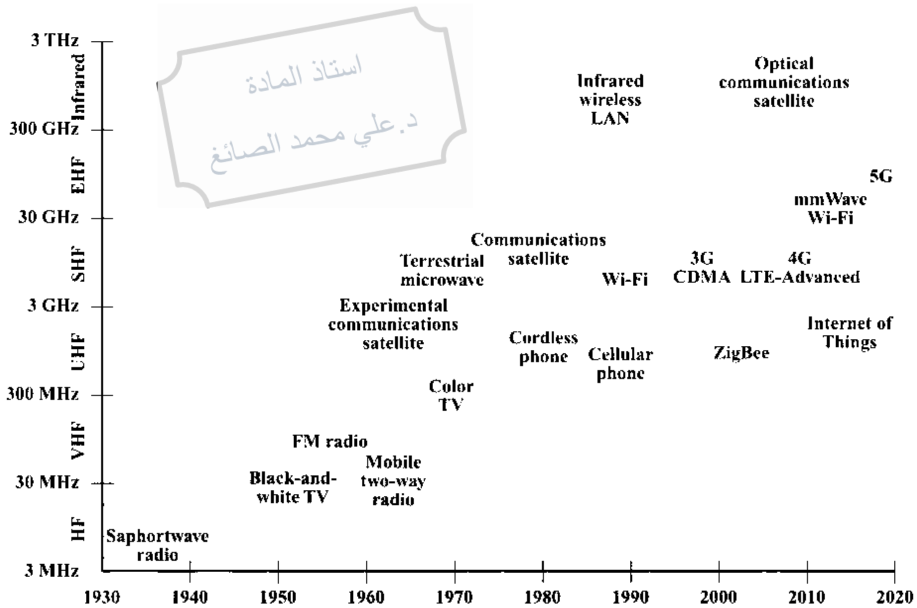
Wireless Communication System

History of wireless communications

- Guglielmo Marconi invented the wireless telegraph in 1896, he sent telegraphic signals across the Atlantic Ocean (about 3200 km).
- Over the last century, advances in wireless technologies have led to the radio, the television, the mobile telephone, and communications satellites.
- Wireless networking is allowing businesses to develop WANs, MANs, and LANs without a cable plant.
- Communications satellites launched in 1960s
- The first-generation wireless phones used analog technology. These devices were heavy and coverage was patchy. The current generation of wireless devices is built using digital technology. Digital networks carry much more traffic and provide better reception and security than analog networks.

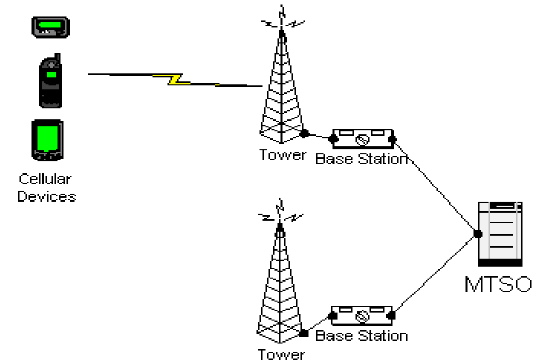


Some milestones in Wireless Communications

Evolution of mobile communications

- The first version of a mobile radio telephone being used in 1924.
- In 1926 telephone service in trains on the route between Hamburg and Berlin was approved.

- In 1935, Edwin Armstrong demonstrated FM and it has been the primary modulation technique used for mobile communication systems throughout the world.



- In 1946, the first public mobile telephone service was launched by BELL Laboratories in USA (543 users).
- A solution to this capacity problem emerged during the 50's and 60's when researchers at Bell Laboratories developed the ***cellular concept***.
- In 1973, Martin Cooper (a Motorola researcher and executive) made the first mobile telephone call from handheld subscriber equipment.

- In 1983, the first analog cellular system deployed in Chicago, USA.

Classification of mobile radio transmission system

Mobile radio transmission systems may be classified as simplex, half-duplex or full-duplex.

a. **Simplex systems**: communication is possible in only one direction.

(a) simplex

b. **Half-duplex**: radio systems allow two-way communication using the same radio channel for both transmission and reception.

(b) half-duplex

c. **Full duplex**: systems allow simultaneous radio transmission and reception between a subscriber and a base station, by providing two simultaneous but separate channels (frequency division duplex, or FDD) or adjacent time slots on a single radio channel (time division duplex, or TDD) for communication to and from the user.

(c) full-duplex

Frequency division & Time division

- Provides simultaneous radio transmission channels for the subscriber and the base station, so that they both may constantly transmit while simultaneously receiving signals from one another.

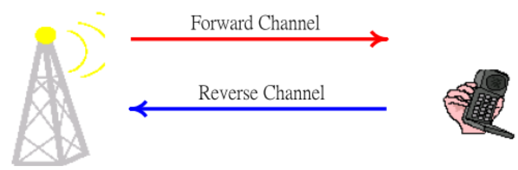
Frequency division duplexing (FDD)

Provides simultaneous radio transmission channels for the subscriber and the base station, so that they both may constantly transmit while simultaneously receiving signals from one another.

- At the base station, separate transmit and receive antennas are used.
- At the subscriber, unit a single antenna is used for both transmission to and reception from the base station, and a device called a duplexer is used inside the subscriber unit to enable the same antenna to be used for simultaneous transmission and reception.

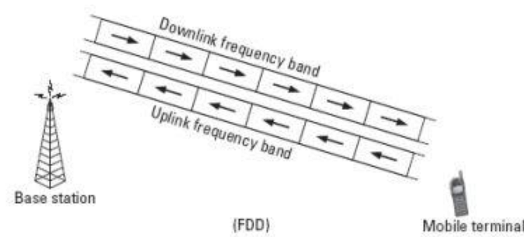
In FDD, a pair of simplex channels with a fixed and known frequency separation is used to define a specific radio channel in the system.

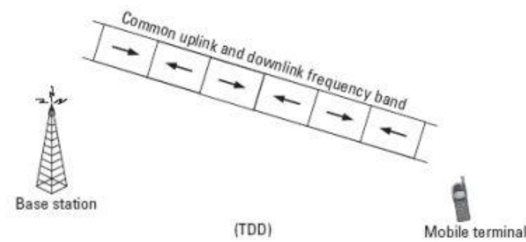
- The channel from a base station to the mobile user is called ***forward channel***.
- The channel from the mobile user to a base station is called the ***reverse channel***.



Time division duplexing (TDD)

Uses the fact that it is possible to share a single radio channel in time, so that a portion of the time is used to transmit from the base station to the mobile, and the remaining time is used to transmit from the mobile to the base station.





- Only possible with digital transmission
- Very sensitive to timing.

Transmission types

- **Unicast** (point-to-point) transmission is made from one device to a single other device. It means that the packet is addressed to one receiver.
- **Broadcast** transmission is made from one device to all other devices. In this case there is just one sender, but the information is sent to all connected receivers.
- **Multicast** transmission is made from one device to a subset of the other available devices. In this case there is just one sender, but the information is sent to a group of receivers.

Types of wireless communication systems

The major types of wireless communication systems are:

a. Paging Systems
b. Cordless Telephone Systems
c. Satellite communication systems
d. Wireless LAN systems
e. Cellular Telephone Systems

The cost, complexity, performance, and types of services offered by each of these mobile systems are different.

a. Paging Systems

Paging systems are *simplex* communication systems that send brief messages to a subscriber. Depending on the type of service, the message may be either text or voice messages.

The paging system then transmits the page throughout the service area using base stations which broadcast the page on a radio carrier.

b. Cordless Telephone Systems

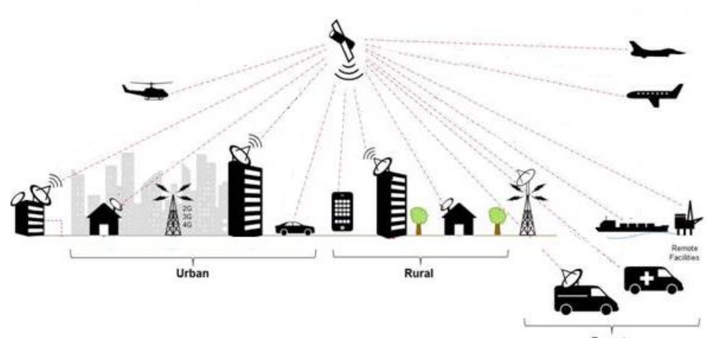
- Provide wireless extension to the telephone network within a limited area.
- Two-way (duplex) communications
- Consists of a portable handset, connected to dedicated base station, which is connected to the telephone network.

- **1st generation:** household environment
- **2nd generation:** allow mobility in workplace and public use with limited coverage in urban areas.

Satellite communication Systems

The main feature of the satellite communication systems

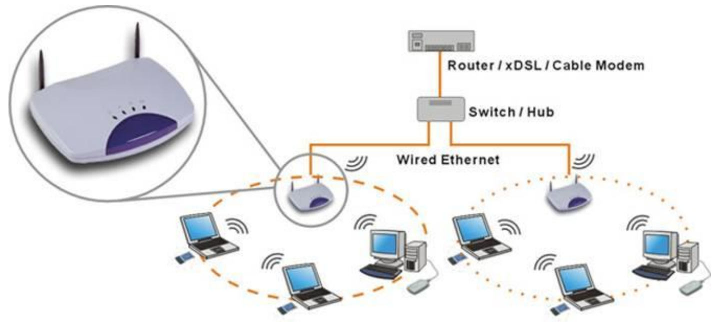
- Very wide range and coverage
- Very useful in sparsely populated areas: rural areas, sea, mountains, etc.
- Expensive base station (satellites) systems



d. Wireless LAN (WLAN)

Characterized by

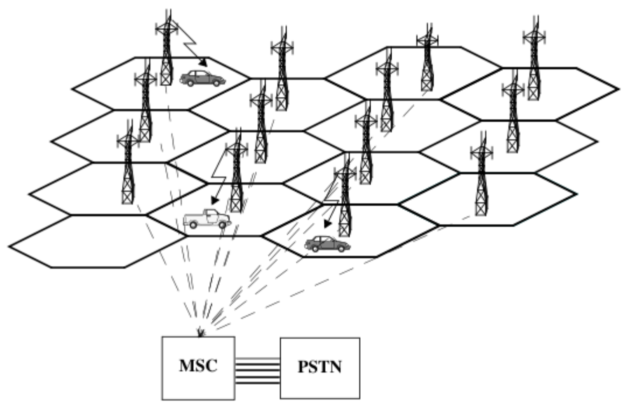
- Low mobility (not for vehicular use)
- High speed data transmission
- Confined regions – buildings and campuses
- Coverage: 100m – 300m per base station
- Uses the following bands (902-928 MHz, 2400-2483.5 MHz, 5725-5850 MHz)



e. Cellular Telephone Systems

The basic cellular system consists of:

a. Mobile station (MS).
b. Base stations (BS).
c. Mobile switching center (MSC): also called Mobile telecommunications switching office (MTSO).



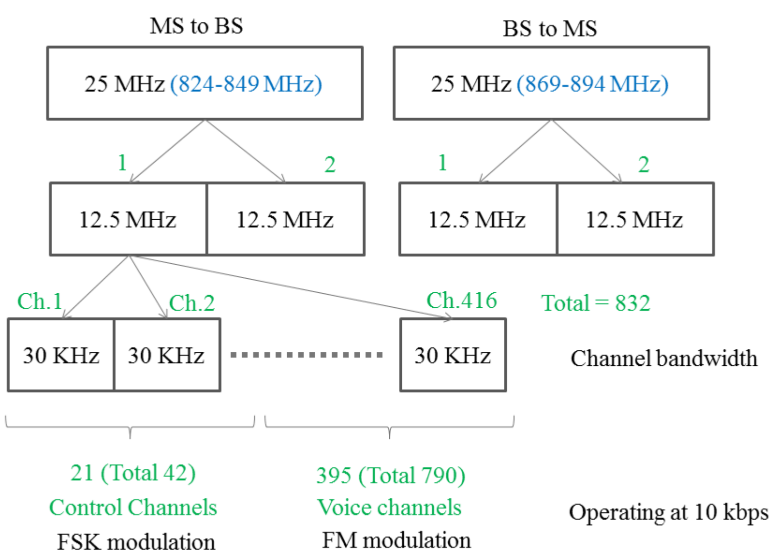
- Cellular systems accommodate a large number of users over a large geographic area, within a limited frequency spectrum.
- Cellular radio systems provide high quality service that is often comparable to that of the landline telephone systems.
- High capacity is achieved by limiting the coverage of each base station transmitter to a small geographic area called a ***cell*** so that the same radio channels may be reused by another base station located some distance away.
- Handoff: is a switching technique that enables a call to proceed uninterrupted when the user moves from one cell to another.

First Generation (1G) systems

- The original cellular telephone networks provided **analog** traffic channels; these are now referred to as first-generation systems.
- Since the early 1980s the most common first-generation system in North America has been the **Advanced Mobile Phone Service (AMPS)**. This approach is also common in South America, Australia, and China.

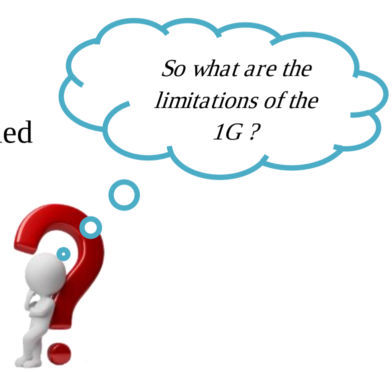
Spectral Allocation

- Two 25-MHz bands are allocated to AMPS.
- Each of these bands is split in two. An operator is allocated only 12.5 MHz in each direction for its system.
- The channels are spaced 30 kHz apart, which allows a total of 416 channels per operator.
- 21 channels are allocated for control, leaving 395 to carry calls.
- The control channels are data channels operating at 10 kbps.
- The conversation channels carry the conversations in analog using FM.



Total Access Communication Systems (TACS):

- Deployed in 1985.
- Almost identical to AMPS except that the channel bandwidth is scaled to 25 kHz instead of 30 kHz as in AMPS.



Second Generation (2G) systems

Second-generation systems have been developed in early 90s to provide higher quality signals, higher data rates for support of digital services, and greater capacity. Moreover, The 2G systems provide:

- Digital voice coding and modulation
- Security (Encryption).
- Error detection and correction.
- Multiple channels per cell.

The key differences between the two generations are:

First Generation (1G) systems	Second Generation (2G) systems
Analog systems	Digital systems
Designed to support voice channels using FM, digital traffic is supported only by the use of a modem that converts the digital data into analog form.	Provide digital traffic channels, these readily support digital data; voice traffic is first encoded in digital form before transmitting.
No security.	Capable to encrypt the traffic to prevent eavesdropping (since the user and control traffics are digitized).
Poor voice quality.	Very clear voice reception, because The digital traffic stream of lends itself to the use of error detection and correction techniques.
Each cell supports a number of channels. At any given time a channel is allocated to only one user.	Provide multiple channels per cell, but each channel is dynamically shared by a number of users using TDMA or CDMA.
No message service	Enable message service such as short message service (SMS) and Multimedia message service (MMS)

Beginning around 1990, a number of different second-generation systems have been deployed, such as Global system for mobile communications (GSM), and Interim Standard (IS-95) scheme. The table below lists some key characteristics of three of the most important of these systems.

	GSM	IS-95
Year introduced	1990	1993
Developed in	Europe	North America
BS transmission band	935~960 MHz	869~894 MHz
MS transmission band	890~915 MHz	824~849 MHz
Spacing between forward and reverse channels	45 MHz	45 MHz
Channel bandwidth	200 KHz	1250 KHz
No. of duplex channels	125	20
Mobile unit maximum power	20 W	0.2 W
Users per channel	8	35
Modulation	GMSK	QPSK
Carrier bit rate	270.8 kbps	9.6 kbps

The GSM standard has gained worldwide acceptance as the first universal digital cellular system with modern network features extended to each mobile user

2.5G systems

- 2.5G is a technology between the 2G and 3G; it is sometimes described as 2G technology combined with GPRS.
- 2.5G is an interim solution designed to allow for improved data rates before 3G implementation. A variety of 2.5G techniques are being employed to improve the speed of data for enhanced e-mail and Internet access.
- The main features of the 2.5G are:
  - Ability to send and receive Email messages.
  - Web browsing,
  - Speed: 64-144 kbps

Moreover, Built-in camera can be included in the mobile station (Camera phones).

General Packet Radio Service (GPRS)

- GPRS is packet switched technology which based on existing GSM cellular network infrastructure and adds new packet-switching network equipment.
- The GPRS gives GSM subscribers access to data communication application such as e-mail and internet using their mobile phone.
- Speed: up to 114 kbps
- The GPRS allows multiple slots of a GSM radio channel be dedicated to an individual user (Physical channel can be shared between different mobile users).
- Physical channel is only assigned when data needs to be transmitted or received.

Enhanced Data Rates for GSM Evolution (EDGE)

- Provides up to 384 kbps rate.
- It is also referred to as Enhanced GPRS (EGPRS). EGPRS is therefore an add-on to GPRS and cannot work alone.

Third Generation (3G) systems

The objective of the third generation (3G) of wireless communication is to provide fairly high-speed wireless communications to support multimedia, data, and video in addition to voice. 3G developed in the early 2000s, the main features of the 3G systems are:

- **High transmission rate and the support of multimedia services:** Multiple-megabit internet services, video calls, and mobile TV using a single mobile device.
- **Data rate:** around 2Mbps. Bandwidth: in the order of MHz

The ITU's International Mobile Telecommunications for the year 2000 (IMT-2000) initiative has defined the ITU's view of third-generation capabilities as

- Voice quality comparable to the public switched telephone network.
- 144-kbps data rate available to users in high-speed motor vehicles over large areas.
- 384 kbps available to pedestrians standing or moving slowly over small areas.
- Support for 2.048 Mbps for office use.
- Support for both packet-switched and circuit-switched data services.
- An adaptive interface to the Internet.

Generally, the technology planned is digital using TDMA or CDMA to provide efficient use of the spectrum and high capacity.

3G enhancements

3G has the following enhancements over previous networks:

1. Enhanced audio and video streaming
2. Several times higher data speed
3. Video-conferencing support
4. Web and WAP browsing at higher speeds
5. IPTV (TV through the Internet) support

Universal Mobile Telecommunications System (UMTS)

UMTS is a third generation mobile cellular system for networks based on the GSM standard**,** developed and maintained by the 3GPP (3rd Generation Partnership Project).

High Speed Packet Access (HSPA)

HSPA extends and improves the performance of existing 3G mobile telecommunication networks utilizing the WCDMA protocols (also referred to as 3.5G). The HSPA specifications:

- increased peak data rates of up to
  - 14 Mbit/s in the downlink
  - 5.76 Mbit/s in the uplink.
- reduced latency
- Up to five times more system capacity in the downlink up to twice as much system capacity in the uplink compared with WCDMA.

Pre-4G technology (3.9G)

- Mobile WiMAX standard (first used in South Korea in 2007),
- Evolved HSPA (HSPA+): Released in 2008 with worldwide adoption in 2010.
- Long Term Evolution (LTE) standard (first released in Oslo, Norway and Stockholm, Sweden since 2009).

Long Term Evolution (LTE)

LTE is a standard for wireless communication of high-speed data for mobile phones and data terminals. It is based on the GSM/EDGE and UMTS network technologies, increasing the capacity and speed using a different radio interface together with core network improvements. The standard is developed by the 3GPP. The LTE features are:

- Downlink peak rates of 300 Mbit/s,
- Uplink peak rates of 75 Mbit/s
- Quality of Service (QoS) provisions permitting a transfer latency of less than 5 ms in the radio access network (RAN).
- Has the ability to manage fast-moving mobiles
- Supports scalable carrier bandwidths, from 1.4 MHz to 20 MHz.
- Orthogonal frequency-division multiple access (OFDMA) for the downlink, Single-carrier FDMA for the uplink to conserve power.
- Supports both FDD and TDD.

Fourth Generation (4G) systems

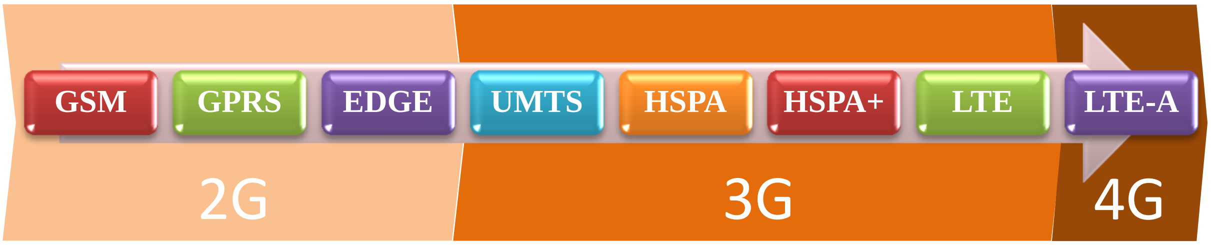
4G provides mobile broadband Internet access, with higher data rate and expanded multimedia services. The main features of the 4G systems are

- ❖ Higher speed 0.1~1 Gbps.
- ❖ More security.
- ❖ Higher capacity.
- ❖ Lower cost than previous generations.
- ❖ Provides digital system with voice over-IP (VOIP) technology.
- ❖ IPv6 Core.
- ❖ Orthogonal frequency-division multiplexing (OFDM) is used instead of CDMA.

One of the main differences between 3G and 4G technology is the elimination of circuit switching, instead employing an all-IP network. Other differences are:

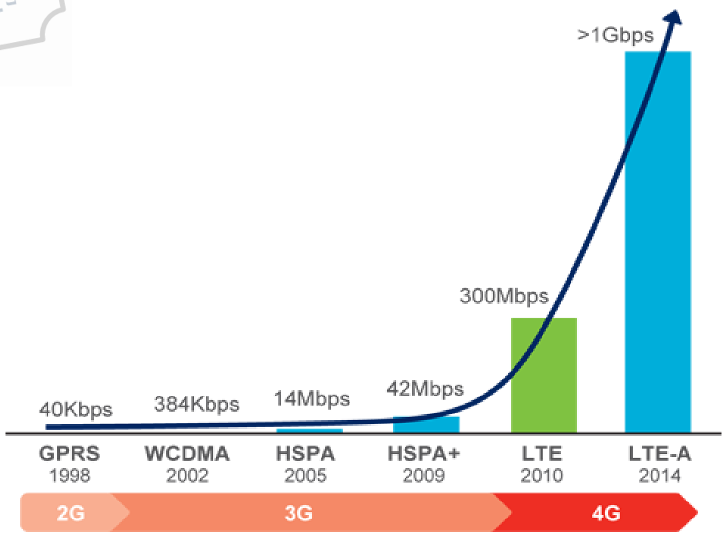
Technology	*3G*	*4G*
Data Transfer Rate	*3.1 MB/sec*	*100 MB/sec*
Internet Services	*Broadband*	*Ultra Broadband*
Mobile - TV Resolution	*Low*	*High*
Bandwidth	*5-20 MHz*	*100MHz*
Frequency	*1.6-2 GHz*	*2-8 GHz*
Download and upload	*5.8 Mbps*	*14 Mbps*

The 4G system are able to provide a comprehensive IP solution where voice, data and streamed multimedia can be given to users on an "Anytime, Anywhere" basis.



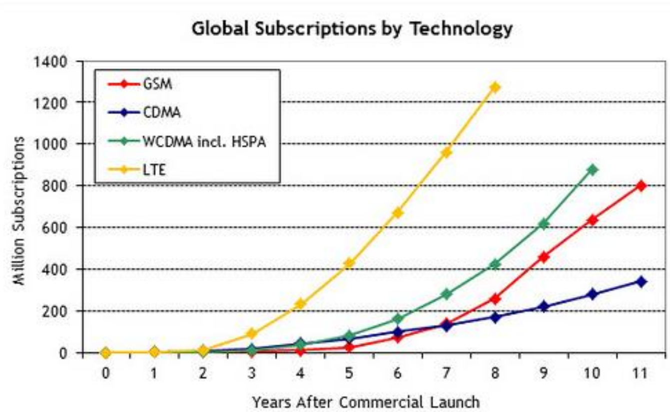
LTE Advanced (LTE-A)

LTE Advanced is a mobile communication standard and a major enhancement of the Long Term Evolution (LTE) standard. It was formally submitted as a candidate 4G system to ITU in late 2009 as meeting the requirements of the IMT-Advanced standard, and was standardized by the 3GPP in March 2011.



The main features of the LTE-Advanced are:

- Higher capacity,
- Increased peak data rate,
  - Downlink 3 Gbps,
  - Uplink 1.5 Gbps
- Higher spectral efficiency (30 bps/Hz)
- Increased number of simultaneously active subscribers.
- LTE-Advanced can use up to 8×8 MIMO and 128 QAM in downlink direction.



LTE-Advanced is now available in 31 countries (including South Korea, Australia, France, Germany, U.K. and the U.S.).

LTE Advanced Pro (LTE-A Pro)

- LTE-A Pro (Known as 4.5G) is released in the late 2015.
- It Incorporates several new technologies associated with 5G.
- 256-QAM.
- Massive MIMO.
- LTE-Unlicensed and LTE IoT.

Fifth Generation (5G) systems

5G denotes the next major phase of mobile telecommunications standards beyond 4G. 5G can be a complete wireless communication without limitation, which bring us perfect real world wireless, supportable to the World Wide Wireless Web (WWWW). According to the Group Special Mobile Association (GSMA) to qualify for a 5G a connection should meet most of these eight criteria:

- ✓ One to 10Gbps connections to end points in the field
- ✓ One millisecond end-to-end round trip delay
- ✓ 1000x bandwidth per unit area
- ✓ 10 to 100x number of connected devices
- ✓ (Perception of) 99.999 percent availability
- ✓ (Perception of) 100 percent coverage
- ✓ 90 percent reduction in network energy usage
- ✓ Up to ten-year battery life for low power, machine-type devices.

The Next Generation Mobile Networks Alliance feels that 5G should be rolled out by 2020 to meet business and consumer demands. In addition to providing simply faster speeds, they predict that 5G networks also will need to meet the needs of new use cases, such as:

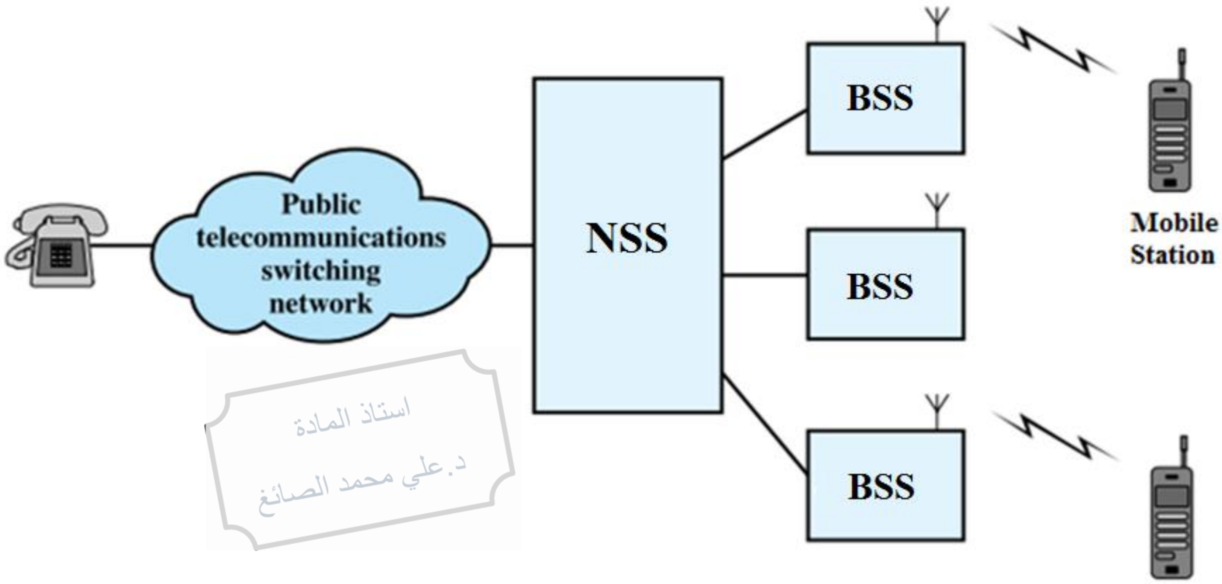
- Internet of Things (IoT).
- broadcast-like services and lifeline communication in times of natural disaster.

Cellular Mobile Systems

Cellular radio is a technique that was developed to *increase the capacity* available for mobile radio telephone service.

The principal elements of a cellular system include:

a. The Base Station Subsystem BSS,
b. Network Switching subsystem NSS (Mobile Switching Center, Location registers).
c. Mobile unit (or mobile station MS).



1. Base Station Subsystem (BSS)

- A fixed or non-moving station serves as a bridge between all mobile users in the cell
- Generally have towers which support several transmitting and receiving antennas.

The BSS includes:

- **Base station Controller (BSC)**: used to handle the call process between the mobile unit and the rest of the network.
- **Base transceiver station (BTS)**: contains number of transmitters and receivers with antennas hanged in towers: used for communicating on the channels assigned to cell.

2. Network Switching Subsystem (NSS)

- Responsible for:
  - Switching,
  - Mobility management,
  - Interconnection to other networks,
  - System control.

- Components:

a. Mobile Switching Center (MSC)

- High performance digital ISDN switches.
- Controls all connections via separated network to/from a mobile terminal within the domain of the MSC.
- Several BSC can belong to one MSC

The MSC plays a central role in GSM

- switching functions
- mobility support
- management of network resources
- interworking via Gateway MSC (GMSC)
- integration of several registers

<u>Functions of a MSC:</u>

a) Assigns the voice channel to each call.
b) Performs handoffs.
c) Monitors the call for billing information

b. Location registers

- <u>important:</u> scalability, high capacity, and low delay

i. *Home Location Register (HLR):* Central master database containing user data, permanent and semi-permanent data of all subscribers assigned to the HLR.

ii. *Visitor Location Register (VLR):* Local database for a subset of user data, including data about all user currently in the domain of the VLR.

Communication between the base station and the mobiles is defined by a standard common air interface (CAI) that specifies four different channels (2 voice channels, 2 control channels).

a. *Voice channels (Traffic channels):*

The channels used for voice transmission from the base station to mobiles are called forward voice channels (FVC), and the channels used for voice transmission from mobiles to the base station are called reverse voice channels (RVC).

b. *Control channels (setup channels)*

The two channels responsible for initiating mobile calls are the forward control channels (FCC) and reverse control channels (RCC). Control channels transmit and receive data messages that carry call initiation and service requests, and are monitored by mobiles when they do not have a call in progress.

3. Mobile station (MS)

The mobile station contains a transceiver, an antenna, and control circuitry.

Mobile Terminated Call

1: calling a GSM subscriber

2: forwarding call to GMSC

3: signal call setup to HLR

4, 5: request MSRN from VLR

6: forward responsible MSC to GMSC

7: forward call to current MSC

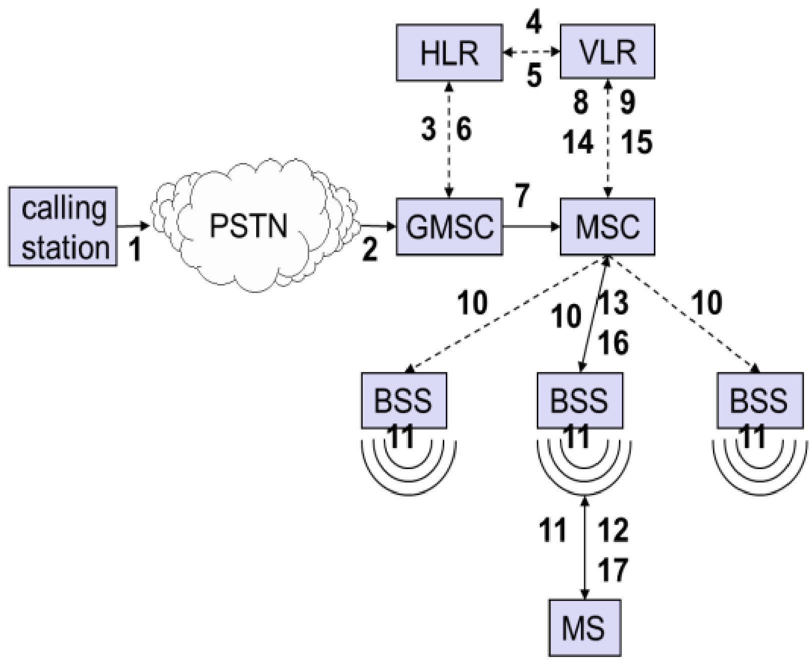
8, 9: get current status of MS

10, 11: paging of MS

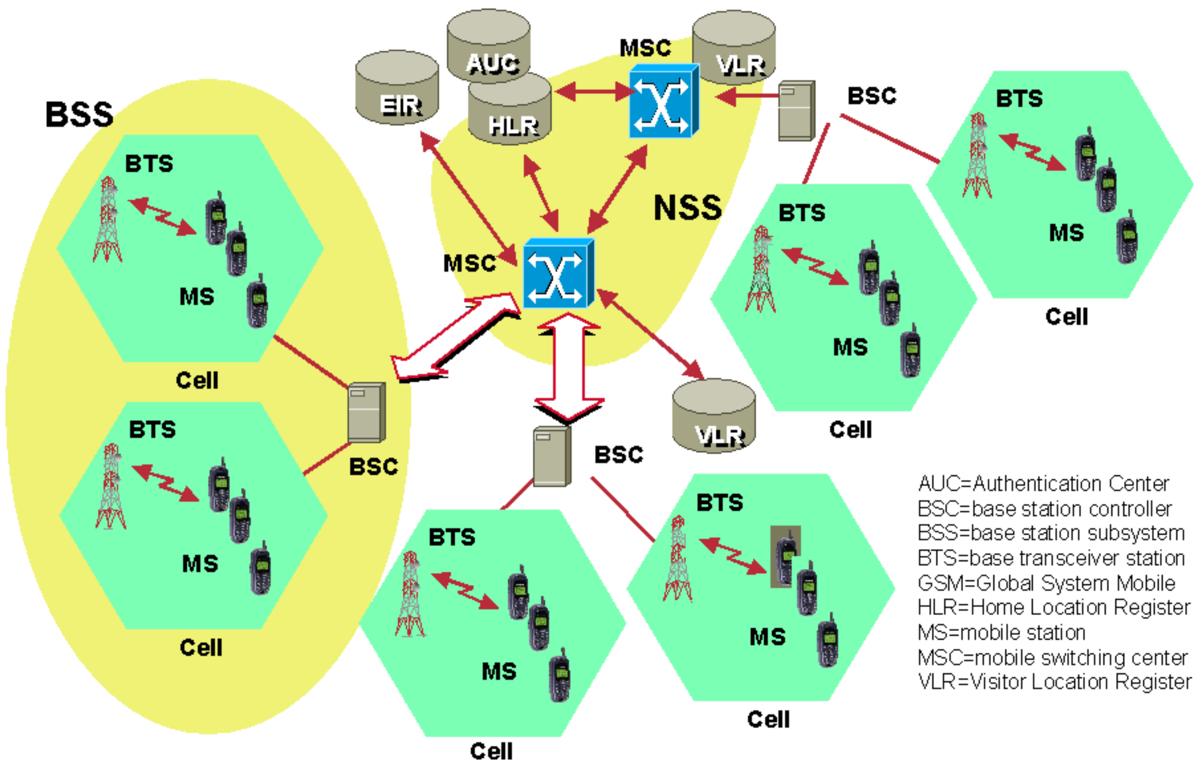
12, 13: MS answers

14, 15: security checks

16, 17: set up connection



Cellular system operation



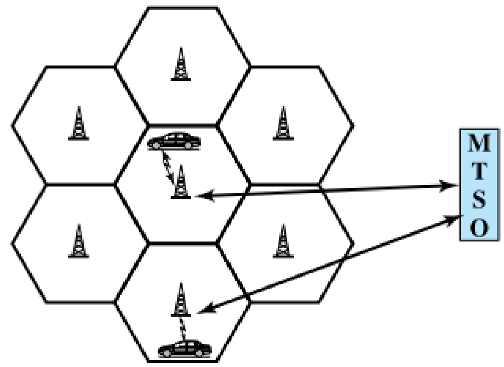
<u>According to the diagram above, it can be understood simply by:</u>

- Mobile device is connected to BTS (Antenna).
- BTS is connected to the Switching system called BSC.
- BSC is connected to the main switching system called MSC.
- MSC contains its own VLR (VLR: is a temporary database which stores the information of the visitors under its coverage area. VLR stands for Visitor Location register. When you roam in a different place VLR stores your user information.).
- MSC's are connected to GMSC which is connected to HLR. (HLR stands for Home location register, it is the main database where the documents or information of user is stored. All the documents that you give during the purchase of a SIM card is stored in this HLR.
- VLR Takes your information from HLR when you Roam in other state or region.

HLR also provides authentication by AuC. AuC is connected with HLR. If you initiate a call HLR and AuC will see if you are a genuine Mobile user with valid IMEI (*International Mobile Equipment Identity*) number and Plan.and then the call is set up from source to the destination device.

<u>Other functions performed by the system include the following:</u>

- **Handoff (Handover):** If a mobile unit moves out of range of one cell into the range of another during a connection, the traffic channel has to change to one assigned to the BS in the new cell. The system makes this change without either interrupting the call or alerting the user.



- **Call blocking:** During the mobile-initiated call stage, if all the traffic channels assigned to the nearest BS are busy, then the mobile unit makes a preconfigured number of repeated attempts. After a certain number of failed tries, a busy tone is returned to the user.

- **Call termination:** When one of the two users hangs up, the MTSO is informed and the traffic channels at the two BSs are released.

- **Call drop:** During a connection, because of interference or weak signal spots in certain areas, if the BS cannot maintain the minimum required signal strength for a certain period of time, the traffic channel to the user is dropped and the MTSO is informed.

- **Calls to/from fixed and remote mobile subscriber:** The MTSO connects to the public switched telephone network (PSTN). Thus, the MTSO can set up a connection between a mobile user in its area and a fixed subscriber via the telephone network.

RF Planning

RF Planning is the process of assigning frequencies, transmitter locations and parameters of a wireless communications system to provide sufficient coverage and capacity for the services required. The RF plan of a cellular communication system has two objectives: coverage and capacity.

a. Coverage relates to the geographical footprint within the system that has sufficient RF signal strength to provide for a call/data session.
b. Capacity relates to the capability of the system to sustain a given number of subscribers. Capacity and coverage are interrelated.

To improve coverage, capacity has to be sacrificed, while to improve capacity, coverage will have to be sacrificed. **It is necessary to restructure radiotelephone system to achieve high capacity with limited spectrum.**

- **Increase the capacity of the system**: by using lower-power systems with shorter radius and to use numerous transmitters/receivers (Base stations). Thereby providing additional radio capacity with no additional increase in radio spectrum.

- **Distributing the available channels throughout geographic region**: by systematically spacing base stations and their channel groups. The available channels can be reused as long as the interference between co-channel stations is kept below acceptable level.

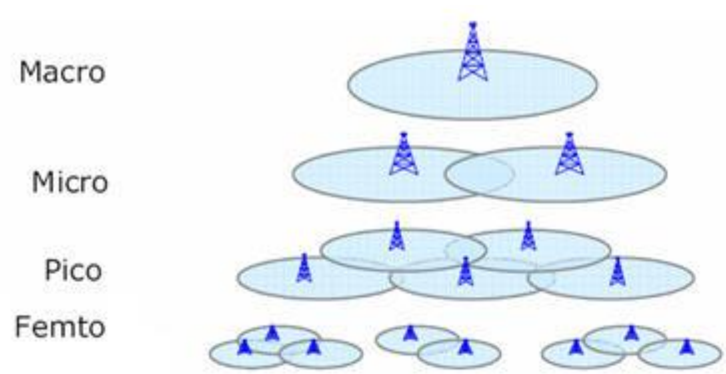
Cell types

- **<u>Macro cell</u>**: their coverage is large (aprox. 6 miles in diameter); used in remote areas, high-power transmitters and receivers are used

- **<u>Micro cell</u>**: their coverage is small (half a mile in diameter) and are used in urban zones; low-powered transmitters and receivers are used to avoid interference with cells in other clusters

- **<u>Pico cell</u>**: is a small cellular system typically covering a small area, such as in-building (offices, shopping malls, train stations) . In cellular networks, picocells are typically used to extend coverage to indoor <u>areas where outdoor signals do not reach well</u>.

- **<u>Selective cells</u>**: located at the <u>entrances of tunnels</u> where a coverage of 360 degrees is not needed this case, a selective cell with a coverage of 120 degrees is used**.**



Decreasing the cell size gives:

- ❖ Increased user capacity
- ❖ Increased number of handovers per call
- ❖ Increased complexity in locating the subscriber
- ❖ Lower power consumption in mobile terminal: so it gives longer talk time, safer operation

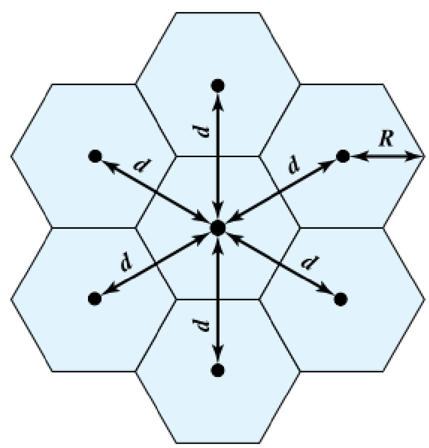
Cellular Network Coverage

The essence of a cellular network is the use of multiple low-power transmitters, on the order of 100 W or less. Because the range of such a transmitter is small, an area can be divided into cells, each one served by its own antenna.

- Each cell is allocated a band of frequencies and is served by a base station (consisting of transmitter, receiver, and control unit).
- Adjacent cells are assigned different frequencies to avoid interference or crosstalk. However, cells sufficiently distant from each other can use the same frequency band.

While it might seem natural to choose a circle to represent the coverage area of a base station, adjacent circles cannot be overlaid upon a map without leaving gaps or creating overlapping regions.

The hexagon has:



- No gaps or overlapping
- The largest area compared with square and triangle.
- Fewest number of cells can cover a geographic region,
- Closely approximates a circular radiation pattern which would occur for an omnidirectional base station antenna and free space propagation.
- A hexagonal pattern provides for equidistant antennas.
- When using hexagons to model coverage areas, base station transmitters are depicted as either:
  - In the center of the cell (center-excited cells): omnidirectional antennas are used in center-excited cells.
  - On three of the six cell vertices (edge-excited cells): sectored directional antennas are used in corner-excited cells.

- The radius of a hexagon is defined to be the radius of the circle that circumscribes it (equivalently, the distance from the center to each vertex; also equal to the length of a side of a hexagon).

  For a cell radius *R*, the distance between the cell center and each adjacent cell center is

$$d = \sqrt{3}R$$

Therefore the area of the hexagon is

$$Area = \frac{3\sqrt{3}}{2}R^2$$

- In practice, a precise hexagonal pattern is not used. Variations from the ideal are due to:
    - Topographical limitations.
    - Local signal propagation conditions.
    - Practical limitation on siting antennas.

Frequency Reuse

In a cellular system, each cell has a base transceiver.

The transmission power is carefully controlled

- To allow communication within the cell using a given frequency
- To limit the power at that frequency that escapes the cell into adjacent ones.

- ❖ The objective is to use the same frequency in other nearby cells, thus allowing the frequency to be used for multiple simultaneous conversations.
- ❖ Generally, 10 to 50 frequencies are assigned to each cell, depending on the traffic expected.
- ❖ The essential issue is to determine how many cells must intervene between two cells using the same frequency so that the two cells do not interfere with each other. Various patterns of frequency reuse are possible.

Frequency reuse (frequency planning): is the design process of selecting and allocating channel groups for all of the cellular base stations within a system.

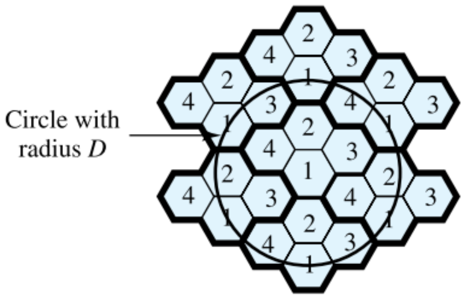
If the pattern consists of *N* cells and each cell is assigned the same number of frequencies, each cell can have ***K/N*** frequencies, where *K* is the total number of frequencies allotted to the system.

- For Advanced Mobile Phone System (AMPS), $K = 395$, and $N = 7$ is the smallest pattern that can provide sufficient isolation between two uses of the same frequency. This implies that there can be at most 57 frequencies per cell on average.

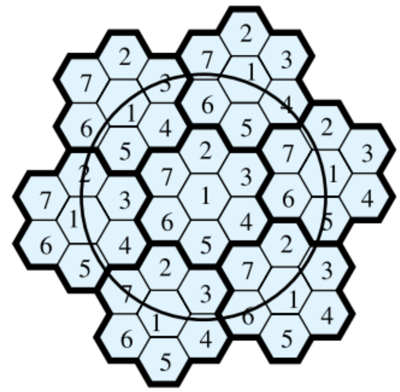
- In a hexagonal cell pattern: in order to tessellate (to connect without gaps between adjacent cells), only the following values of *N* are possible:

$N = I^2 + J^2 + (I \times J)$ $\qquad$ $I, J = 0, 1, 2, 3, \ldots$

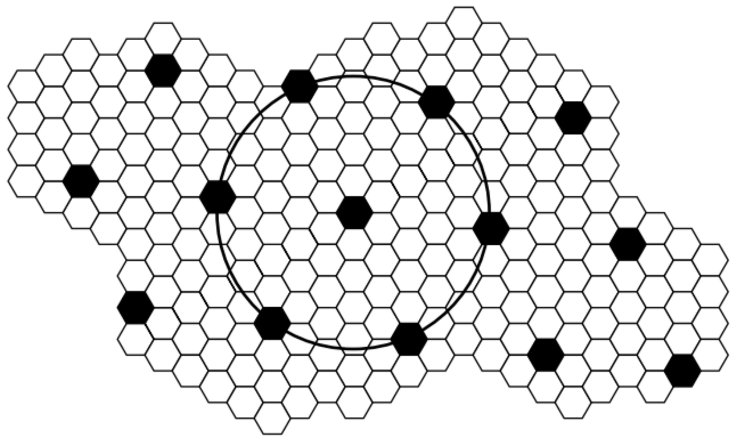
Therefore, possible values of *N* are 1, 3, 4, 7, 9, 12, 13, 16, 19, 21, and so on.



(a) Frequency reuse pattern for $N = 4$



(b) Frequency reuse pattern for $N = 7$



(c) Black cells indicate a frequency reuse for $N = 19$

Choice of N (assuming constant cell size)

Small N:

- More clusters are required to cover the service area
- More capacity
- Higher probability of co-channel interference

Large N:

- Less clusters are required to cover the service area
- Less capacity
- Less probability of co-channel interference

- In characterizing frequency reuse, the following parameters are commonly used:

  D = minimum distance between centers of cells that use the same frequency band (called co-channels)

  R = radius of a cell

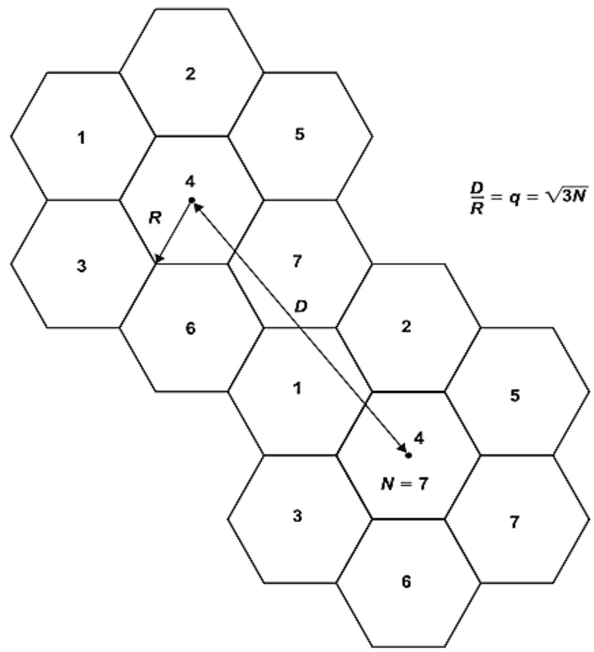
  d = distance between centers of adjacent cells $d = \sqrt{3}R$

  N = number of cells in a pattern (Cluster size)

  (Each cell in the pattern uses a unique set of frequency bands), termed the ***reuse factor***

The following relationship holds:

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



Where q is the reuse ratio.

This can also be expressed as

$$\frac{D}{d} = \sqrt{N}$$

Consider a cellular system which has a total of K duplex channels available for use. If each cell is allocated a group of C channels ($C < K$), and if the K channels are divided among N cells into channel groups which each have the same number of channels, the total number of available radio channels can be expressed as

$$K = C\,N\_$$

where

$$K = \frac{Spectrum\ bandwidth\ \ (or\ Total\ bandwidth)}{Channel\ bandwidth}$$

The N cells which collectively use the complete set of available frequencies is called a cluster. If a cluster is replicated M times within the system, the total number of duplex channels, can be used as a measure of capacity and is given

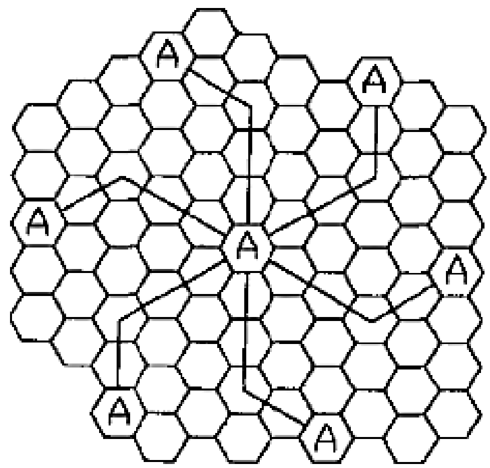
$$Capacity = MCN = MK\_$$

- The capacity of a cellular system is directly proportional to the number of times a cluster is replicated in a fixed service area.
- The cluster size (N) is typically equal to 4, 7, or 12.

- If N is reduced while the cell size is kept constant, more clusters are required to cover a given area and hence more capacity is achieved.
  - A large cluster size indicates that the ratio between the cell radius and the distance between co-channel cells is large.
  - A small cluster size indicates that co-channel cells are located much closer together.
- From a design viewpoint, the smallest possible value of N is desirable in order to maximize capacity over a given coverage area.

To find the nearest co-channel neighbors of a particular cell, one must do the following:

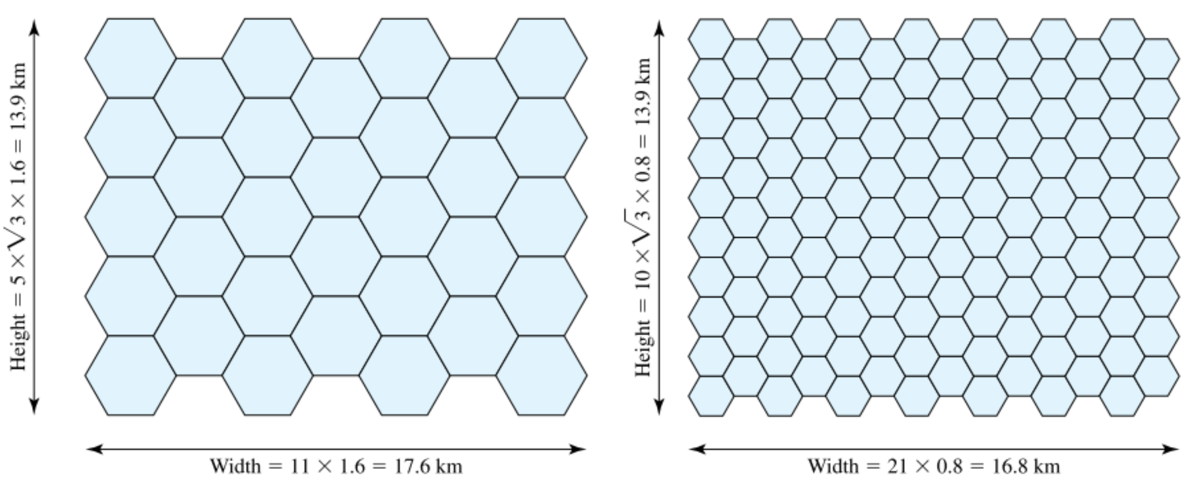
(1) Move i cells along any chain of hexagons and then
(2) Turn 60 degrees counter-clockwise and move j cells. This is illustrated in Figure below for i = 3 and j = 2 (example, N = 19).



Example 1

Assume a system of 32 cells with a cell radius of 1.6 km, a total of 32 cells, a total frequency bandwidth that supports 336 traffic channels, and a reuse factor of N = 7.

(a) If there are 32 total cells, what geographic area is covered, how many channels are there per cell, and what is the total number of concurrent calls that can be handled?
(b) Repeat for a cell radius of 0.8 km and 128 cells.



(a) Cell radius = 1.6 km **(b) Cell radius = 0.8 km**

Solution:

(a)

The area of a hexagon of radius *R* is

$$Area_a = \frac{3\sqrt{3}}{2}R^2 = \frac{3\sqrt{3}}{2}(1.6)^2 = 6.65\,\text{km}^2$$

The total area covered is 6.65 × 32 = 213 km^2.
For $N = 7$, the number of channels per cell is $K/N = 336/7 = 48$,
Total number of concurrent calls that can be handled is

$$Capacity = 48 \times 32 = 1536 \text{ channels}$$

(b)

The area of a hexagon of radius *R* is

$$Area_b = \frac{3\sqrt{3}}{2}R^2 = \frac{3\sqrt{3}}{2}(0.8)^2 = 1.66\,\text{km}^2$$

The area covered is 1.66 × 128 = 213 km^2.
The number of channels per cell is $K/N = 336/7 = 48$,
Total number of concurrent calls is

$$Capacity = 48 \times 128 = 6144 \text{ calls}$$

Example 2

Consider a cellular system in which total available voice channels to handle the traffic are 960. The area of each cell is 6 km^2 and the total coverage area of the system is 2000 km^2. Calculate:

(a) The system capacity if the cluster size *N* is 4
(b) The system capacity if the cluster size is 7.

- How many times would a cluster of size 4 have to be replicated to cover the entire cellular area?
- Does decreasing *N* increase the system capacity? Explain.

Solution

Cell area = 6 km^2

Total coverage area = 2000 km^2

(a) $N = 4$

Area of a cluster = 4 × 6 = 24 km^2

Number of clusters for covering total area = 2000/24 = 83.33 ~ 83

Number of channels per cell = 960/4 = 240

System capacity = 83 × 960 = 79, 680 channels

(b) $N = 7$

Area of cluster = 7 × 6 = 42 km^2

Number of clusters for covering total area = 2000/42 = 47.62 ~ 48

Number of channels per cell = 960/7 = 137.15 ~ 137

System capacity = 48 × 960 = 46,080 channels

It is evident when we decrease the value of N from 7 to 4, we increase the system capacity from 46,080 to 79,680 channels. Thus, decreasing N increases the system capacity.

Channel Assignment Strategies

For efficient utilization of the radio spectrum, a frequency reuse scheme that is consistent with the objectives of increasing capacity and minimizing interference is required. A variety of channel assignment strategies have been developed to achieve these objectives.

Channel assignment strategies can be classified as either fixed or dynamic. The choice of channel assignment strategy impacts the performance of the system, particularly as to how calls are managed when a mobile user is handed off from one cell to another.

a) **Fixed channel assignment strategy**: each cell is allocated a predetermined set of voice channels.
   - Any call attempt within the cell can only be served by the unused channels in that particular cell.
   - If all the channels in that cell are occupied, the call is blocked and the subscriber does not receive service.
   - *Borrowing strategy*: a cell is allowed to borrow channels from a neighboring cell if all of its own channels are already occupied. The mobile switching center (MSC) supervises such borrowing procedures and ensures that the borrowing of a channel does not disrupt or interfere with any of the calls in progress in the donor cell.

b) **Dynamic channel assignment strategy**: voice channels are not allocated to different cells permanently. Instead,

- Each time a call request is made, the serving base station requests a channel from the MSC.
- The switch then allocates a channel to the requested cell following an algorithm that takes into account the likelihood of
    - Future blocking within the cell,
    - The frequency of use of the candidate channel,
    - The reuse distance of the channel,
    - Other cost functions.
- Accordingly, the MSC only allocates a given frequency if that frequency is not presently in use in the cell or any other cell which falls within the minimum restricted distance of frequency reuse to avoid co-channel interference.

Advantage:

- Dynamic channel assignment reduces the likelihood of blocking, which increases the trunking capacity of the system, since all the available channels in a market are accessible to all of the cells.
- Increases the channel utilization and decreases probability of a blocked call.

Disadvantage:

- Require the MSC to collect real-time data on channel occupancy, traffic distribution, and radio signal strength indications (RSSI) of all channels on a continuous basis. This increases the storage and computational load on the system.

Co-channel Interference

The *S/I* ratio at the desired mobile receiver is given as:

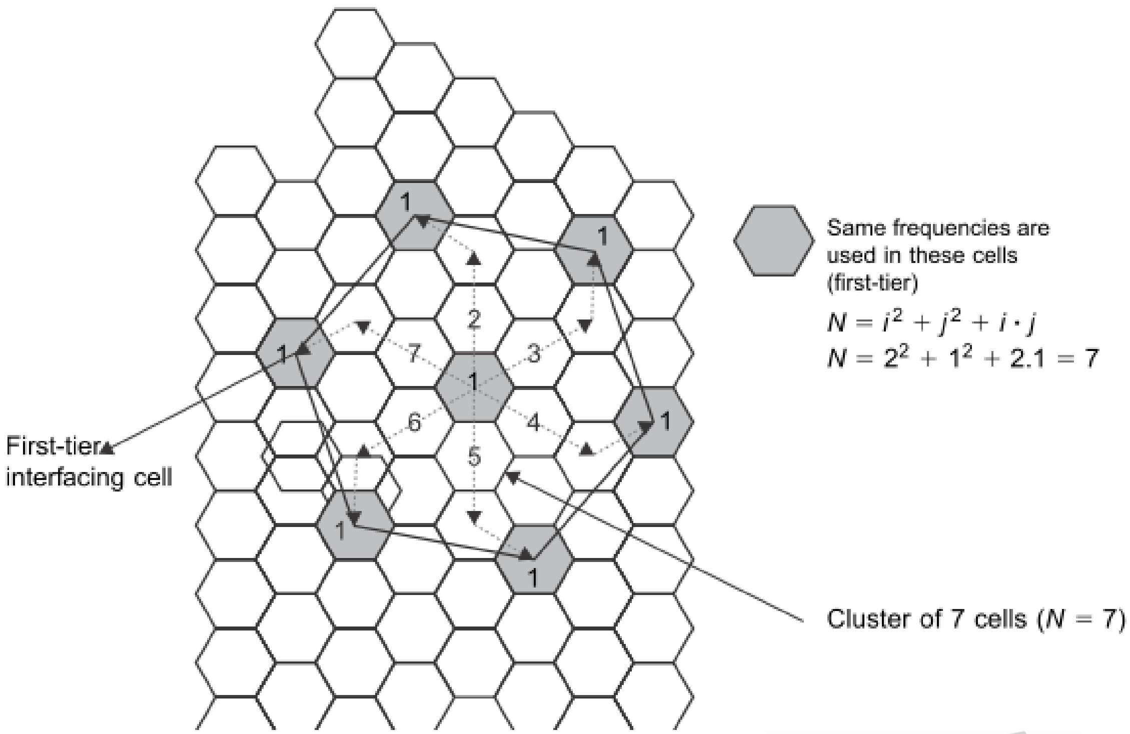
$$\frac{S}{I} = \frac{S}{\sum_{k=1}^{N_I} I_k}$$

where:

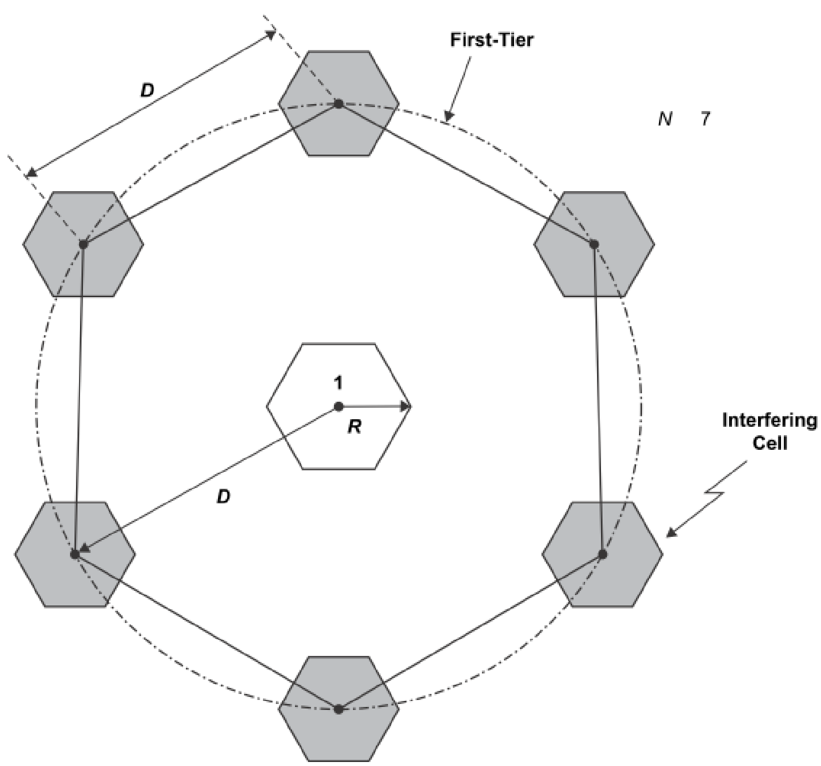
I_k = the interference due to the kth interferer

N_I = the number of interfering cells in the first tier.

In a fully equipped hexagonal-shaped cellular system, there are always six co-channel interfering cells in the first tier (i.e., $N_I = 6$).



- Most of the co-channel interference results from the first tier.
- Interference from second and higher tiers amounts to less than 1% of the total interference (ignored).



- Co-channel interference can be experienced both at the cell site and the mobile stations in the center cell.
- In a small cell system, interference will be the dominating factor and thermal noise can be neglected. Thus the *S/I* ratio can be given as:

$$\frac{S}{I} = \frac{1}{\sum_{k=1}^{6}\left(\frac{D_k}{R}\right)^{-\gamma}}$$

where:

$2 \le \gamma \le 5$: the propagation path loss, and γ depends upon the terrain environment.
D_k : the distance between mobile and kth interfering cell
R : the cell radius

If we assume D_k is the same for the six interfering cells for simplification, or $D = D_k$, then Equation above becomes:

$$\frac{S}{I} = \frac{1}{6(q)^{-\gamma}} = \frac{q^{\gamma}}{6}$$

Therefore

$$\therefore q = \left[6\left(\frac{S}{I}\right)\right]^{1/\gamma}$$

Since $q = \sqrt{3N}$, therefore

$$N = \frac{1}{3}\left[6\left(\frac{S}{I}\right)\right]^{\frac{2}{\gamma}}$$

and

$$\frac{S}{I} = \frac{\left(\sqrt{3N}\right)^{\gamma}}{6}$$

Example 1

Consider the advanced mobile phone system (AMPS) in which an *S/I* ratio of 18 dB is required for the accepted voice quality. Assume $\gamma = 4$.

(a) What should be the reuse factor for the system?
(b) What will be the reuse factor of the Global System of Mobile (GSM) system in which an *S/I* of 12 dB is required?

Solution

(a)

$$N = \frac{1}{3}\left[6\left(\frac{S}{I}\right)\right]^{\frac{2}{\gamma}}$$

$$N_{AMPS} = \frac{1}{3}\left[6\left(10^{\frac{18}{10}}\right)\right]^{\frac{2}{4}} = 6.486 \approx 7$$

(b)

$$N_{GSM} = \frac{1}{3}\left[6\left(10^{\frac{12}{10}}\right)\right]^{\frac{2}{4}} = 3.251 \approx 4$$

Example 2

Consider a cellular system with 395 total allocated voice channel frequencies. Calculate the mean *S/I* ratio for cell reuse factor equal to 4, 7, and 12. Assume omnidirectional antennas with six interferers in the first tier and a slope for path loss of 40 dB/decade (γ = 4). Discuss the results.

Solution

For a reuse factor N = 4, the number of voice channels per cell site = K/N = 395/4 = 99.

$$N = \frac{1}{3}\left[6\left(\frac{S}{I}\right)\right]^{\frac{2}{\gamma}}$$

$$4 = \frac{1}{3}\left[6\left(\frac{S}{I}\right)\right]^{\frac{2}{4}}$$

$$\frac{S}{I} = 24\ (13.8\,dB)$$

The results for N = 7 and N = 12 are given in Table (right).

N	**Voice channels per cell**	**Mean *S/I* (dB)**
4	99	13.8
7	56	18.7
12	33	23.3

It is evident from the results that, by increasing the reuse factor from N = 4 to N = 12, the mean *S/I* ratio is improved from 13.8 to 23.3 dB.

Co-channel Interference Reduction

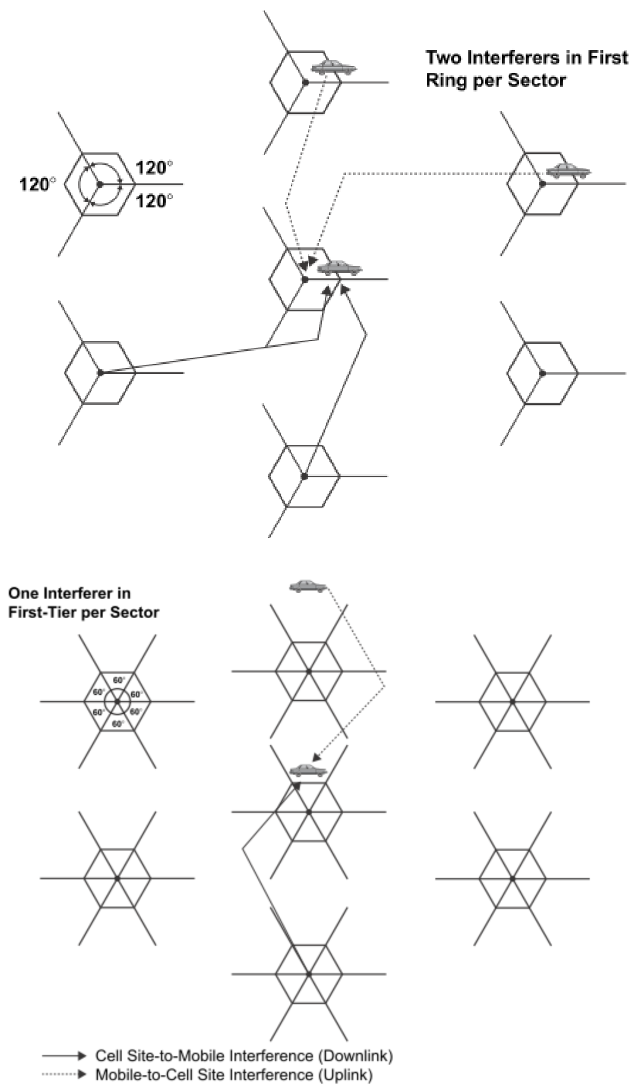
In the case of increased call traffic, the frequency spectrum should be used efficiently. We should avoid increasing the number of cells N in a frequency reuse pattern. As N increases, the number of frequency channels assigned to a cell is reduced, thereby decreasing the call capacity of the cell.

Instead of increasing N, we either

a. Perform cell splitting to subdivide a congested cell into smaller cells.

Or

b. Use a directional antenna arrangement (sectorization) to reduce co-channel interference. In this case, each cell is divided into three or six sectors and uses three or six directional antennas at the base station to reduce the number of co-channel interferers



Co-channel interference with 120° sectorized cells.

Co-channel interference with 60° sectorized cells.

Each sector is assigned a set of channels (frequencies) (either 1/3 or 1/6 of the frequencies of the omnidirectional cell).

Adjacent Channel Interference (ACI)

Signals which are adjacent in frequency to the desired signal cause adjacent channel interference. ACI is brought about primarily because of imperfect receiver filters which allow nearby frequencies to move into the pass band, and nonlinearity of the amplifiers.

The ACI can be reduced by:

(1) Using modulation schemes which have low out-of-band radiation.
(2) Carefully designing the band-pass filter (BPF) at the receiver front end.
(3) Assigning adjacent channels to different cells in order to keep the frequency separation between each channel in a given cell as large as possible.

The effects of ACI can also be reduced using advanced signal processing techniques that employ equalizers.

Review

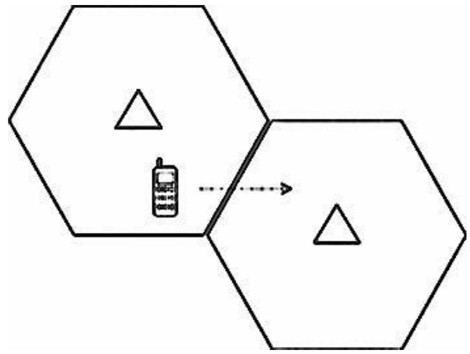
We developed a relationship between the reuse ratio (q) and cell cluster size (N) for the hexagonal geometry. Co-channel interference ratios for the omnidirectional and sectorized cell were derived. A numerical example was given to demonstrate that, for a given cluster size, sectorization yields a higher S/I ratio, but reduces spectral efficiency. However, it is possible to achieve a higher spectral efficiency by reducing the cluster size in a sectorized system without lowering the S/I ratio below the minimum requirement.

Handoff (Handover) Strategies

When a mobile moves into a different cell while a conversation is in progress, the MSC automatically transfers the call to a new channel belonging to the new base station.

The Handoff decision is made depending on:

a. Power
b. Traffic
c. Channel quality
d. Distance
e. Administration



The handoff operation involves:

1. Identifying a new base station,
2. Allocate the voice and control signals to channels associated with the new base station.

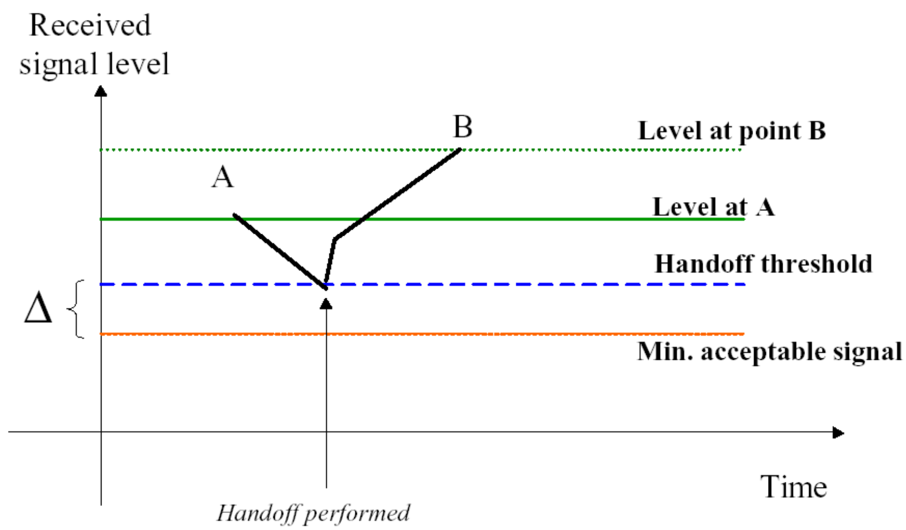
- Once a particular signal level is specified as the minimum usable signal for acceptable voice quality at the base station receiver (normally taken as between -90 dBm and -100 dBm), a slightly stronger signal level is used as a threshold at which a handoff is made. This margin (cannot be too large or too small) is given by

$$\Delta = P_{r_{Handoff}} - P_{r_{Minimum\ usable}}$$

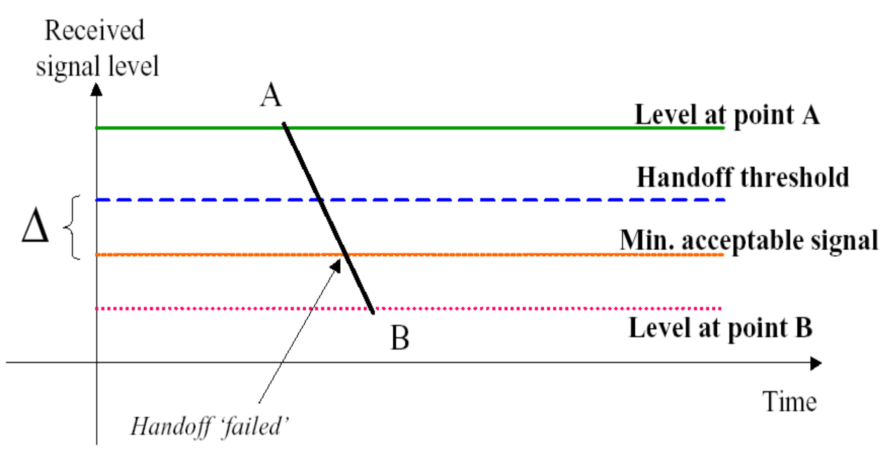
  - If Δ is too large, unnecessary handoffs which burden the MSC may occur.
  - If Δ is too small, there may be insufficient time to complete a handoff before a call is lost due to weak signal conditions.

  Therefore, Δ is chosen carefully to meet these conflicting requirements.

The figure below demonstrates the case where a handoff is not made and the signal drops below the minimum acceptable level to keep the channel active. This dropped call event can happen when there is an excessive delay by the MSC in assigning a handoff, or when the threshold Δ is set too small for the handoff time in the system.



The value of delta is large enough. When the handoff threshold is reached, the MSC initiates the handoff



The MSC is unable to perform the handoff before the signal level dropped below the minimum level → so the connection (call) is lost.

Excessive delays may occur during high traffic conditions due to

- Computational loading at the MSC
- No channels are available on any of the nearby base stations.

- **The length of time needed to decide if a handoff is necessary depends on the speed at which the vehicle is moving.**

Handoff Types

- Handoff can be categorized as hard handoff, soft handoff, and softer handoff.
- If the hand-off is needed between two cells (BTS) controlled by the same Base Station Controller (BSC), the MSC is not needed as the BSC does it all.

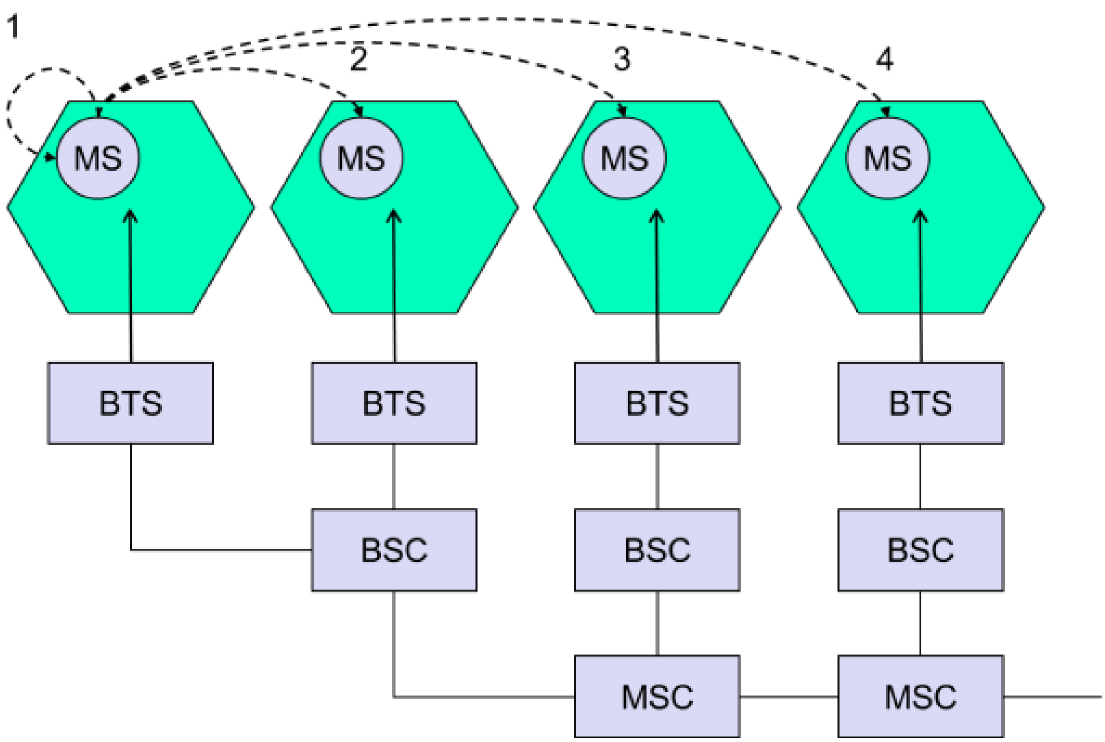
Types of hand-off are:

1. **INTRA-CELL**: within a cell, narrow-band interferences could make transmission at a certain frequency impossible. The BSC decides to change the carrier frequency.

2. **INTRA BSS**: between cells controlled by the same BSC. The BSC performs the handover, assigns a new radio channel in the new cell and releases the old one.

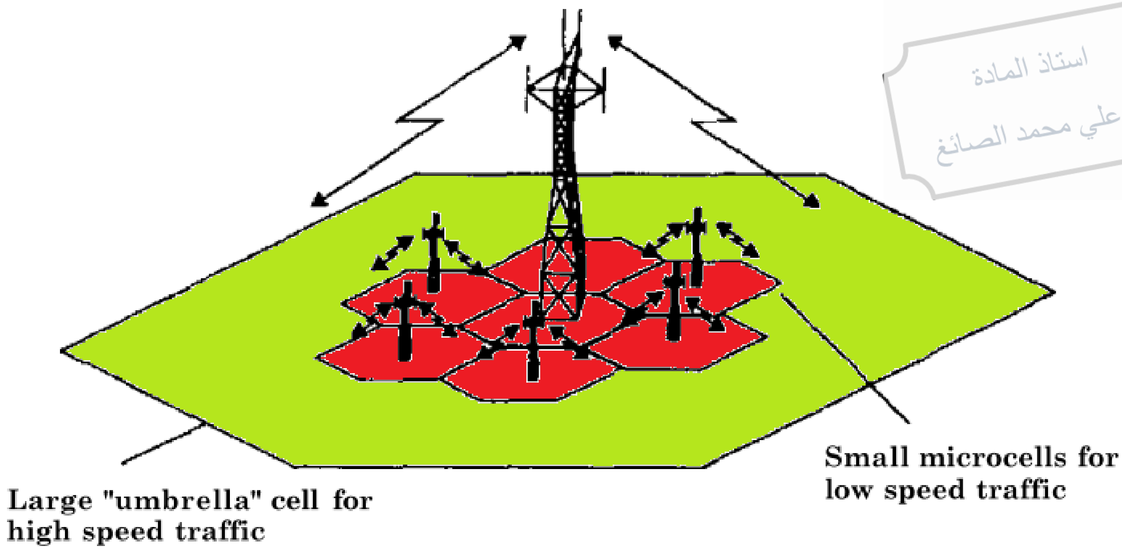
3. **INTER BSS**: between cells controlled by different BSCs, and the MSC is involved.

4. **INTER MSC**: from region to region where more than one MSC is involved. Between two cells belonging to different MSCs. Both MSCs perform the handover together.



Umbrella cell approach

- By using different antenna heights (often in the same building or tower) and different power levels, it is possible to provide "large" and "small" cells which are co-located at a single location. This technique is called the umbrella cell approach
- Used to provide:
  - ❖ Large area coverage (Large cell) to high speed users → fewer handoffs
  - ❖ Small area coverage (Small cell) to users traveling at low speeds.



- The umbrella cell approach ensures that the number of handoffs is minimized for high speed users and provides additional microcell channels for pedestrian users.

- The speed of each user may be estimated by the base station or MSC by evaluating how rapidly the short term average signal strength changes over time, or more sophisticated algorithms may be used to evaluate and partition users.

- If a high speed user in the large umbrella cell is approaching the base station, and its velocity is rapidly decreasing, the base station may decide to hand the user into the co-located microcell, without MSC intervention.

Traffic Engineering

Trunking and Grade of Service

A. Trunking

- A trunk: *is a communication line or link designed to carry multiple signals simultaneously to provide network access between two points*.
- One of the most important steps in telecommunication engineering is to determine the number of trunks required on a route or a connection between MSCs.
- In a trunked radio system, each user is allocated a channel on a per call basis, and upon termination of the call, the previously occupied channel is immediately returned to the pool of available channels.

- The telephone company uses trunking theory to determine the number of telephone circuits that need to be allocated and this same principle is used in designing cellular radio systems.
- As the number of phone lines decreases, it becomes more likely that all circuits will be busy for a particular user.
- In a trunked mobile radio system,
  - When a particular user requests service and all of the radio channels are already in use, the user is blocked, or denied access to the system.
  - In some systems, a queue may be used to hold the requesting users until a channel becomes available.
- To design trunked radio systems that can handle a specific capacity at a specific "grade of service", it is essential to understand trunking theory and queuing theory.
- The fundamentals of trunking theory were developed by Erlang, a Danish who, in the late 19th century.
- One Erlang represents the amount of traffic intensity carried by a channel that is completely occupied (i.e. 1 call-hour per hour or 1 call-minute per minute).
  For example, a radio channel that is occupied for thirty minutes during an hour carries 0.5 Erlangs of traffic.

- Traffic is measured in either:
  - Erlangs,
  - Centrum (100) call seconds (CCS).

B. **The *grade of service (GOS)***: *is a measure of the ability of a user to access a trunked system during the busiest hour*.

- The grade of service is a benchmark used to define the desired performance of a particular trunked system by specifying a desired probability of a user obtaining channel access given a specific number of channels available in the system.

- It is the wireless designer's job to estimate the maximum required capacity and to allocate the proper number of channels in order to meet the GOS.
- GOS is typically given as the probability that a call is blocked, or the probability of a call experiencing a delay greater than a certain queuing time.

Traffic intensity: is the average number of calls simultaneously in progress during a particular period of time. It is measured either in units of *Erlangs* or *CCS*.

The traffic intensity offered by each user is equal to the call request rate multiplied by the holding time (in hours). That is, each user generates a traffic intensity of A_U Erlangs given by

$$A_U = \lambda H$$

where

H is the average duration of a call (Holding time).
λ is the average number of call requests per unit time.

For a system containing U users and an unspecified number of channels, the total offered traffic intensity A, is given as

$$A = UA_U$$

And

Overflow (O)= (Offered load) – (Carried load)

- *CCS to Erlang conversion*

An average of one call in progress during an hour represents a traffic intensity of 1 *Erlang*; thus 1 *Erlang* equals 1 × 3600 call seconds (36 *CCS*). The Erlang is a dimensionless number.

Example 1

In a wireless network each subscriber generates two calls per hour on the average and a typical call holding time is 120 seconds. What is the traffic intensity?

Solution

$$A_u = \lambda H = 2 \times \frac{120}{3600} = 0.0667\,Erlangs = 2.4\,CCS$$

Example 2

In order to determine voice traffic on a line, we collected the following data during a period of 90 minutes. Calculate the traffic intensity in *Erlangs* and *CCS*.

Traffic data used to estimate traffic intensity.

Call no.	Duration of call (s)
1	60
2	74
3	80
4	90
5	92
6	70
7	96
8	48
9	64
10	126

Solution

$$\lambda = \frac{10}{1.5} = 6.667\, calls\ /\ hour$$

Average call holding time:

$$H = \frac{(60+74+80+90+92+70+96+48+64+126)}{10} = 80\ \ sec/call$$

$$A_u = \lambda H = 6.667 \times \frac{80}{3600} = 0.148\, Erlangs = 5.33\, CCS$$

Example 3

We record data in the Table below by observing the activity of a single customer line during an eight-hour period from 9:00 A.M. to 5:00 P.M. Find the traffic intensity during the eight-hour period, and during busy hour (BH) which occurs between 4:00 P.M. and 5:00 P.M.

Call no.	Call started	Call ended	Call duration (min.)
1	9:15	9:18	3.0
2	9:31	9:41	10.0
3	10:17	10:24	7.0
4	10:24	10:34	10.0
5	10:37	10:42	5.0
6	10:55	11:00	5.0
7	12:01	12:02	1.0
8	2:09	2:14	5.0
9	3:15	3:30	15.0
10	4:01	4:35	34.0
11	4:38	4:43	5.0

Solution

$$\lambda = \frac{11}{8} = 1.375\,calls\,/\,hour$$

Total call minutes = 3 + 10 + 7 + 10 + 5 + 5 + 1 + 5 + 15 + 34 + 5 = 100 minutes

The average holding time in hours per call is:

$$H = \frac{100}{11} \times \frac{1}{60} = 0.1515\,hours\,/\,call$$

The traffic intensity is

$$A = \lambda H = 1.375 \times 0.1515 = 0.208\,Erlangs = 7.5\,CCS$$

The busy hour (BH) is between 4:00 P.M. and 5:00 P.M. Since there are only two calls between this period, we can write:

Call arrival rate = 2 calls/hour

The average call holding time during BH:

$$H = \frac{34+5}{2} = 19.5\,\text{min}/\,call = 0.325\,hours\,/\,call$$

The traffic intensity during BH is

$$A = \lambda H = 2 \times 0.325 = 0.65\,Erlangs = 23.4\,CCS$$

Example 4

If the mean holding time in Example 5 is 100 seconds, find the average number of busy hour call attempts (BHCAs).

Solution

A_u *= 0.0375 Erlangs = 135 call/sec*

$$\lambda_{BH} = \frac{A_u}{100} = 1.35$$

In a C channel trunked system, if the traffic is equally distributed among the channels, then the traffic intensity per channel, A_c, is given as

$$A_C = \frac{UA_U}{C}$$

When the offered traffic exceeds the maximum capacity of the system, the carried traffic becomes limited due to the limited capacity (i.e. limited number of channels).

- The maximum possible carried traffic is the total number of channels, *C*, in *Erlangs*.
- The AMPS cellular system is designed for a *GOS* of 2% blocking. This implies that the channel allocations for cell sites are designed so that 2 out of 100 calls will be blocked due to channel occupancy during the busiest hour.

- There are two types of trunked systems which are commonly used
  a. **no queuing** (**blocked calls cleared**) – Erlang B
  b. **queue** (**blocked calls delayed**) – Erlang C

(a) The first type offers **no queuing** for call requests. That is, for every user who requests service, it is assumed there is no setup time and the user is given immediate access to a channel if one is available. If no channels are available, the requesting user is blocked without access and is free to try again later. This type of trunking is called **blocked calls cleared**.

- The Erlang B formula (probability of blocking) is given by

$$P_r[blocking] = \frac{\dfrac{A^C}{C!}}{\sum_{k=0}^{C} \dfrac{A^k}{k!}} = GOS$$

where *C* is the number of trunked channels offered by a trunked radio system and *A* is the total offered traffic.

- The capacity of a trunked radio system where blocked calls are lost is tabulated for various values of *GOS* and numbers of channels in Table below

Number of channels *C*	Capacity (*Erlangs*) for *GOS*			
	0.01	**0.005**	**0.002**	**0.001**
2	0.153	0.105	0.065	0.046
4	0.869	0.701	0.535	0.439
5	1.36	1.13	0.9	0.762
10	4.46	3.96	3.43	3.09
20	12	11.1	10.1	9.41
24	15.3	14.2	13	12.2
40	29	27.3	25.7	24.5
70	56.1	53.7	51	49.2
100	84.1	80.9	77.4	75.2

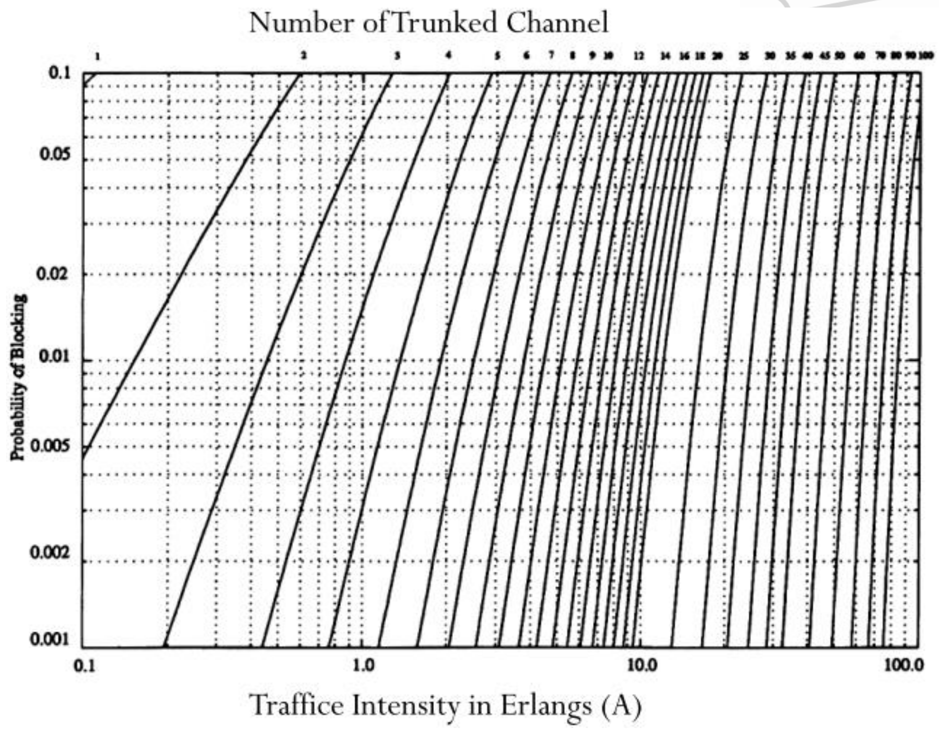
(b) The second kind of trunked (also called **Blocked Calls Delayed**) system is one in which a **queue** is provided to hold calls which are blocked.

- If a channel is not available immediately, the call request may be delayed until a channel becomes available.
- This type of trunking is a measure of *GOS* and is defined as the probability that a call is blocked after waiting a specific length of time in the queue.
- The probability of a call not having immediate access to a channel is determined by the *Erlang C formula*

$$P_r[delay > 0] = \frac{A^C}{A^C + C!\left(1 - \frac{A}{C}\right)\sum_{k=0}^{C-1}\frac{A^k}{k!}}$$

- If no channels are immediately available the call is delayed, and the probability that the delayed call is forced to wait more than *t* seconds is given by the probability that a call is delayed, multiplied by the conditional probability that the delay is greater than *t* seconds.

The *Erlang B* formulas are plotted in graphical form in the Figure below. This graph is useful for determining *GOS* in rapid fashion.



To use the figure:

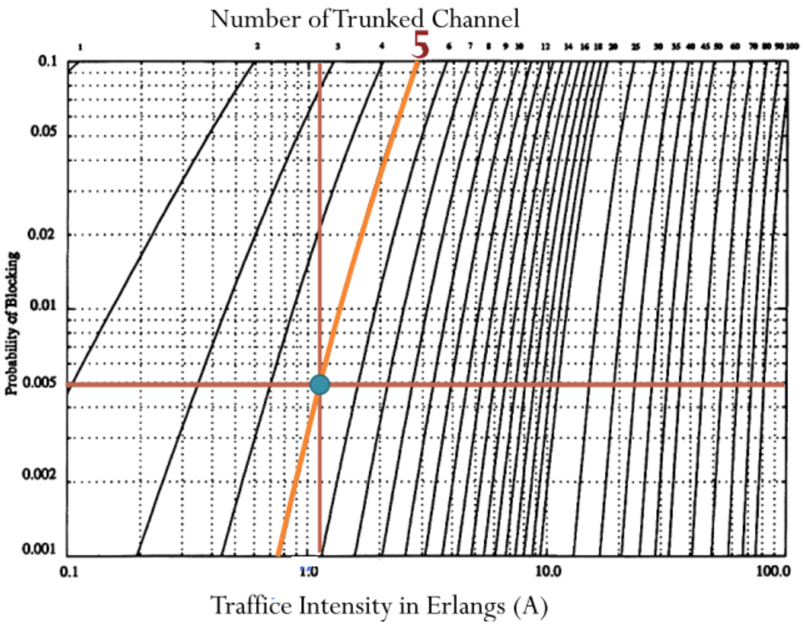
a. Locate the number of channels on the top portion of the graph.
b. Locate the traffic intensity of the system on the bottom portion of the graph.
c. The blocking probability $P_r[blocking]$ is shown on the abscissa of the figure. With two of the parameters specified it is easy to find the third parameter.

Example 1

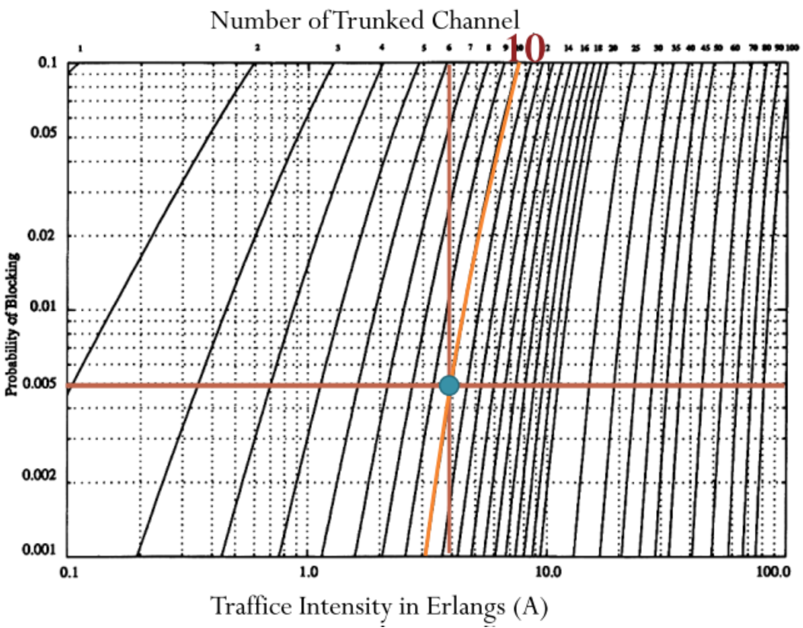
How many users can be supported for 0.5% blocking probability for 5 and 10 trunked channels in a blocked calls cleared system? Assume each user generates A_U = 0.1 *Erlangs* of traffic.

Solution

(a) From Erlang B chart, we obtain $A \approx 1$, therefore, total number of users, $U = A/A_U$ = 1 /0.1 = 10 users.



(b) From Erlang B chart, we obtain $A \approx 4$, Therefore, total number of users, $U = A/A_U$ = 4 /0.1 = 40 users.



Example 2

How many users can be supported for 0.5% blocking probability for the following number of trunked channels in a blocked calls cleared system? (a) 1, (b) 5, (c) 10, (d) 20, and (e) 100. Assume each user generates 0.1 *Erlangs* of traffic.

Solution

(a) Given $C = 1$, $A_U = 0.1$, $GOS = 0.005$

From Erlang B chart, we obtain $A = 0.005$

Therefore, total number of users, $U = A/A_U = 0.005 /0.1 = 0.05$ users.

But, actually one user could be supported on one channel. So, $U = 1$

(b) Given $C = 5$, $A_U = 0.1$, GOS = 0.005

From Erlang B chart, we obtain $A = 1.13$

Therefore, total number of users, $U = A/A_U = 1.13/0.1 = 11$ users.

(c) Given $C = 10$, $A_U = 0.1$, GOS = 0.005

From Erlang B chart, we obtain $A = 3.96$ *Erlangs*

Therefore, total number of users, $U = A/A_U = 3.96/0.1 \approx 39$ users.

(d) Given $C = 20$, $A_U = 0.1$, GOS = 0.005

From Erlang B chart, we obtain $A = 11.10$

Therefore, total number of users, $U = A/A_U = 11.1/0.1 = 110$ users.

(e) Given $C = 100$, $A_U = 0.1$, GOS = 0.005

From Erlang B chart, we obtain $A = 80.9$

Therefore, total number of users, $U = A/A_U = 80.9/0.1 = 809$ users.

Example 3

An urban area has a population of 2 million residents. Three competing trunked mobile networks (systems A, B, and C) provide cellular service in this area. System A has 394 cells with 19 channels each, system B has 98 cells with 57 channels each, and system C has 49 cells, each with 100 channels. Find the number of users that can be supported at 2% blocking if each user averages 2 calls per hour at an average call duration of 3 minutes. Assuming that all three trunked systems are operated at maximum capacity compute the percentage market penetration of each cellular provider.

Solution

System A

Given:

Probability of blocking = 2% = 0.02

Number of channels per cell used in the system, $C = 19$

Traffic intensity per user, $A_u = \lambda H = 2 \times (3/60) = 0.1$ *Erlangs*

For *GOS* = 0.02 and *C* = 19, from the Erlang B chart, the total carried traffic, *A*, is obtained as 12 *Erlangs*.

Therefore, the number of users that can be supported per cell is $U = A/A_u = 12/0.1 = 120$.

Since there are 394 cells, the total number of subscribers that can be supported by System *A* is equal to 120 × 394 = 47280.

System B

Given:

Probability of blocking = 2% = 0.02

Number of channels per cell used in the system, *C* = 57

Traffic intensity per user, $A_u = \lambda H = 2 \times (3/60) = 0.1$ *Erlangs*

For GOS = 0.02 and *C* = 57, from the Erlang B chart, the total earned traffic, *A*, is obtained as 45 *Erlangs*.

Therefore, the number of users that can be supported per cell is

$U = A/A_u = 45/0.1 = 450$.

Since there are 98 cells, the total number of subscribers that can be supported by System B is equal to 450 × 98 = 44100

System C

Given:

Probability of blocking = 2% = 0.02

Number of channels per cell used in the system, *C* = 100

Traffic intensity per user, $A_u = \lambda H = 2 \times (3/60) = 0.1$ *Erlangs*

For *GOS* = 0.02 and *C* = 100, from the Erlang B chart, the total carried traffic, *A*, is obtained as 88 *Erlangs*.

Therefore, the number of users that can be supported per cell is $U = A/A_u = 88/0.1 = 880$.

Since there are 49 cells, the total number of subscribers that can be supported by System *C* is equal to 880 × 49 = 43120

Therefore, total number of cellular subscribers that can be supported by these three systems are 47280 + 44100 + 43120 = 134500 users.

Since there are 2 million residents in the given urban area and the total number of cellular subscribers in System A is equal to 47280, the percentage market penetration is equal to

47280/2000000 = 2.36%

Similarly, market penetration of System B is equal to

44100/2000000 = 2.205%

And the market penetration of System C is equal to

43120/ 2000000 = 2.156%

The market penetration of the three systems combined is equal to

134500/2000000 = 6.725%

Exercise 1

A certain city has an area of 1300 square miles and is covered by a cellular system using a 7-cell reuse pattern. Each cell has a radius of 4 miles and the city is allocated 40 MHz of spectrum with a full duplex channel bandwidth of 60 kHz. Assume a *GOS* of 2% for an Erlang B system is specified. If the offered traffic per user is 0.03 Erlangs, compute

(a) The number of cells in the service area,
(b) The number of channels per cell,
(c) Traffic intensity of each cell,
(d) The maximum carried traffic,
(e) The total number of users that can be served for 2% *GOS*,
(f) The number of mobiles per channel, and
(g) The theoretical maximum number of users that could be served at one time by the system.

Trunking efficiency

- It's a measure of the number of users which can be offered a particular GOS with a particular configuration of fixed channels. The way in which channels are grouped can substantially alter the number of users handled by a trunked system.

  For example, from the table of the capacity of an Erlang B system, 10 trunked channels at a *GOS* of 0.01 can support 4.46 *Erlangs* of traffic, whereas 2 groups of 5 trunked channels can support 2×1.36 *Erlangs*, or 2.72 *Erlangs* of traffic.

- Clearly, 10 channels trunked together support 60% more traffic at a specific *GOS* than do two 5 channel trunks! It should be clear that the allocation of channels in a trunked radio system has a major impact on overall system capacity.

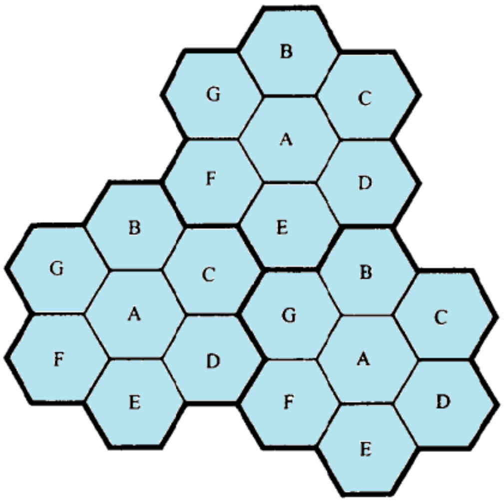
Improving Capacity in Cellular Systems

- As the demand for wireless service increases, the number of channels assigned to a cell eventually becomes insufficient to support the required number of users. At this point, cellular design techniques are needed to provide more channels per unit coverage area.

- Techniques such as cell splitting and sectoring approaches are used in practice to expand the capacity of cellular systems.

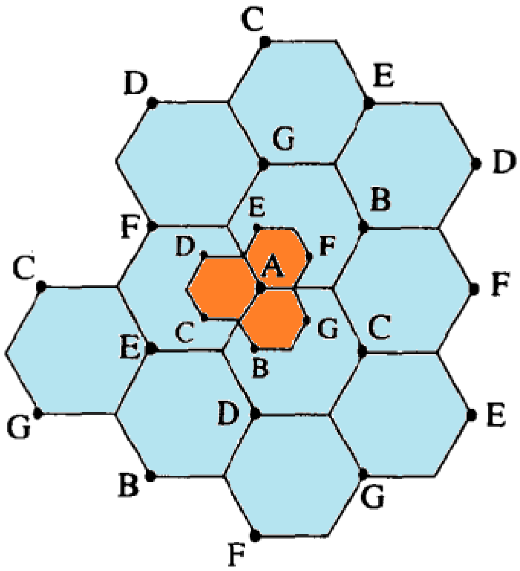
A. *Cell Splitting*

- It is the process of subdividing a congested cell into smaller cells, each with its own base station and a corresponding reduction in antenna height and transmitter power.
- Cell splitting increases the capacity of a cellular system since it increases the number of times that channels are reused.
- By defining new cells which have a smaller radius than the original cells and by installing these smaller cells (called microcells) between the existing cells, capacity increases due to the additional number of channels per unit area.



- Imagine if every cell in the Figure (right) were reduced in such a way that the radius of every cell was cut in half.
- In order to cover the entire service area with smaller cells, approximately four times as many cells would be required.
- This can be easily shown by considering a circle with radius *R*.
- The area covered by such a circle is four times as large as the area covered by a circle with radius *R/2*.
- The increased number of cells would increase the number of clusters over the coverage region, which in turn would increase the number of channels, and thus capacity, in the coverage area.
- Cell splitting allows a system to grow by replacing large cells with smaller cells, while not upsetting the channel allocation scheme required to maintain the minimum co-channel reuse ratio between co-channel cells.

Example of cell splitting: is shown in the Figure below.



- ❖ The base stations are placed at corners of the cells, and the area served by base station A is assumed to be saturated with traffic (i.e., the blocking of base station A exceeds acceptable rates).
- ❖ New base stations are therefore needed in the region to increase the number of channels in the area and to reduce the area served by the single

base station. Note in the figure that the original base station A has been surrounded by six new microcell base stations.

- ❖ In the example shown in Figure, the smaller cells were added in such a way as to preserve the frequency reuse plan of the system.
- ❖ For example, the microcell base station labeled G was placed half way between two larger stations utilizing the same channel set G. This is also the case for the other microcells in the figure.
- ❖ As can be seen from Figure, cell splitting merely scales the geometry of the cluster. In this case, the radius of each new microcell is half that of the original cell.

- For the new cells to be smaller in size, the transmit power of these cells must be reduced.
- The transmit power of the new cells with radius half that of the original cells can be found by examining the received power P_r at the new and old cell boundaries and setting them equal to each other.
- This is necessary to ensure that the frequency reuse plan for the new microcells behaves exactly as for the original cells.

$$P_r[\text{at old cell boundry}] \propto P_{t1} R^{-n}$$

and

$$P_r[\text{at new cell boundry}] \propto P_{t2} \left(\frac{R}{2}\right)^{-n}$$

where

P_{tl} an P_{t2} are the transmit powers of the larger and smaller cell base stations, respectively,

n is the path loss exponent.

If we take n = 4 and set the received powers equal to each other, then

$$P_{t2} = \frac{P_{t1}}{16}$$

In other words, the transmit power must be reduced by 12 dB in order to fill in the original coverage area with microcells, while maintaining the *S/I* requirement.

- When there are two cell sizes in the same region, the last equation shows that one cannot simply use the original transmit power for all new cells or the new transmit power for all the original cells.
  a. If the larger transmit power is used for all cells, some channels used by the smaller cells would not be sufficiently separated from co-channel cells.
  b. If the smaller transmit power is used for all the cells, there would be parts of the larger cells left unserved.

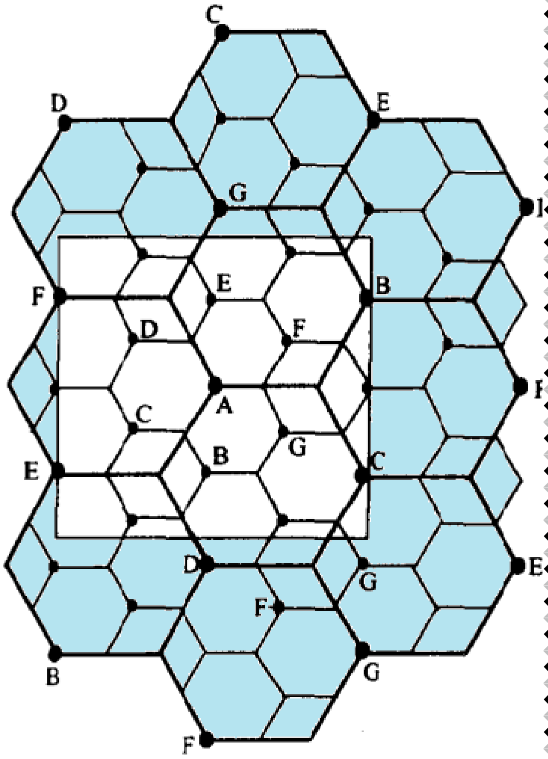
- For this reason, channels in the old cell must be broken down into two channel groups, one that corresponds to the smaller cell reuse requirements and the other that corresponds to the larger cell reuse requirements.

Example

Consider Figure shown. Assume each base station uses 60 channels, regardless of cell size. If each original cell has a radius of 1 km and each microcell has a radius of 0.5 km, find the number of channels contained in a 3 km by 3 km square centered around A,

(a) Without the use of microcells,
(b) When the lettered microcells as shown in the Figure are used,
(c) If all the original base stations are replaced by microcells.

Assume cells on the edge of the square to be contained within the square.



Solution

(a) Without the use of microcells:

A cell radius of 1 km implies that the sides of the larger hexagons are also 1 km in length. To cover the 3 km by 3 km square centered around base station A, we need to cover 1.5 km (1.5 times the hexagon radius) towards the right, left, top, and bottom of base station A.

We see that this area contains 5 base stations. Since each base station has 60 channels, the total number of channels without cell splitting is equal to $5 \times 60 = 300$ channels.

(b) With the use of the microcells as shown in Figure:

The base station A is surrounded by 6 microcells. Therefore, the total number of base stations in the square area under study is equal to $5 + 6 = 11$.

Since each base station has 60 channels, the total number of channels will be equal to $11 \times 60 = 660$ channels. This is a 2.2 times increase in capacity when compared to case (a).

(c) If all the base stations are replaced by microcells:

From Figure, we see that there are a total of $5 + 12 = 17$ base stations in the square region under study.

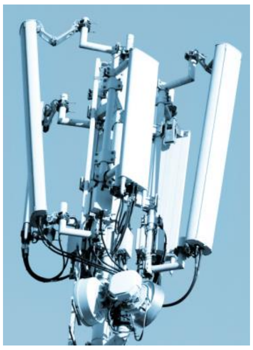
Since each base station has 60 channels, the total number of channels will be equal to 17 × 60 = 1020 channels. This is a 3.4 times increase in capacity when compared to case (a).

Theoretically, if all cells were microcells having half the radius of the original cell, the capacity increase would approach 4.

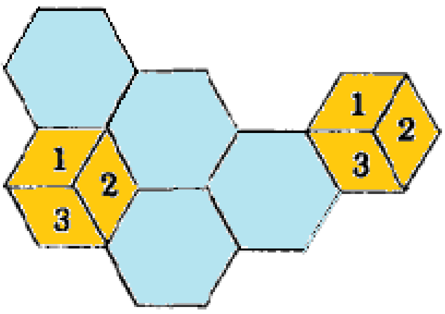
B. Sectoring

Cell splitting achieves capacity improvement by essentially rescaling the system.

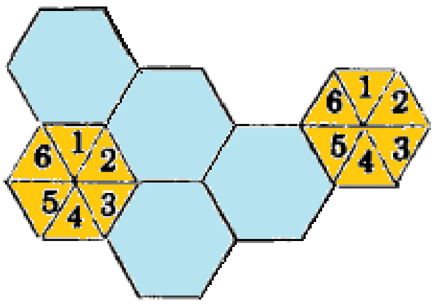
- In this approach, capacity improvement is achieved by reducing the number of cells in a cluster and thus increasing the frequency reuse. In order to do this, it is necessary to reduce the relative interference without decreasing the transmit power.
- The co-channel interference in a cellular system may be decreased by replacing a single omnidirectional antenna at the base station by several directional antennas, each radiating within a specified sector.
- By using directional antennas, a given cell will receive interference and transmit with only a fraction of the available co-channel cells.

- The technique for decreasing co-channel interference and thus increasing system capacity by using directional antennas is called sectoring.
- A cell is normally partitioned into three 120° sectors or six 60° sectors as shown in Figures below.
- When sectoring is employed, the channels used in a particular cell are broken down into sectored groups and are used only within a particular sector.



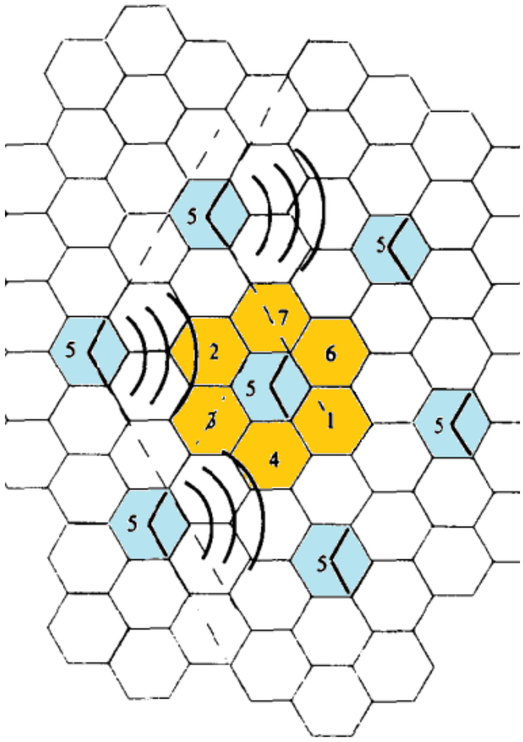
120° Sectoring



60° Sectoring

- Assuming 7-cell reuse, for the case of 120° sectors, the number of interferers in the first tier is reduced from 6 to 2. This is because only 2 of the 6 co-channel cells receive interference with a particular sectored channel group.

Referring to Figure (right), consider the interference experienced by a mobile located in the right-most sector in the center cell labeled "5".

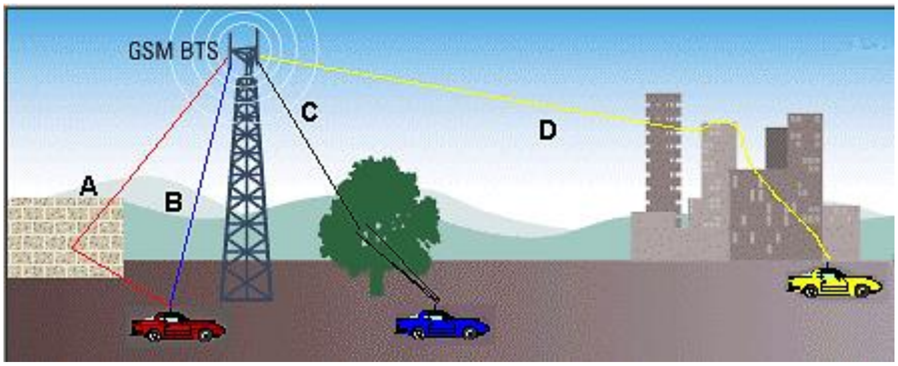


- ❖ There are 3 co-channel cell sectors labeled "5" to the right of the center cell, and 3 to the left of the center cell.
- ❖ Out of these 6 co-channel cells, only 2 cells have sectors with antenna patterns which radiate into the center cell, and hence a mobile in the center cell will experience interference on the forward link from only these two sectors.
- ❖ The resulting *S/I* for this case can be found to be 24.2 dB, which is a significant improvement over the omni-directional case, where the worst case *S/I* was shown to be 17 dB.
- ❖ In practical systems, further improvement in *S/I* is achieved by downtilting the sector antennas such that the radiation pattern in the vertical (elevation) plane has a notch at the nearest co-channel cell distance.

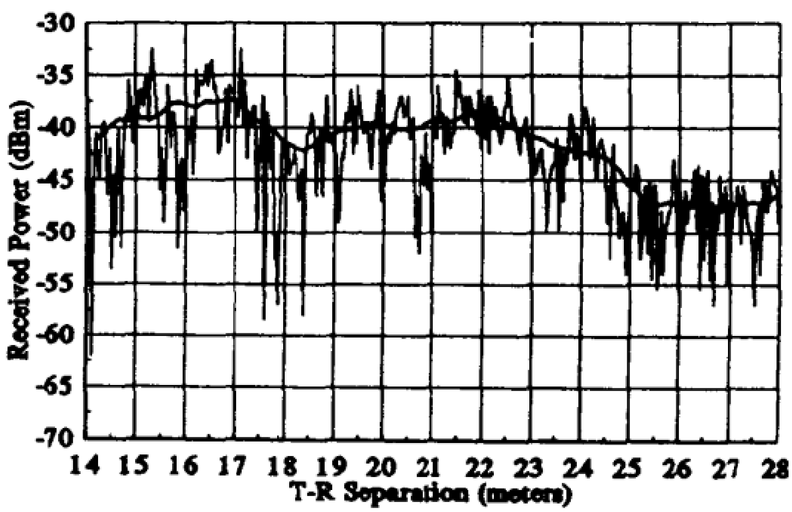
- The improvement in *S/I* implies that with 120° sectoring, the minimum required *S/I* of 18 dB can be easily achieved with 7-cell reuse.
- Thus, sectoring reduces interference, which amounts to an increase in capacity by a factor of 12/7, or 1.714.
- In practice, the reduction in interference offered by sectoring enable planners to reduce the cluster size N, and provides an additional degree of freedom in assigning channels.
- The disadvantage for improved *S/I* and the resulting capacity improvement is an increased number of antennas at each base station, and a decrease in trunking efficiency due to channel sectoring at the base station.

Mobile Radio Propagation

- The transmission path between the transmitter and the receiver can be either:
  a. Simple line-of-sight (LOS), or
  b. Obstructed by buildings, mountains, and foliage.



- The speed of motion impacts how rapidly the signal level fades as a mobile terminal moves.
- The signal strength decreases as the distance between the transmitter and receiver increases.
- Propagation models have focused on predicting the average received signal strength at a given distance from the transmitter.
  a. **Large-scale propagation models**: used for estimating the radio coverage area of a transmitter for large T-R separation distances.
  b. **Small-scale fading models:** models that characterize the rapid fluctuations of the received signal strength over very short travel distances.



- As mobile moves over very small distances, the instantaneous received signal strength may fluctuate rapidly giving rise to small-scale fading. The reason for this is that the received signal is a sum of many rays coming from different directions.

Free Space Propagation loss

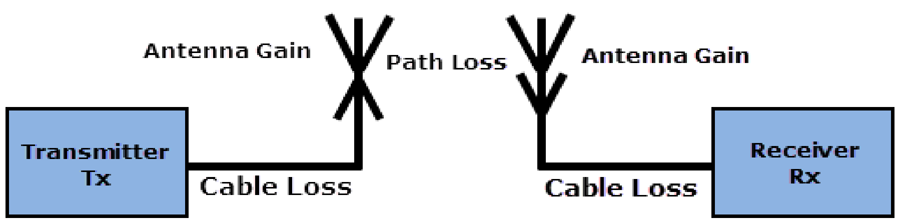
- The free space propagation model is used to predict received signal strength when the transmitter and receiver have a clear, unobstructed LOS path between them.
- As with most large-scale radio wave propagation models, the free space model predicts that received power decays as a function of the T-R separation distance raised.

The free space power received by a receiver antenna which is separated from a radiating transmitter antenna by a distance *d*, is given by the Friis free space equation,

$$P_r(d) = \frac{P_t G_t G_r}{L}\left(\frac{\lambda}{4\pi d}\right)^2$$

where

P_t is the transmitted power in watts,
$P_r(d)$ is the received power which is a function of the T-R separation in watts,
G_t is the transmitter antenna gain,
G_r is the receiver antenna gain,
d is the T-R separation distance in meters,
L is the system loss factor not related to propagation ($L \geq 1$),
λ is the wavelength in meters.



The gain of an antenna is related to its effective aperture A_e by

$$G = \frac{4\pi A_e}{\lambda^2}$$

The effective aperture A_e is related to the physical size of the antenna, and λ is related to the carrier frequency by

$$\lambda = \frac{c}{f} = \frac{2\pi c}{\omega_c}$$

where

f is the carrier frequency in Hertz (*Hz*),
ω_c is the carrier frequency in radians per second (*rad/s*),
c is the speed of light ($\approx 3\times10^8$ *m/s*).

- The values for P_t and P_r must be expressed in the same units, and G_t and G_r are dimensionless quantities.
- The losses L ($L \geq 1$) are usually due to transmission line attenuation, filter losses, cable loss, and antenna losses in the communication system.
- A value of $L = 1$ indicates no loss in the system hardware.
- An isotropic radiator is an ideal antenna which radiates power with unit gain uniformly in all directions, and is often used to reference antenna gains in wireless systems.

The effective isotropic radiated power (*EIRP*) is defined as

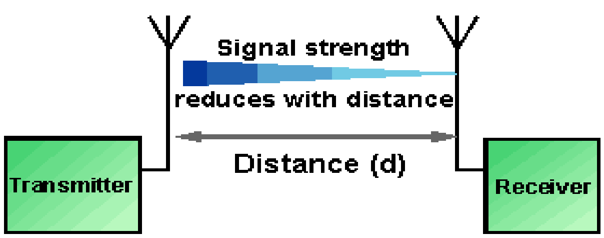
$$EIRP = P_t\, G_t$$

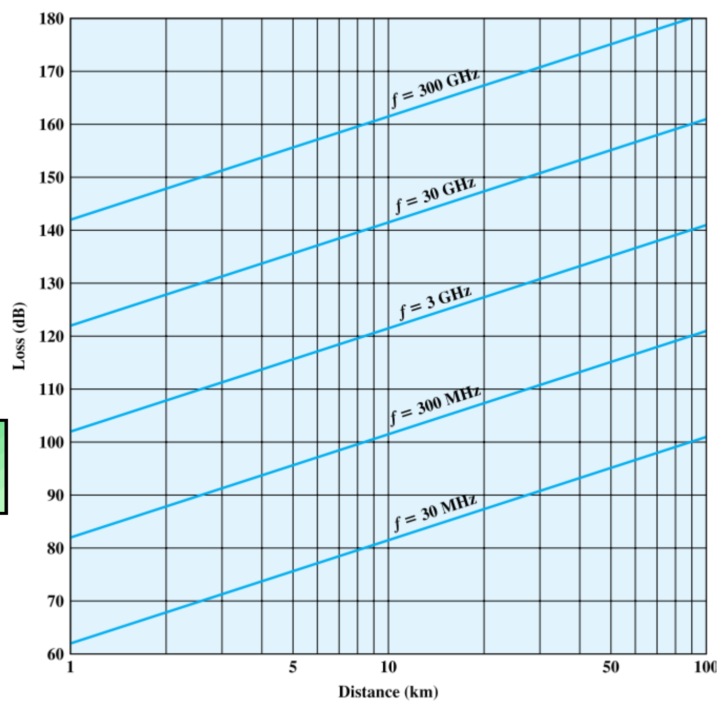
- In practice, antenna gains are given in units of *dBi* (*dB* gain with respect to an isotropic source) or *dBd* (dB gain with respect to a half-wave dipole).
- The Friis free space model is only a valid predictor for P_r for values of d which are in the far-field of the transmitting antenna.

The **path loss** represents signal attenuation as a positive quantity measured in *dB*, is defined as the difference between the transmitted power and the received power.

$$PL(dB) = -20\log\left(\frac{\lambda}{4\pi d}\right)$$

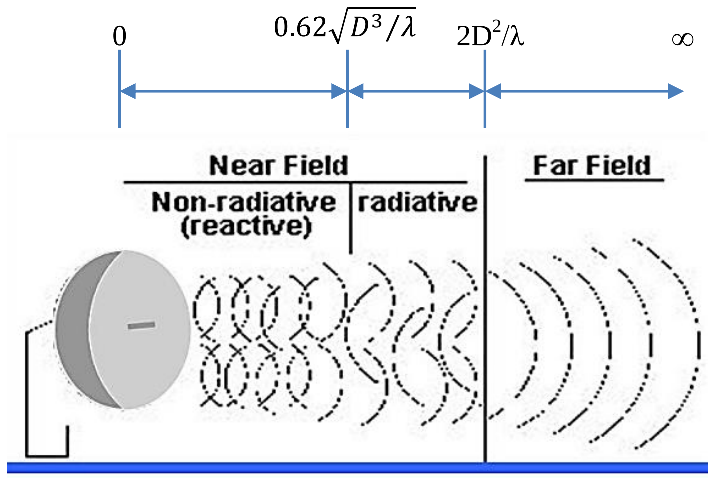
For the same antenna dimensions and separation, the longer the carrier wavelength λ (lower the carrier frequency *f*), the higher is the path loss.





Antenna Field Distances

The fields surrounding an antenna are divided into 3 main regions:



1. Reactive Near Field: is the region where the fields are reactive (the E and H fields are out of phase by 90 degrees to each other). For propagating or radiating fields, the fields must be orthogonal to each other but in phase.

$$Reactive\ near\ field \le 0.62\sqrt{\frac{D^3}{\lambda}}$$

2. Radiating Near Field (Fresnel region) : is the region between the reactive near and far field. The shape of the radiation pattern varies significantly with distance (unlike the far field region).

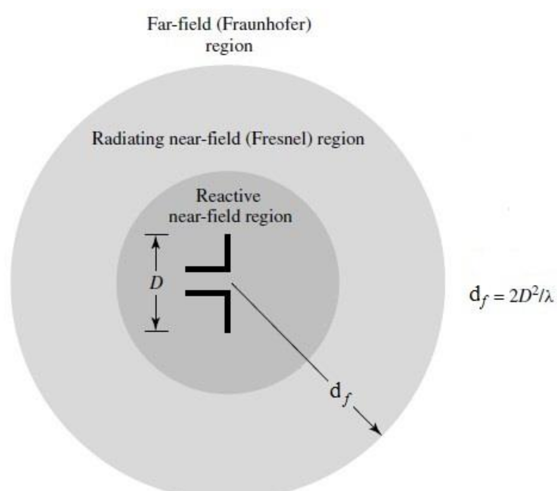
$$Radiating\ near\ field\ (Fresnel\ region) \le \frac{2D^2}{\lambda}$$

3. Far Field (Fraunhofer region): the region beyond the far-field distance d_f. In the far field, the radiation pattern does not change in shape as the distance increases.

$$Far\ field\ (Fraunhofer\ region) \ge \frac{2D^2}{\lambda}$$

The Fraunhofer distance is given by

$$d_f = \frac{2D^2}{\lambda}$$



where D is the largest physical linear dimension of the antenna.

- Friis equation does not hold for $d = 0$. For this reason, large-scale propagation models use a close-in distance, d_0, as a known received power reference point.
- The received power, $P_r(d)$, at any distance $d > d_0$, may be related to P_r at d_0.
- The value $P_r(d_0)$ may be predicted from Friis equation, or may be measured in the radio environment by taking the average received power at many points located at a close-in radial distance d_0 from the transmitter.
- The reference distance must be chosen such that it lies in the far-field region, that is, $d_0 \geq d_f$, and d_0 is chosen to be smaller than any practical distance used in the mobile communication system. Thus, using Friis equation, the received power in free space at a distance greater than d_0 is given by

$$P_r(d) = P_r(d_0) \times \left(\frac{d_0}{d}\right)^2$$

where $d \geq d_0 \geq d_f$

- Because of the large dynamic range of received power levels, often *dBm* or *dBW* units are used to express received power levels. This is done by simply taking the logarithm of both sides and multiplying by 10.

Therefore, the received power is given by

$$P_r(d) = 10\log\left[P_r(d_0)\right] + 20\log\left(\frac{d_0}{d}\right)$$

where $P_r(d_0)$ is in units of watts.

Example 1

Find the far-field distance for an antenna with maximum dimension of 1*m* and operating frequency of 900 *MHz*.

Solution

Given:
Largest dimension of antenna, $D = 1m$,
Operating frequency, $f = 900\ MHz$,

$$\lambda = \frac{c}{f} = \frac{3\times10^8}{900\times10^6} = 0.33m$$

$$d_f = \frac{2D^2}{\lambda} = \frac{2(1)^2}{0.33} = 6m$$

Example 2

If a transmitter produces 50 *watts* of power, express the transmit power in units of

a. *dBm*,
b. *dBW.*

If 50 *watts* is applied to a unity gain antenna with a 900 *MHz* carrier frequency, find the received power in *dBm* at a free space distance of 100*m* from the antenna. What is P_r *(10 km)*? Assume unity gain for the receiver antenna.

Solution:

Given: $P_t = 50\ W,\ f = 900\ MHz$

(a)

$$P_t(dBm) = 10\log\left[P_t(mW)\right] = 10\log[50\times10^3] = 47\ dBm$$

(b)

$$P_t(dBm) = 10\log\left[P_t(W)\right] = 10\log\left[50\right] = 17\ dBW$$

$$P_r(d) = \frac{P_t G_t G_r}{L}\left(\frac{\lambda}{4\pi d}\right)^2 = \frac{50\times1\times1}{1}\left(\frac{0.33}{4\pi\times100}\right)^2 = 3.5\times10^{-6}W = 3.5\times10^{-3}mW$$

$$P_r(dBm) = 10\log P_r(mW) = 10\log(3.5\times10^{-3}\ mW) = -24.5\,dBm$$

The received power at 10 *km* can be expressed in terms of *dBm* as

$$P_{r(dBm)}(10\,km) = P_{r(dBm)}(100) + 20\log\left(\frac{100}{10000}\right) = -24.5\,dBm - 40\,dB = -64.5\ dBm$$

Example 3

Determine the isotropic free space loss at 4 *GHz* for the 3.5 *km* path to a receiver from transmitter.

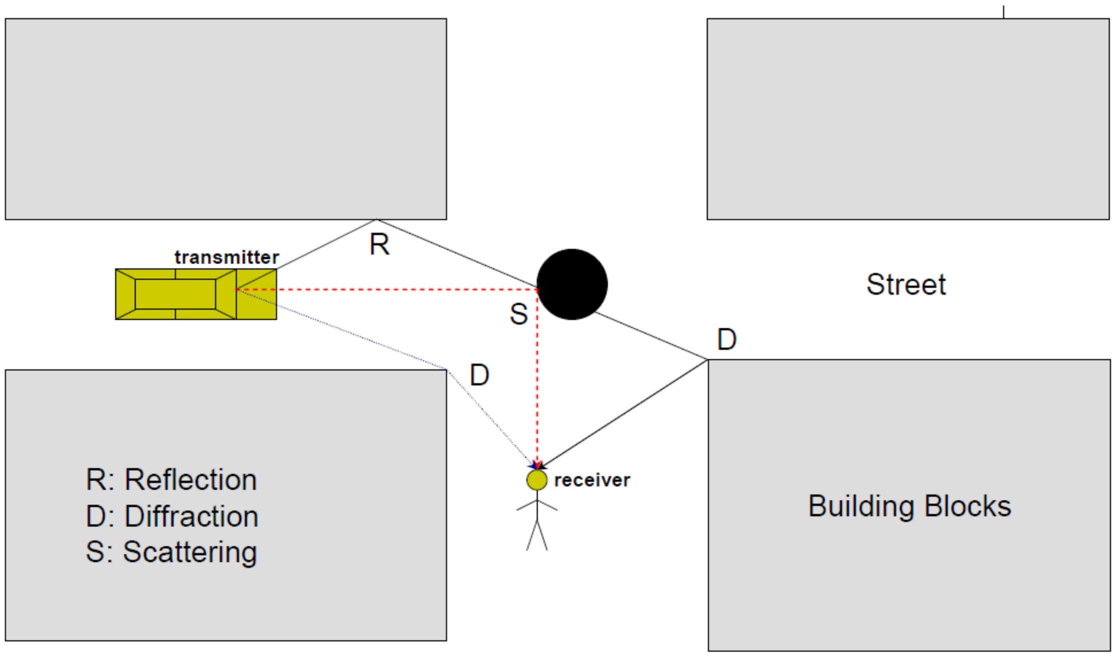
Solution:

$$\lambda = \frac{c}{f} = \frac{3\times10^8}{4\times10^9} = 0.075\,m$$

$$PL(dB) = -20\log\left(\frac{0.075}{4\pi\times3.5\times10^3}\right) = 115.4\ dB$$

Basic Propagation mechanisms

- Apart from LOS communication, the mechanisms behind electromagnetic wave propagation can generally be attributed to
    a. Reflection,
    b. Diffraction,
    c. Scattering.



A. Reflection

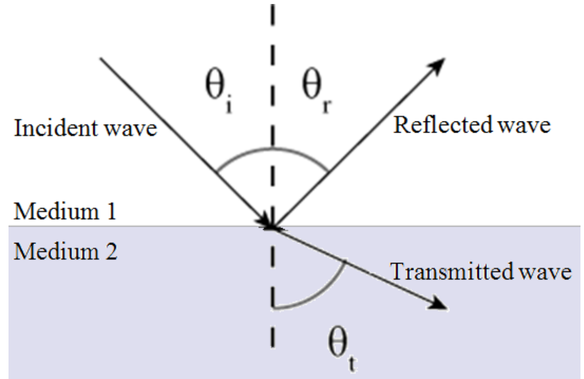
❖ <u>Occurs when EM waves impinge upon an obstruction that is much larger in size compared to the wavelength of the signal.</u>

Example: Reflections occur from the surface of the earth and from buildings and walls, these reflections may interfere with the original signal constructively or destructively

- Interaction of electromagnetic (EM) waves with materials having different electrical properties than the material through which the wave is traveling leads to transmitting of energy.

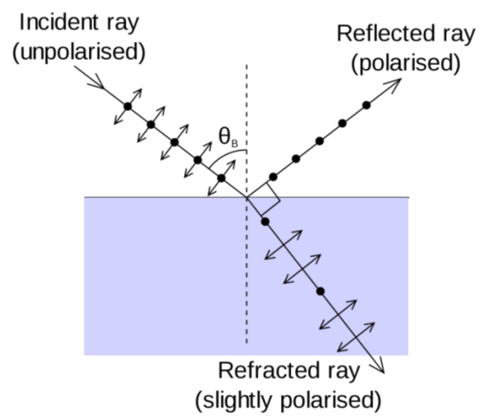
- When a radio wave falls on another medium having different electrical properties, a part of it is transmitted into it, while some energy is reflected back.

- If the medium is a **dielectric**, some energy is reflected back and some energy is transmitted.
- If the medium is a perfect **conductor**, all energy is reflected back to the first medium.



- The amount of energy that is reflected back depends on the polarization of the EM wave.

- **Brewster's angle** (also known as the polarization angle) is an angle of incidence at which wave with a particular polarization is perfectly transmitted through a dielectric surface, with no reflection (reflection coefficient is equal to zero).



- By applying laws of electromagnetics, it is found to be

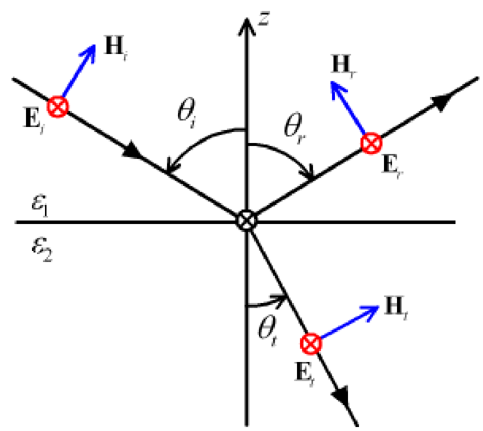
$$\sin\theta_B = \sqrt{\frac{\varepsilon_1}{\varepsilon_1+\varepsilon_2}}$$

- For the case when the first medium is free space and the second medium has a relative permittivity ε_r, Brewster's angle can be expressed as

$$\sin\theta_B = \frac{\sqrt{\varepsilon_r - 1}}{\sqrt{\varepsilon_r^2 - 1}}$$

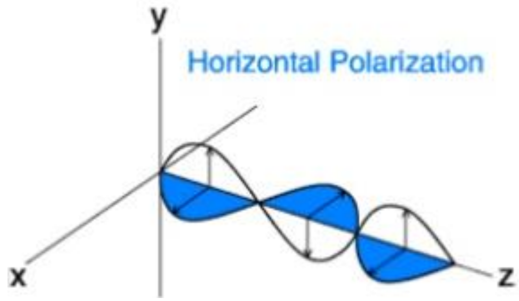
Note that the Brewster angle occurs only for vertical (i.e. parallel) polarization.

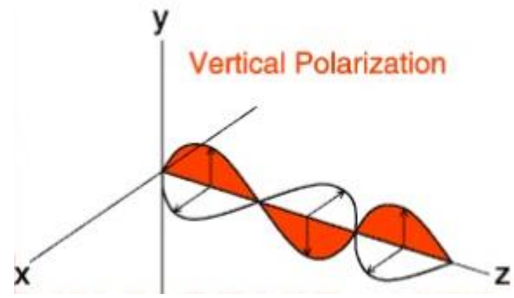
- The reflection coefficient depends on:
  - (a) Wave polarization
  - (b) Angle of incidence,
  - (c) Frequency of the propagating wave.



- For example, as the EM waves cannot pass through conductors, all the energy is reflected back with angle of incidence equal to the angle of reflection and reflection coefficient Γ= −1.

- In general, EM waves are polarized, meaning they have instantaneous electric field components in orthogonal directions in space.





Example

Calculate the Brewster angle for a wave impinging on ground having a permittivity of $\varepsilon_r = 4$.

Solution:

$$\sin\theta_B = \frac{\sqrt{\varepsilon_r - 1}}{\sqrt{\varepsilon_r^2 - 1}} = \frac{\sqrt{4-1}}{\sqrt{4^2 - 1}} = \frac{\sqrt{3}}{\sqrt{15}} = \sqrt{\frac{1}{5}}$$

$$\theta_B = \sin^{-1}\sqrt{\frac{1}{5}} = 26.56^o$$

Reflection from perfect conductor

- The electric field inside the perfect conductor is always zero. Hence all energy is reflected back. Therefore

$$\theta_i = \theta_r$$

a. For vertical polarization, and

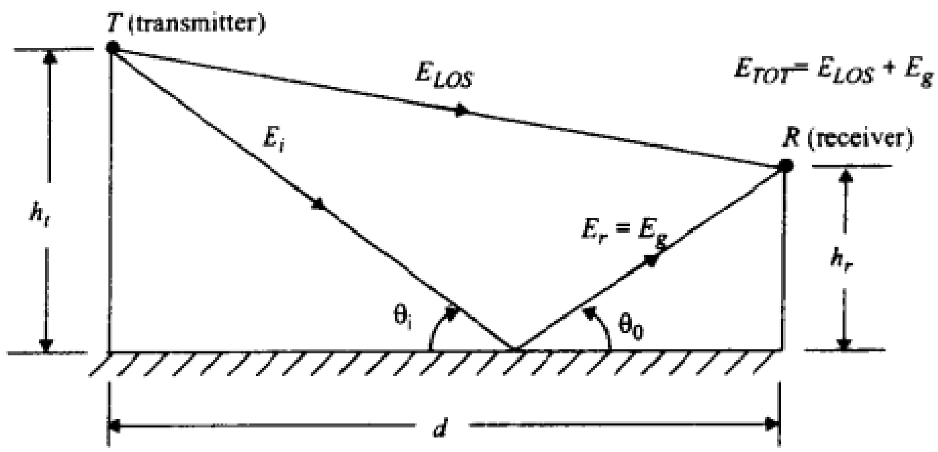
$$E_i = E_r$$

b. For horizontal polarization.

$$E_i = -E_r$$

Ground Reflection (2-ray) Model

- A single direct path between the base station and a mobile is seldom.
- The 2-ray ground reflection model (shown in Figure below) is a useful propagation model that is based on geometric optics, and considers both the direct path and a ground reflected propagation path between transmitter and receiver.
- This model is reasonably accurate for predicting the large-scale signal strength over distances of several kilometers for mobile radio systems that use tall towers (heights which exceed 50*m*), as well as for LOS microcell channels in urban areas.
- In most mobile communication systems, the maximum T-R separation distance is only a few tens of kilometers, and the earth may be assumed to be flat.
- The total received E-field (E_{TOT}) is a result of the direct LOS component (E_{LOS}), and the ground reflected component (E_g).



- Referring to Figure, h_t is the height of the transmitter and h_r is the height of the receiver.
- Two propagating waves arrive at the receiver:
  - The **direct wave** (LOS) that travels a distance *d'*
  - The **reflected wave** that travels a distance *d''*.

- The power received power at a distance *d* from the transmitter can be expressed as

$$P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4}$$

As seen from the equation above at large distances $d >> \sqrt{h_t h_r}$, the received power falls off with distance raised to the fourth power, or at a rate of 40 dB/decade. This is a much more rapid path loss than is experienced in free space.

- The received E-field at a distance *d* from the transmitter can be approximated as

$$E_{TOT}(d) \approx \frac{2E_0 d_0}{d} \frac{2\pi h_t h_r}{\lambda d} \ \ V/m$$

where *d* is the distance over a flat earth between the bases of the transmitter and receiver antennas,

Example

A mobile is located 5 *km* away from a base station and uses a vertical *λ/4* monopole antenna with a gain of 2.55 dB to receive cellular radio signals. The E-field at 1*km* from the transmitter is measured to be 10^{-3} *V/m*. The carrier frequency used for this system is 900 *MHz*.

a) Find the length and the effective aperture of the antenna.

b) Find the received power at the mobile using the 2-ray ground reflection model assuming the height of the transmitting antenna is 50*m* and the receiving antenna is 1.5*m* above ground.

Solution

a)

$$\lambda = \frac{c}{f} = \frac{3\times10^8}{900\times10^6} = 0.333m$$

Thr Length of the antenna = *λ/4* = 0.333/4 = 0.0833 *m* = 8.33 *cm*.

The effective aperture of the *λ/4* monopole antenna can be obtained using

$$A_e = \frac{G\lambda^2}{4\pi} = \frac{10^{\frac{2.55\,dB}{10}} \times (0.33)^2}{4\pi} = 0.01588\ m^2 = 158.8\ cm^2$$

b) Since $d >> \sqrt{h_t h_r}$, the electric field is given by

$$E_{TOT}(d) \approx \frac{2E_0 d_0}{d} \frac{2\pi h_t h_r}{\lambda d} = \frac{2\times10^{-3}\times1\times10^3}{5\times10^3}\left[\frac{2\pi\times50\times1.5}{0.333\times5\times10^3}\right] = 113.1\times10^{-6}\ V/m$$

The received power can be obtained using

$$P_r = \frac{|E|^2}{120\pi} A_e = \frac{|E|^2}{120\pi}\left(\frac{G\lambda^2}{4\pi}\right) = \frac{\left(113.1\times10^{-6}\right)^2}{377}\left(\frac{1.8\times(0.333)^2}{4\pi}\right)$$

$$= 5.4\times10^{-13}\ W = -122.68\,dBW\ or\ -92.68\,dBm$$

B. Scattering

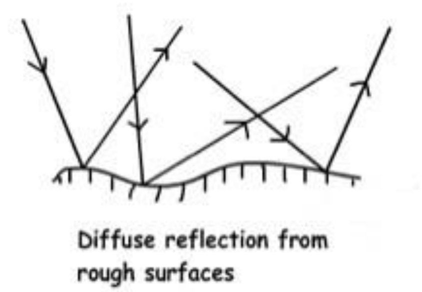
❖ Occurs when the radio channel contains objects whose sizes are on the order of the wavelength or less of the propagating wave and also when the number of obstacles are quite large.

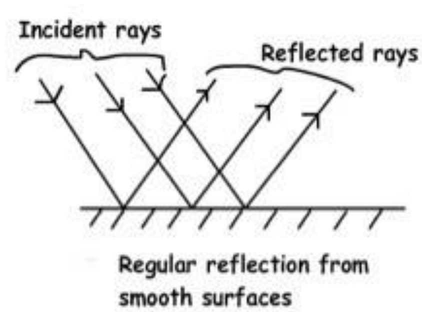
- Produced by small objects, rough surfaces and other irregularities.
- Follows the same principles of diffraction
- Causes the transmitter energy to be radiated in many directions. This provides extra energy at the receiver.
- Trees, lamp posts and street signs may cause scattering.
- The actual received power at the receiver is stronger than claimed by the models of reflection and diffraction.

- Roughness is tested by a Rayleigh criterion, which defines a critical height h_c of surface protuberances for a given angle of incidence θ_i , given by,

$$h_c = \frac{\lambda}{8 \sin \theta_i}$$

a. The surface is *smooth* if its minimum to maximum protuberance h is less than h_c,
b. The surface is *rough* if protuberance is greater than h_c.



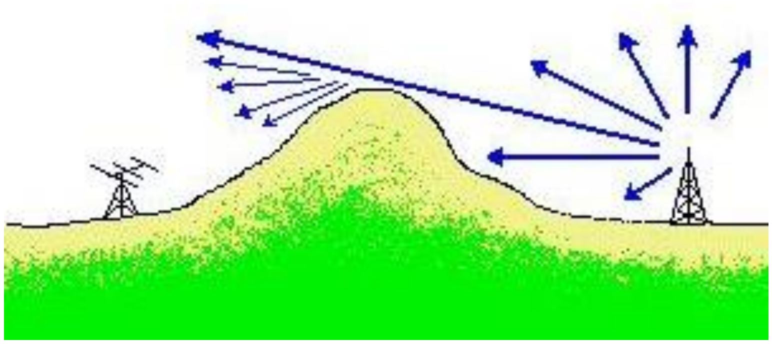


- In case of rough surfaces, the surface reflection coefficient needs to be multiplied by a scattering loss factor ρ_S, The equivalent reflection coefficient is given by,

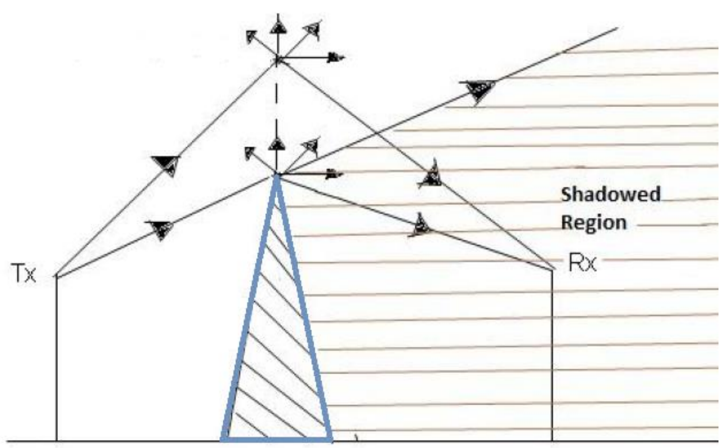
$$\Gamma_{rough} = \rho_S \Gamma$$

C. Diffraction

- Diffraction is the phenomena that occur when radio waves encounter obstacles that have sharp irregularities (edges). The secondary waves resulting from the obstructing surface are present throughout the space and even behind the obstacle.



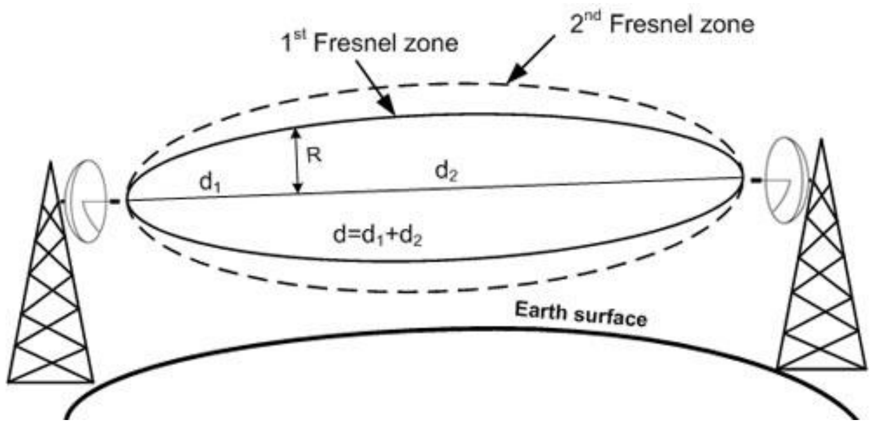
- The radio wave changes in amplitude and phase and penetrates the shadow zone, deviating from a straight line path.
- Diffraction is explained by Huygens-Fresnel principle which states that all points on a wavefront can be considered as the point source for secondary wavelets which form the secondary wavefront in the direction of the prorogation.
- In mobile communication, diffraction, scattering and reflection have a great advantage since the receiver is able to receive the signal even when not in line of sight of the transmitter.
- At high frequencies, diffraction, like reflection, depends on the geometry of the object, as well as the amplitude, phase, and polarization of the incident wave at the point of diffraction.



- Knife-edge diffraction model is one of the simplest diffraction models to estimate the diffraction loss. It considers the object like hill or mountain as a knife edge sharp object.

Fresnel Zones

- As mentioned before, the more is the object in the shadowed region greater is the diffraction loss of the signal.
- The effect of diffraction loss is explained by Fresnel zones as a function of the path difference.
- The successive Fresnel zones have phase difference of π which means they alternatively provide constructive and destructive interference to the received the signal.
- The radius of the each Fresnel zone is maximum at middle of transmitter and receiver (i.e. when $d_1 = d_2$) and decreases as moved to either side.



- It is seen that the loci of a Fresnel zone varied over d_1 and d_2 forms an ellipsoid with the transmitter and receiver at its focii.
    a. If there's no obstruction, then all Fresnel zones result in only the direct LOS prorogation and no diffraction effects are observed.
    b. If an obstruction is present, resulting in diffraction and also the loss of energy.
- The height of the obstruction can be positive zero and negative also.
- The diffraction losses are minimum as long as obstruction doesn't block volume of the 1st Fresnel zone.
- Diffraction effects are negligible beyond 55% of 1st Fresnel zone.

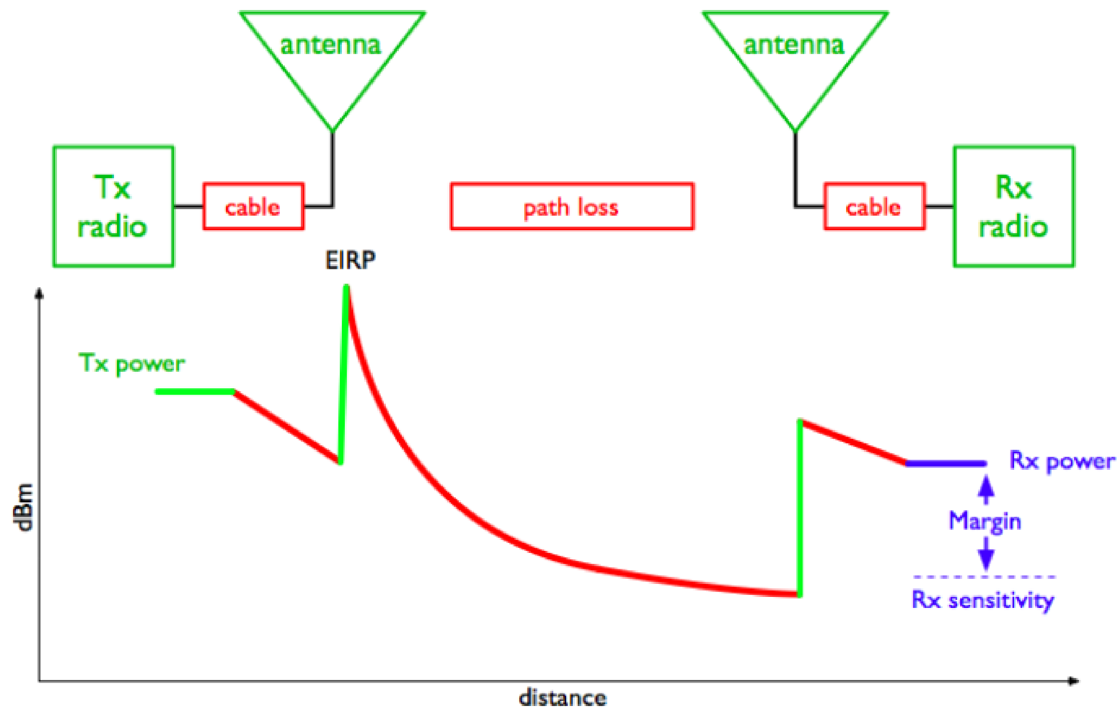
Link Budget Analysis

- The performance of any communication link depends on the quality of the equipment being used.
- Link budget is a way of quantifying the link performance.
- The received power is determined by three factors: transmit power, transmitting antenna gain, and receiving antenna gain.
- If that power, minus the free space loss of the link path, is greater than the minimum received signal level of the receiving radio, then a link is possible.

If	$P_t - Free\ Space\ Loss\ > P_r$	$\rightarrow The\ link\ is\ possible$ ✓
If	$P_t - Free\ Space\ Loss\ \leq P_r$	$\rightarrow The\ link\ is\ not\ possible$ ✗

- The difference between the minimum received signal level and the actual received power is called the **link margin**.

- The link margin must be positive, and should be maximized (should be at least 10dB or more for reliable links).



Example:

Let's estimate the feasibility of a 5 km link. One access point and one client radio. The access point is connected to an antenna with 10 dBi gain, with a transmitting power of 20 dBm and a receive sensitivity of -89 dBm.

The client is connected to an antenna with 14 dBi gain, with a transmitting power of 15 dBm and a receive sensitivity of -82 dBm. The cables in both systems are short, with a loss of 2dB at each side at the 2.4 GHz frequency of operation

Solution:

A) AP to Client link

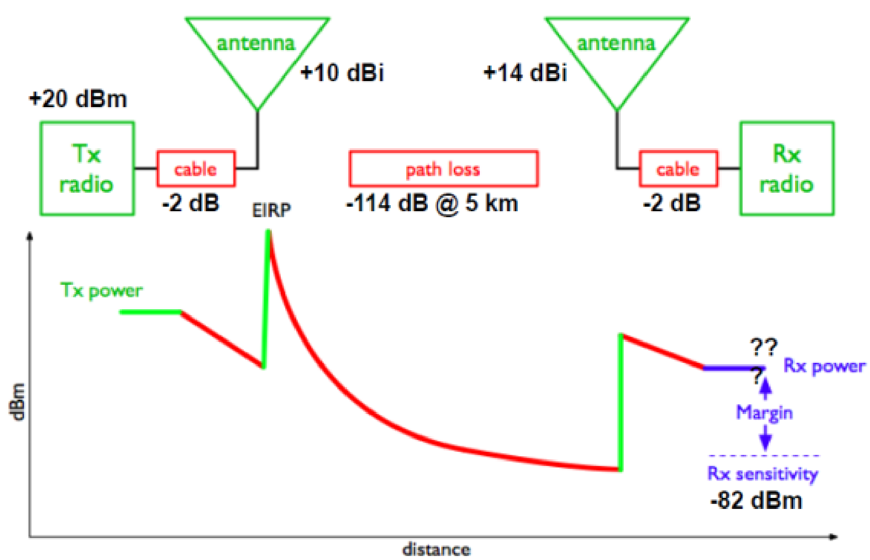
$$Total\ gain = Tx\ Power(AP) + Antenna\ Gain\ (AP) - Cable\ loss(AP)$$
$$+Antenna\ gain(Client) - Cable\ loss(Client)$$
$$= 20\ dB + 10\ dB - 2\ dB + 14\ dB - 2\ dB = 40\ dB$$

$$\lambda = \frac{c}{f} = \frac{3\times10^8}{2.4\times10^9} = 0.125m$$

$$Free\,Space\,Loss(PL) = -20\log\left(\frac{\lambda}{4\pi d}\right) = -20\log\left(\frac{0.125}{4\pi\times5000}\right) = 114\,dB$$

$$Expected\ P_r = Total\ gain - Path\ Loss\ (PL)$$
$$=\ 40\ dB - 114\ dB =\ -74\ dBm$$

$$Link\ Margin = Expected\ P_r - Sensitivity\ of\ Client$$
$$=\ -74 - (-82) = 8\ dB$$



B) Client to AP link

$$Total\ gain = Tx\ Power(Client) + Antenna\ Gain\ (Client) - Cable\ loss(Client)$$

$$+Antenna\ gain(AP) - Cable\ loss(AP)$$

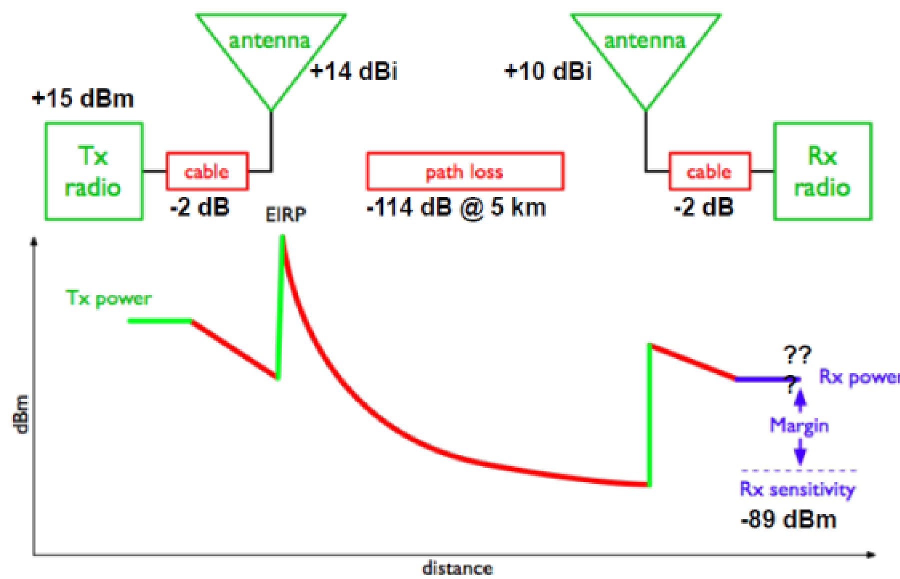
$$= 15\ dB + 14\ dB - 2\ dB + 10\ dB - 2\ dB = 35\ dB$$

$$Expected\ P_r = Total\ gain - Path\ Loss\ (PL)$$

$$= 35\ dB - 114\ dB = -79\ dBm$$

$$Link\ Margin = Expected\ P_r - Sensitivity\ of\ AP$$

$$= -79 - (-89) = 10\ dB$$



Multiple Access Techniques

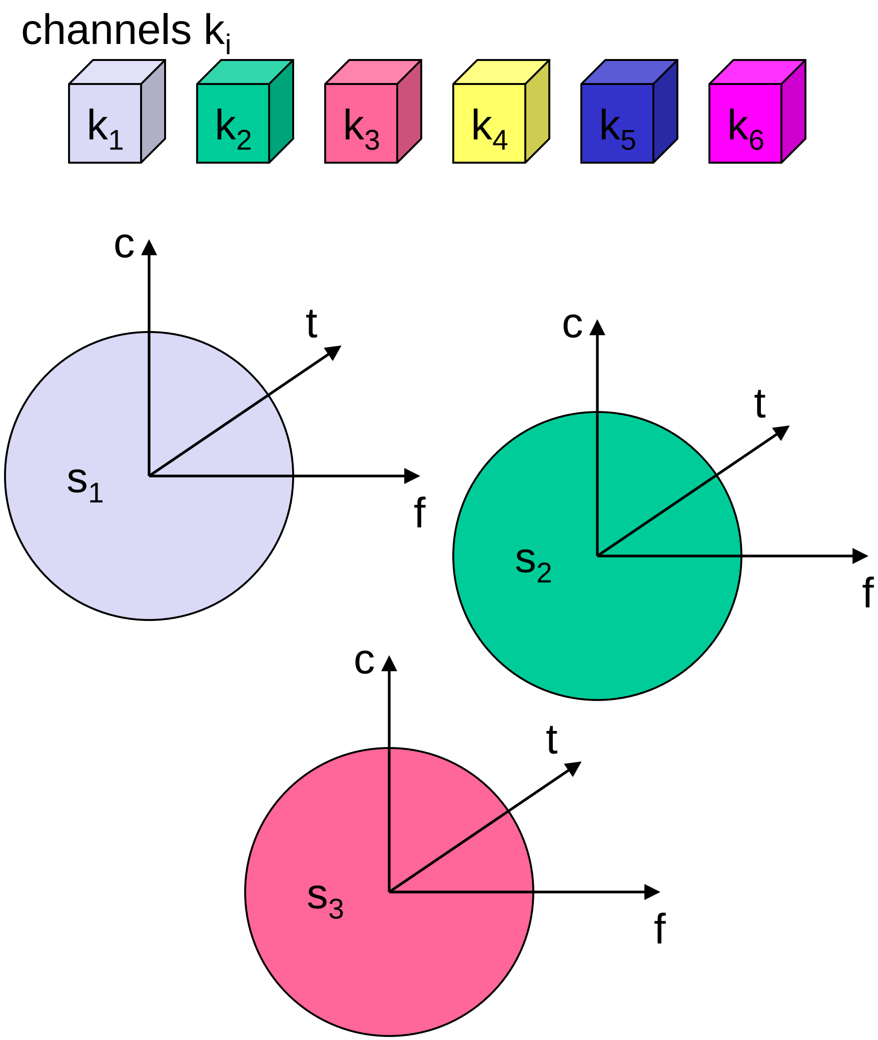
1. Multiplexing

Multiplexing in 4 dimensions

- space (s_i)
- time (t)
- frequency (f)
- code (c)

Goal: multiple use of a shared medium

Important: guard spaces needed!



1.1 Frequency multiplex

Separation of the whole spectrum into smaller frequency bands

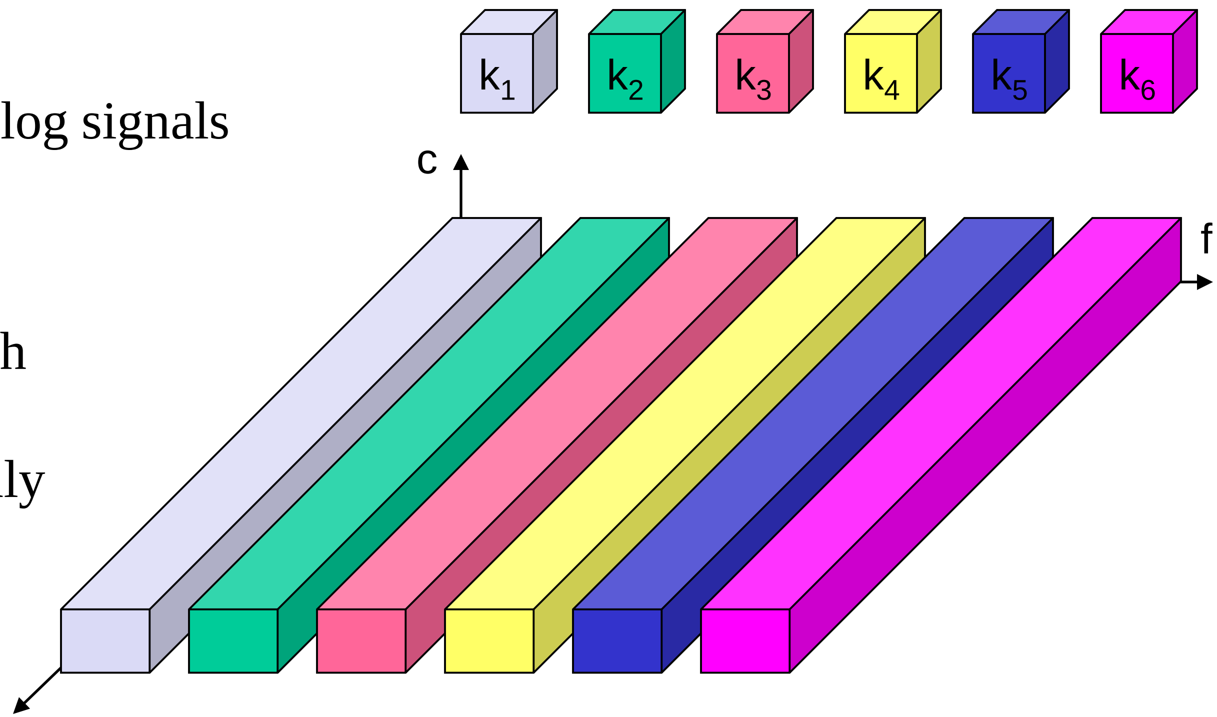
A channel gets a certain band of the spectrum for the whole time

Advantages:

- no dynamic coordination necessary
- works also for analog signals

Disadvantages:

- waste of bandwidth if the traffic is distributed unevenly
- inflexible
- guard spaces



1.2 Time multiplex

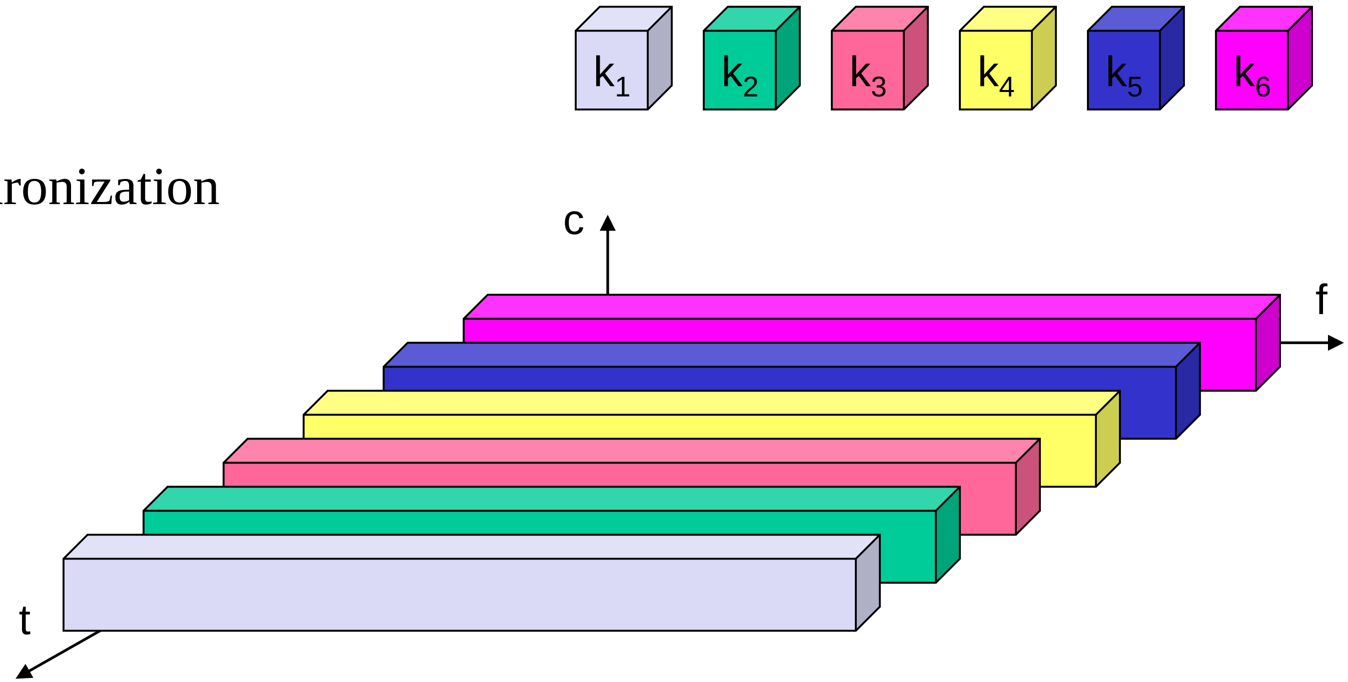
A channel gets the whole spectrum for a certain amount of time

Advantages:

- only one carrier in the medium at any time
- throughput high even for many users

Disadvantages:

- precise synchronization necessary



1.3 Time and frequency multiplex

Combination of both methods

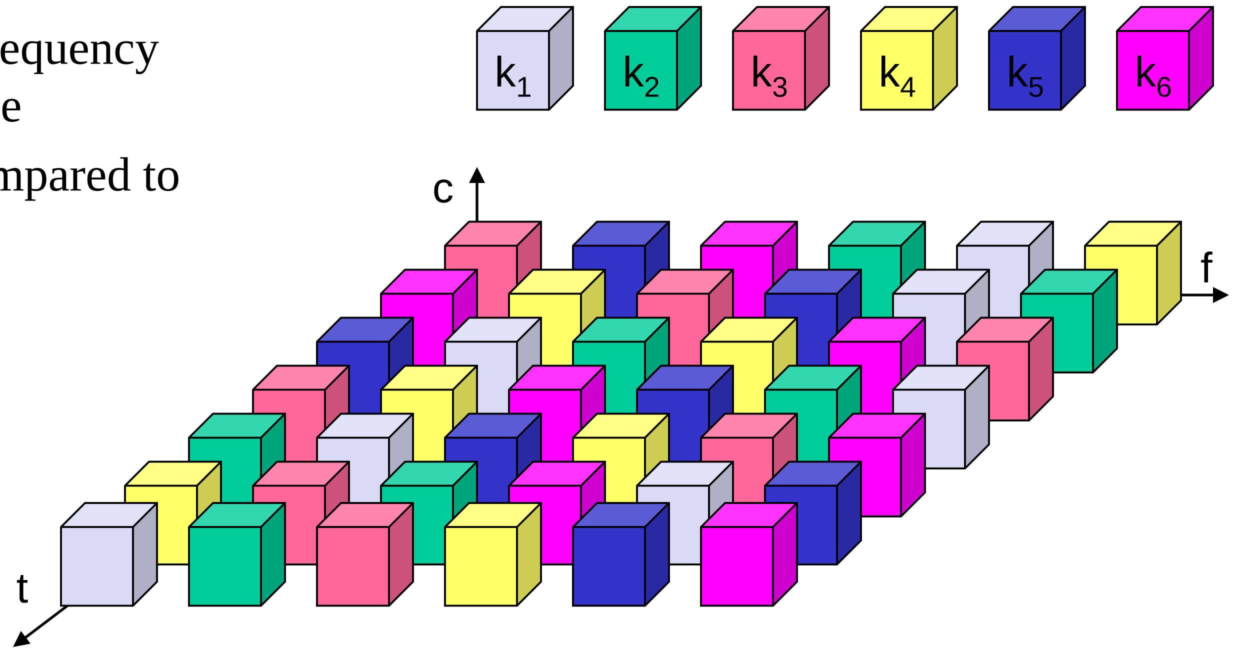
A channel gets a certain frequency band for a certain amount of time

Example: GSM

Advantages:

- better protection against tapping
- protection against frequency selective interference
- higher data rates compared to code multiplex

but: precise coordination required



1.4 Code multiplex

Each channel has a unique code

All channels use the same spectrum at the same time

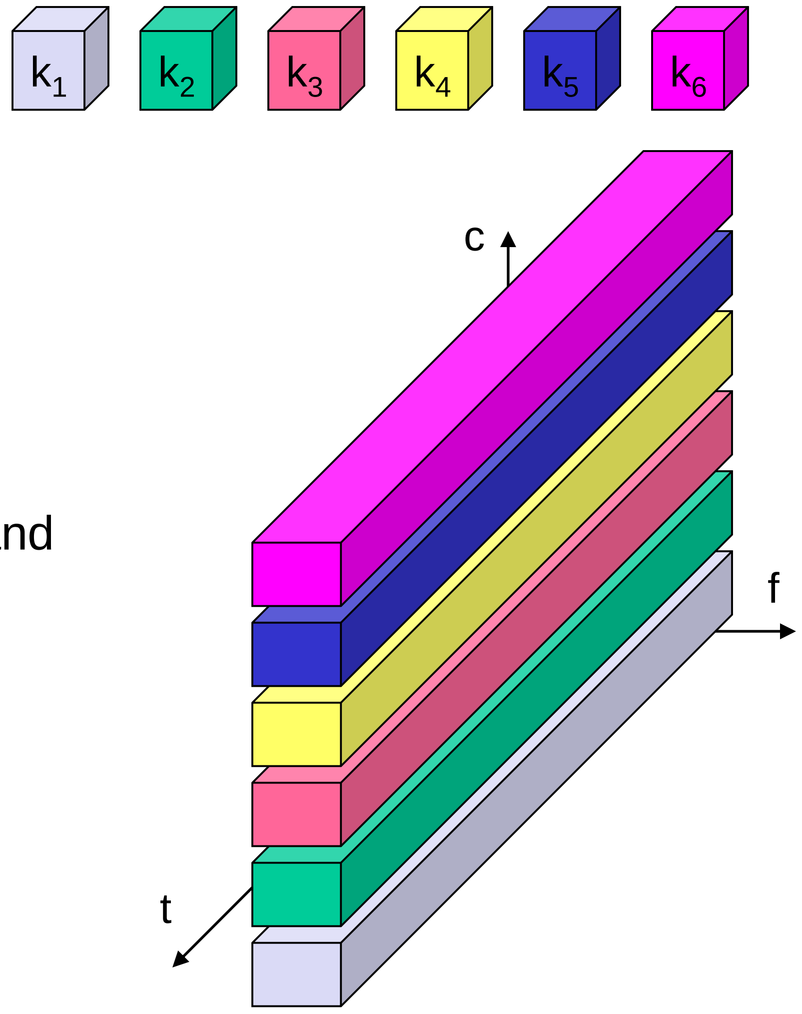
Advantages:

- bandwidth efficient
- no coordination and synchronization necessary
- good protection against interference and tapping

Disadvantages:

- lower user data rates
- more complex signal regeneration

Implemented using spread spectrum technology



6.2 Multiple Division Techniques

To accommodate a number of users, many traffic channels need to be made available.

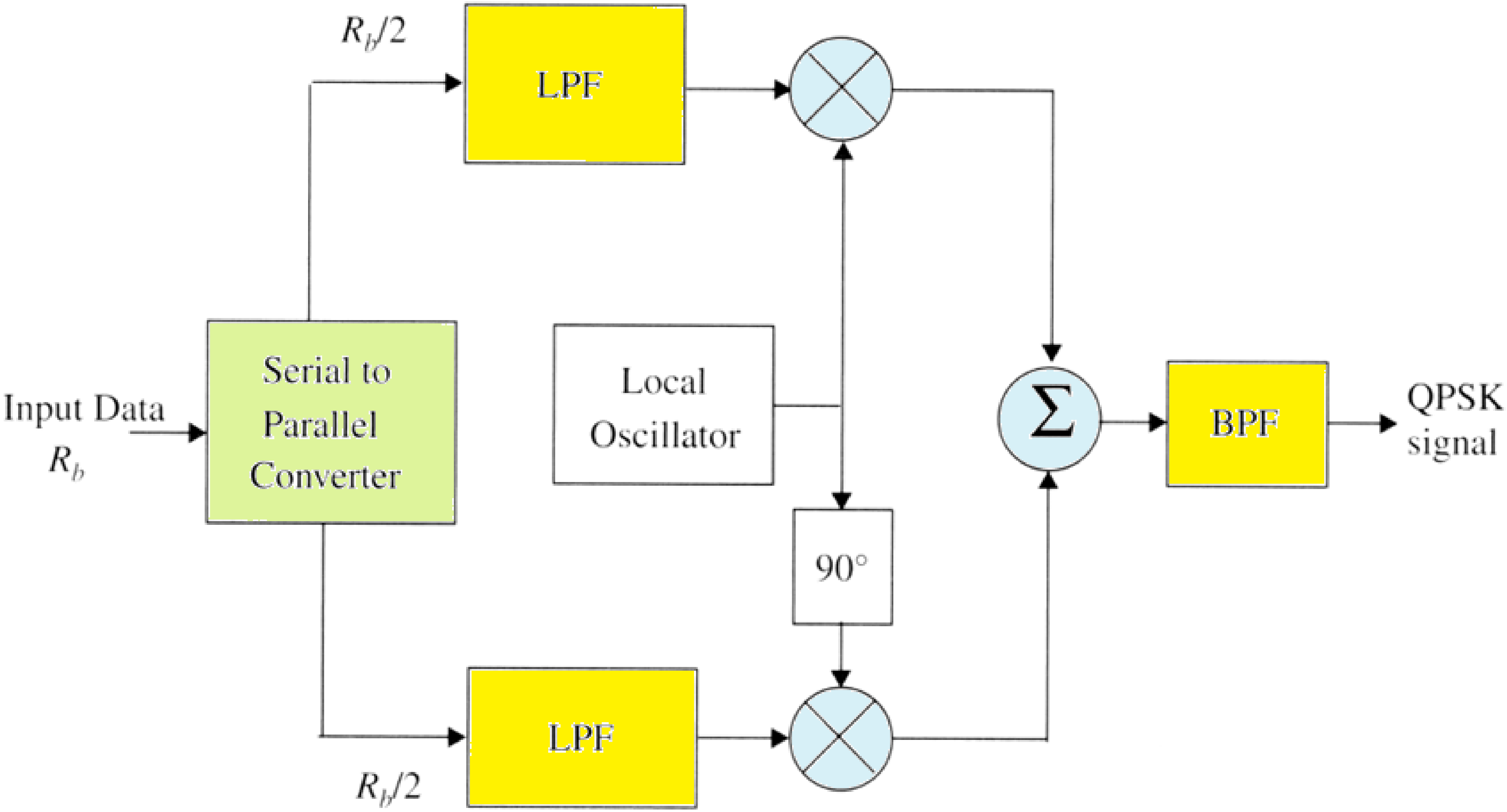
In principle, there are three basic ways to have many channels within an allocated bandwidth:

- Frequency Division Multiple Access (FDMA)
- Time Division Multiple Access (TDMA)
- Code Division Multiple Access (CDMA)

- System employs different carrier frequency – FDMA system.
- System uses distinct time – TDMA system.
- System uses different code – CDMA system.
- In wireless communications, it is necessary to utilize limited frequency bands at the same time, allowing multiple users(MSs) to share radio channel simultaneously.
- To provide simultaneous two-way communication (duplex communication) :
  - Frequency division duplexing (FDD)
  - Time Division Duplexing (TDD)

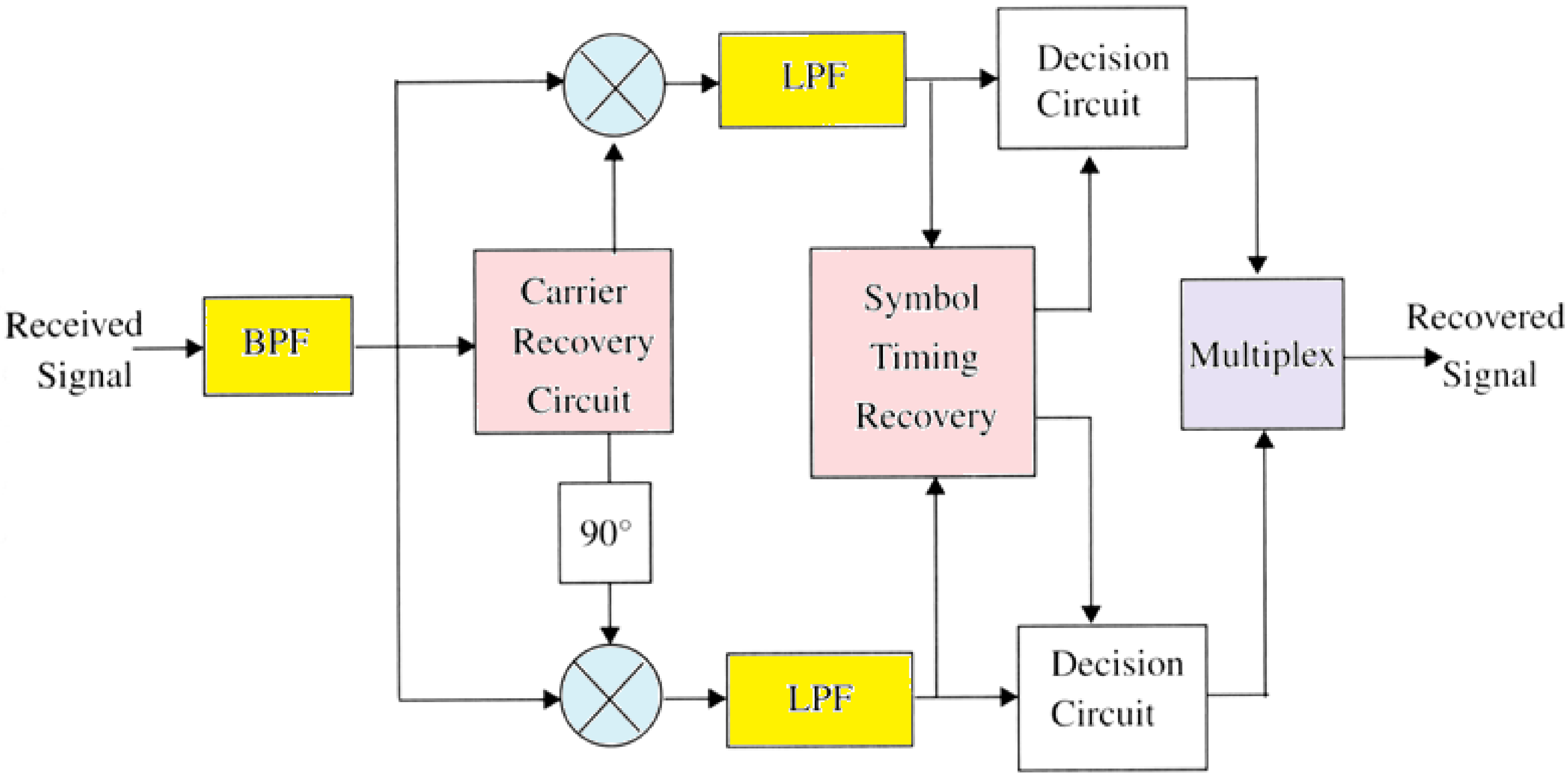
FDMA uses FDD, TDMA & CDMA uses TDD & FDD

3.1. QPSK modulation



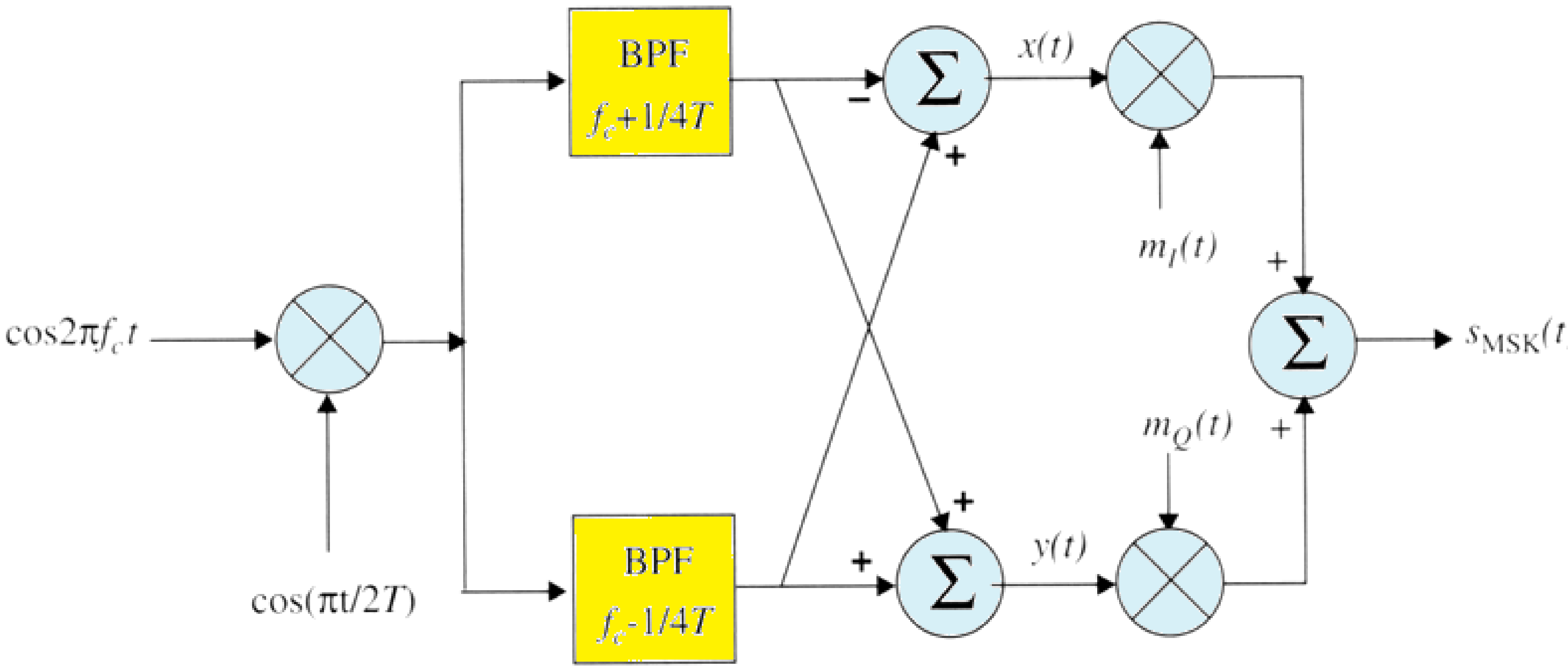
Block diagram of a QPSK transmitter.

3.2. QPSK receiver



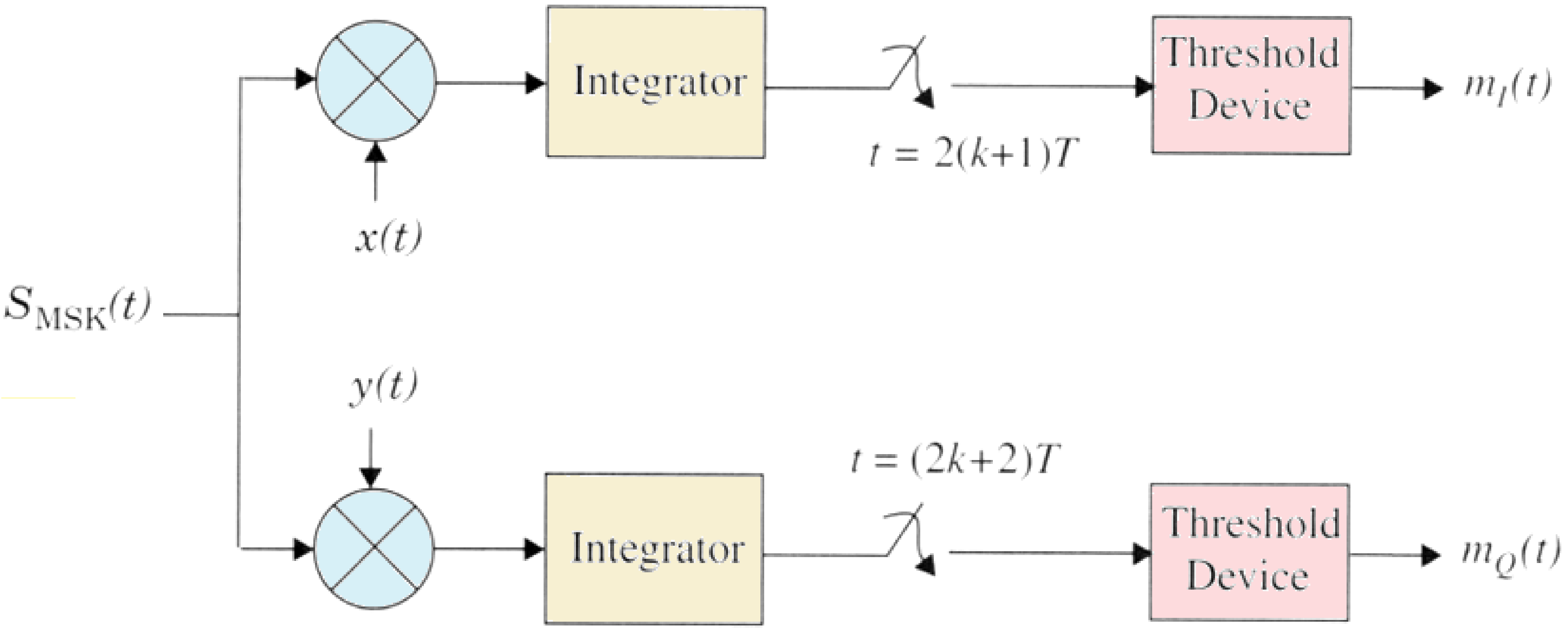
Block diagram of a QPSK receiver

4.1. MSK modulation



Block diagram of an MSK transmitter. Note that $m_I(t)$ and $m_Q(t)$ are offset by T_b.

4.2. MSK receiver



Block diagram of an MSK receiver.

Wireless Systems

IS-95 Interfaces

- A Interface (BSC-MSC) .. This interface is between the BSC and the MSC. It supports both the control plane and user plane
- Abis Interface (BTS-BSC)—This is the interface between the BSC and BTS. This is internal interface and generally proprietary
- B Interface (MSC-VLR) This interface is defined by TIA IS-41
- C Interface (MSC-HLR) This interface uses IS-41 messaging as well
- D Interface (HLR-VLR) – HLR-VLR signaling is based on IS-41 as well. It sits on top of SS7
- E Interface (MSC-MSC)– Inter MSC signaling is defined in IS-41
- L interface (MSC-IWF) This interface allows the ability for circuit switched data in second generation networks
- Um Interface (BS-MS) – This is the air interface between the mobile and the network

Code-Division Multiple Access (CDMA)

- unique digital codes are used to differentiate subscribers
- codes are shared by both MS and BS
- all users share the same range of radio spectrum

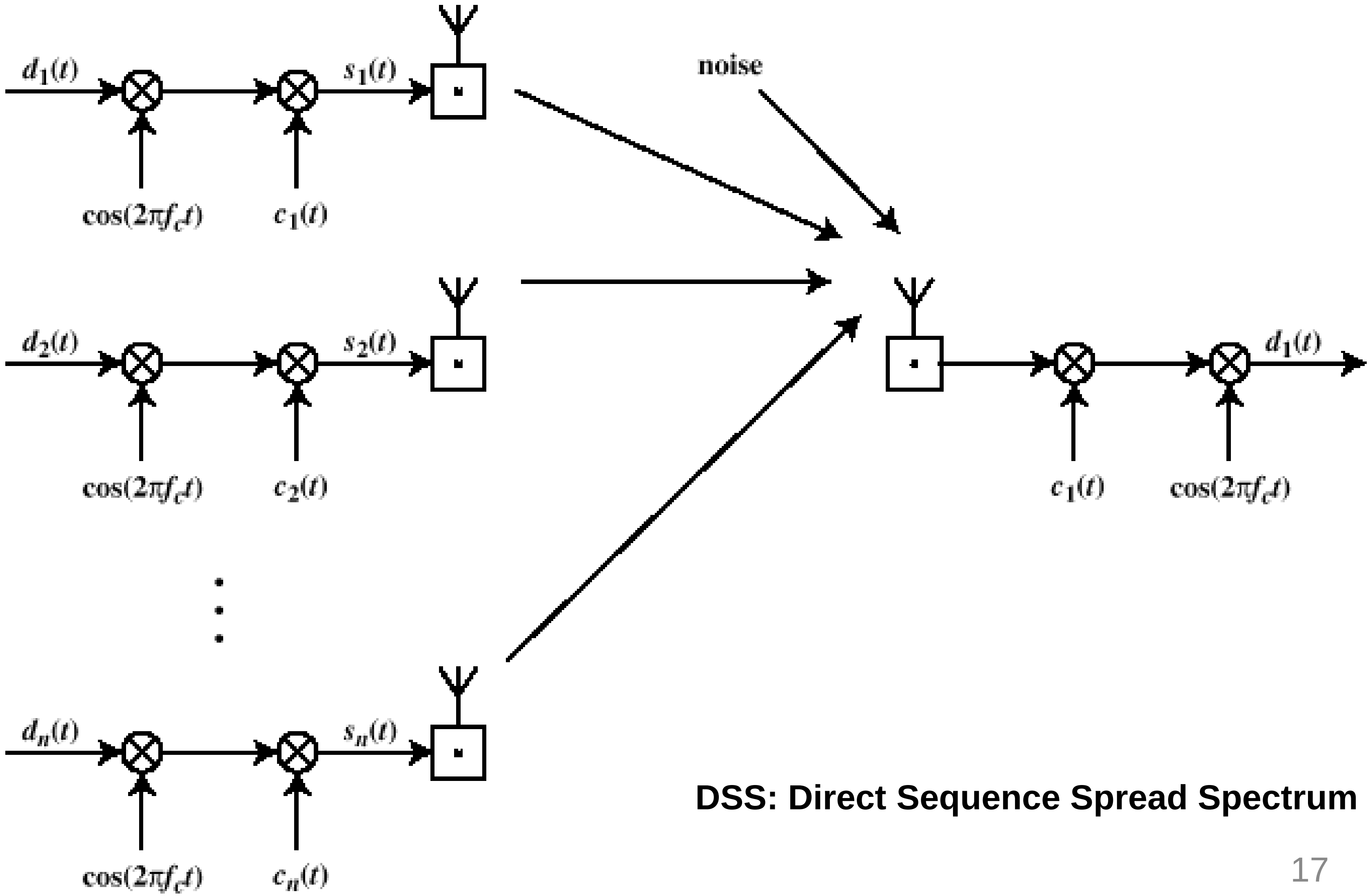
- Benefits of CDMA:
  1) Capacity increases: 4 to 5 times (GSM)
  2) Improved call quality
  3) Simplified system planning
  4) Enhanced privacy

Code-Division Multiple Access (CDMA)

5) Improved coverage characteristics
6) Increased talk time for portables
7) Bandwidth on demand

- Disadvantages
  - Receiver must be precisely synchronized with the transmitter to apply the decoding correctly
  - Receiver must know the code and must separate the channel with user data from the background noise composed of other signals and environmental noise

CDMA for DSSS



DSS: Direct Sequence Spread Spectrum

GPRS

- General Packet Radio Service (GPRS) is a new bearer service for GSM that greatly improves and simplifies wireless access to packet data networks

- GPRS applies packet radio principal to transfer user data packets in an efficient way b/w MS & external packet data network

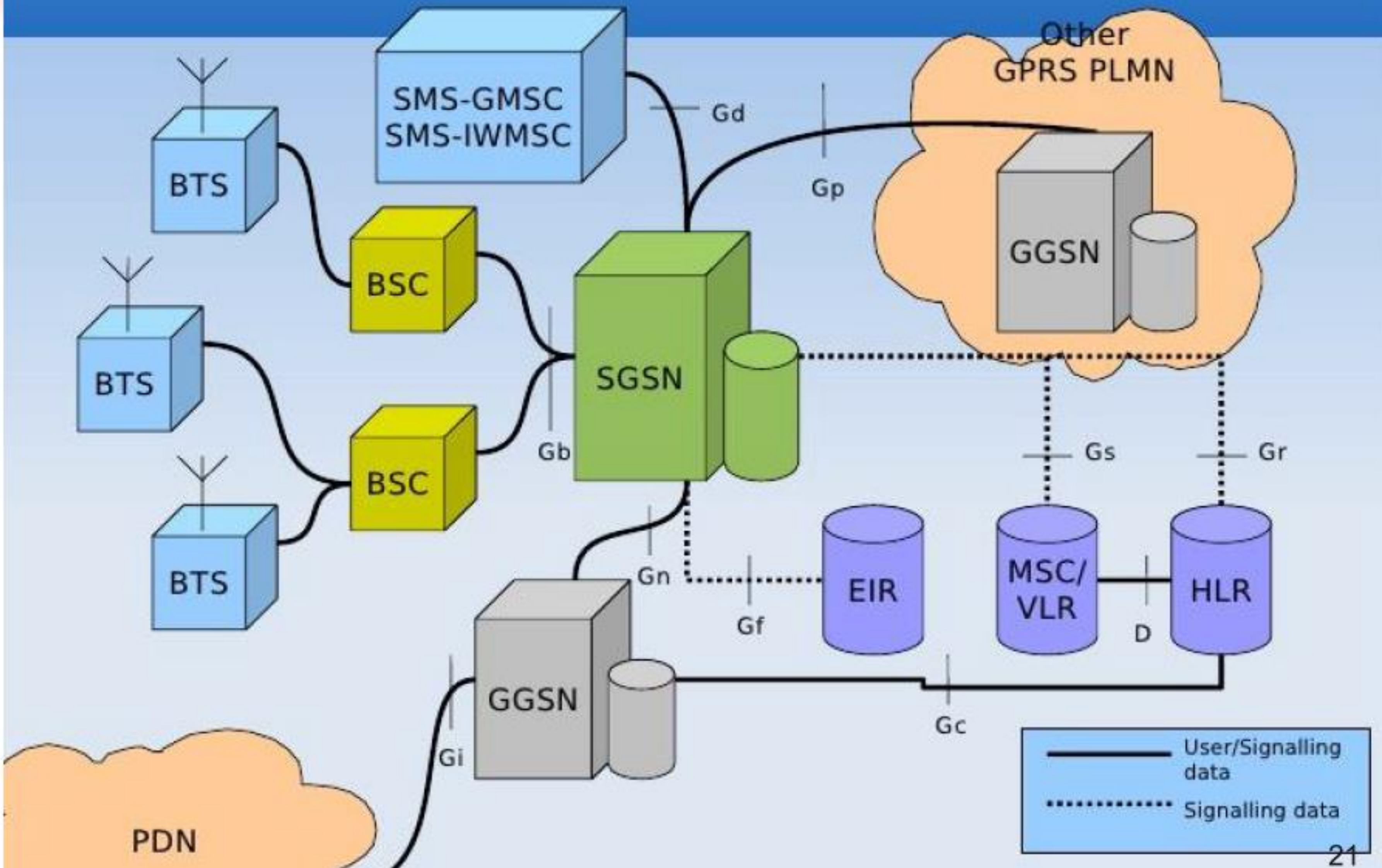
GPRS Mobile stations

New Mobile Station are required to use GPRS services because existing GSM phones do not handle the enhanced air interface or packet data. A variety of MS can exist, including a high-speed version of current phones to support high-speed data access, a new PDA device with an embedded GSM phone, and PC cards for laptop computers. These mobile stations are backward compatible for making voice calls using GSM

Benefits of GPRS

- New Data Services
- High Speed (Data Rate 14.4 – 115 kbps)
- Efficient use of radio bandwith (Statistical Multiplexing)
- Circuit switching & Packet Switching can be used in parallel
- Constant connectivity

GPRS System Architecture



WiFi, Bluetooth and ZigBee

Wireless Technology Differences

Standard	Family	Downlink (Mbps)	Uplink (Mbps)	Coverage
WiFi	802.11	11/54/150/300		100m
WiMAX	802.16e	144	35	10km
UMTS (3G) /HSPA (3.5G)	3GPP	14.4	5.76	30km
LTE (4G)	3GPP	360	80	30km

WiFi vs. WiMAX

	IEEE 802.11	IEEE 802.16a
Max Speed	54Mbps (a&g)	10-100Mbps
Range	100m	40 km
Coverage	Indoor	Outdoor
Users	Hundred	Thousand
Service Level	None	Yes

Bluetooth vs. WiFi

	Bluetooth	**Wifi**
Specifications authority	Bluetooth SIG	IEEE, WECA
Year of development	1994	1991
Bandwidth	Low (800 Kbps)	High (11 Mbps)
Hardware requirement	Bluetooth adaptor on all the devices connecting with each other	Wireless adaptors on all the devices of the network, a wireless router and/or wireless access points
Cost	Low	High
Power Consumption	Low	High
Frequency	2.4 GHz	2.4 GHz
Security	It is less secure	It is more secure
Range	10 meters	100 meters
Primary Devices	Mobile phones, mouse, keyboards,office and industrial autom ation devices	Notebook computers, desktopcompu ters, servers
Ease of Use	Fairly simple to use. Can be used to connect upto seven devices at a time. It is easy to switch between devices or find and connect to any device.	It is more complex and requires configuration of hardware and software.

8.4 Bluetooth vs. ZigBee

	Bluetooth (v1)	**ZigBee**
Protocol Stack	250 kb	< 32 kb (4kb)
Range	10 - 100 meters	30 - 100 meters
Link Rate	1 Mbps	250 kbps
Battery	rechargeable	non-rechargeable
Devices	8	2^16
Air Interface	FHSS	DSSS
Usage	frequently	infrequently
Network Join Time	long	short
Extendibility	no	yes
Security	PIN, 64 bit, 128 Bit	128 bit, AES