Fundamentals of Mobile Communication Systems

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Fundamentals of Mobile Communication Systems

This book presents the main concepts and the fundametals of mobile communication systems, and also illustrates the development and the evaluation of celluler systems towards 5G systems. Besides, the book had focused on the arcchitecture, and analysed the functional structure of the LTE, LTE-Advanced as a current generation. Furthermore, in this book, the concepts of celluler systems are explained in sides of base station, switching, operation, RF planning, celluler network coverage, channel assignment stratigies, channel reduction and interface, handoff types and stratigies. Aslo, the book deels deeply with mobile radio propagation and the loss, anntenna and field distance, and propagation mechanisms, truncking, and the approaches to improving the capacity in celluler systems.

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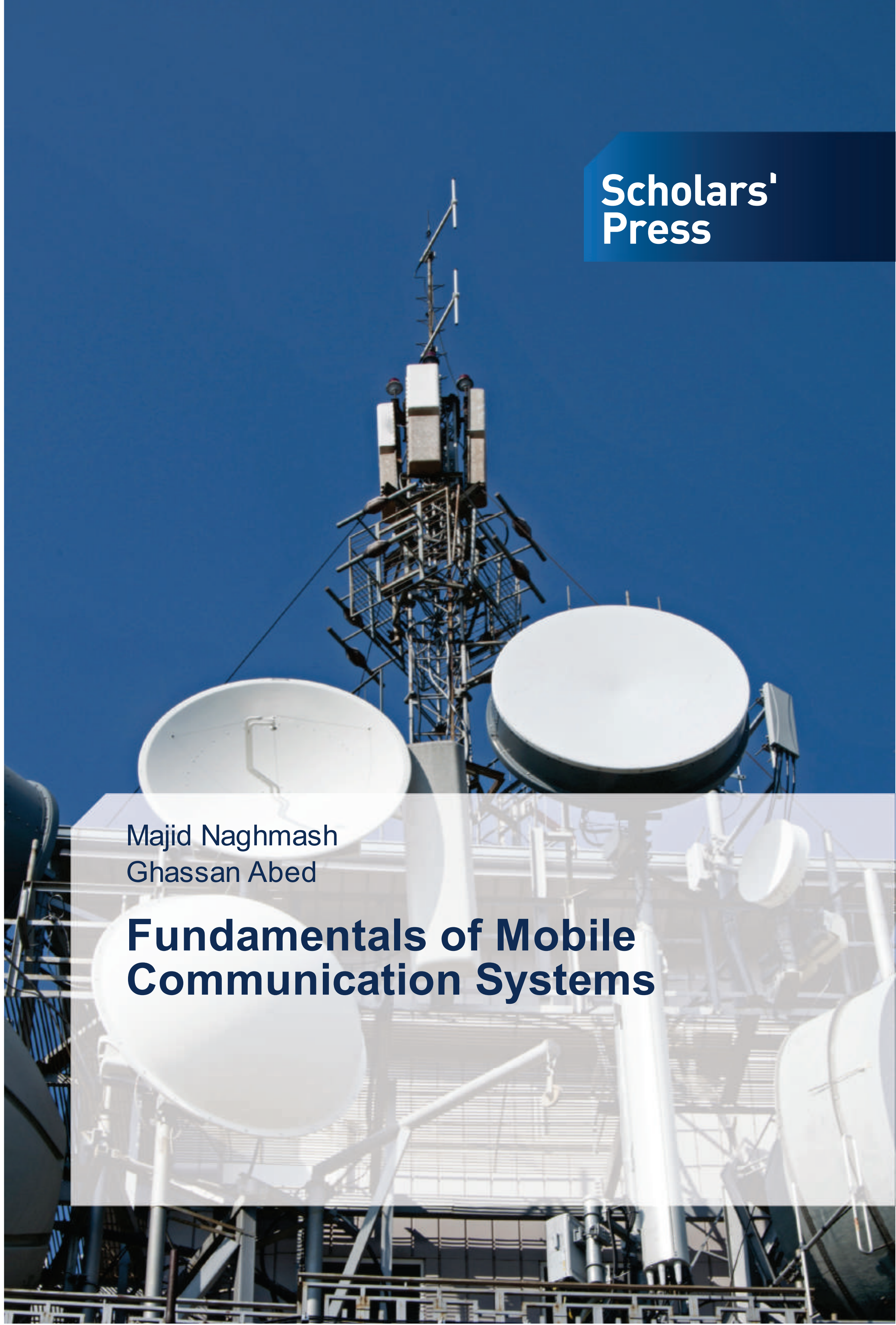

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CHAPTER ONE

INTRODUCTION TO MOBILE COMMUNICATION SYSTEMS

The era of future communication systems is upon us, and finally, it will enter into our lives and change the way we live, because many technological innovations and developments have actually come from our needs in life. The development of mobile systems and the prospect of wireless and cellular communications enquire several questions of the operators, developers, manufacturers, designers, and scientists, working in this field. The communications world is open to several alternatives, such as thoughts, ideas, suggestions, and activities of the near future, which may possibly provide the answers to these open points and indicate the next trends of the communications world, especially over wireless links.

Since 50 years ago, the peoples start to change the communication way to communicate with each other while progress has been impressive much more to communicating with anyone or any device at any place and any time until the software radio (SR) technology is coming in hands. From the beginning of 20th century, the two-way mobile telephone systems used powerful transmitters to cover a distance of 50 km from a high tower. Nonetheless, the reuse of any channels for a different call required in this case their separation of more than 100km.

Consequently, this concept had very low spectral efficiency. The most mobile radio channels was chosen for the first time to backup and community services until the cellular concept was created.

Early 1983, the first cellular system was coming into operation based on the reusing of same limited radio frequency channels in-group of cells arranged in a cellular structure to serve an unlimited number of users and the calls are automatically handles off from cell to other cells.

1.1 Evolution to 5G

The fourth generation (4G) of mobile systems is now replacing the 3G and 2G families of standards. A new mobile generation has always appeared every 10 years since the first generation system in 1981. The second generation in 1992, and the third generation, which was released in 2001, followed this. The development of 4G systems began in 2002. Figure 1.1 shows the evolution of the radio access technologies from the first generation up to the LTE-Advanced in terms of user speed and data rates.

The Advanced Mobile Phone System (AMPS) was the first generation cellular technology that uses separate frequencies, or "channels", for each conversation that was released through the 1980s with limited data rates. Then, it was evaluated to Code Division Multiple Access (CDMA).

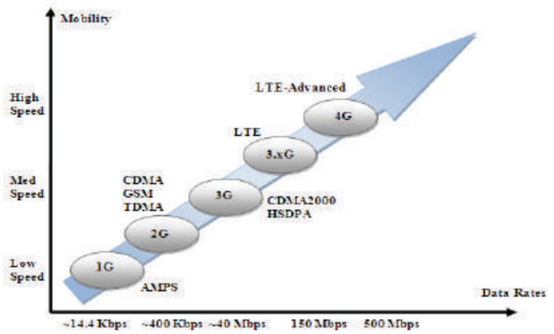


Figure 1.1 Evolution of the radio access technologies

Time Division Multiple Access (TDMA) and CDMA are characterized as a channel access method used by various radio communication technologies and they represent the second generation. In particular, CDMA2000 is a family of the third generation which uses CDMA channel access to send voice, data, and signalling data between mobile phones and cell sites.

However, the real new revolution began with Third Generation Partnership Project (3GPP) in December 1998. 3GPP concept was established through the cooperation of wireless communications associations to issue a globally viable third generation system, with standard specifications, inside the range of the International Mobile Telecommunications-2000 project (IMT-2000) of the International Telecommunication Union (ITU).

Meanwhile, the 3GPP specifications and standards are based on a Global System for Mobile communications (GSM) specifications. The ITU has devised the IMT-Advanced term to recognize the new mobile systems, which is capable of going beyond the International Mobile Telecommunications 2000 (IMT 2000). In specific, the requirements of the data rate have been amplified. Third generation systems were developed to support high performance multimedia communication links, which made enhancements in user-to-user telecommunication links and provided a high quality platform for images and video transfers.

Furthermore, the access to information and services on public, private, and heterogeneous networks would be enhanced by higher rate of data transfer capability and a new flexible communication ability to achieve the users' needs. 3GPP's Long-Term Evolution (LTE) networks achieved the next step towards high data rate transfers and the support of all multimedia functions and requirements. LTE networks were developed to improve the Universal Mobile Telecommunication System (UMTS) mobile phone standards to face future requirements. LTE network approach was not a standard itself, but it resulted in the newly evolved Release 8 of UMTS standard and contained most (if not all) of the extensions, expansions, and modifications of UMTS standards.

The first generation cellular wireless mobile systems (1G) before the 1990s were analog and based on frequency division multiple access (FDMA) technology with large and weighty. The digital technology bring the second upgrading for cellular industry represented by second-generation (2G) standards belong the European GSM (Global System for Mobile) system and the two US standards represented by TDMA and IS-136.

The new generation improve the voice quality and the security of transmission, which reduce the cost of handset leading to the further acceleration in industry to growth since the mid-1990s up to now. Early 21st century, the third generation (3G) systems are organized and developed represented by 3GPP and 33GPP2 to address the issue of data limitation and capability of 2G standards. In 3G systems, the data rate become 144 kbit/s, 348 kbit/s and 2Mbit/s for vehicular, pedestrian and environments respectively. The software-defined radio (SDR) technology is established first time in 3G with WCDMA, intelligent antenna and DSP techniques, which are greatly, improved the spectral efficiency of these systems. Early 2008, the 4G is introduced to provide the data rate up to 100 Mbit/s compared with 3G as show in Figure 2.1. The specifications of 1G,2G,3G and 4G is illustrated in Table 1.

Figure 2. 1 4G Vs 3G

Table 1.1 The general specifications of 1G,2G,3G and 4G systems

Technology	1G	2G	2.5G	3G	4G
Design Began	1970	1980	1985	1990	2000
Implementation	1984	1991	1999	2002	2010?
Service	Analog voice, synchron-ous data to 9.6 kbps	Digital voice, short messages	Higher capacity, packetized data	Higher capacity, broadband data up to 2 Mbps	Higher capacity, completely IP-Oriented, multimedia, data to hurdreds Of megabits
Standards	AMPS, TAGS, INMT, etc.	TDMA, CDMA, GSM, PDC	GPRS, EDGE, 1XRTT	WCDMA, CDMA2000	Single standard
Data Bandwidth	1.9 kbps	14.4 kbps	384 kbps	2 Mbps	200 Mbps
Multiplexing	FDMA	TDMA, CDMA	TDMA, CDMA	CDMA	CDMA?
core Network	PSTN	PSTN	P3TK, packet network	Packet network	internet

Five generation (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). The Next Generation Mobile Networks Alliance defines the high speed and high capacity.

1.2 General Concept and Features of LTE

With the deployment of Long Term Evolution (LTE) networks, the wireless revolution will achieve an important milestone. For the first time, a wide-area wireless network will be universally designed for Internet Protocol (IP) broadband data (rather than voice). LTE networks are also rapidly becoming a dominant global standard for the fourth generation cellular networks, with nearly all the major cellular players behind it and working towards its success. The standardization of LTE in 3GPP is gotten an established state, and the modifications in the design are narrow.

Since the end of 2009, the LTE system has been installed as a normal growth of GSM and UMTS. LTE specified by 3GPP as very high flexible for radio interfacing. LTE deployment started in the last of 2009 and the first LTE release is supported data rate up to 300 Mbps and delay of radio network not as much than 5 ms. In addition, LTE provided a spectrum significant increasing in spectrum efficiency if comparing with any other cellular systems.

Furthermore, it takes into account different architecture in radio network that designed to speed-up the operations and to decreasing the cost (Astély et al. 2009). LTE systems are supporting Frequency Division Duplex (FDD) with Time Division Duplex (TDD) technique as a varied array of bandwidths to operating in a wide amount of dissimilar spectrum allocations.

3GPP is also conducted a research with the objective to identify the required enhancements for LTE systems to achieve the requirements of IMT-Advanced. In September 2009, the partners of 3GPP prepared the official suggestion to the proposed new ITU systems, which was represented by LTE with Release 10 and beyond to be the appraised and the candidate towards IMT-Advanced. After attaining the requirements, the main object to bring LTE to IMT-Advanced is that IMT systems must be candidates for the novel spectrum bands is still to be acknowledged. In order to achieve this goal, 3GPP is presently evolving LTE-Advanced as a development of the standard of LTE.

1.3 Why LTE-Advanced?

LTE-Advanced is applying various bands of the spectrum, which are already valid in LTE, along with the future of the bands of IMT-Advanced. More developments of the spectral efficiency in the downlink and uplink are embattled specifically if users serve at edge of cell. In addition, LTE-Advanced aims at quicker exchanging between the resource of the radio states and between the additional enhancements of the figures of latency, but all at once, the “bit cost” must be decreased.

The IMT-Advanced represents the next generation in the systems of wireless communications, which aim to accomplish other main advance of the current third generation systems by reaching up to the uplink (UL) rate of 500 Mbps and 1 Gbps in the downlink (DL).

With LTE-Advanced starting, there are many keys of requests and features that up come to the light. There are various high level purposes for the new specifications of LTE-Advanced, which have not been considered in the system specifications. It is needed to verify, while much effort rests to be accepted before fixing it in the specifications.

At present, several core significant intentions for the LTE-Advanced can be illustrated as follows:

1. The data rate with the peak uplink of 500 Mbps and the peak downlink of 1 Gbps.

2. Provide spectrum efficiency with more than three times that that provided by LTE.

3. and offer spectrum efficiency in the uplink 15 bps/Hz and in downlink 30 bps/Hz.

4. The link latency in the case from idle status to the connected status is a smaller than 50 ms and less than 5 ms for one-way in a single packet transferring.

5. The edge throughput of users' cell to be doubles than that in the LTE.

6. The average throughput of any user is to be triple than that in the LTE.

7. The mobility environments are similar to that used in the LTE.

Then, LTE-Advanced or the fourth generation system of mobile communications is the most impressive technology of the next wireless generation networks. Previously, many researchers, developers, and scientists worldwide worked on the projects that are supported by governments and other institutions, aiming at more efficient and faster wireless networks through the integration of all available technologies.

They sought to adapt the newly enhanced telecommunication systems, which could provide users with superior quality, efficiency, and opportunities, where the classic wireless communications are no longer feasible.

Some researchers define the fourth generation concept as a significant enhancement of the third generation systems. However, for other scientists, 4G combines both cellular and wireless local area networks to introduce the new routing techniques, efficient solutions for sharing dedicated frequency bands. Moreover, they can introduce the development of transmission over transport layer, increasing mobility, or enlarge the available bandwidth of the network path.

1.4 General Architecture of LTE/LTE-Advanced

In Release 8, 3GPP identifies the requirements and the features of the architecture of (EPC) to serve as the base for the next generation systems. This identification specifies two main work objects, LTE and System Architecture Evolution (SAE).

In addition, EPC combines with Evolved Universal Terrestrial Radio Access Network (E-UTRAN) and Evolved Universal Terrestrial Radio Access (E-UTRA) to construct the network core. This core is responsible to arrange the system air interface and the radio access of the network link and terminals. The EPC provides IP connection between the external packet data network and the User Equipment (UE) using E-UTRAN. In the environment of 4G systems, the radio access network and the air interface are actuality improved, while the architecture of core network (EPC) does not need large modifications from the previous architecture of SAE. Figure 3.1 shows E-UTRAN and EPC architecture of LTE-Advanced networks.

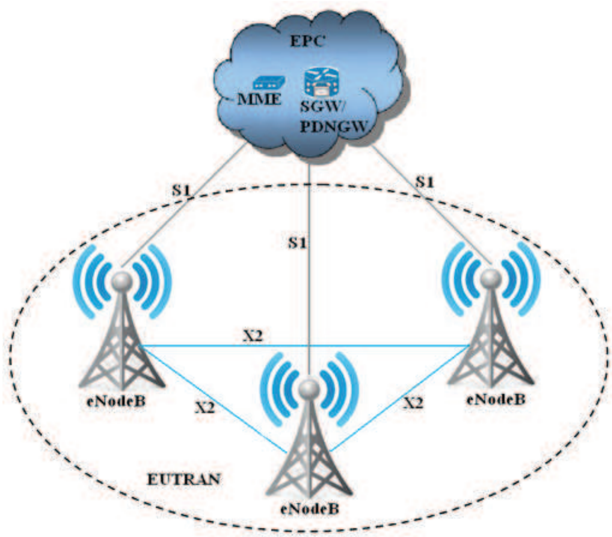


Figure 3.1 E-UTRAN and EPC architecture of LTE-Advanced

The main part in the architecture of E-UTRAN is the enhanced base station Node B (eNB or eNodeB). This provides the air interface between the control plane protocol terminations and the user plane towards the user equipment. The eNodeBs are logical element that can serve one or more E-UTRAN cells. The interfaces of LTE-Advanced network are completely built on IP protocols. The link interfacing between the eNodeBs is termed as X2 interface. The eNodeBs are connected by X2 interface and to the Mobility Management Entity/Gateway (MME/GW) by S1 interface as illustrated in Figure 3.1. The interface S1 supports many relationships between eNodeBs and MME/GW. The functions splitting between MME/GW and eNodeB are shown in Figure 4.1.

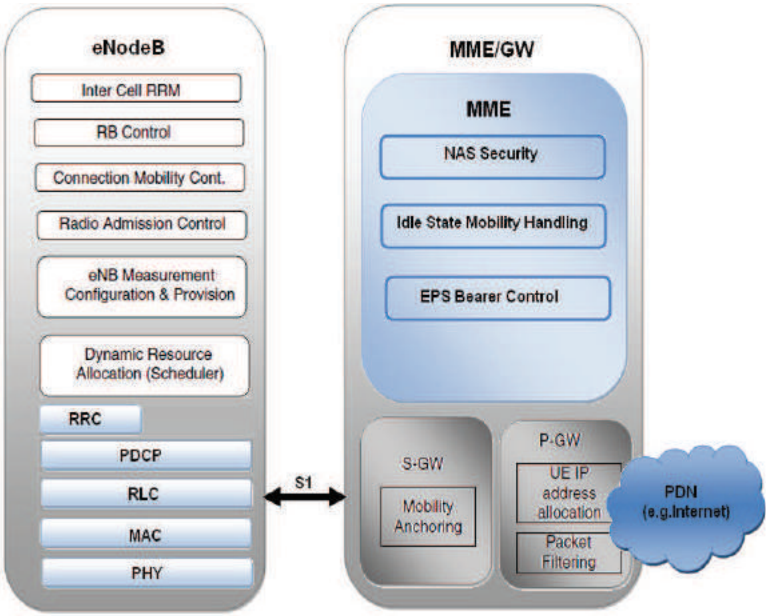


Figure 4.1 Functions splitting between MME/GW and eNodeB

The two entities of the logical gateway are Serving Gateway (S-GW) and Packet Data Network Gateway (P-GW). The Serving Gateway (S-GW) acts as limited anchor for the mobility service, and used to receive and forward packets from and to eNodeB, and this operation is used to serve the UE.

The P-GW is an interfacing element used to the linking with exterior Packet Data Networks (PDNs), and this represents Internet Multimedia Server (IMS) or Internet. In addition, P-GW provides other IP functions such as, packet filtering, routing, policy statement, and address allocation. The main benefit of separating network entities is to indicate if the capacity of network for traffic and signalling can independently grow.

The main tasks of MME are to idle the reachability of UE and to control the retransmission of paging, roaming, authorization, P-GW/S-GW selection, tracking area list management, bearer management and bearer establishment, authentication, security negotiations and signalling of Non-Access Stratum (NAS) . The eNodeBs implement the functions of eNodeB along with the protocols that are usually applied in Radio Network Controller (RNC).

The eNodeB functions include ciphering, packet reliable delivery, and header compression, while in controlling side, the functions of eNodeB are (3GPP 2009b):

1. Radio resource management (radio bearer control, radio admission, connection mobility control, and dynamic scheduling).

2. Routing user plane data towards SAE Gateway.

The stack of user plane protocol is shown in Figure 5.1. The Radio Link Control (RLC) and the Packet Data Convergence Protocol (PDCP) layers are usually included in RNC on the network side, but now they are included in eNodeB side.

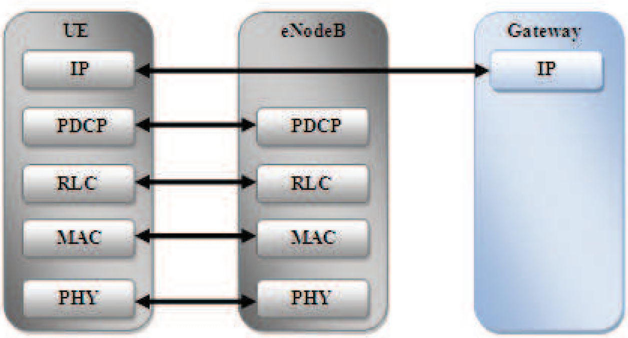


Figure 5.1 User plane protocol

The control plane protocol stack is illustrated in Figure 6.1. The functionality of Radio Resource Control (RRC) is conventionally applied in RNC and is already integrated in eNodeB. The layers of Medium Access Control (MAC) and RLC implement the similar roles to user plane.

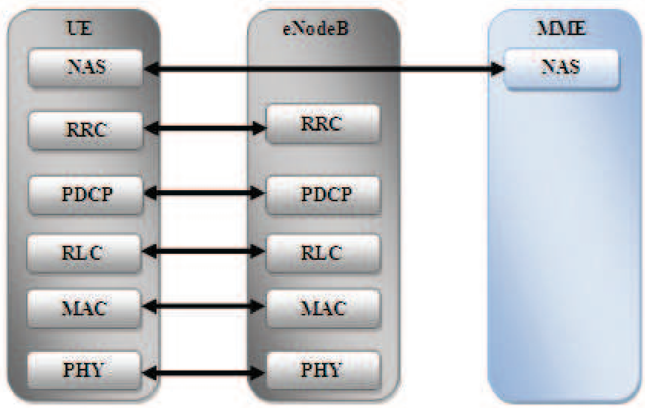


Figure 6.1 Control plane protocol architecture

The functions of RRC include paging, system information broadcast, radio bearer control, and connection management for RRC, measurement reporting to UE, and mobility functions.

In the MME network side, the NAS protocol is terminated, while in the terminal side, the UE executes functions similar to EPS such as, authentication, security control, and bearer management. Figures 7.1 and Figure 8.1, illustrate the interface protocol stacks S1 and X2.

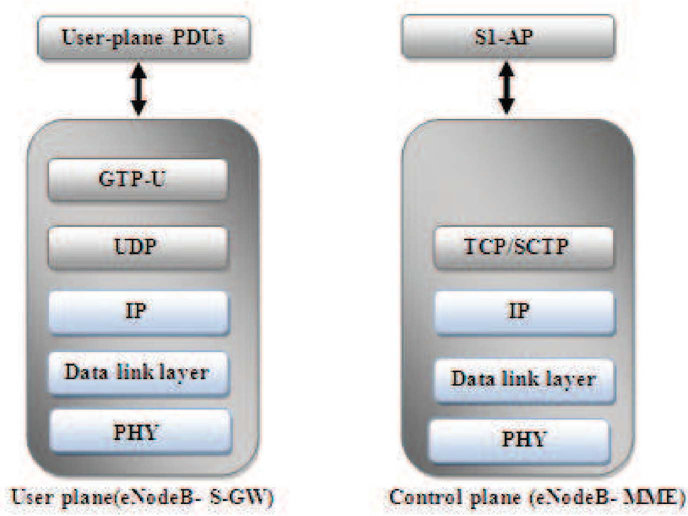


Figure 7.1S1 interface user and control planes

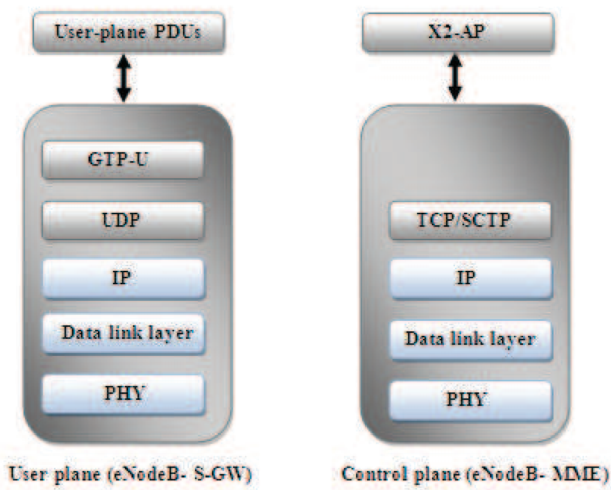


Figure 8.1 X2 interface user and control planes

The interface between S-GW and eNodeB are interconnected by S1 user plane interface (S1-U).This interface uses General Packet Radio Service (GPRS) and Tunnelling Protocol-User Data Tunnelling (GTP-U) over User Datagram Protocol (UDP) UDP/IP transport. In addition, it provides a nonguaranteed delivery to the user plane PDUs between S-GW and eNodeB. The GTP-U is a simple IP based tunnelling protocol that allows many tunnels between ends sets.

Furthermore, S1 interface separates the EPC and the E-UTRAN into two interfaces. The first is S1-U, which transfers data between S-GW and the eNodeBs. The second interface is S1-MME, which signals the interface between the MME and eNodeB. On other hand, X2 is the interface among the eNodeBs and has two interfaces. The X2-C uses the control plane to interface among eNodeBs, while X2-U is used to interface the user plane interface among eNodeBs. It is supposed that always there is an X2 interface between eNodeBs to provide the required communication between each other.

S1-MME represents the S1 control plane interfacing between MME and eNodeB. Similarly, the transport network layer and user plane are based on IP transport and the probable reliable transport; the TCP or SCTP is applied over the top of IP.

The signalling protocol in application layer is mentioned as X2 application protocol (X2-AP) and S1 application protocol (S1-AP) for X2 and S1 interfaces control planes. In S1 interface (and the same applies to the X2 interface), SCTP or TCP is used over the usual IP network layer. There is only one association for S1 interface (or eNodeB to MME relation) and over this association, one SCTP (or TCP) stream is used for all common procedures, such as, the paging between two equipment's and the procedures are supported over limited number of SCTP streams.

CHAPTER TWO

CONCEPTS OF CELLULAR SYSTEMS

Cellular system is a technology used to increase the capacity for mobile radiotelephone services by high power transceivers and 25 channels with effective area of 80km. The basic components of cellular system shown in Figure 1.2. These components of cellular systems include:

1- Base Station (BS)
2- Mobile telecommunications switching office (MTSO) or MSC
3- Mobile unit (or mobile station MS)

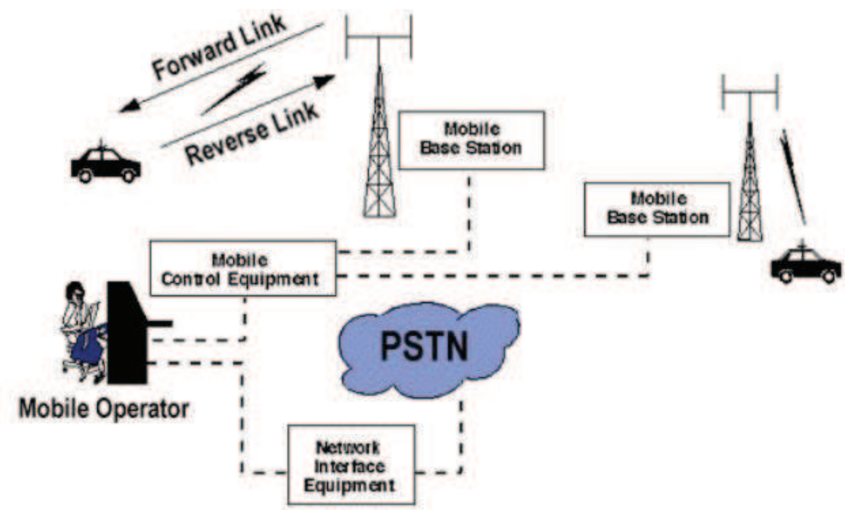


Figure 1.2 Cellular system components and network connection

2.1 Base Station (BS)

The base station is fixed or non-moving station serves as a bridge between all mobile users in the cell, which isA Connects the simultaneous mobile calls via telephone lines or microwave links to the MTSO. The base station consist of several transmitters and receivers which simultaneously handle full duplex communications and have towers to support several transmitting and receiving antennas.

The BS contains;

1- **Antennas**. Hanged in towers which support several transmitting and receiving antennas.

2- **Controller**: used to handle the call process between the mobile unit and the rest of the network.

3- **Number of transceivers**: used for communicating on the channels assigned to that cell.

2.2 Mobile Telecommunications Switching Office (MTSO)

The center which is set up for coordinating the routing of calls, also called a mobile switching center (MSC). The MTSO coordinates the activities of all of the base stations and connects the entire cellular system to the PSTN.

- The link between an MTSO and a BS is by a wire line, although a wireless link is also possible.
- The MTSO connects calls between mobile units.
- The MTSO is also connected to the public telephone or telecommunications network and can make a connection between a fixed subscriber to the public network and a mobile subscriber to the cellular network.
- The main functions of the MTSO are:
    1- Assigns the voice channel to each call.
    2- Performs handoffs.
    3- Monitors the call for billing information.

Thge 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 monitore by mobiles when they do not have a call in progress.

2.3 Mobile Station (MS)

A station intended for use while in motion at unspecified locations. Each mobile communicates via radio with one of the base stations and may be handed-off to any number of base stations throughout the duration of a call. The mobile station contains a transceiver, an antenna, and control circuitry, and may be mounted in a vehicle or used as a portable hand-held unit.

Two types of channels are available between the mobile unit and the base station (BS): **Control channels** and **Traffic channels**.

• Control channels are used to exchange information having to do with setting up and maintaining calls and with establishing a relationship between a mobile unit and the nearest BS.

• Traffic channels carry a voice or data connection between users.

2.4 Cellular System Operation

The simplify structure of the cellular system shown in Figure 2.2 contain all elements of cellular system with connections.

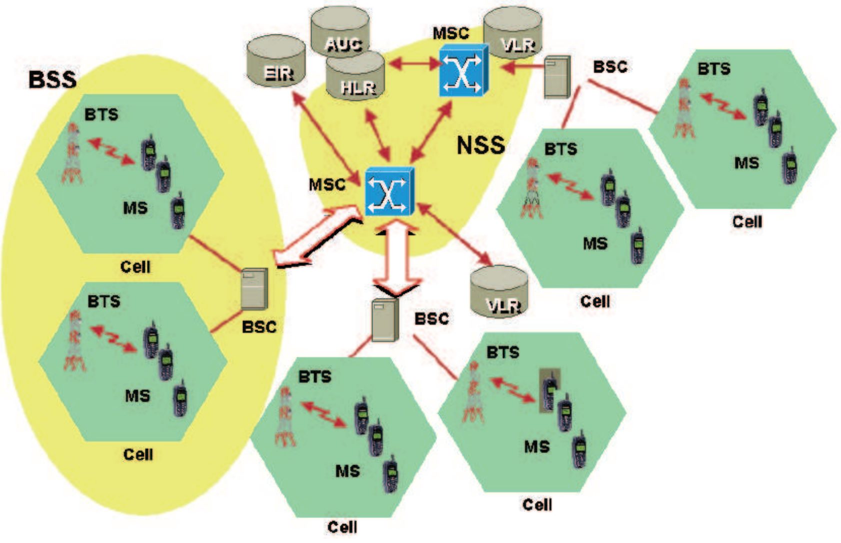


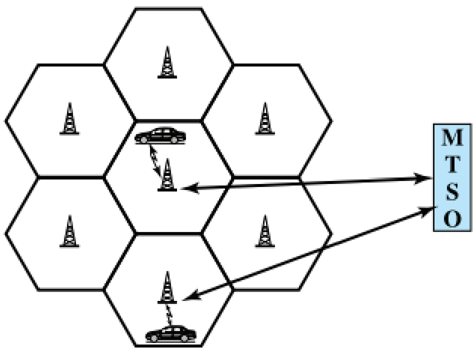
Figure 2.2 Cellular structure systems

- 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 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 number and Plan, and then the call is set up from source to the destination device.

Other functions performed by the system include the following:

- **Handoff (Handover):** If a mobile unit moves out of range of one cell and 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.

2.5 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.**

1- **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.

2- **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.

2.6 Cell Types

- Macro cell – their coverage is large (aprox. 6 miles in diameter); used in remote areas, high-power transmitters and receivers are used

- Micro cell – 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 another clusters

- Pico cell –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 areas where outdoor signals do not reach well.
- Selective cells . located at the entrances of tunnels 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

2.7 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.

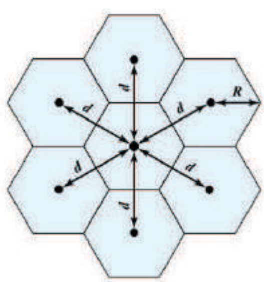
A- Each cell is allocated a band of frequencies and is served by a base station (consisting of transmitter, receiver, and control unit).

B- 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.
  -

$A_{tri} = 1.3R^2$ $A_{sq} = 2.0R^2$ $A_{hex} = 2.6R^2$

2.8 Frequency Reuse

In a cellular system, each cell has a base transceiver. The transmission power is carefully controlled

1-To allow communication within the cell using a given frequency

2-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 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 $\mathbf{d} = \sqrt{3}R$

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***

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

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

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

Choice of N (assuming constant cell size)

Small N:

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

Large N:

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

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:

$$Capacity = MCN = MK\_$$

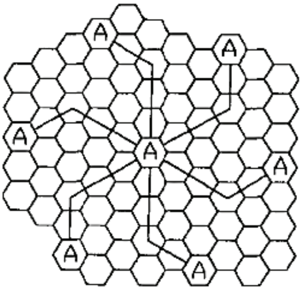
The capacity of a cellular system is directly proportional to the number of times a cluster is replicated in a fixed service area.
The cluster size (N) is typically equal to 4, 7, or 12.

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:

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



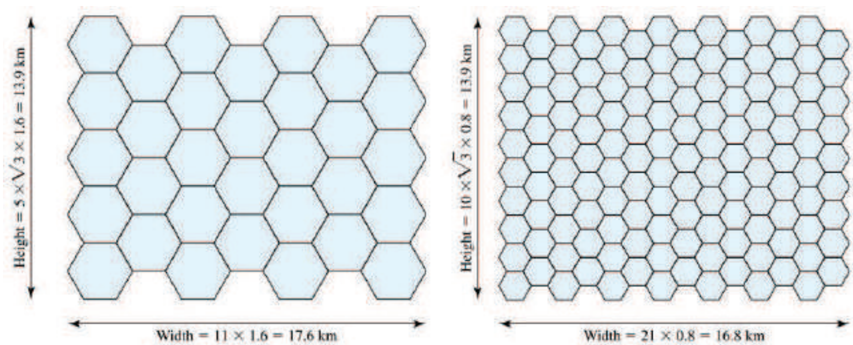
Example 1

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.

(c)



(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 $6.65 \times 32 = 213\ \text{km}^2$.

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 $1.66 \times 128 = 213\ \text{km}^2$.

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

Total available channels =960 , 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.

2.9 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.

2.10 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 *k*th 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:

$2 \leq \gamma \leq 5$: 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

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

Example 3

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

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

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

(b)

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

Example 4

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 ($\gamma = 4$). 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 below.

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.

2.11 Co-channel Interference Reduction

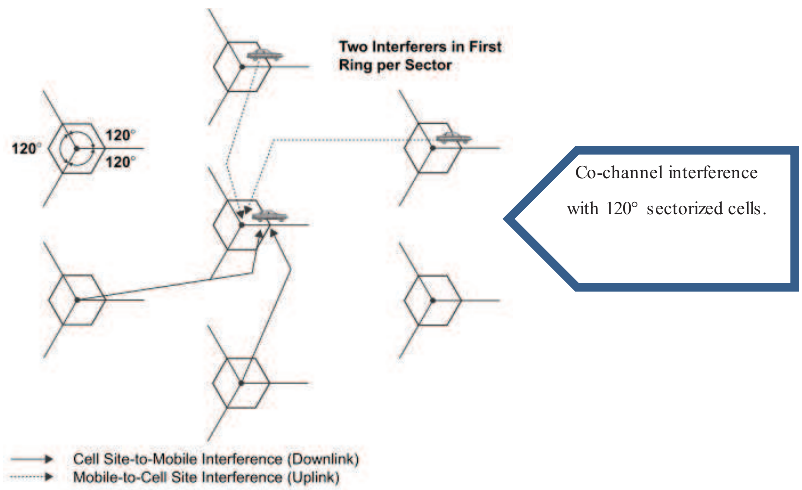
In the case of increased call traffic, the frequency spectrum should be used efficiently. We should avoid increasing the number of cells N in a frequency reuse pattern. As N increases, the number of frequency channels assigned to a cell is reduced, thereby decreasing the call capacity of the cell.

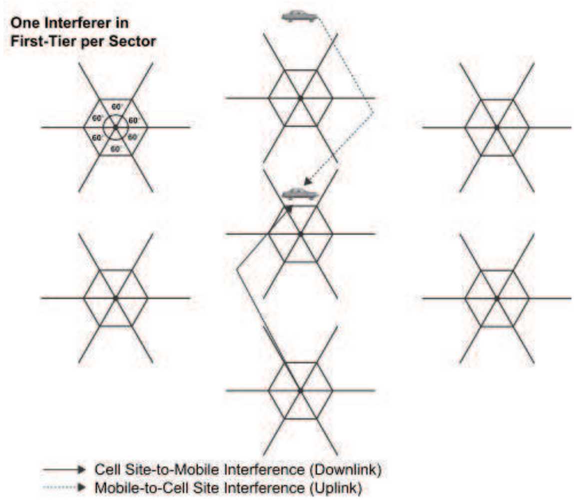
Instead of increasing N, we either

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 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).

2.12 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.

2.13 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.

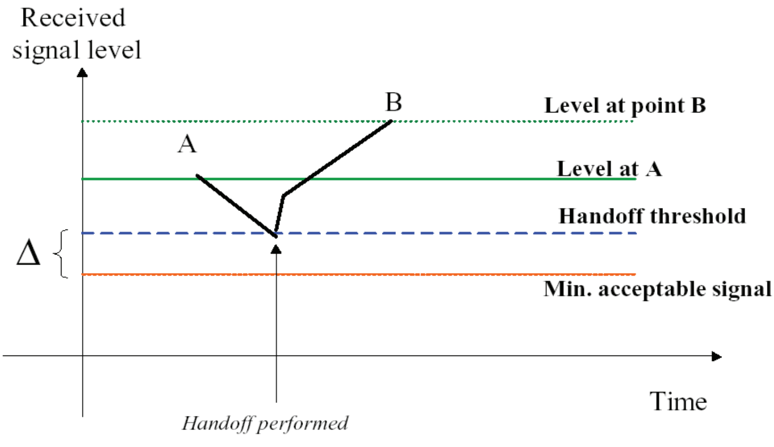
Once a particular signal level is specified as the minimum usable signal for acceptable voice quality at the base station receiver (normally taken as between -90 dBm and -100 dBm), a slightly stronger signal level is used as a threshold at which a handoff is made. This margin (cannot be too large or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

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

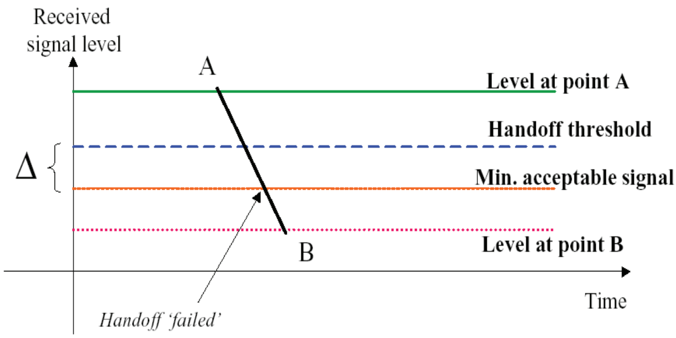
- If A is too large, unnecessary handoffs which burden the MSC may occur.
- If A is too small, there may be insufficient time to complete a handoff before a call is lost due to weak signal conditions.

Therefore, A is chosen carefully to meet these conflicting requirements.
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 A is set too small for the handoff time in the system. ***The length of time needed to decide if a handoff is necessary depends on the speed at which the vehicle is moving***
Excessive delays may occur during high traffic conditions due to

- Either computational loading at the MSC
- Or no channels are available on any of the nearby base stations



Value of delta is large enough. When the $P_{Handoff}$ is reached, the MSC initiates the handoff.



In this case, the MSC was unable to perform the handoff before the signal level dropped below the minimum usable level, and so the call was lost.

2.14 Handoff Types

Handoff can be categorized as hard handoff, soft handoff, and softer handoff.

A. The hard handoff

- Can be further divided into intra-frequency and inter-frequency hard handoffs.
- During the handoff process, if the old connection is terminated before making the new connection, it is called a hard handoff.
- *Inter-frequency hard handoff*: the carrier frequency of the new radio access is different from the old carrier frequency to which the MS was connected.
- *Intra-frequency handoff*: the new carrier frequency, to which the MS is accessed after the handoff procedure, is the same as the original carrier.
- In the 2G TDMA systems, the majority of handoffs are intra-frequency hard handoffs. Inter-frequency handoffs may occur between two different radio access networks, for example, between GSM and UMTS. In this case, it can also be called intersystem handoff.
- An intersystem handoff is always a type of inter-frequency, since different frequencies are used in different systems.

B. The soft handoff

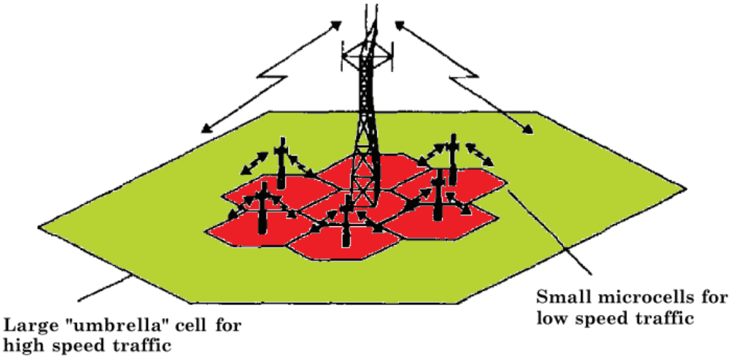
- If the new connection is established before the old connection is released. In the 3G systems, the majority of handoffs are intra-frequency soft handoffs.
- A soft handoff performed between two sectors belonging to different base stations but not necessarily to the same BS is called a 2-way soft handoff.
- A soft handoff may be more than 2-way if the number of sectors involved in the handoff process is more than two.

C. The softer handoff

- The BS transmits through one sector but receives from more than one sector. In this case the MS has active uplink radio connections with the network through more than one sector belonging to the same BS. When soft and softer handoffs occur simultaneously, the term soft-softer handoff is usually used.

2.15 Umbrella Cell Approach

- By using different antenna heights (often on 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 to high speed users while providing small area coverage 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 on the RVC 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.
- **When the speed of the mobile is too high**, the mobile is handed off to the umbrella cell. The mobile will then stay longer in the same cell (in this case the umbrella cell).

- large cell → high speed traffic → fewer handoffs
- small cell → low speed traffic

CHGAPTER THREE

MOBILE RADIO PROPAGATION

- The transmission path between the transmitter and the receiver can be either Simple line-of-sight (LOS), or 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.

3.1 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*),

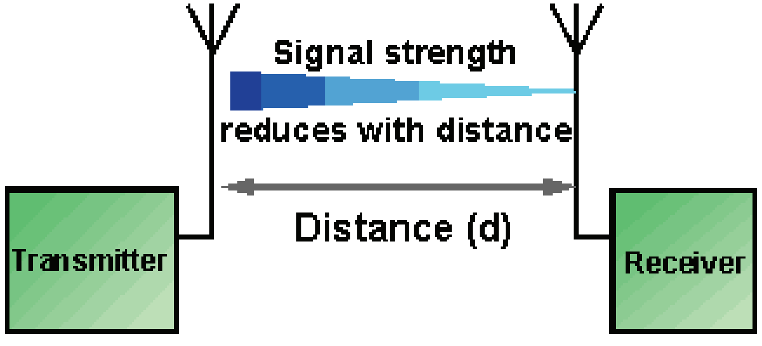
c is the speed of light ($\approx 3 \times 10^8$ *m/s*).

- 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.
-
-

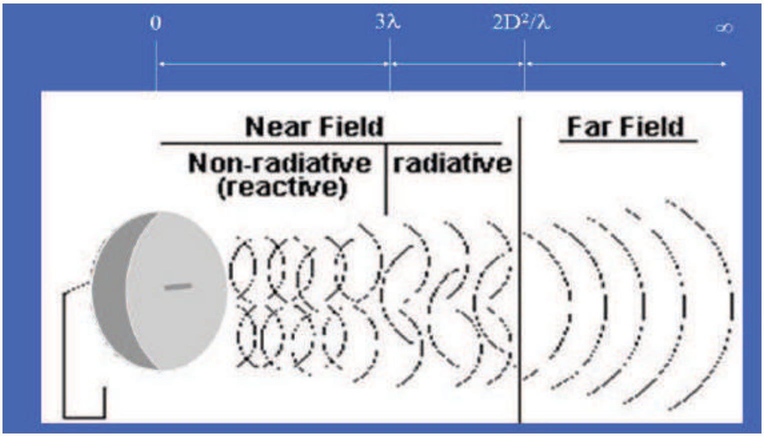


The **path loss** represents signal attenuation as a positive quantity measured in dB, is defined as the difference between the transmitted power and the received power.

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

3.2 Understanding the Antenna near Field & Far Field Distances

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



1- **Reactive Near Field**
   The reactive near field ad the radiating near field. The reactive near field is the region where the fields are reactive i.e 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.

2- **Radiating Near Field (Fresnel region)**
   The radiating near field or Fresnel region is the region between the reactive near and far field. The reactive fields do not dominate in this region. However unlike the far field region, the shape of the radiation pattern varies significantly with distance.

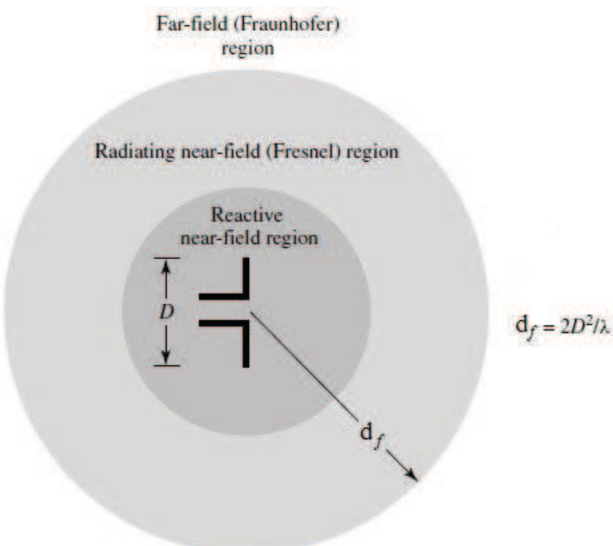
3- **Far Field**
   When talking about antennas the far field is the region that is at a large distance from the antenna. In the far field the radiation pattern does not change shape as the distance increases. There are three conditions which must be satisfied to ensure that the antenna is at a distance which qualifies as the far field.

$$\text{Reactive Near Field} \leq 0.62 \times \sqrt{\frac{D^3}{\lambda}}$$

$$\text{Radiating Near Field (Frensel Region)} \leq \frac{2D^2}{\lambda}$$

$$\text{Far Field } \geq \frac{2D^2}{\lambda}$$

$$\lambda = \frac{\text{Speed of Light}}{\text{Frequency}}$$



The far-field 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:

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

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.

For example, if P_r is in units of *dBm*, the received power is given by:

$$P_r(d)\ dBm = 10\log\left[\frac{P_r(d_0)}{0.001\,W}\right] + 20\log\left(\frac{d_0}{d}\right)$$

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)

$$P_t(dBm) = 10\log\left[P_t(mW)/(1\ mW)\right] = 10\log[50\times10^3] = 47\,dBm$$

(b)

$$P_t(dBm) = 10\log\left[P_t(W)/(1\ W)\right] = 10\log\left[50\right] = 17\,dBW$$

The received power is:

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

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

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

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

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

Example 3

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

Solution:

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

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

3.3 Basic Propagation Mechanisms

The physical mechanisms that govern radio propagation are complex and diverse, but generally attributed to the following three factors

1. Reflection
2. Diffraction
3. Scattering

1- Reflection

Occurs when waves impinges upon an obstruction that is much larger in size compared to the wavelength of the signal

Example: reflections from earth and buildings , these reflections may interfere with the original signal constructively or destructively

2- Diffraction

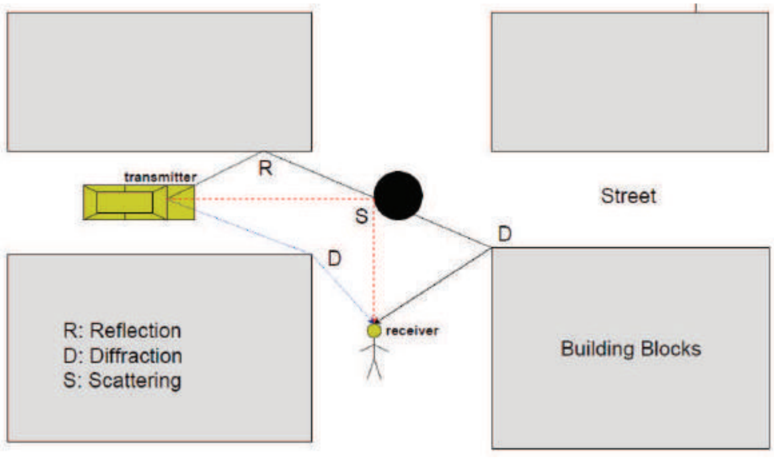
Occurs when the radio path between sender and receiver is obstructed by an impenetrable body and by a surface with sharp irregularities (edges)

Explains how radio signals can travel urban and rural environments without a line-of-sight path

3- 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.

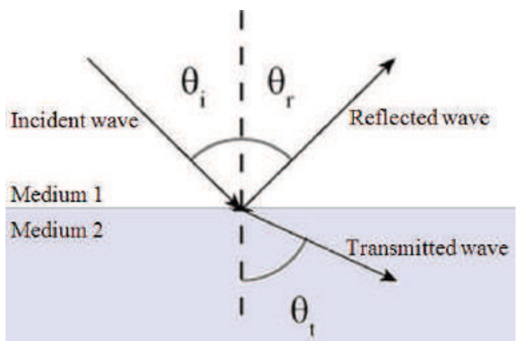
- They are produced by small objects, rough surfaces and other irregularities on the channel
- Follows same principles with diffraction
- Causes the transmitter energy to be radiated in many directions
- Lamp posts and street signs may cause scattering



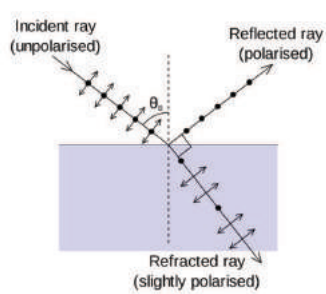
Reflection

Reflection occurs when a propagating electromagnetic wave impinges upon an object which has very large dimensions when compared to the wavelength of the propagating wave. Reflections occur from the surface of the earth and from buildings and walls.

- 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 electro-magnetics, 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:

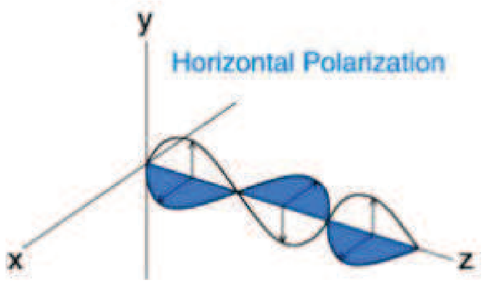
$$\sin\theta_B = \frac{\sqrt{\varepsilon_r - 1}}{\sqrt{\varepsilon_r^2 - 1}}$$

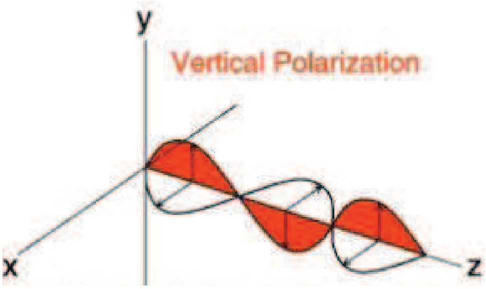
Note that the Brewster angle occurs only for vertical (i.e. parallel) polarization.

- 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 $\Gamma = -1$.

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





Example 4

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

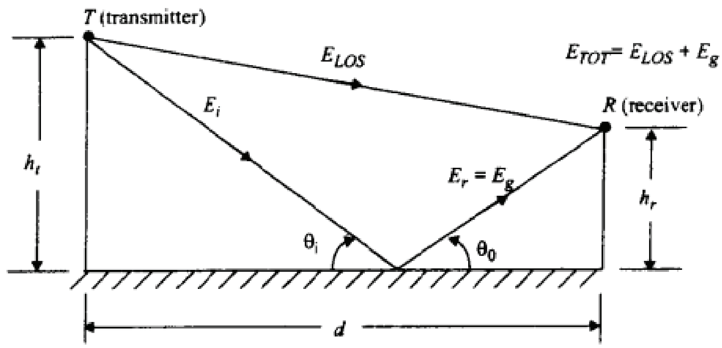
$$E_i = E_r$$

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

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

where

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

k is a constant related to E_0, the antenna heights, and the wavelength.

- 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 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.

Note also that at large values of d, the received power and path loss become independent of frequency.

Example 5

A mobile is located 5 *km* away from a base station and uses a vertical $\lambda/4$ 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 gain of the receiving 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.

Solutio:

Given:

T-R separation distance = 5 *km*

E-field at a distance of 1*km*

Frequency of operation, *f* = 900 *MHz*

a)

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

Length of the antenna, $L = \lambda/4 = 0.333/4 = 0.0833m = 8.33cm$.

Gain of $\lambda/4$ monopole antenna can be obtained using

$$G = \frac{4\pi A_e}{\lambda^2} = 1.8 = 2.55\ dB\,.$$

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

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

$$= \frac{2\times10^{-3}\times1\times10^3}{5\times10^3}\left[\frac{2\pi\times50\times1.5}{0.333\times5\times10^3}\right] = 113.1\times10^{-6}\ V/m$$

The received power at a distance *d* can be obtained using

$$P_r(d) = \frac{|E|^2}{120\pi}A_e = \frac{|E|^2}{120\pi}\left(\frac{G\lambda^2}{4\pi}\right)$$

$$P_r(d) = \frac{\left(113.1\times10^{-6}\right)^2}{377}\left(\frac{1.8\times(0.333)^2}{4\pi}\right)$$

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

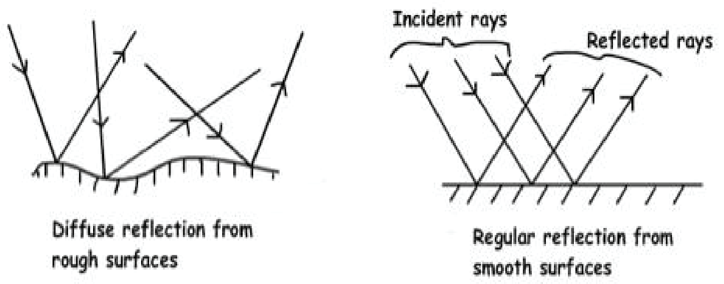
Scattering

- The actual received power at the receiver is stronger than claimed by the models of reflection and diffraction.
- The cause of scattering is that the trees, buildings and lamp-posts scatter energy in all directions. This provides extra energy at the receiver.

- 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,

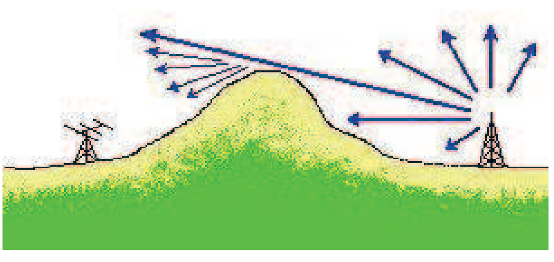
$$h_c = \frac{\lambda}{8\sin\theta_i}$$

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.

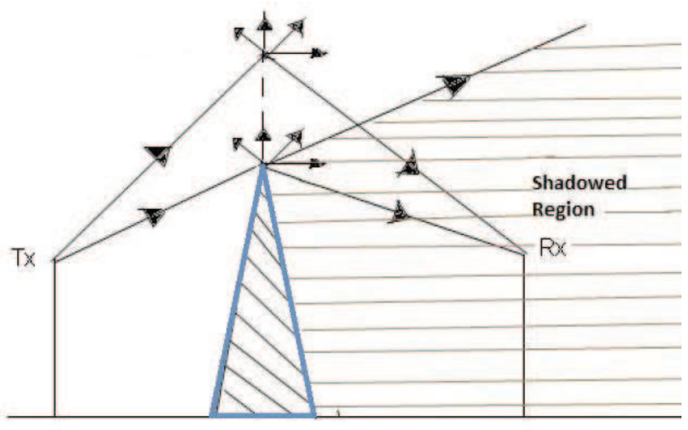


Diffraction

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.



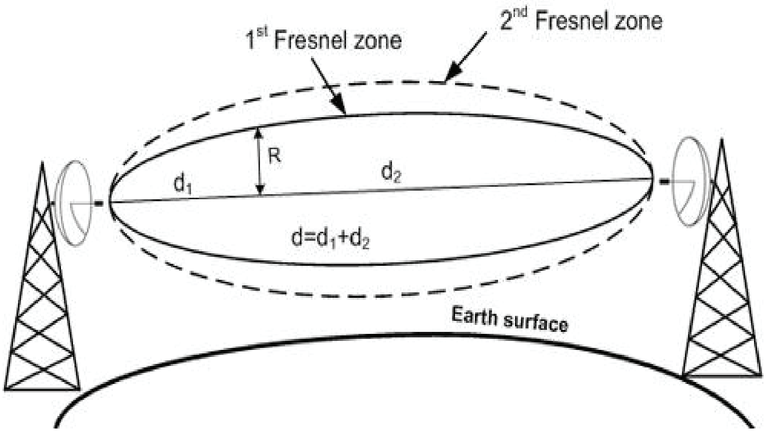
- The radio wave changes in amplitude and phase and penetrates the shadow zone, deviating from a straight line path.
- Diffraction is explained by Huygens-Fresnel principle which states that all points on a wave front can be considered as the point source for secondary wavelets which form the secondary wave front 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

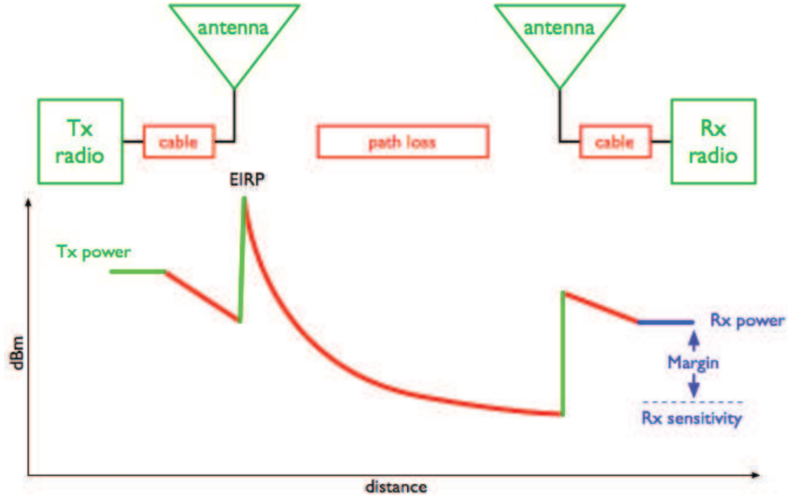
- As mentioned before, the more is the object in the shadowed region greater is the diffraction loss of the signal.
- The effect of diffraction loss is explained by Fresnel zones as a function of the path difference.
- The successive Fresnel zones have phase difference of π which means they alternatively 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.

3.4 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 in an 802.11 link 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.
- 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).

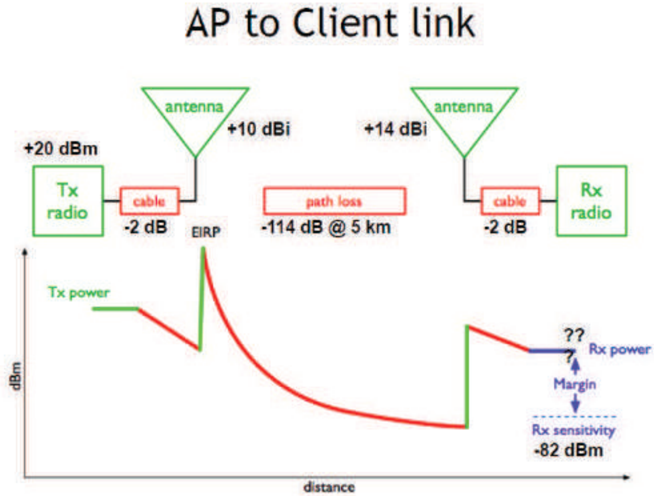


Example link budget calculation

Let's estimate the feasibility of a **5 km** link, with 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

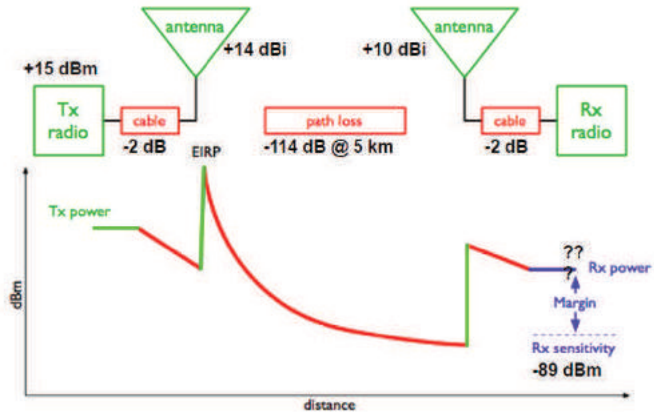
Sol

A) AP to Client link



- Total Gain = 20 dBm (TX Power AP) + 10 dB (Antenna Gain AP) – 2 dB (Cable Losses AP) + 14 dB (Antenna Gain Client) – 2 dB (Cable Losses Client) = 40 dB Total Gain
- expected received signal level = 40 dB Total Gain -114 dB (free space loss @5 km) = -74
- *link margin = -74 dBm (expected received signal level) --82 dBm (sensitivity of Client) = 8 dB (link margin)*

B) : Client to AP link



- Total Gain = 15 dB (TX Power client) + 14 dB (Antenna Gain) - 2 dB (Cable Losses Client) + 10 dB (Antenna Gain AP) - 2 dB (Cable Losses AP) = 35 dB Total Gain

- received signal = 35 dB Total Gain -114 dB (free space loss @5 km) = -79

link margin = -79 dB (expected received signal level) - - 89 dBm (sensitivity of AP) = 10 dB (link margin)

3.6 Trunking and Grade of Service

A- Trunking

- A trunk: is a communications line or link designed to carry multiple signals simultaneously to provide network access between two points. The number of trunks connecting the MSC 1 with another MSC 2 is the number of voice pairs used in the connection.

- 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. To dimension a route correctly, we must have some idea of its usage, that is, how many subscribers are expected to talk at one time over the route.
- The concept of trunking allows a large number of users to share the relatively small number of channels in a cell by providing access to each user, on demand, from the available channels.
- 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.
- 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).

- Traffic is measured in either:
  - Erlangs,
  - Percentage of occupancy,
  - 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

If the carried load for a component is 3000 *CCS* at 5% blocking, what is the offered load?

Solution:

$$Offered\ load = \frac{3000}{(1-0.05)} \approx 3158\,CCS$$

Overflow = (Offered load) – (Carried load) = 3158 – 3000 = 158 CCS

Example 2

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 3

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:

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

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

Example 4

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:

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

The traffic intensity during BH is

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

Example 5

The average mobile user has 500 minutes of use per month; 90% of traffic occurs during work days (i.e., only 10% of traffic occurs on weekends). There are 20 work days per month. Assuming that in a given day, 10% of traffic occurs during the BH, determine the traffic per subscriber per BH in *Erlangs*.

Solution:

$$\text{Average busy hour usage per subscriber} = (\text{minutes of use/month}) \times (\text{fraction during work day}) \times \frac{(\text{Percentage in busy hour})}{\text{Work days / month}}$$

Average busy hour usage per subscriber = 500 × 0.9 × 0.1/20 = 2.25 minutes of use per subscriber per busy hour.

$A_u = 2.25/60 = 0.0375$ *Erlangs*

Example 6

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.

1- **no queuing**
2- **queuing**

(1) 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** and assumes that calls arrive as determined by a Poisson distribution. Furthermore, it is assumed that there are an infinite number of users as well as the following:

(a) there are memory- less arrivals of requests, implying that all users, including blocked users, may request a channel at any time;
(b) the probability of a user occupying a channel is exponentially distributed, so that longer calls are less likely to occur as described by an exponential distribution;
(c) There are a finite number of channels available in the trunking pool. This is known as an M/M/m queue, and leads to the derivation of the Erlang B formula (also known as the blocked calls cleared formula).

The Erlang B formula determines the probability that a call is blocked and is a measure of the *GOS* for a trunked system which provides no queuing for blocked calls.

The Erlang B formula is given by:

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

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

While it is possible to model trunked systems with finite users, the resulting expressions are much more complicated than the Erlang B result, and the added complexity is not warranted for typical trunked systems which have users that outnumber available channels by orders of magnitude.
Furthermore, the Erlang B formula provides a conservative estimate of the *GOS*, as the finite user results always predict a smaller likelihood of blocking. 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:

Table 3.1
Capacity of an Erlang B system

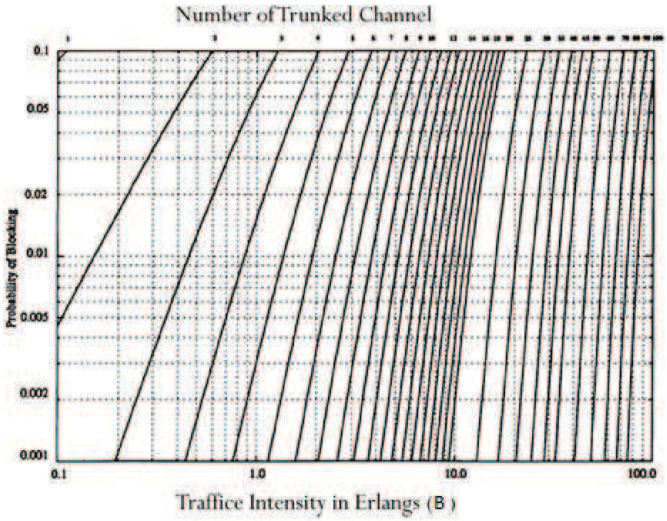
Number of channels *C*	**Capacity (*Erlangs*) for *GOS***			
	0.01	**0.005**	**0.002**	**0.001**
2	0.153	0.105	0.065	0.046
4	0.869	0.701	0.535	0.439
5	1.36	1.13	0.9	0.762
10	4.46	3.96	3.43	3.09
20	12	11.1	10.1	9.41
24	15.3	14.2	13	12.2
40	29	27.3	25.7	24.5
70	56.1	53.7	51	49.2
100	84.1	80.9	77.4	75.2

(2) The second kind of trunked 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 called **Blocked Calls Delayed**, and its measure of *GOS* is defined as the probability that a call is blocked after waiting a specific length of time in the queue.
- To find the GOS, it is first necessary to find the likelihood that a call is initially denied access to the system. The likelihood 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.



Example 1

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. 5

b. 10

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:

From the table of the capacity of an Erlang B system, we can find the total capacity in *Erlangs* for the 0.5% *GOS* for different numbers of channels.
By using the relation $A = UA_U$, we can obtain the total number of users that can be supported in the system.

(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.

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.

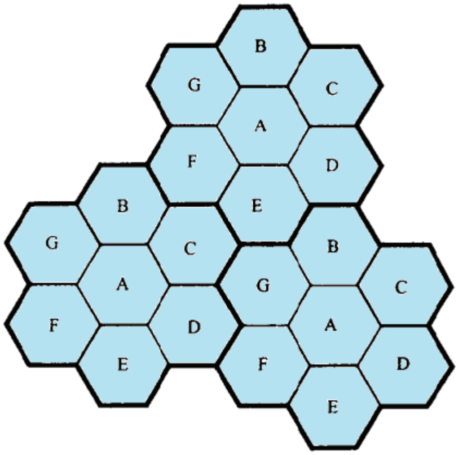
3.6 Improving Capacity in Cellular Systems

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.

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.

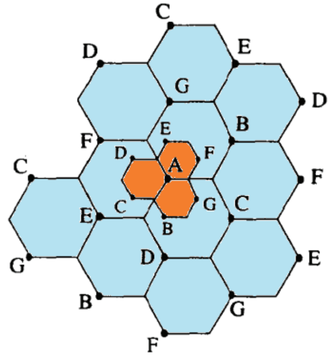
➢ Imagine if every cell in the Figure below were reduced in such a way that the radius of every cell was cut in half.



- 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.

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

And

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

where P_{t1} 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:

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

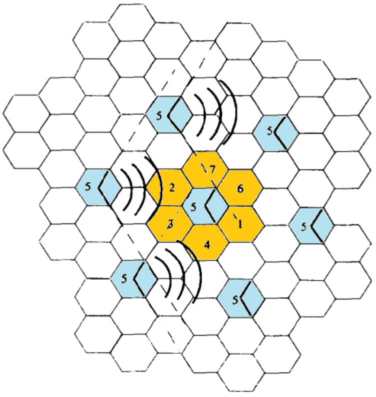
In other words, the transmit power must be reduced by 12 dB in order to fill in the original coverage area with microcells, while maintaining the *S/I* requirement.

- In practice, not all cells are split at the same time. It is often difficult for service providers to find real estate that is perfectly situated for cell splitting.
- Therefore, different cell sizes will exist simultaneously. In such situations, special care needs to be taken to keep the distance between co-channel cells at the required minimum, and hence channel assignments become more complicated.
- Handoff issues must be addressed so that high speed and low speed traffic can be simultaneously accommodated (the umbrella cell approach is commonly used).
- 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.
- The larger cell is usually dedicated to high speed traffic so that handoffs occur less frequently.

Sectoring

Cell splitting achieves capacity improvement by essentially rescaling the system.

- By decreasing the cell radius *R* and keeping the co-channel reuse ratio *D/R* unchanged, cell splitting increases the number of channels per unit area.
- Another way to increase capacity is to keep the cell radius unchanged and seek methods to decrease the *D/R* ratio.
- 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.
- The factor by which the co-channel interference is reduced depends on the amount of sectoring used.
- 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.
- 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, as compared to 12-cell reuse for the worst possible situation in the unsectored case.
- ▪ 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 penalty 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.

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