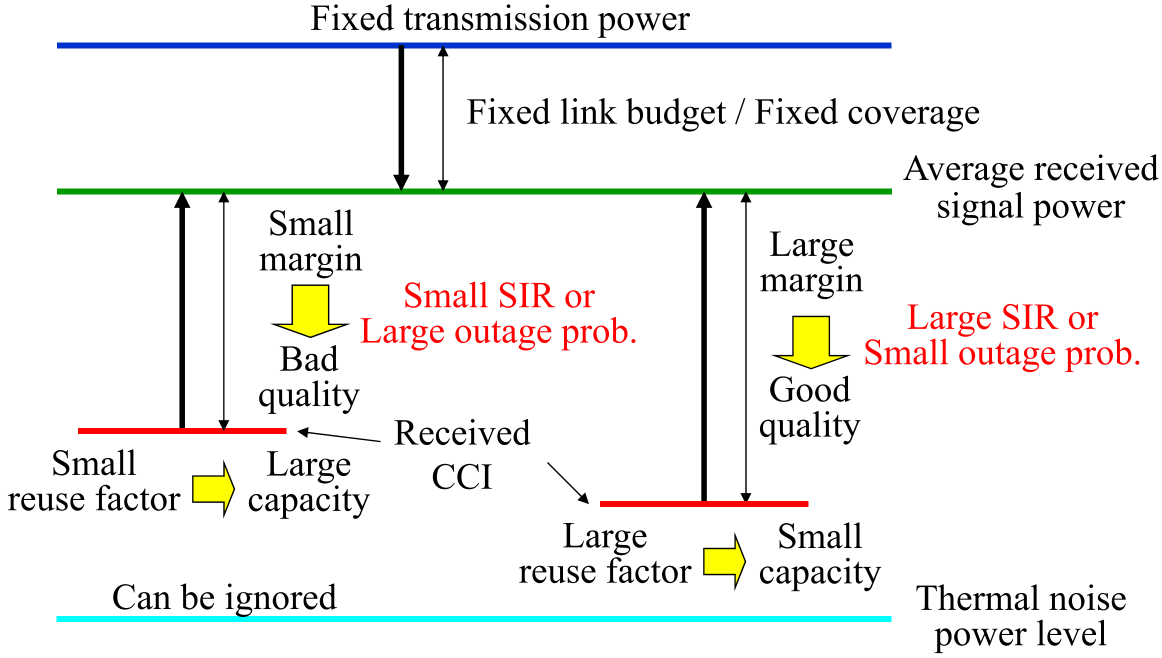
- $\mu_\Omega(R) = P_{(\text{dB})} - 50 - 40 \times \log_{10}(10) = -100 + 25.4$

$\Rightarrow P = 15.4$ dBW $\approx$ 35W

$$\boxed{\mu_{\Omega(\text{dB})} = \mu_{\Gamma(\text{dB})} + P^{Noise}_{(\text{dB})}}$$

Co-channel Reuse Distance

- For co-channel interference (CCI): $O = \Pr(\Lambda < \Lambda_{th})$



Co-channel Reuse Distance

- The desired signal and co-channel signals are characterized by **independent** log-normal shadowing fading
- Assume that each BS transmits the same average power
- The average forward link carrier-to-interference ratio is

$$\Lambda_{(\mathrm{dB})}(d) = \Omega_{(\mathrm{dB})}(d) - 10\log_{10}\left[\sum_{k=1}^{N_I} 10^{\Omega_{(\mathrm{dB})}(d_k)/10}\right]$$

  – The total interference power should be summed in **linear** scale

- The probability of CCI:

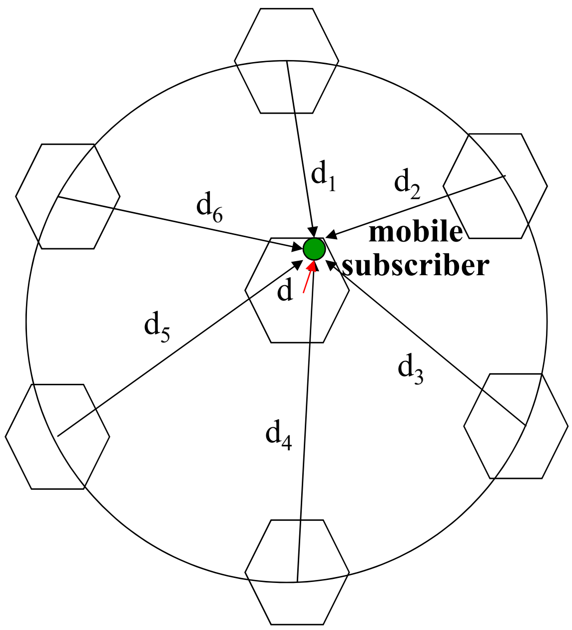
$$O(d) = \Pr(\Lambda_{(\mathrm{dB})}(d) < \Lambda_{th(\mathrm{dB})})$$

- The co-channel interference may not be the same on the forward and reverse channels

  $\Rightarrow$ **link imbalance**

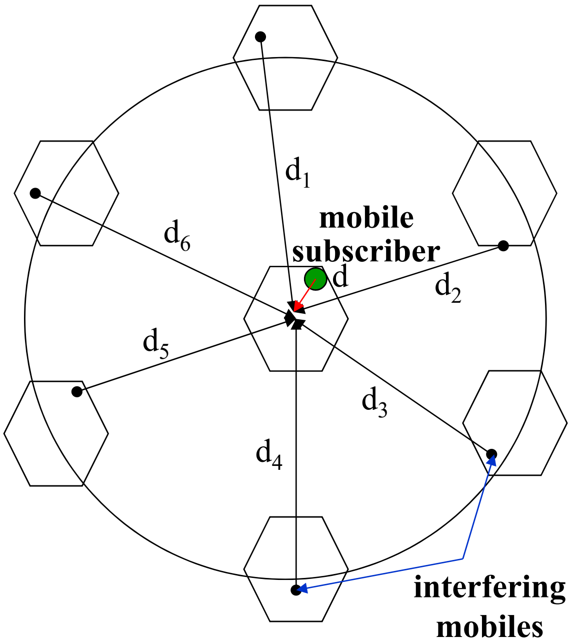
Co-channel Reuse Distance

- Forward channel:



Co-channel Reuse Distance

- Reverse channel:

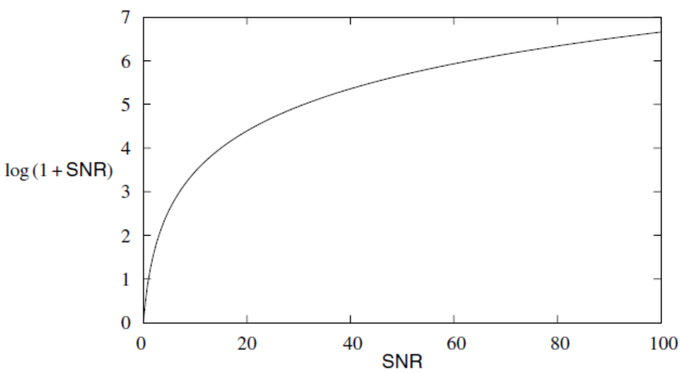


Spectral Efficiency (AWGN Channel)

- Consider a continuous-time AWGN channel with bandwidth W Hz, power constraint P watts, and additive white Gaussian noise with power spectral density $N_0/2$.
- The capacity of the AWGN channel is

$$C_{AWGN}(P,W) = \log\left(1+\frac{P}{N_0 W}\right) = \log(1+SNR) \quad \text{bits/s/Hz}$$

  - where $SNR = P/(N_0 W)$
- This formula measures the **maximum achievable** spectral efficiency through an AWGN channel as a function of the SNR



Spectral Efficiency (Fading Channel)

- Consider a **flat fading channel** with the distribution of the received SNR $p(\gamma)$ **known** to the transmitter and receiver
- The capacity of the fading channel is

$$C_{\text{Fading}} = \int_0^\infty \log(1+\gamma)\, p(\gamma)\, d\gamma \le \log(1+\bar{\gamma}) \quad \text{bits/s/Hz}$$

  - Averaged over **multiple fading intervals**
  - The duration of a **coding block** must be **much larger** than several fading intervals

Spectral Efficiency (Circuit/Packet Switching)

- There are a variety of definitions for **spectral efficiency**, but an appropriate definition measures spectral efficiency in terms of the **spatial traffic density per unit bandwidth**.
- The definition of spectral efficiency depends on the carried traffic types:
  - **Circuit Switching** (Telecommunications): a dedicated channel (circuit) through the network is allocated to each communication link between two nodes
    - The **number of simultaneous links** supported in the system is the key metric
  - **Packet Switching** (Data communications): multiple communication links share a common channel pool
    - The **total data rate** that can be supported on average in the entire system is the key metric

Spectral Efficiency (Circuit Switching)

- For a circuit-switching cellular system (a common data rate per link is assumed), the spectral efficiency η_s can be expressed as

$$\eta_s = \frac{N_c \times G_c}{W_{sys} \times A} \quad \text{Erlangs/m}^2\text{/Hz}$$

  - G_c: offered traffic per channel (Erlangs/channel)
  - N_c: number of channels per cell
  - W_{sys}: total system bandwidth (Hz)
  - A: coverage area per cell (m^2)
- If the cellular deployment consists of N-cell reuse clusters

$$N_c = \frac{W_{sys}}{W_c \times N}$$

  - W_c is the bandwidth per channel

Spectral Efficiency (Circuit Switching) (Cont.)

- **Erlang** is a unit of **traffic** measurement in telecommunications systems
  - One hour of call traffic during one hour of operation in a telephone system
  - 0.5 Erlang $\Rightarrow$ 0.5 hour of call traffic during one hour of operation
- Assume that
  - $\lambda = 600$ calls/hour
  - $\mu = 3$ minutes
- The total offered traffic

$$\rho = \lambda\mu = \frac{600 \times 3}{60} = 30 \quad \text{Erlangs}$$

Spectral Efficiency (Circuit Switching) (Cont.)

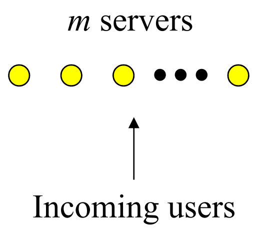
- **Spectral efficiency** can be written as the product of

$$\eta_s = \frac{1}{W_c} \times \frac{1}{N \times A} \times G_c$$
$$= \eta_B \times \eta_C \times \eta_T$$

- η_B: **bandwidth efficiency**
  - Low bit rate **source coding** (audio or video only)
  - Bandwidth efficient modulation
- η_C: **spatial efficiency**
  - Minimize the area per cell
  - Minimize the co-channel reuse distance
    - Error control coding, antenna diversity, adaptive equalization, interleaving, sectorization, power control, …

Spectral Efficiency (Circuit Switching) (Cont.)

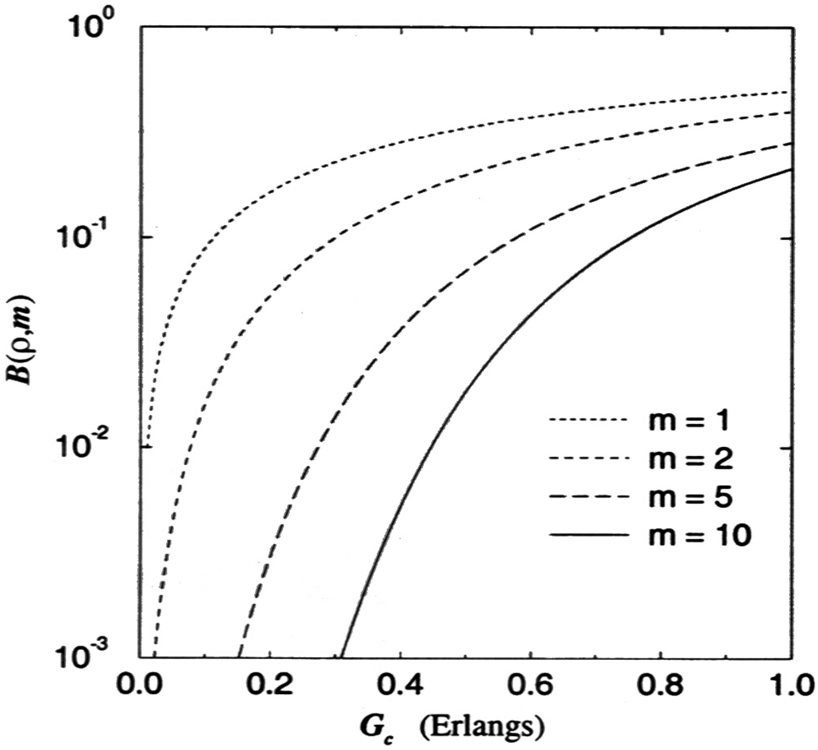
- η_T: **trunking efficiency**
  - Depend on channel assignment scheme
  - A Trade-off between QoS
  - Based on **Erlang B** formula



Blocking Prob. $B(\rho, m) = \dfrac{\rho^m}{m! \sum_{k=0}^{m} \dfrac{\rho^k}{k!}}$

- m: the total number of channels in the trunk
- $\rho = \lambda\mu$: the total offered traffic
  - λ: the call arrival rate (Poisson call arrivals)
  - μ: the mean call duration (exponentially distributed)
- $G_c = \rho/m$: offered traffic per channel

Spectral Efficiency (Circuit Switching) (Cont.)



Erlang B Table

	A, erlangs							
	B							
m	1.0%	1.2%	1.5%	2%	3%	5%	7%	10%
1	.0101	.0121	.0152	.0204	.0309	.0526	.0753	.111
2	.153	.168	.190	.223	.282	.381	.470	.595
3	.455	.489	.535	.602	.715	.899	1.06	1.27
4	.869	.922	.992	1.09	1.26	1.52	1.75	2.05
5	1.36	1.43	1.52	1.66	1.88	2.22	2.50	2.88
6	1.91	2.00	2.11	2.28	2.54	2.96	3.30	3.76
7	2.50	2.60	2.74	2.94	3.25	3.74	4.14	4.67
8	3.13	3.25	3.40	3.63	3.99	4.54	5.00	5.60
9	3.78	3.92	4.09	4.34	4.75	5.37	5.88	6.55
10	4.46	4.61	4.81	5.08	5.53	6.22	6.78	7.51
11	5.16	5.32	5.54	5.84	6.33	7.08	7.69	8.49
12	5.88	6.05	6.29	6.61	7.14	7.95	8.61	9.47
13	6.61	6.80	7.05	7.40	7.97	8.83	9.54	10.5
14	7.35	7.56	7.82	8.20	8.80	9.73	10.5	11.5
15	8.11	8.33	8.61	9.01	9.65	10.6	11.4	12.5
16	8.88	9.11	9.41	9.83	10.5	11.5	12.4	13.5
17	9.65	9.89	10.2	10.7	11.4	12.5	13.4	14.5
18	10.4	10.7	11.0	11.5	12.2	13.4	14.3	15.5
19	11.2	11.5	11.8	12.3	13.1	14.3	15.3	16.6
20	12.0	12.3	12.7	13.2	14.0	15.2	16.3	17.6

ρ

Erlang B Table (Cont.)

26	17.0	17.3	17.8	18.4	19.4	20.9	22.2	23.9
27	17.8	18.2	18.6	19.3	20.3	21.9	23.2	24.9
28	18.6	19.0	19.5	20.2	21.2	22.9	24.2	26.0
29	19.5	19.9	20.4	21.0	22.1	23.8	25.2	27.1
30	20.3	20.7	21.2	21.9	23.1	24.8	26.2	28.1
31	21.2	21.6	22.1	22.8	24.0	25.8	27.2	29.2
32	22.0	22.5	23.0	23.7	24.9	26.7	28.2	30.2
33	22.9	23.3	23.9	24.6	25.8	27.7	29.3	31.3
34	23.8	24.2	24.8	25.5	26.8	28.7	30.3	32.4
35	24.6	25.1	25.6	26.4	27.7	29.7	31.3	33.4
36	25.5	26.0	26.5	27.3	28.6	30.7	32.3	34.5
37	26.4	26.8	27.4	28.3	29.6	31.6	33.3	35.6
38	27.3	27.7	28.3	29.2	30.5	32.6	34.4	36.6
39	28.1	28.6	29.2	30.1	31.5	33.6	35.4	37.7
40	29.0	29.5	30.1	31.0	32.4	34.6	36.4	38.8
41	29.9	30.4	31.0	31.9	33.4	35.6	37.4	39.9
42	30.8	31.3	31.9	32.8	34.3	36.6	38.4	40.9
43	31.7	32.2	32.8	33.8	35.3	37.6	39.5	42.0
44	32.5	33.1	33.7	34.7	36.2	38.6	40.5	43.1
45	33.4	34.0	34.6	35.6	37.2	39.6	41.5	44.2
46	34.3	34.9	35.6	36.5	38.1	40.5	42.6	45.2
47	35.2	35.8	36.5	37.5	39.1	41.5	43.6	46.3
48	36.1	36.7	37.4	38.4	40.0	42.5	44.6	47.4
49	37.0	37.6	38.3	39.3	41.0	43.5	45.7	48.5
50	37.9	38.5	39.2	40.3	41.9	44.5	46.7	49.6

Spectral Efficiency (Packet Switching)

- Considering system performance for **data transmission**, not only the **peak data rates** provided to the end-users are of importance, but also the **total data rate** that can be provided on average from the entire system.
- Spectral efficiency depends on several factors:
  - **Bandwidth efficiency**
    - Transmission technologies (narrowband, CDMA, OFDM, …)
    - Digital modulation schemes (FSK, PSK, QAM, …)
  - **Spatial efficiency**
    - Area per cell (Density of base stations)
    - Co-channel reuse distance (Frequency reuse factor)
    - Spatial reuse (Spatial multiplexing)
  - **Successful decoding probability** (Outage probability)

Spectral Efficiency (Packet Switching) (Cont.)

- ITU-R defines two requirements related to the efficiency of the radio interface for performance evaluation
  - **Cell spectral efficiency:** defining the **operator** perspective
  - **Cell-edge spectral efficiency:** defining the **end-user** perspective
- **Cell spectral efficiency:** The **aggregated throughput** over all users, averaged over all cells and divided by channel bandwidth
  - A measure of the **maximum total "capacity"** available in the system to be shared between users

$$\eta = \frac{\sum_{i=1}^{N} \chi_i}{T \times \omega \times M} \quad \text{bits/s/Hz/cell}$$

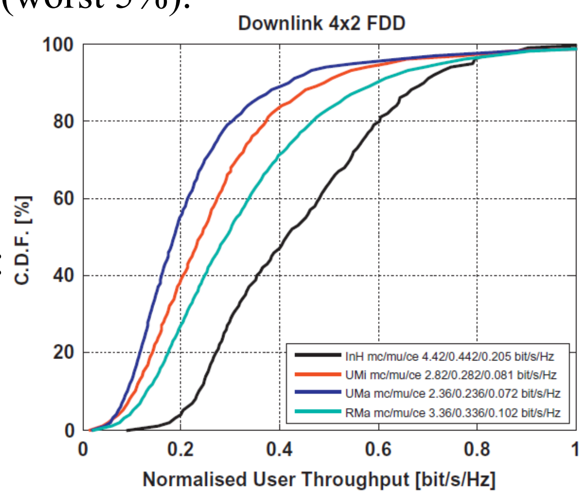
  - where χ_i denotes the number of correctly received bits for user i in a system with N users and M cells, ω is the channel bandwidth, and T is the time over which the data bits are received

Spectral Efficiency (Packet Switching) (Cont.)

- **Cell-edge spectral efficiency:** Based on the **distribution** of the **normalized user throughput**, which is defined as the average user throughput divided by the channel bandwidth
  - The **5%** point of the cumulative distribution function (CDF) of the normalized user throughput (worst 5%).
  - A measure of the **end-user perceived "quality of service"** for the **5%** of the users with the **lowest** user throughput.
- The normalized user throughput:

$$\gamma_i = \frac{\chi_i}{T_i \times \omega} \quad \text{bits/s/Hz}$$

  - T_i is the active time for user i.



Spectral Efficiency (Packet Switching) (Cont.)

- The requirements defined by **ITU-R** for peak spectral efficiency, cell spectral efficiency and cell-edge user spectral efficiency are listed in the tables.

Peak Spectral Efficiency	ITU Requirement (bit/s/Hz)	LTE Fulfillment			
		Release 8		Release 10	
		FDD	TDD	FDD	TDD
Downlink	15	15.3	15.0	30.6	30.0
Uplink	6.75	4.2	4.0	16.8	16.0

Test Environment and Corresponding Deployment Scenario	Cell Spectral Efficiency (bit/s/Hz/cell)		Cell-Edge User Spectral Efficiency (bit/s/Hz)	
	Downlink	Uplink	Downlink	Uplink
Indoor (InH)	3	2.25	0.1	0.07
Microcellular (UMi)	2.6	1.8	0.075	0.05
Base coverage, urban (UMa)	2.2	1.4	0.06	0.03
High speed (RMa)	1.1	0.7	0.4	0.015

Spectral Efficiency (Packet Switching) (Cont.)

- How to achieve the demand of high spectral efficiency?
  - Spatial Multiplexing (MIMO)
  - The resources are **reused** in the same cell in the spatial domain