Unit-1

Cellular Mobile Communication Concepts

Source: Theodore S. Rappaport, Wireless Communications Principles and Practice, 2nd Edition, Pearson Education, 2003.

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1.1. Introduction

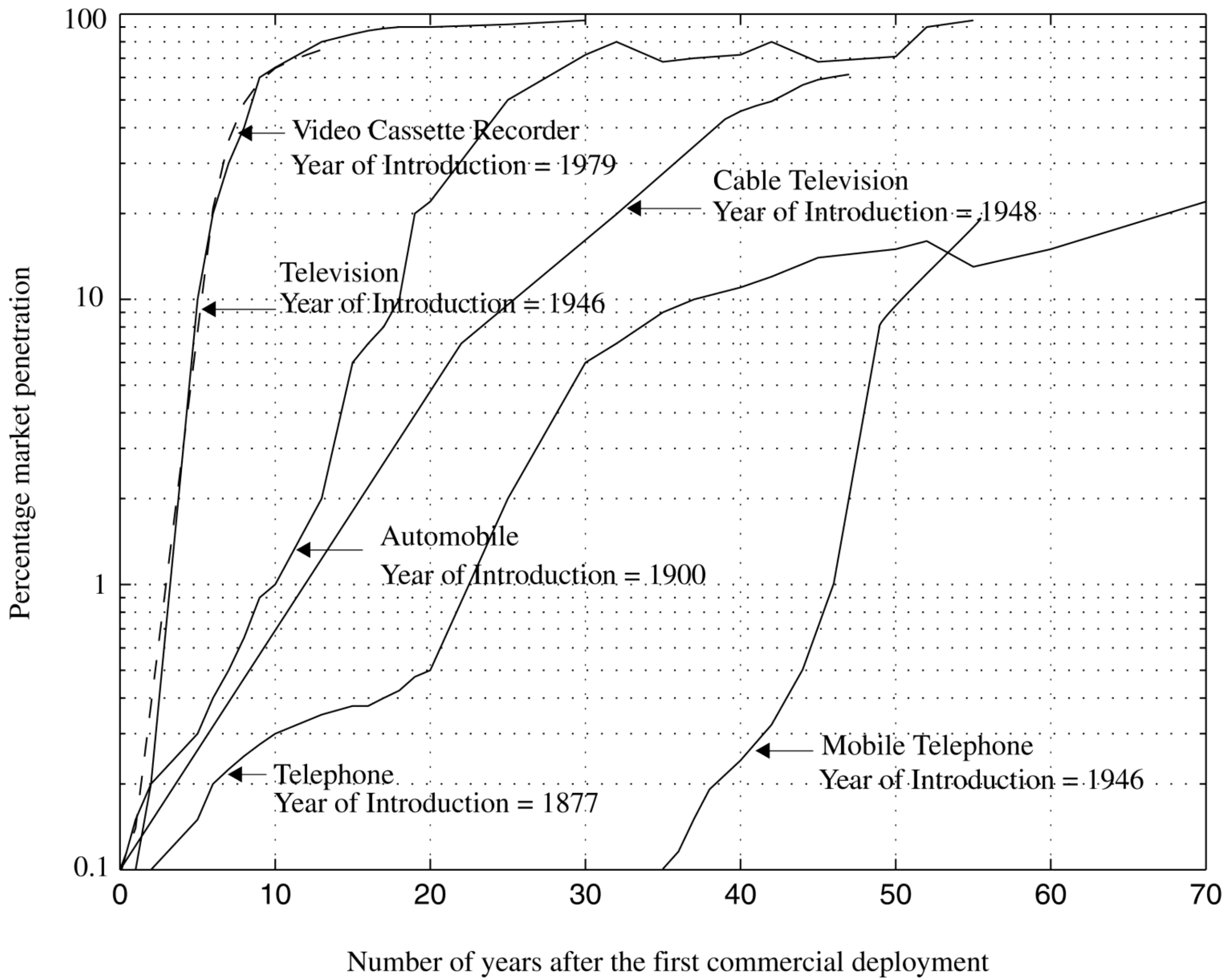


Figure 1.1 The growth of mobile telephony as compared with other popular inventions of the 20th century.

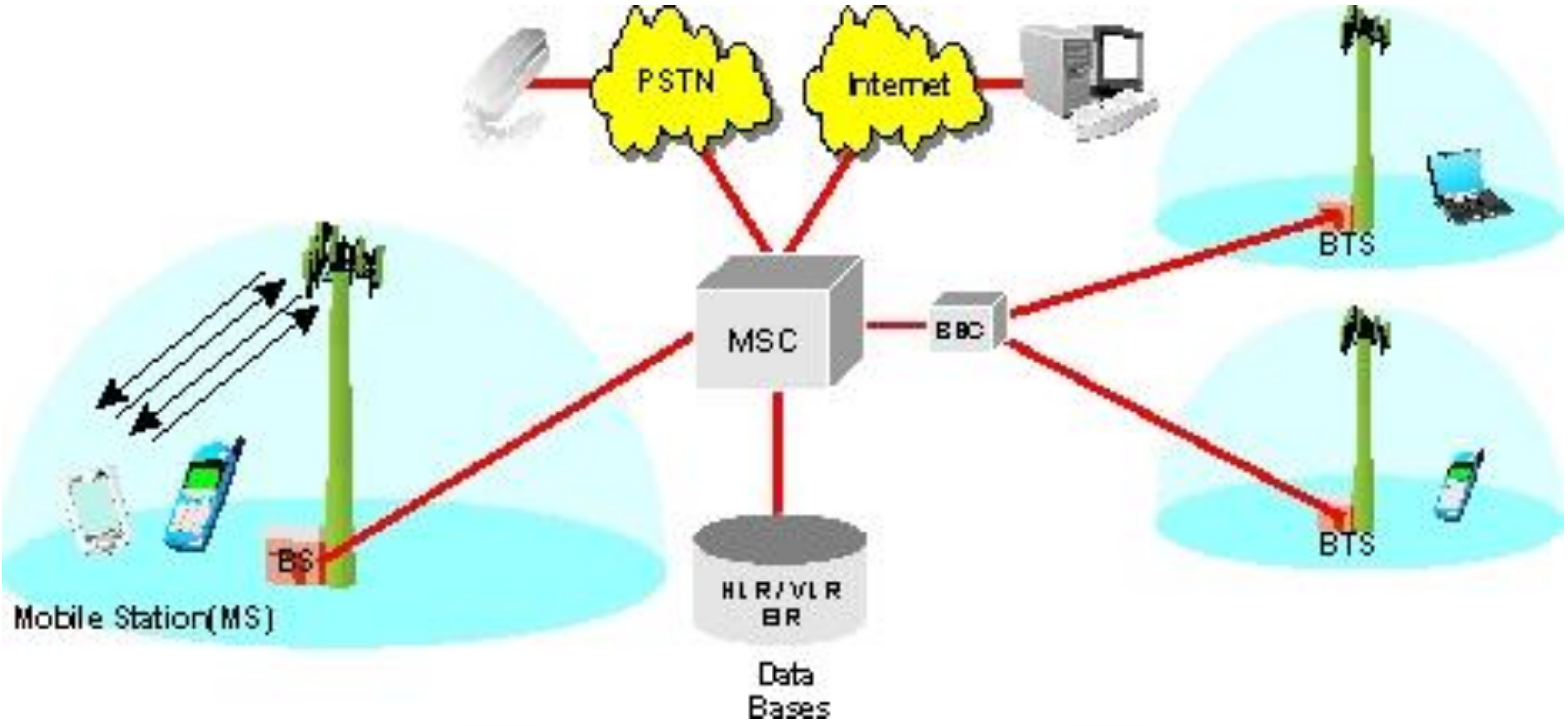
Wireless Communications System Definitions

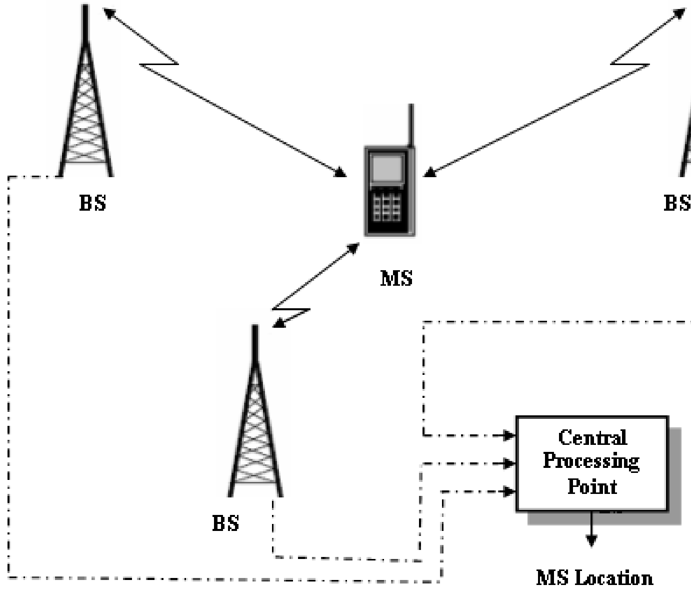
- *Mobile:* It describes *any radio terminal that could be moved during operation*. It is used to describe a radio terminal that is attached to a *high-speed mobile platform*.
  - e.g. a cellular telephone in a fast moving vehicle.

- *Portable:* It describes *a radio terminal that can be hand-held* and used by someone *at walking speed.*
  - e.g. a walkie-talkie or cordless telephone inside a home.

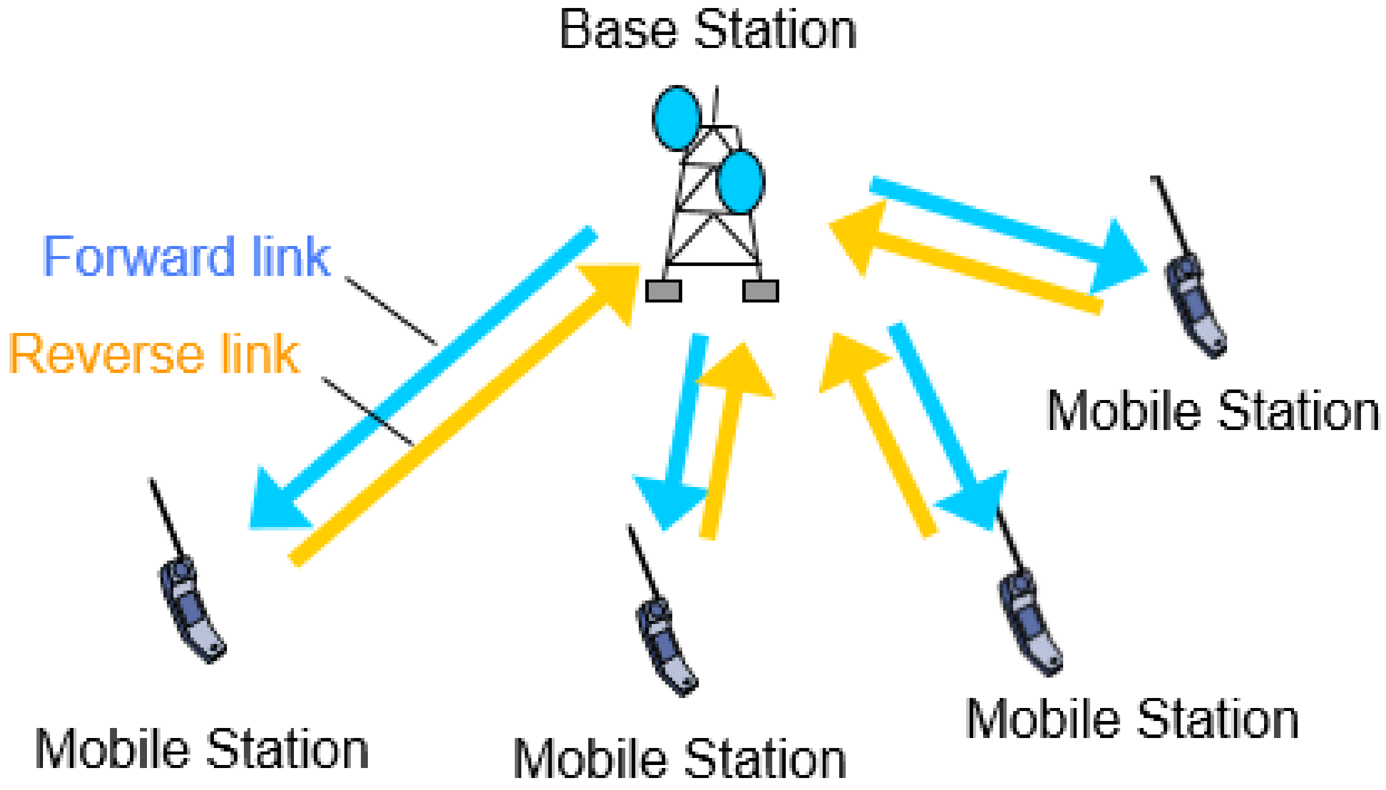
- *Subscriber:* A *mobile or portable user who pays subscription charges* for using a mobile communications system.
- *Subscriber unit:* It describes each *user's communication device.*

Base Station	A fixed station in a mobile radio system used for radio communication with mobile stations. Base stations are located at the center or on the edge of a coverage region and consist of radio channels and transmitter and receiver antennas mounted on a tower.
Mobile Station	A station in the cellular radio service intended for use while in motion at unspecified locations. Mobile stations may be hand-held personal units (portables) or installed in vehicles (mobiles).
Mobile Switching Center	Switching center which coordinates the routing of calls in a large service area. In a cellular radio system, the MSC connects the cellular base stations and the mobiles to the PSTN. An MSC is also called a mobile telephone switching office (MTSO).

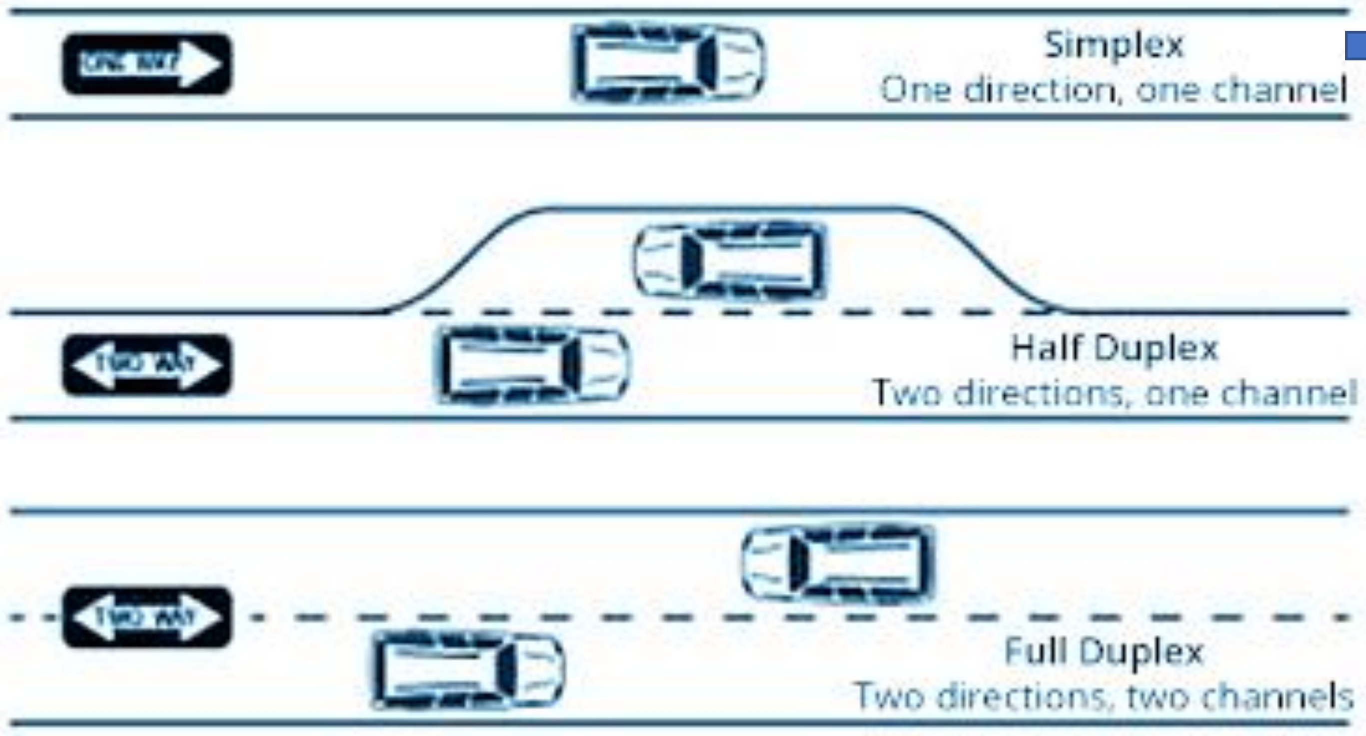

PSTN
Internet
MSC
BSC
BTS
BTS
BS
Mobile Station(MS)
HLR/VLR
EIR
Data
Bases

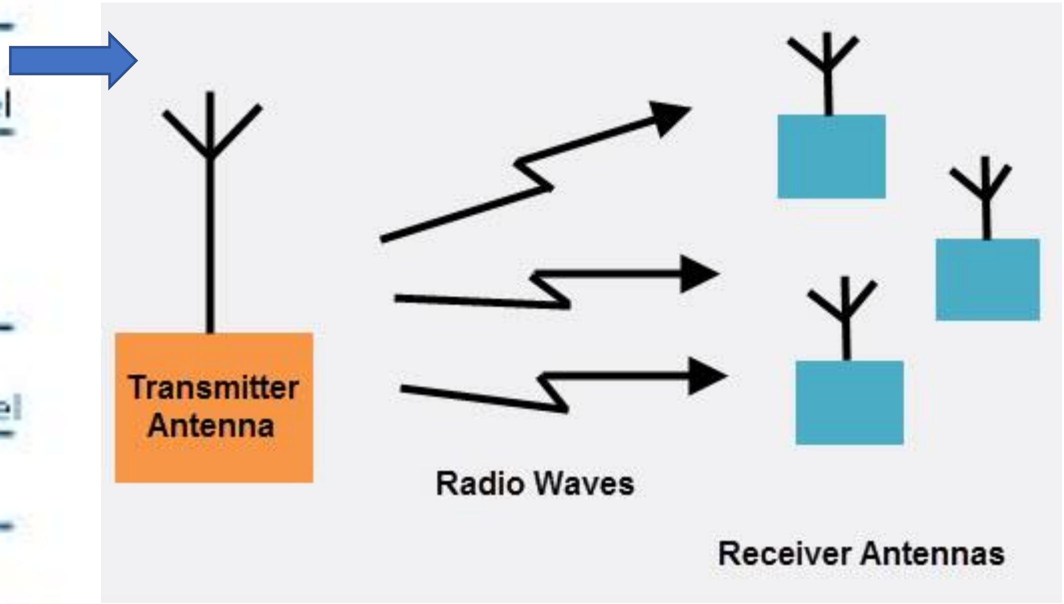

BS
BS
MS
BS
Central
Processing
Point
MS Location

Forward Channel	Radio channel used for transmission of information from the base station to the mobile.
Reverse Channel	Radio channel used for transmission of information from the mobile to base station.
Control Channel	Radio channels used for transmission of call setup, call request, call initiation, and other beacon or control purposes.

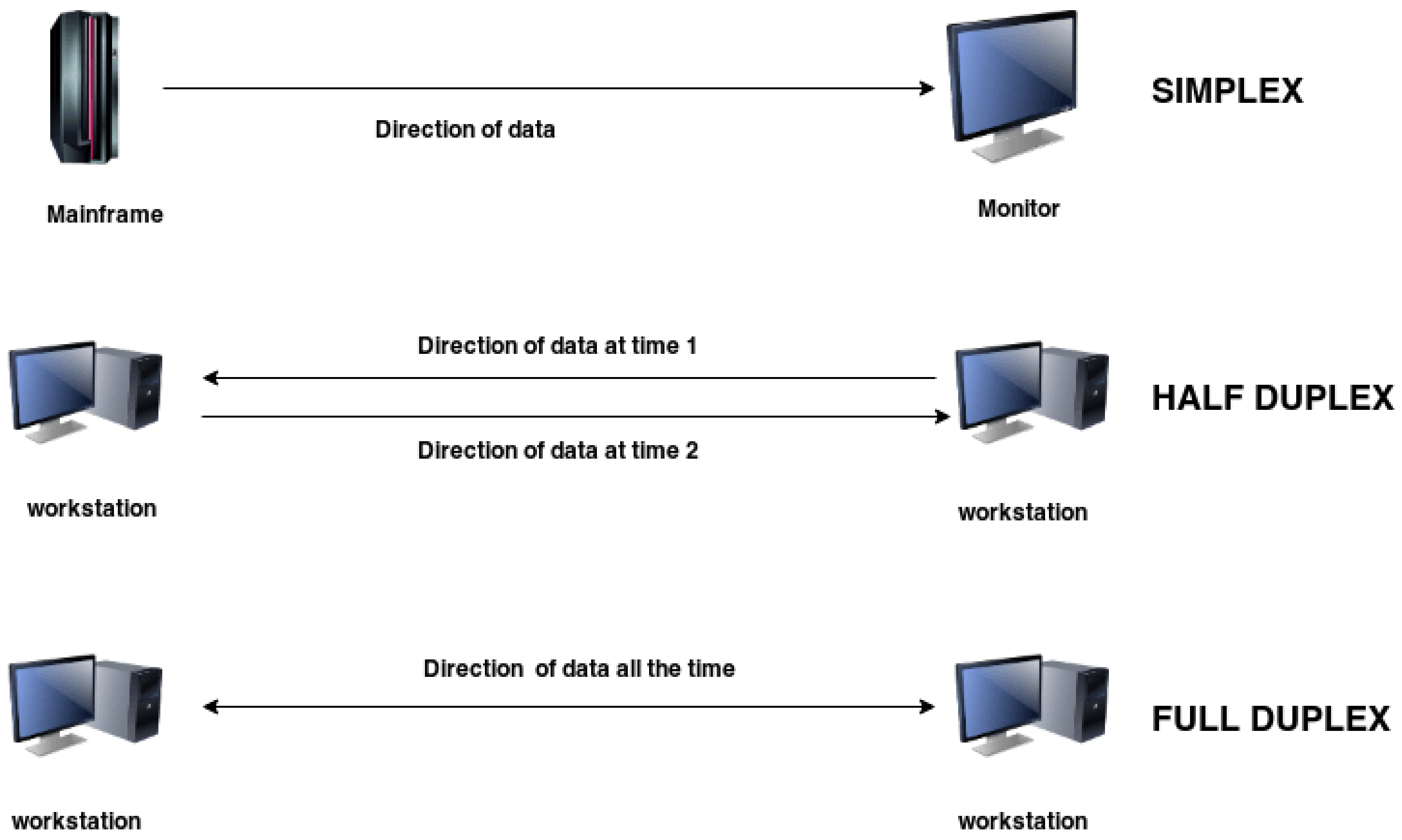


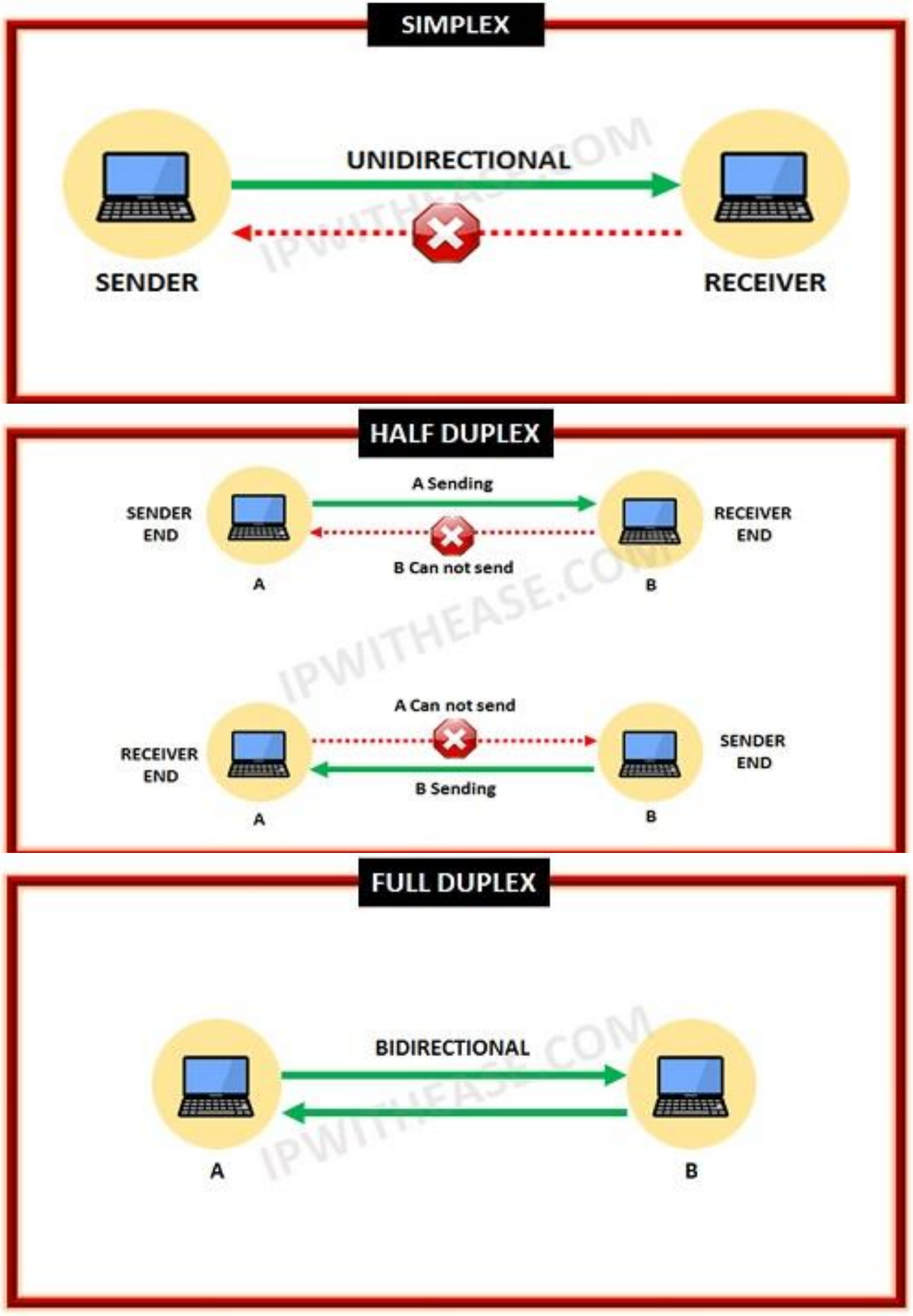
Simplex Systems	Communication systems which provide only one-way communication.
Half Duplex Systems	Communication systems which allow two-way communication by using the same radio channel for both transmission and reception. At any given time, the user can only either transmit or receive information.
Full Duplex Systems	Communication systems which allow simultaneous two-way communication. Transmission and reception is typically on two different channels (FDD) although new cordless/PCS systems are using TDD.



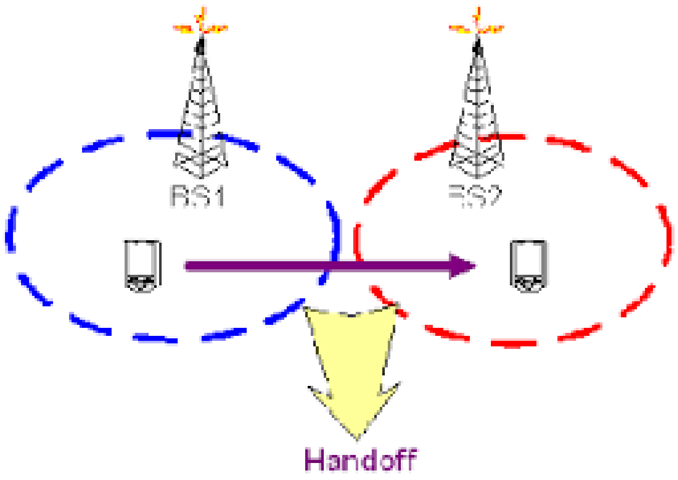


Simplex mode	Half-duplex mode	Full-duplex mode
The communication is unidirectional.	The communication is bidirectional, but one at a time.	The communication is bidirectional.
A device can only send data but cannot receive it or it can only receive data but cannot send it.	Both the devices can send and receive the data, but one at a time.	Both the devices can send and receive the data simultaneously.
The lowest performance among the mods.	The performance is better than simplex but less than full duplex.	The highest performance among the mods.
Examples are radio, keyboard, and monitor.	Example is Walkie-Talkies.	Example is a telephone or mobile network.

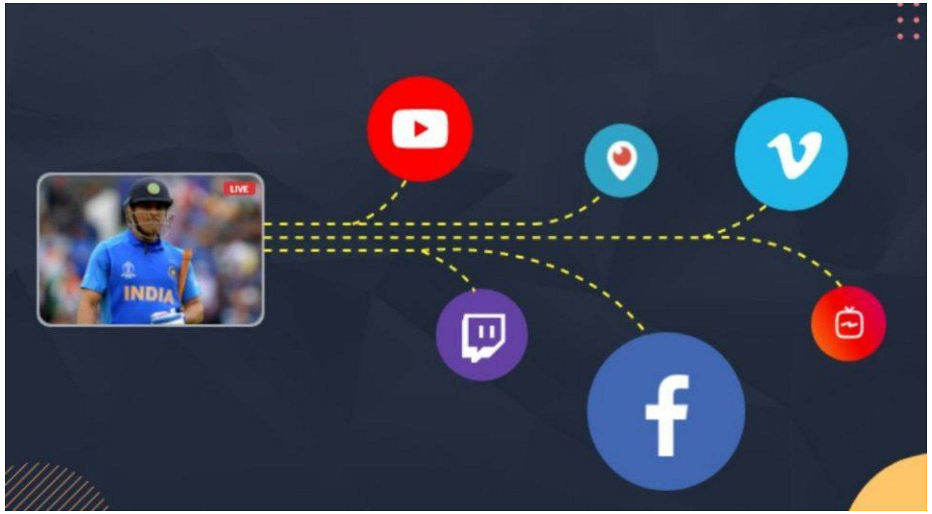

Direction of data
Mainframe
Monitor
SIMPLEX
Direction of data at time 1
Direction of data at time 2
workstation
workstation
HALF DUPLEX
Direction of data all the time
workstation
workstation
FULL DUPLEX

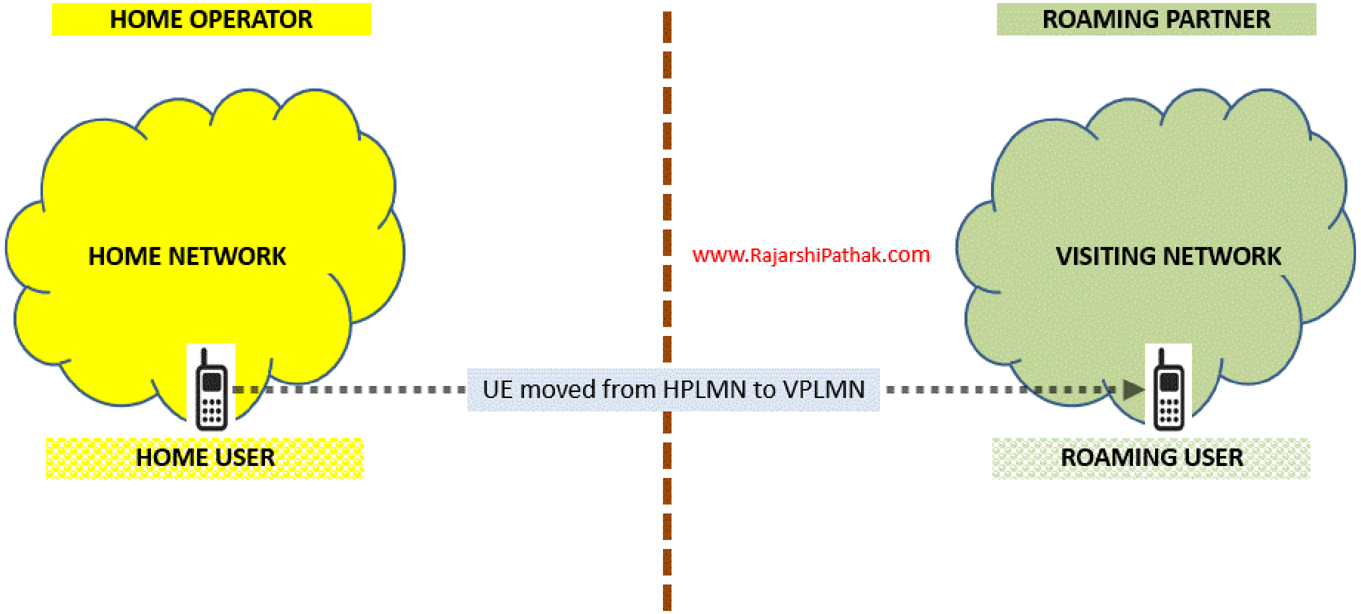

SIMPLEX
UNIDIRECTIONAL
SENDER
RECEIVER
HALF DUPLEX
SENDER END
A Sending
B Can not send
RECEIVER END
A
B
RECEIVER END
A Can not send
B Sending
SENDER END
A
B
FULL DUPLEX
BIDIRECTIONAL
A
B

Handoff	The process of transferring a mobile station from one channel or base station to another.

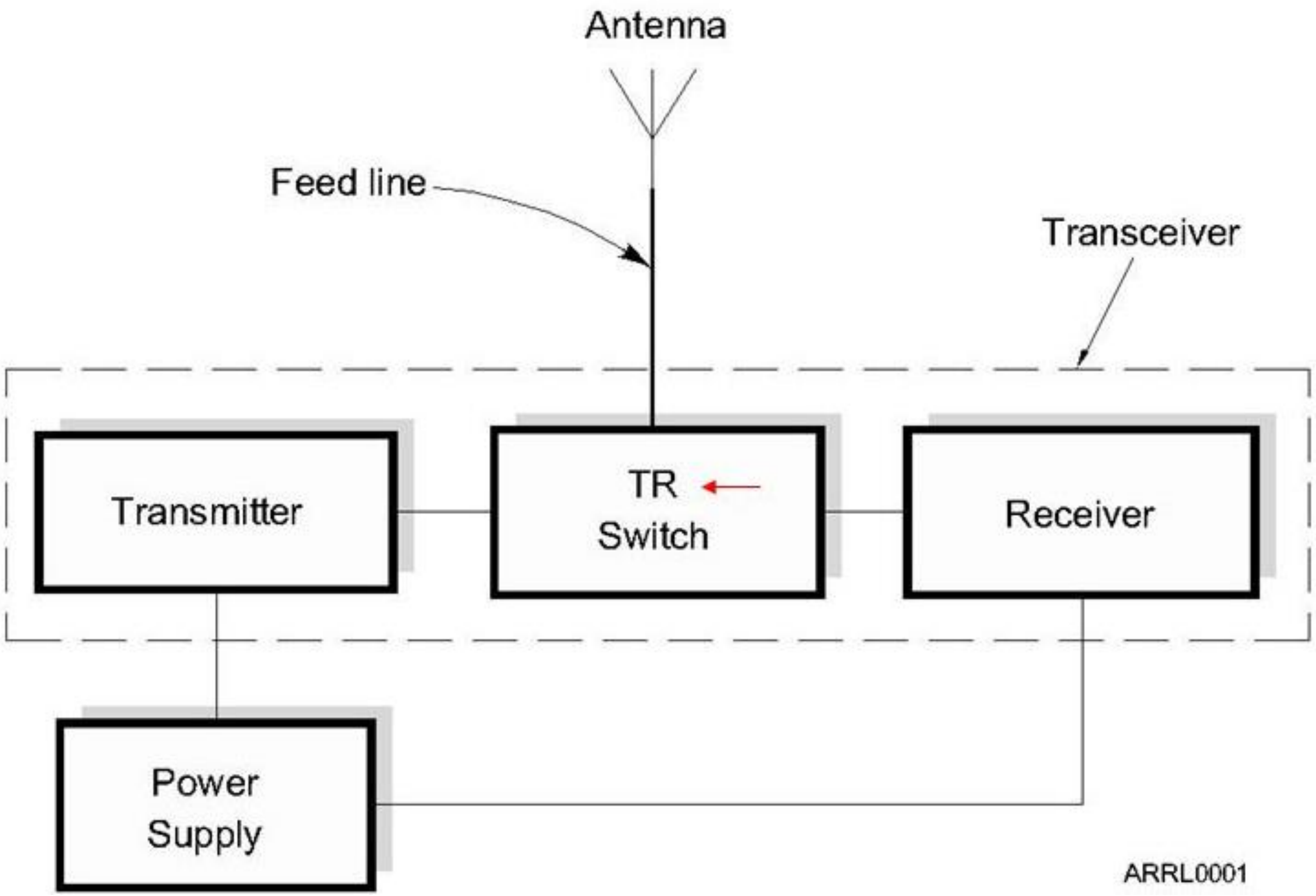


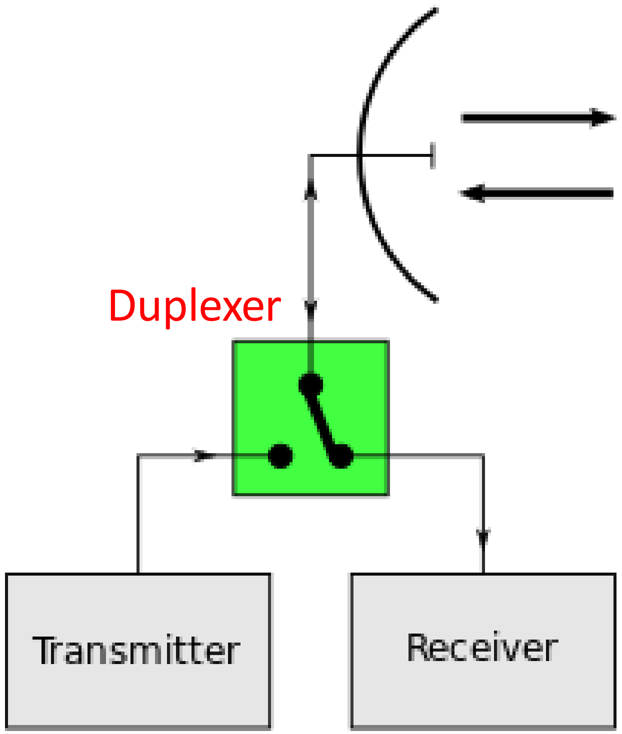
Page	A brief message which is broadcast over the entire service area, usually in a simulcast fashion by many base stations at the same time.
Roamer	A mobile station which operates in a service area (market) other than that from which service has been subscribed.



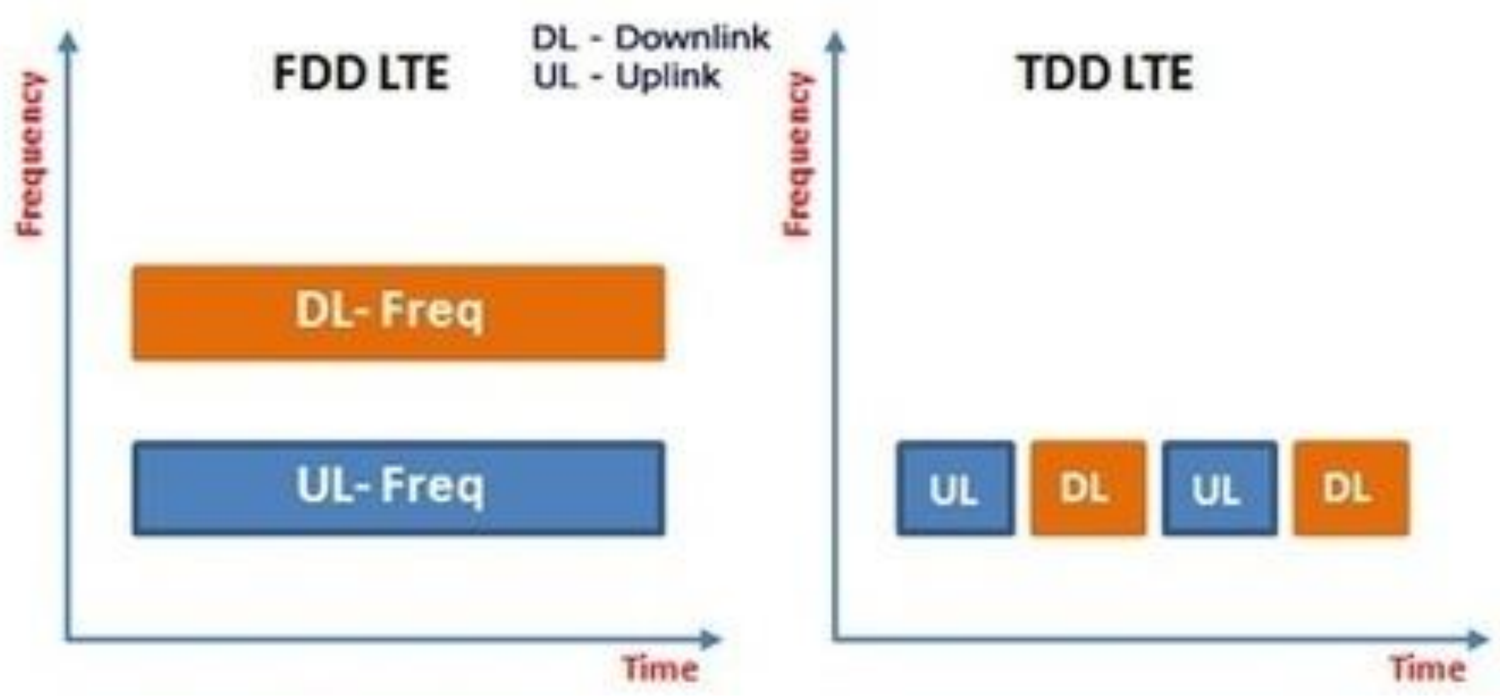


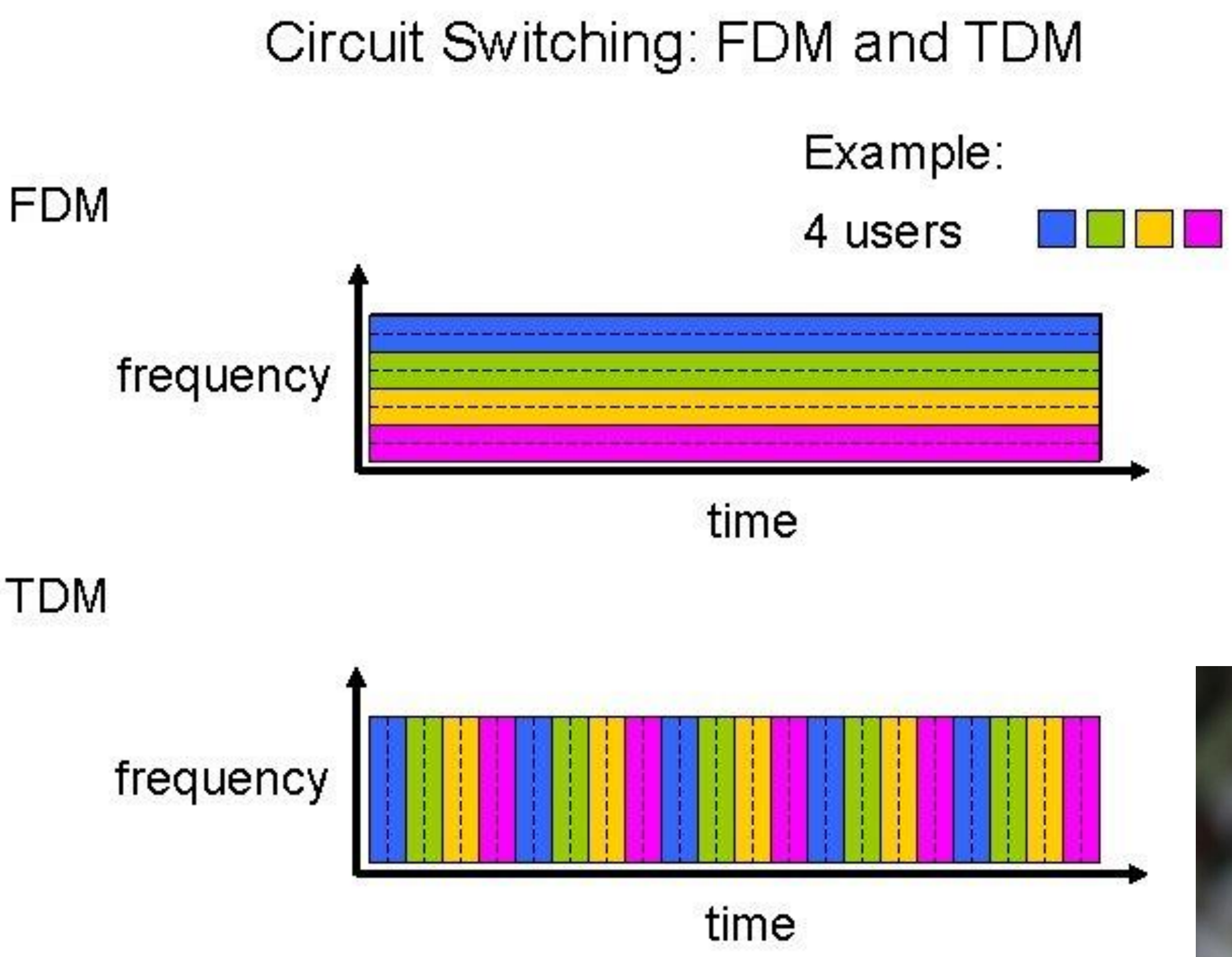
Transceiver	A device capable of simultaneously transmitting and receiving radio signals.
Duplexer	It is a device used inside the subscriber unit to enable simultaneous transmission and reception from the base station.





Frequency division duplexing (FDD)	It provides simultaneous radio transmission channels for the subscriber and the base station, so that they both may constantly transmit while simultaneously receiving signals from one another.
Time division duplexing (TDD)	In this, it is possible to share a single radio channel in time, so that a portion of the time is used to transmit from the base station to the mobile, and the remaining time is used to transmit from the mobile to the base station.




Circuit Switching: FDM and TDM
Example:
4 users
FDM
frequency
time
TDM
frequency
time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INDIA

2. Examples of mobile radio communication systems

Garage door openers

Remote controllers for home entertainment equipment

Pagers (also called paging receivers or "beepers")

Cordless telephones

Hand-held walkie-talkies

Cellular telephones.

However,

- the cost,
- complexity,
- performance, and
- types of services offered

by each of these mobile systems are vastly different.

2.1 Paging Systems

- Paging systems send *brief messages to a subscriber*.
- The message may be either a *numeric message, an alphanumeric message, or a voice message*.
- These used to *notify a subscriber of the need* to call a particular telephone number or travel to a known location to receive further instructions.
- In modern paging system, *news headline, stock quotations and faxes, may be sent*.
- A message is sent to a paging subscriber via the *paging system access number* (usually a toll-free telephone number) with a telephone keypad or modem.

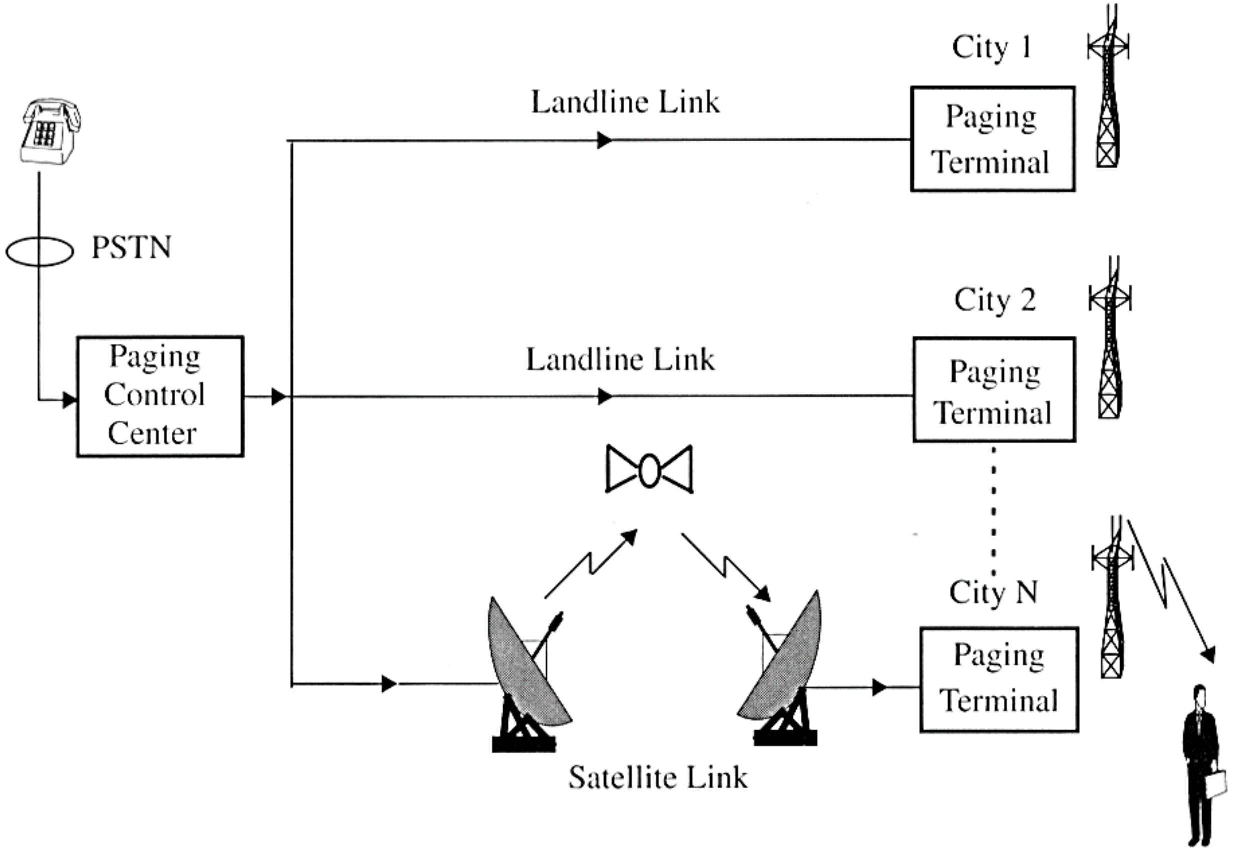


Figure 1.3 A wide area paging system. The paging control center dispatches pages received from the PSTN throughout several cities at the same time.

- The issued message is called a *page*.
- The paging system then *transmits the page throughout the service area* using base stations which broadcast the page on a radio carrier.
- Simple paging systems may cover a limited range of 2 km to 5 km, or may even be confined to within individual buildings, wide area paging systems can provide worldwide coverage.
- Paging receivers are simple and inexpensive, the transmission system required is quite sophisticated.

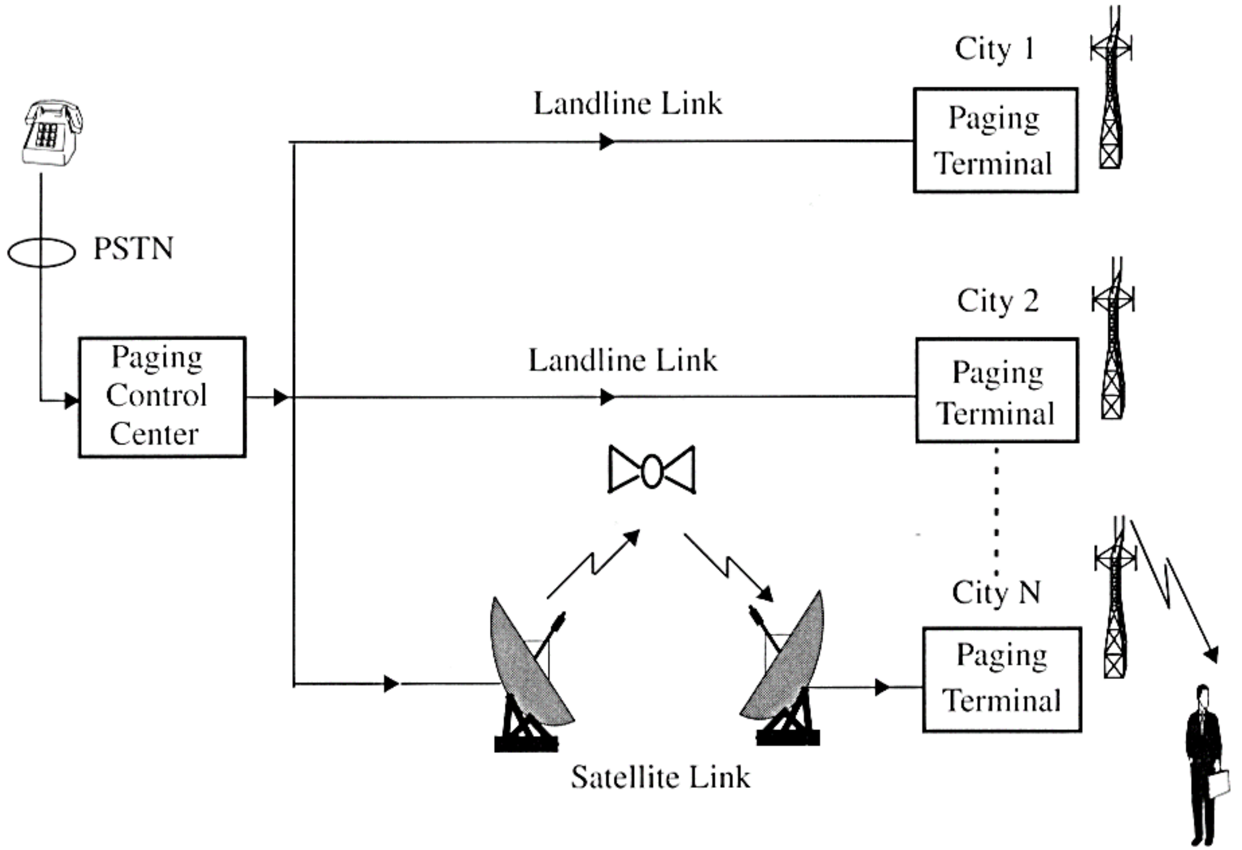


Figure 1.3 A wide area paging system. The paging control center dispatches pages received from the PSTN throughout several cities at the same time.

- *Wide area paging systems* consist of a network of telephone lines, many base station transmitters, and large radio towers that simultaneously broadcast a page from each base station (this is called simulcasting).

2.2 Cordless Telephone Systems

- Cordless telephone systems are full duplex communication systems.
- It use wireless link to connect a portable handset to a dedicated base station, which is then connected to a dedicated telephone line with a specific telephone number on the public switched telephone network (PSTN).

- First generation cordless phone:
  - –Portable unit communicates to only to the dedicated base unit
  - –Covers only few tens of meters
  - –Primarily used in indoor
- Second generation cordless phone:
  - –Portable unit can communicate in outdoor locations also.
  - –Sometimes combined with paging receivers
  - –Covers few hundred meters per station

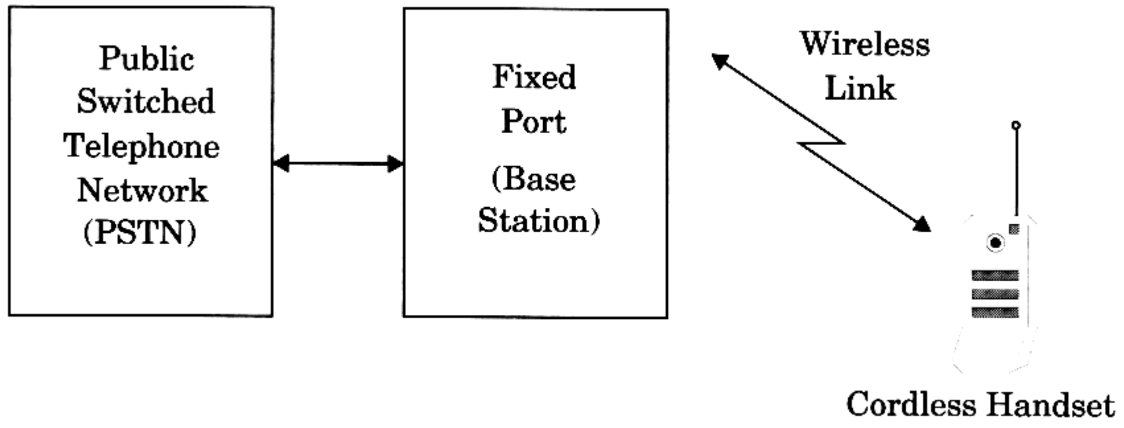


Figure 1.4 A cordless telephone system.

Limitations:

- Provide user with limited range and mobility
- Not possible to maintain a call if the user travels outside the range of base station.

2.3. Cellular Telephone Systems

- Provides a *wireless connection* to the PSTN for *any user location* within the radio range of the system.
- **Characteristics of cellular system:**
  - –It Accommodate *large number of users* over a *large geographic area* within *limited frequency spectrum*.
  - –It provide *high quality service* than landline telephone systems.
  - –*High capacity* is achieved by using *cell concept*.
  - –*Reuse of the radio frequency* by the concept of "cell".
  - –Handoff switching technique enables uninterrupted call when the user moves from one cell to another.

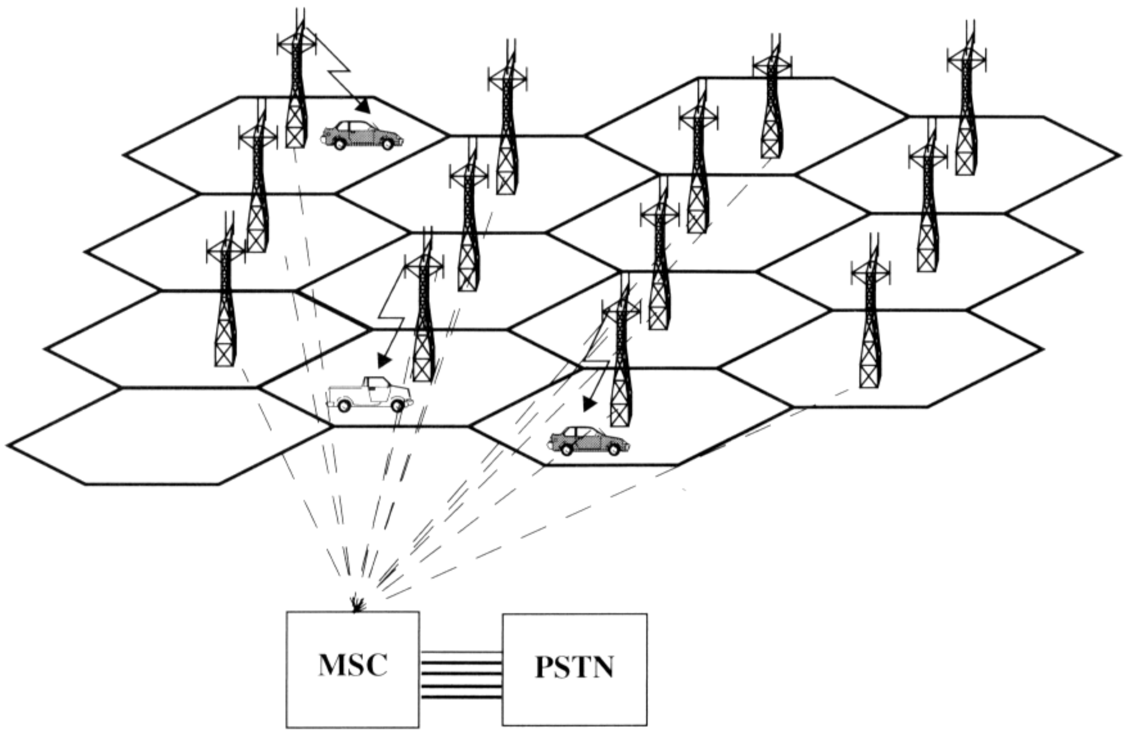
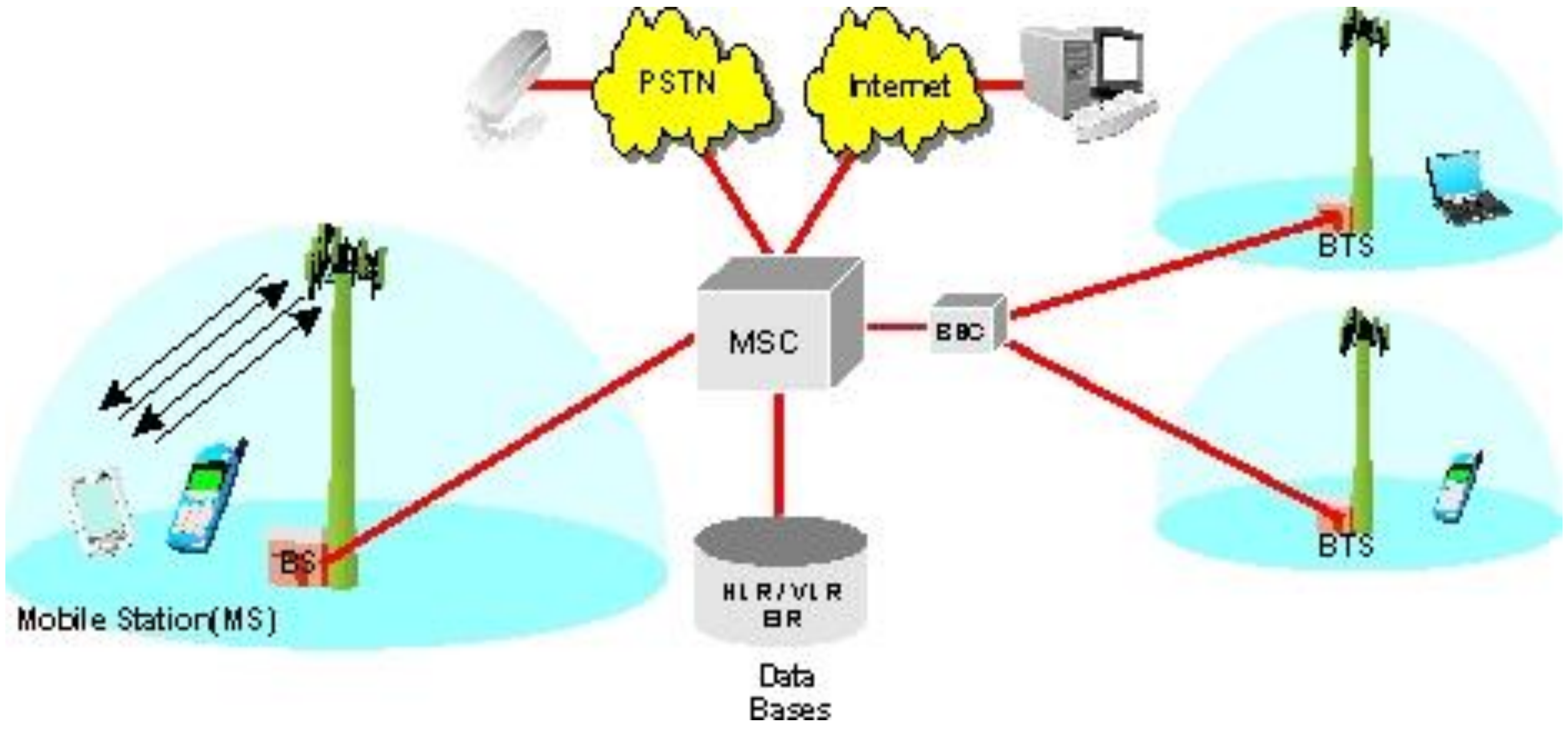
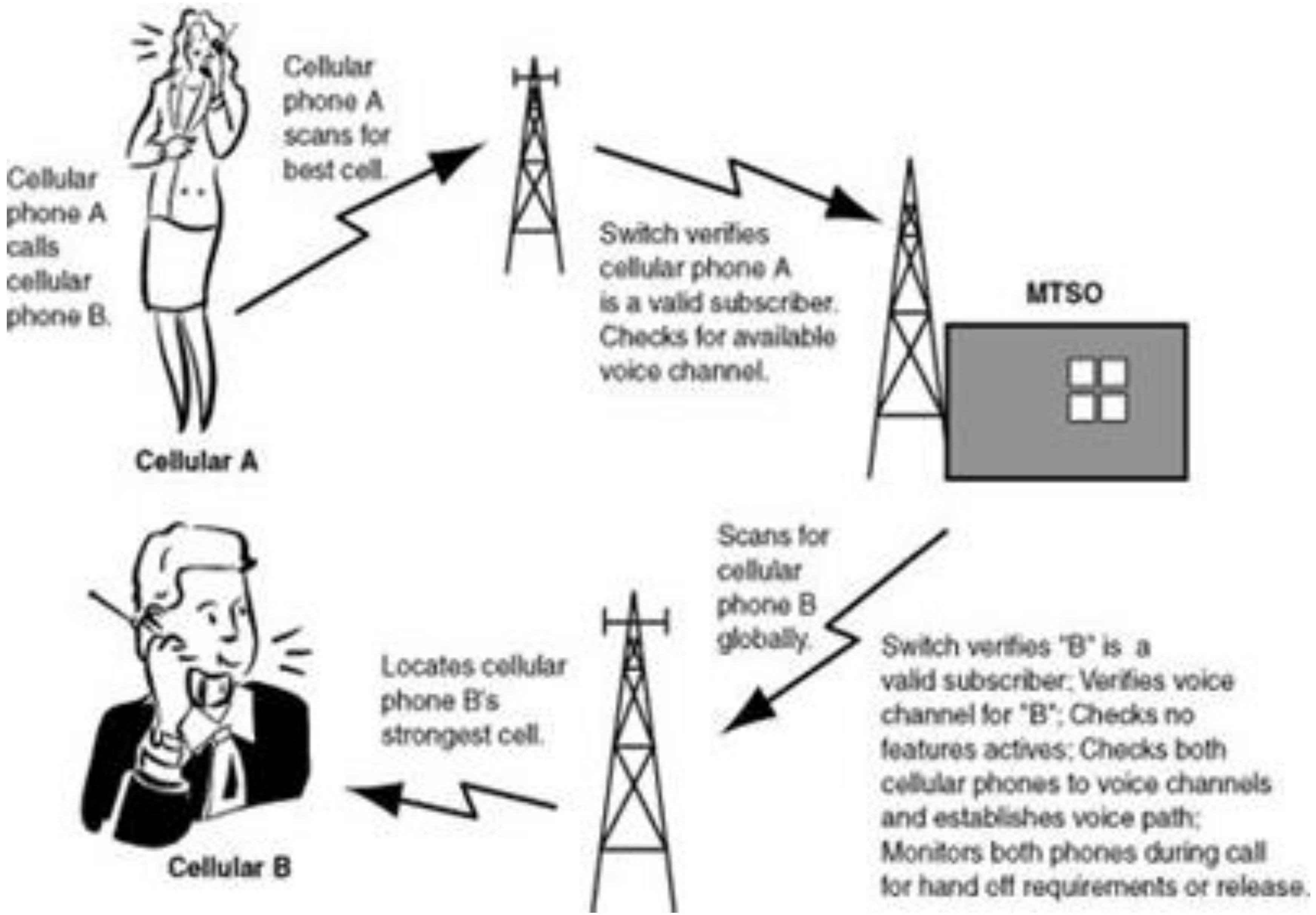


Figure 1.5 A cellular system. The towers represent base stations which provide radio access between mobile users and the mobile switching center (MSC).

- Basic cellular system: mobile stations, base stations, and mobile switching center (MSC) or MTSO.
- MSC is responsible for connecting all mobiles to the PSTN.

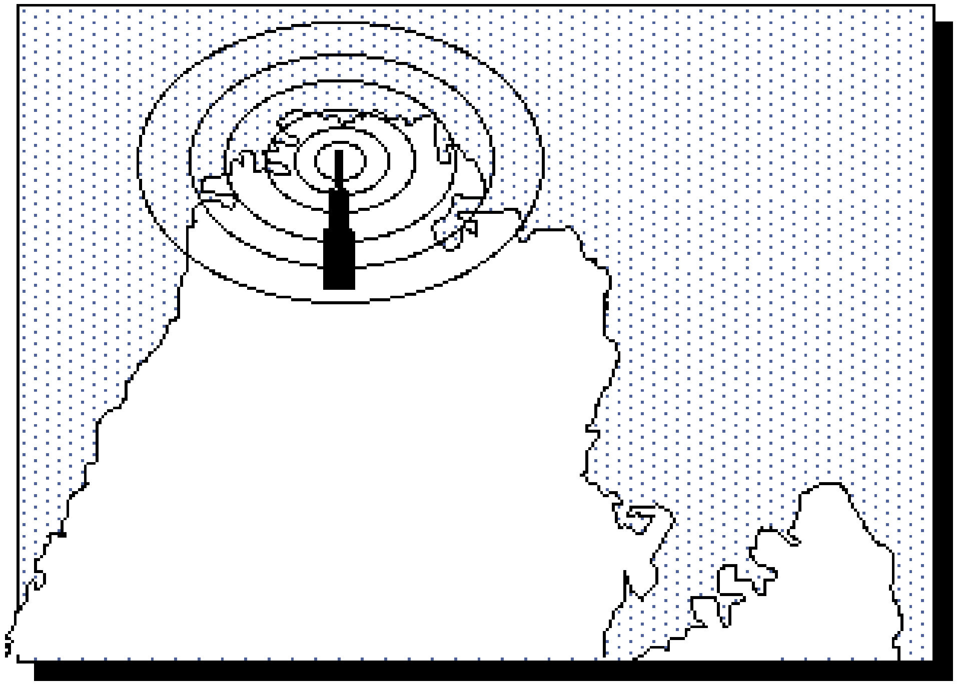
- Communication between the base station and mobiles is defined by the standard *common air interface (CAI)*
  - –forward voice channel (FVC): voice transmission from base station to mobile
  - –reverse voice channel (RVC): voice transmission from mobile to base station
  - –forward control channels (FCC): initiating mobile call from base station to mobile
  - –reverse control channel (RCC): initiating mobile call from mobile to base station


PSTN
Internet
MSC
BBC
BTS
BTS
BS
Mobile Station(MS)
HLR/VLR
EIR
Data
Bases


Cellular phone A scans for best cell.
Cellular phone A calls cellular phone B.
Cellular A
Switch verifies cellular phone A is a valid subscriber. Checks for available voice channel.
MTSO
Scans for cellular phone B globally.
Switch verifies "B" is a valid subscriber; Verifies voice channel for "B"; Checks no features actives; Checks both cellular phones to voice channels and establishes voice path; Monitors both phones during call for hand off requirements or release.
Locates cellular phone B's strongest cell.
Cellular B

Early Mobile Telephone System:

- Its objective is to achieve a *large coverage area* (Aprox. 50kms) by *using a single high-powered transmitter* with an antenna mounted on a tall tower.
- This approach achieved very good coverage.



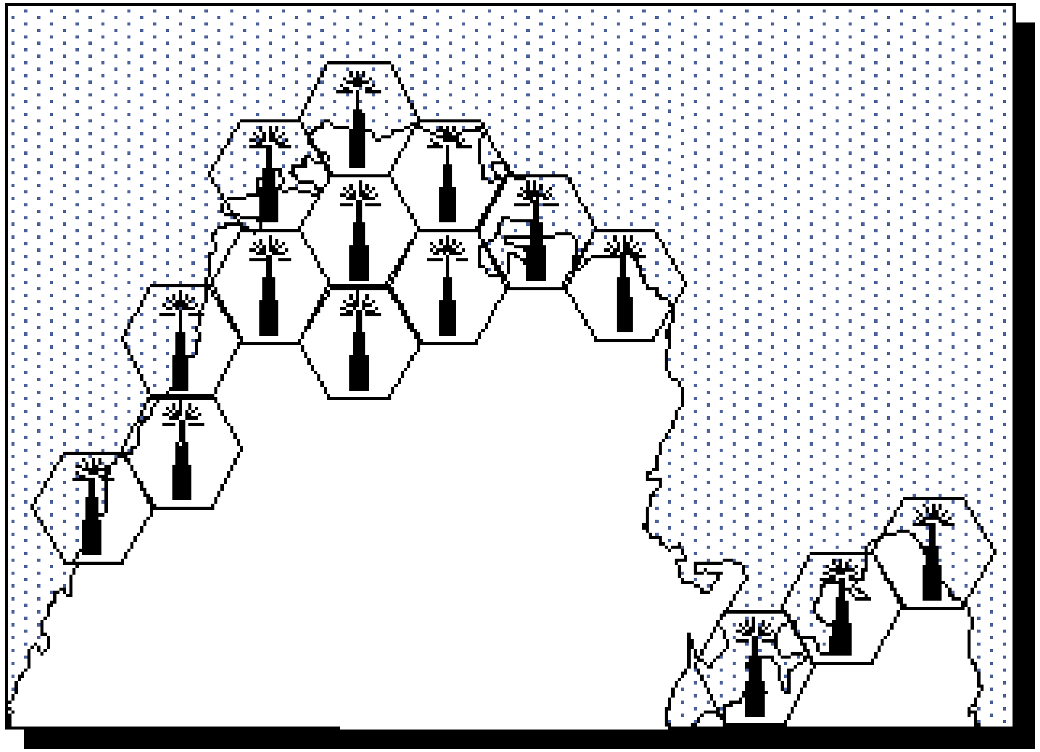
- **Limitations** of Early Mobile Telephone System:
  - It was ***impossible to reuse those same frequencies*** throughout the system (any attempts to achieve frequency reuse would result in interference).
  - **Low system capacity**: For example, the Bell mobile system in New York City in the 1970s could only support a **maximum of twelve simultaneous calls** over a thousand square miles.
  - The government regulatory agencies could not make spectrum allocations in proportion to the increasing demand for mobile services.
- So, there is a ***need to restructure the radio telephone system*** **to achieve high capacity with limited radio spectrum, while at the same time covering very large areas.**

3. Introduction to Cellular Concept

- The ***cellular concept*** was a **major breakthrough** in solving the problem of **spectral congestion** and **user capacity**.

- It offered **very high capacity** in a limited spectrum allocation without any major technological changes.

- It **replaces** a single, high-power transmitter (large cell) with many low power transmitters (small cells), each providing coverage to only a small portion of the service area.



Large geographical area is divided into small geographic regions called **cells** hence the name **cellular technology** and the conventional radio phones got the names **Cell phones**.

- Each base station is allocated a portion of the total number of channels available to the entire system.

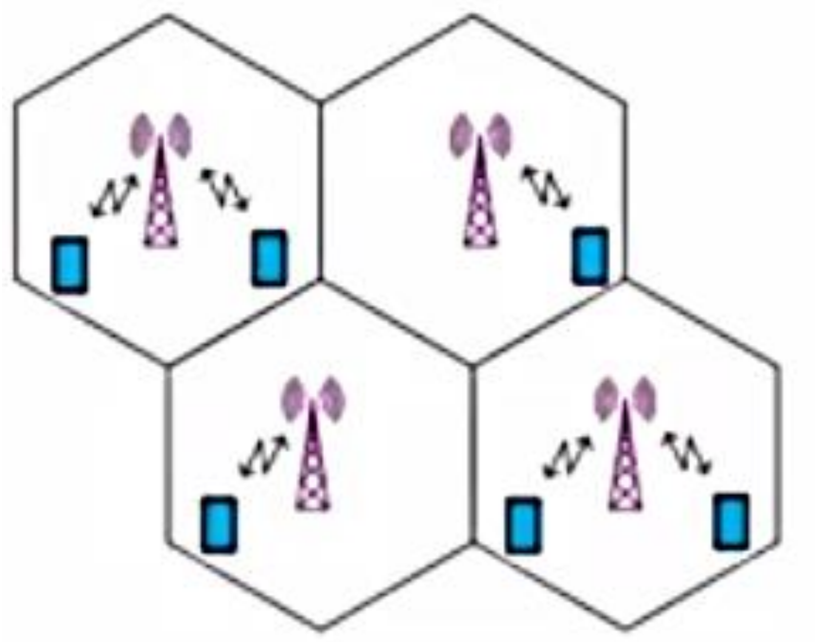
- And, neighboring base stations are assigned with different groups of channels so that the interference between base stations is minimized.

- By **systematically spacing** the base stations and theirs channels, available channels are distributed throughput the geographic region and **may be reused** as many times as necessary.

- As the demand for service increases (i.e., as more channels are needed within a particular market), the number of base stations may be increased (along with a corresponding decrease in transmitter power to avoid added interference), thereby providing additional radio capacity with no additional increase in radio spectrum.

3.1. Cell Structure

- A **cell** is a small geographic area**.**
- Every cell consist of a **base station transmitter/receiver** (antenna).
- Each cellular base station is **allocated a group of radio channels** to be used within the cell**.**
- Base stations in adjacent cells are assigned with completely different channels (frequencies).
- The base station antennas are designed to achieve the desired coverage within the particular cell.



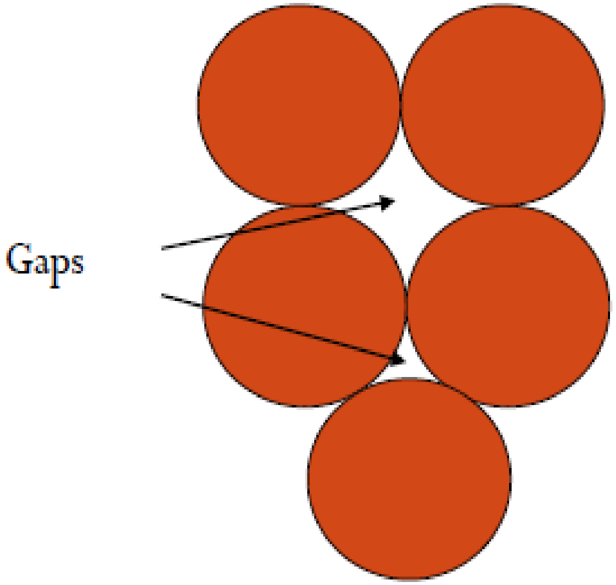
- By limiting the coverage area to within the boundaries of a cell, the same group of channels may be used to cover different cells that are separated from one another by large enough distances to keep interference levels within tolerable limits.

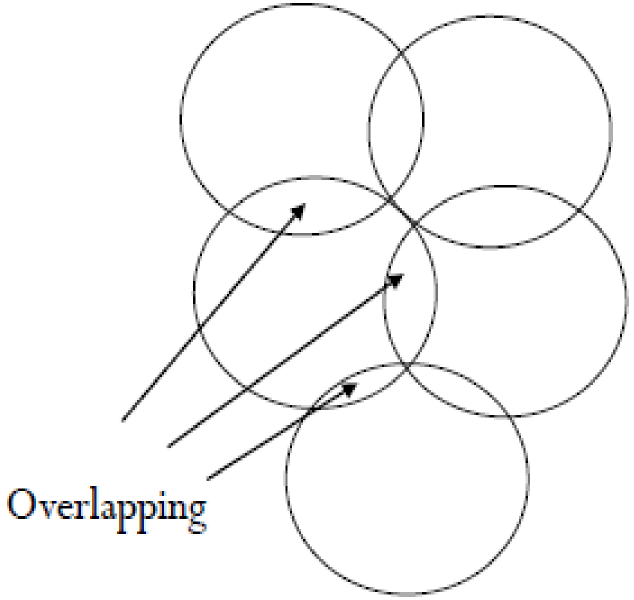
Factors to be consider for selection of cell structure:

-Cell should have equal area (Should more and more represent a circle)
-No overlap between the cells
-Cells should be regular in nature/ symmetrical

a. Circle:

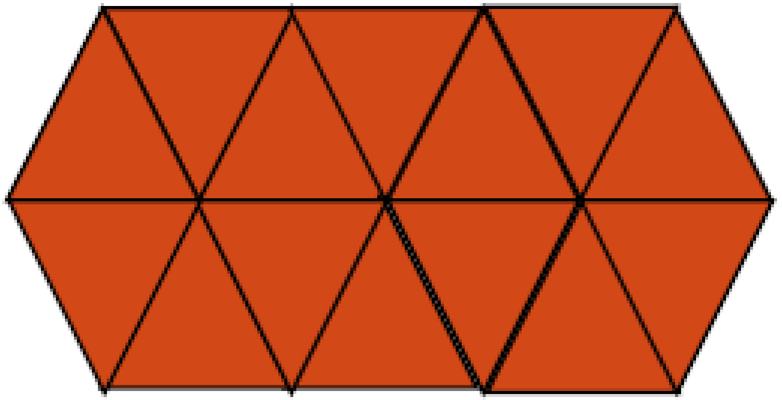
- Adjacent circles cannot be covered upon a map without leaving gaps or creating overlapping regions.



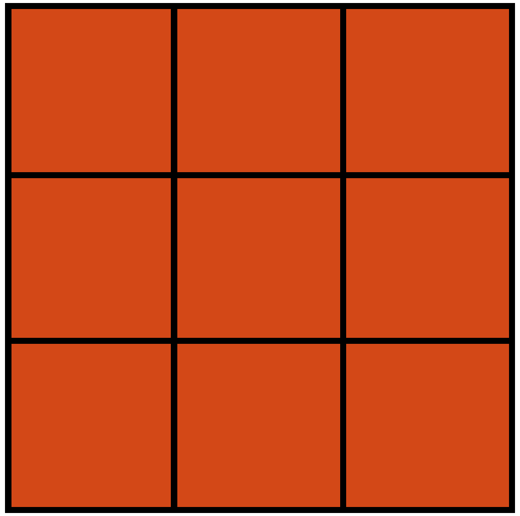


- **Gaps between cells Leads to loss of coverage**
- **Overlapping Leads to Interference of signal**

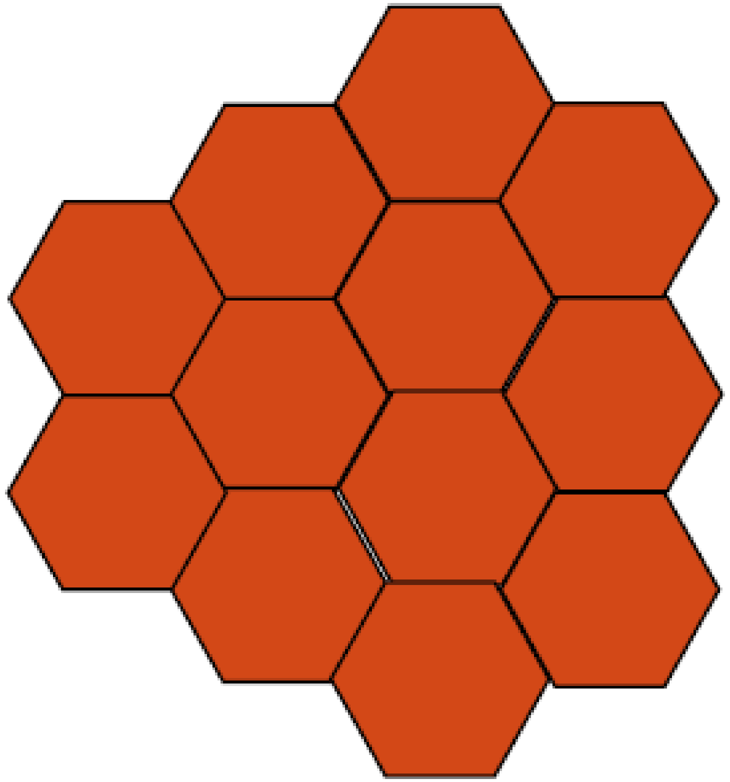
- Thus, when considering geometric shapes which cover an entire region **without overlap** and with **equal area**, there are three sensible choices—a **square, an equilateral triangle, and a hexagon.**



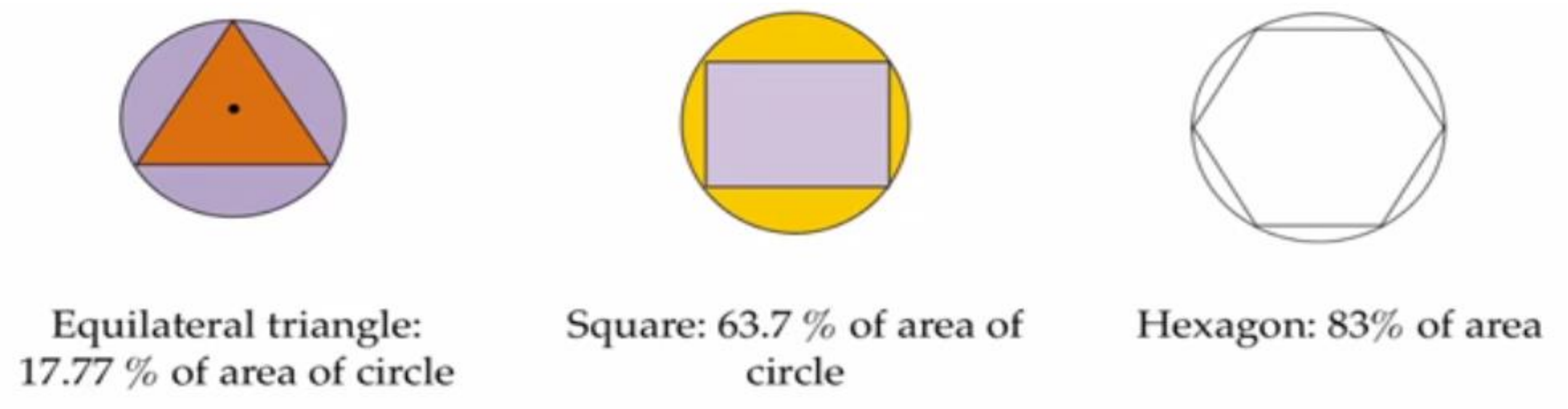
Triangles



Squares

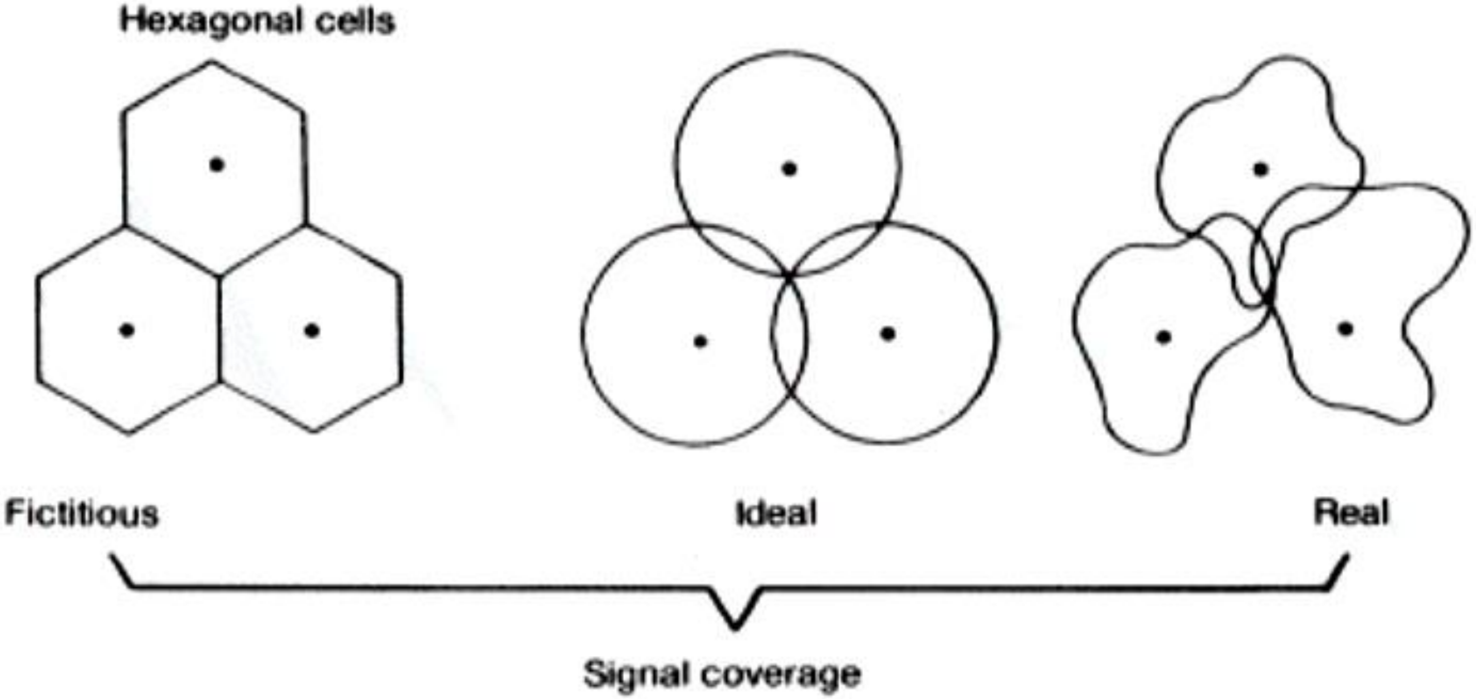


Hexagons

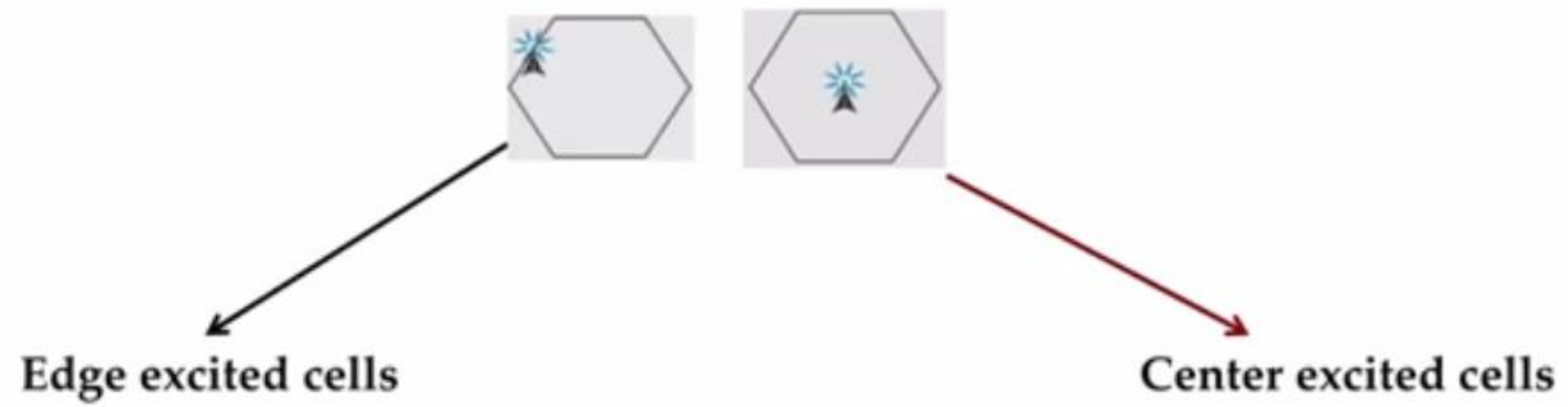


- The ***hexagonal cell shape*** is conceptual and is a simplistic model of the radio coverage for each base station.
- Hexagon shape has been universally adopted as a cell shape.

- The actual radio coverage of a cell is known as the ***footprint*** and is determined from field measurements or propagation prediction models.
- Actual cellular footprint is determined by the ***contour*** of a given transmitting antenna.



- When using hexagons to model coverage areas, base station transmitters are placed:
  - In the center of the cell (**center-excited cells**) or
  - on three of the six cell vertices (**edge-excited cells**)
  - Normally, omnidirectional antennas are used in center-excited cells.



4. Frequency Reuse

- The cellular system rely on an ***intelligent allocation and reuse of channels*** throughout a coverage region.
- The **design process of selecting and allocating channel groups for all of the cellular base stations within a system** is called ***<u>frequency reuse or frequency planning.</u>***
- One important characteristic of cellular networks is the ***<u>reuse of frequencies</u>*** in different cells.
- By reuse frequencies, a ***<u>high capacity</u>*** can be achieved.
- However, the ***<u>reuse distance has to be high enough</u>***, so that the interference caused by subscribers using the same frequency (or an adjacent frequency) in another cells is sufficiently low.

- The hexagonal cell shape has been universally adopted.
- Cells with the same letter use the same set of frequencies.
- A cell cluster is outlined in bold and replicated over the coverage area.
- Cluster is a group of ***N*** cells which collectively use the complete set of available frequencies.
- The ***frequency reuse factor*** of a cellular system is given by ***1/N***, since each cell within a cluster is only assigned 1/N of the total available channels in the system.
- In this example, the cluster size *N*=7, and the frequency reuse factor is 1/7.

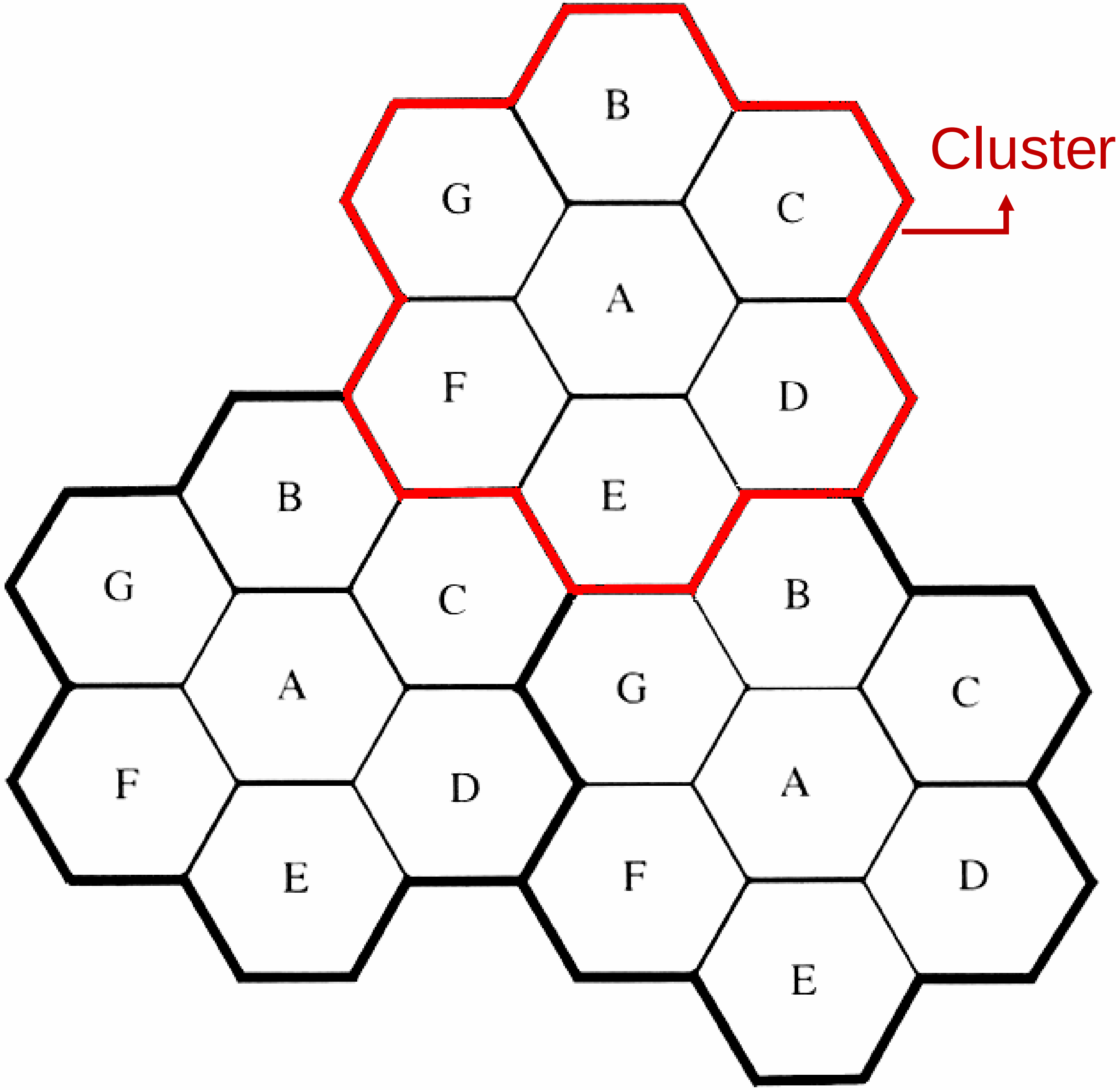


Figure 3.1 Illustration of the cellular frequency reuse concept.

To **understand the frequency reuse concept**:

- Consider a cellular system:
  - Total number of duplex channels available for use: ***S*** channels
  - Cluster size : ***N*** cells
  - No. of channels in each cell : ***k=S/N*** *(where K<S)*
  - The total number of available radio channels can be expressed as ***S= k*N***
  - Capacity of a cluster : ***C = k*N = S Channels***
  - If a cluster is replicated ***M*** times, then the total capacity of the system: ***C = M*k*N = M*S***
- The capacity of a cellular system is directly proportional to the number of times a cluster is replicated in a fixed service area.

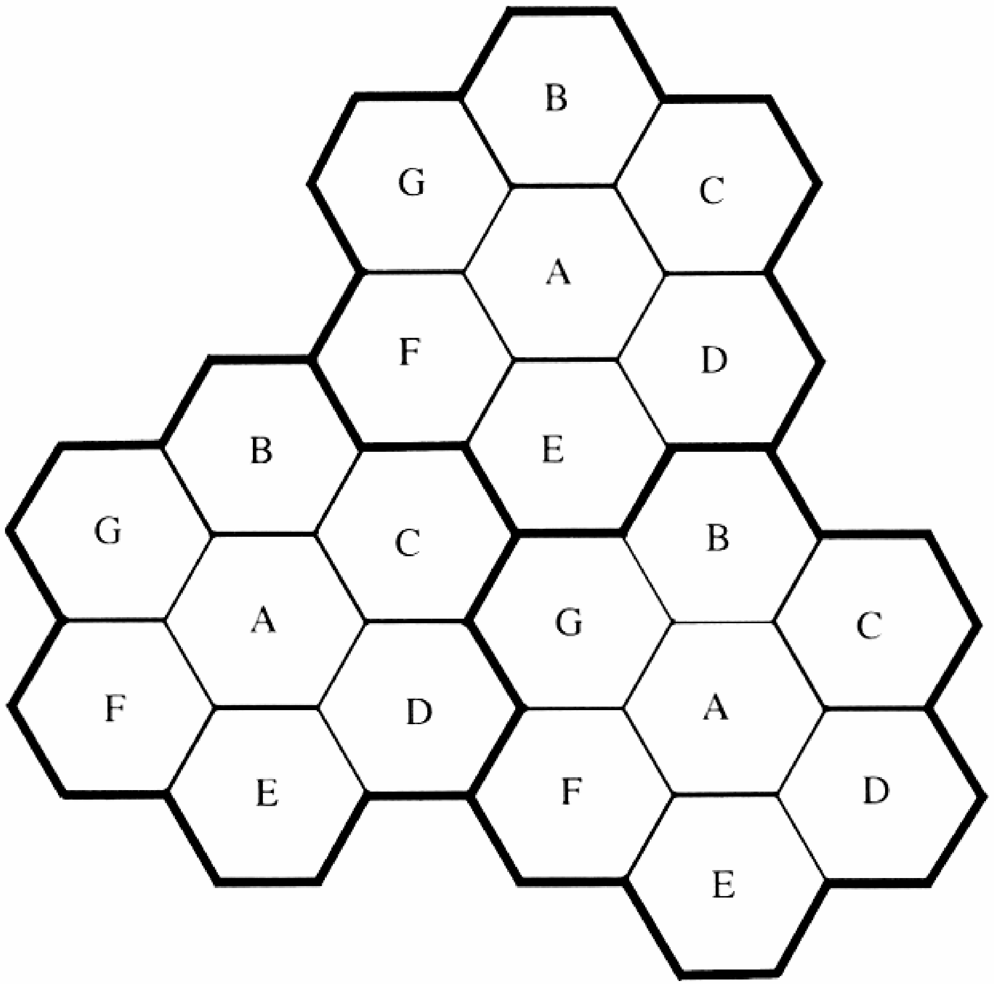


Figure 3.1. Illustration of the cellular frequency reuse concept.

- The factor ***N*** is called the ***cluster size*** and is typically equal to **4, 7, or 12.**
- **If the cluster size *N* is reduced** while the cell size is kept constant, more clusters are required to cover a given area, and hence **more capacity (a larger value of *C*) is achieved.**
- Conversely, a small cluster size indicates that co-channel cells are located much closer together.
- The **value for *N* is a function of how much interference a mobile or base station can tolerate** while maintaining a sufficient quality of communications.
- From a design viewpoint, the **smallest possible value of *N* is desirable in order to maximize capacity** over a given coverage area.

Tradeoff for cluster sizes

SMALLER CLUSTER SIZES

↓

Capacity will be increased but Interference would be more

LARGER CLUSTER SIZES

↓

Capacity will be less but Interference would also be less

Small cluster size with minimum interference level should be used

for efficient frequency reuse

Example 1: If a total of 33 MHz of bandwidth is allocated to a particular FDD cellular telephone system which uses two 25 kHz simplex channels to provide full duplex voice and control channels, compute the number of channels available per cell if a system uses: (a) four-cell reuse, (b) seven-cell reuse, and (c) 12-cell reuse.

Solution

Given:

Total bandwidth = 33 MHz

Channel bandwidth = 25 kHz × 2 simplex channels = 50 kHz/duplex channel

Total available channels = 33,000/50 = 660 channels

(a) For N = 4:

Total number of channels available per cell = 660/4 ≈ 165 channels.

(b) For N = 7:

Total number of channels available per cell = 660/7 ≈ 95 channels.

(c) For N = 12:

Total number of channels available per cell = 660/12 ≈ 55 channels.

Example 2: If 20 MHz of total spectrum is allocated for a duplex wireless cellular system and each simplex channel has 25 kHz RF bandwidth, find:
(a) the number of duplex channels.
(b) the total number of channels per cell site, if N = 4, 7, 12 cell reuse is used.

Solution

Given:

Total bandwidth = 20 MHz

Channel bandwidth = 25 kHz × 2 simplex channels = 50 kHz/duplex channel

(a) Total available channels = 20,000/50 = 400 channels

(b) The total number of channels per cell site if

(i) For N = 4:

Total number of channels available per cell site = 400/4 = 100 channels.

(ii) For N = 7:

Total number of channels available per cell site = 400/7 ≈ 57 channels.

(iii) For N = 12:

Total number of channels available per cell site = 400/12 ≈ 33 channels.

Example 3: A total of 24 MHz of bandwidth is allocated to a particular FDD cellular telephone system that uses two 30 kHz simplex channels to provide full duplex voice. compute the number of channels available per cell if a system uses: (a) four-cell reuse, (b) seven-cell reuse, and (c) 12-cell reuse.

Solution

Given:

Total bandwidth = 24 MHz

Channel bandwidth = 30 kHz × 2 simplex channels = 60 kHz/duplex channel

Total available channels = 24,000/60 = 400 channels

The total number of channels per cell site if

(a) For N = 4:

Total number of channels available per cell site = 400/4 = 100 channels.

(b) For N = 7:

Total number of channels available per cell site = 400/7 ≈ 57 channels.

(c) For N = 12:

Total number of channels available per cell site = 400/12 ≈ 33 channels.

Example 4. The U.S. AMPS cellular telephone system having a total bandwidth of 50 MHz which uses two 25 kHz simplex channels to provide full duplex voice. compute the number of channels available per cell if a system uses: (i) 4-cell reuse, (ii) 7-cell reuse, and (iii) 12-cell reuse.

Solution

Given:

Total bandwidth = 50 MHz

Channel bandwidth = 25 kHz × 2 simplex channels = 50 kHz/duplex channel

Total available channels = 50000/50 = 1000 channels

(i) 4-cell reuse,

total number of channels available per cell = 1000/4 =250 channels.

(ii) 7-cell reuse,

total number of channels available per cell = 1000/7 ≈ 142 channels.

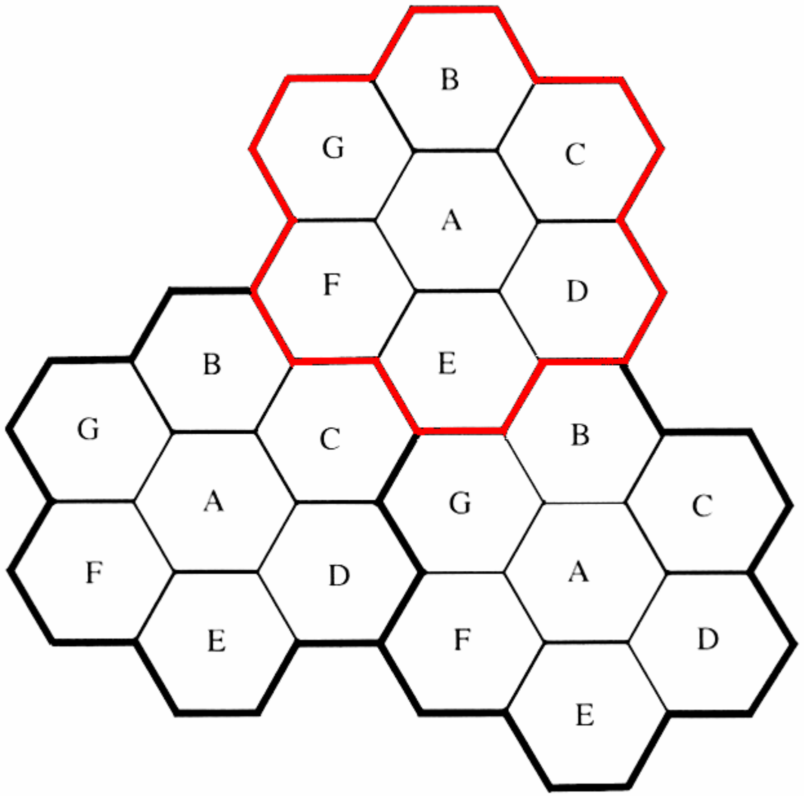
(iii) 12-cell reuse,

total number of channels available per cell = 1000/12 ≈ 83 channels.

Example 5. If the cellular telephone system having total available duplex channels are 665, cluster size is 7, and cluster is repeated for 20 times. Then find the number of channels per cluster and capacity of system.

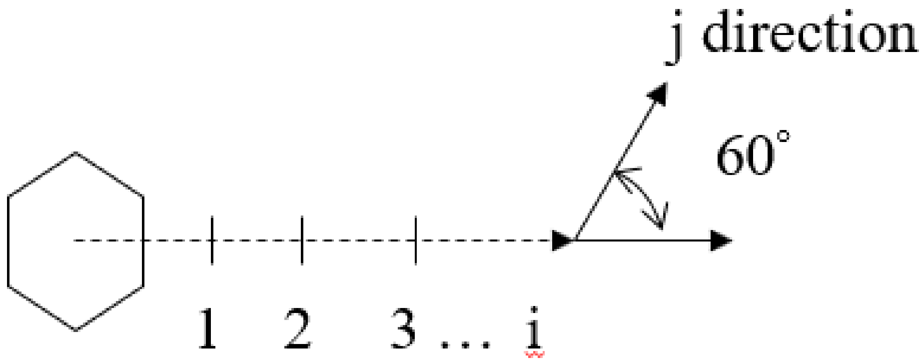
4.1. Design of Cluster

- The hexagonal geometry of Figure 3.1 has exactly six equidistant neighbors.
- And, the lines joining the centers of any cell and each of its neighbors are separated by multiples of 60 degrees.
- So, there are only certain cluster sizes and cell layouts which are possible.
- In order to connect without gaps between adjacent cells, **the number of cells per cluster, *N***, can only have values which satisfy Equation:



$$N = i^2 + ij + j^2$$

where *i* and *j* are non-negative integers.



- To find the **nearest co-channel neighbors** of a particular cell:
  1. move *i* cells along any chain of hexagons and then
  2. Turn 60 degrees counter-clockwise and move *j* cells.

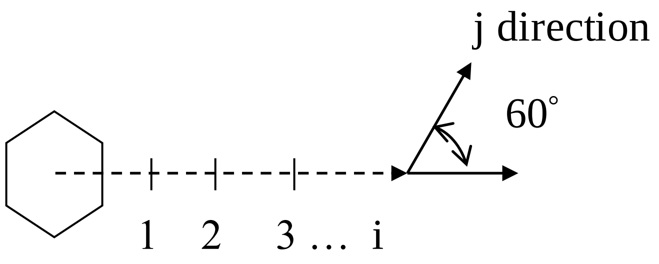
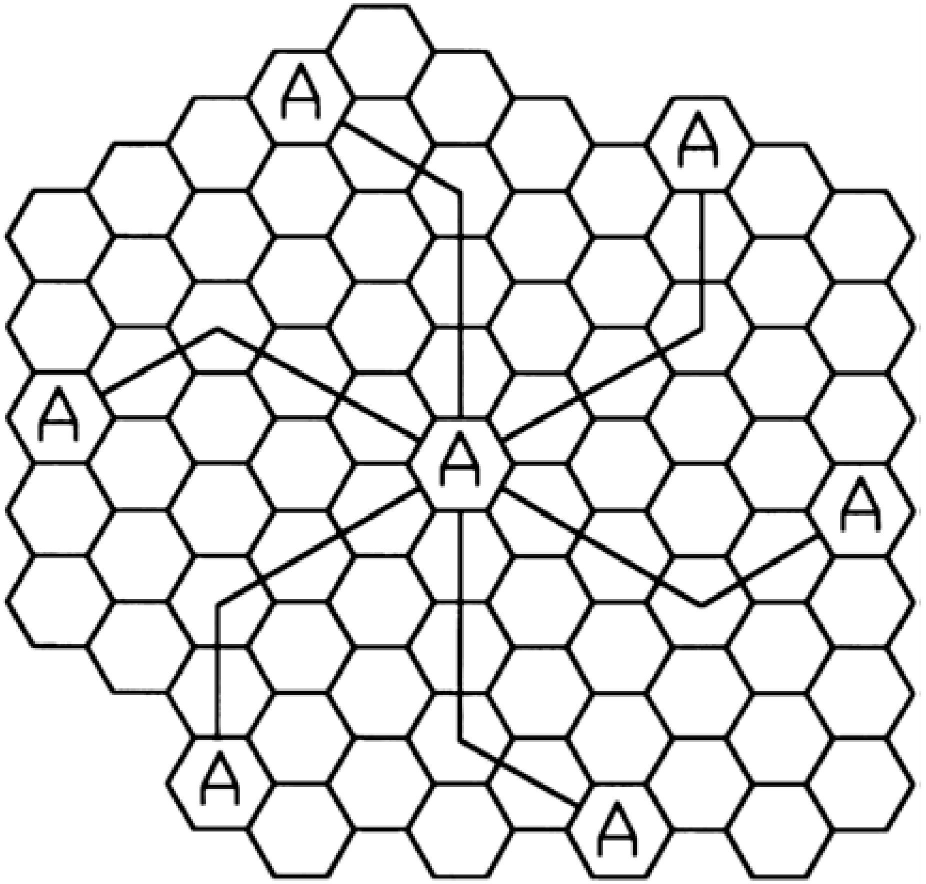
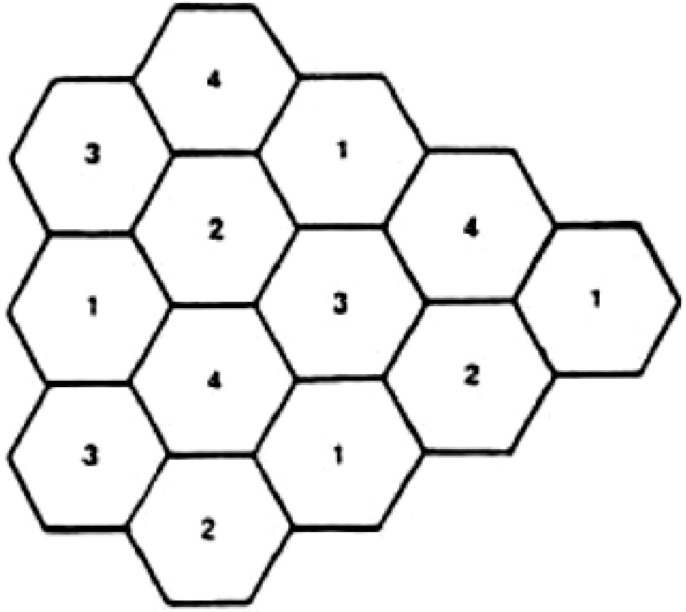


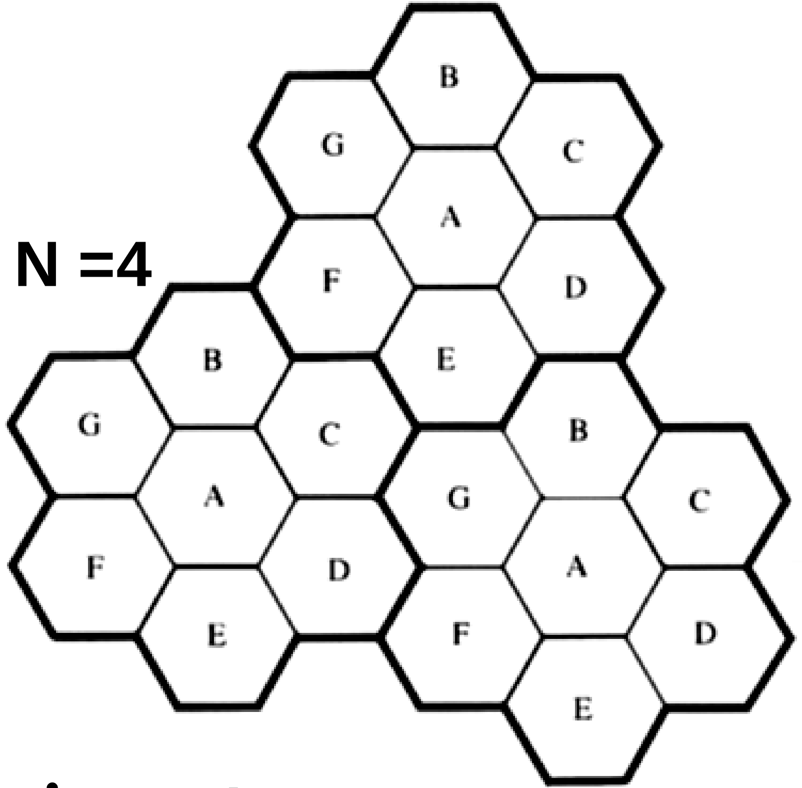
Figure 3.2 Method of locating co-channel cells in a cellular system.

In this example, N = 19 (i.e., i = 3, j = 2).

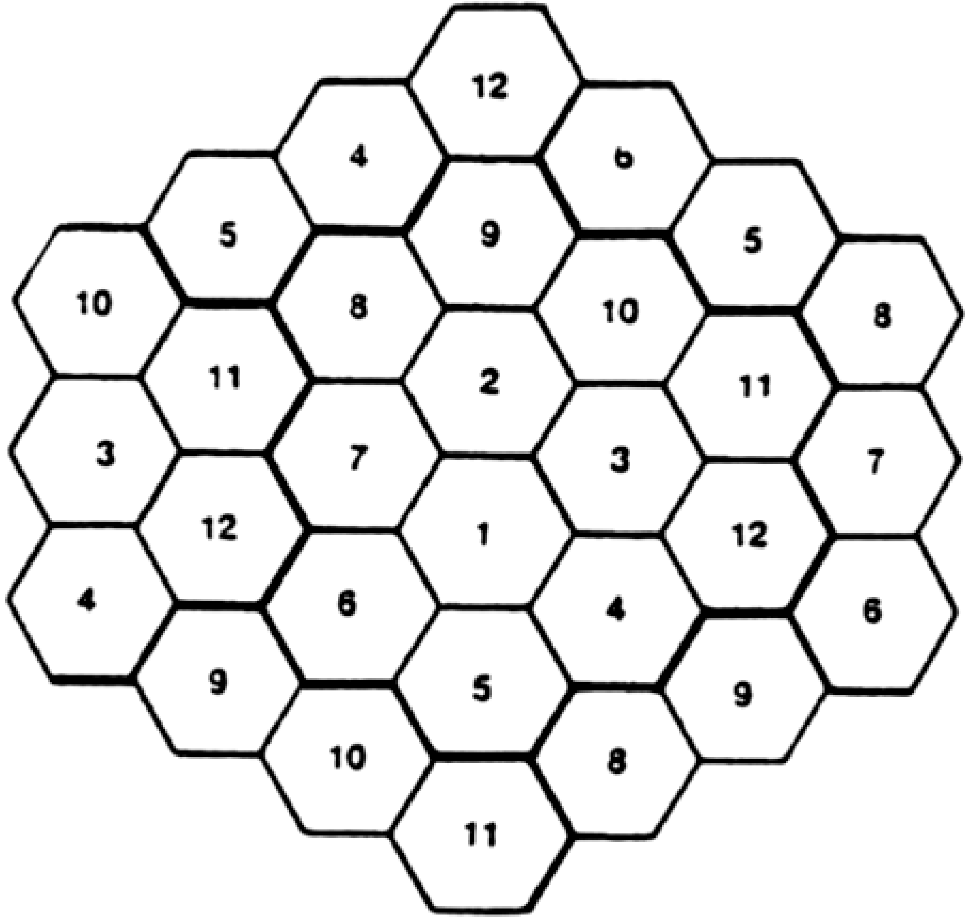




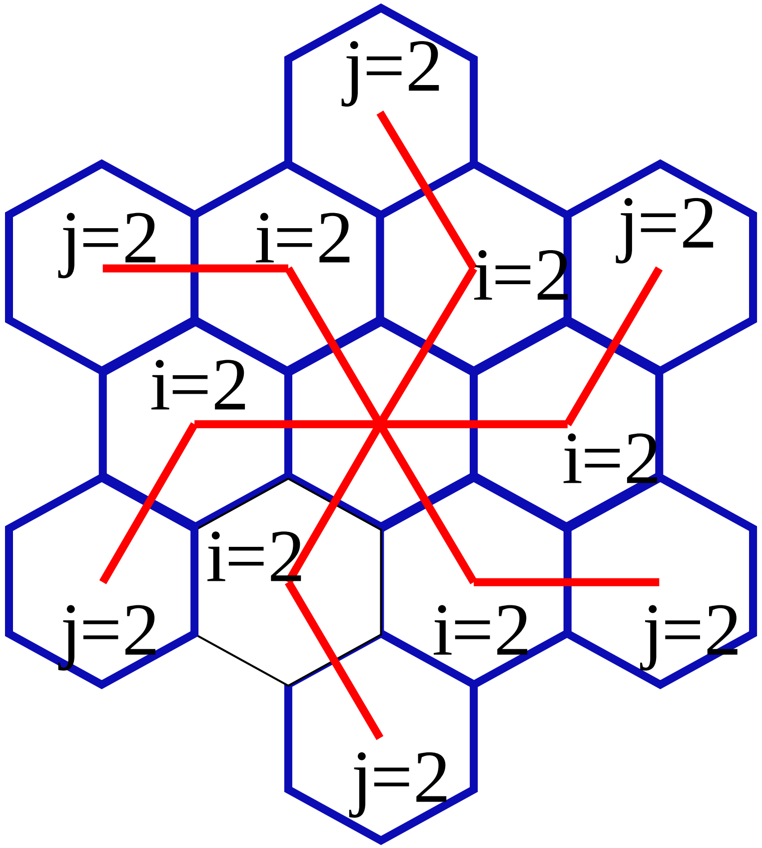
When i = 2, j = 0, then N =4



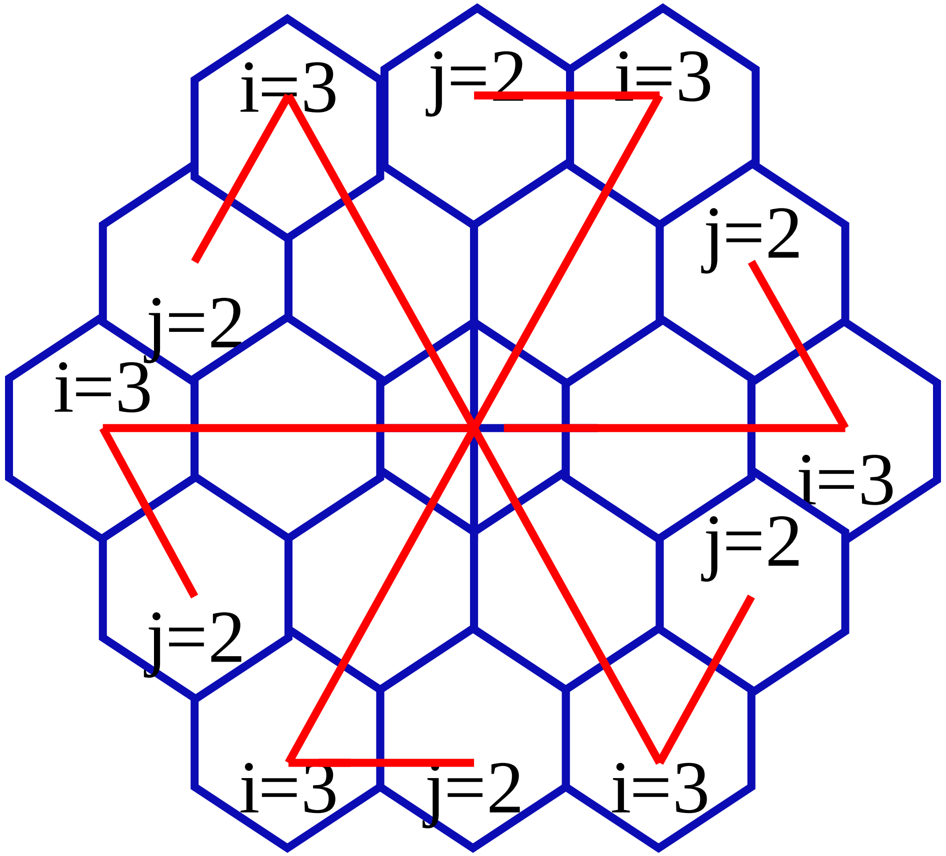
When i = 2, j = 1, then N =7



When i = 2, j = 2, then N =12



(c) Cluster with N =12 with i=2 and j=2



(d) Cluster with N = 19 cells with i=3 and j=2

5. Channel Assignment Strategies

- A variety of channel assignment strategies have been developed to effectively utilize the available channels for the system.

- Channel assignment strategies can be classified as either:
    1. ***Fixed* Channel assignment strategy or**
    2. ***Dynamic* Channel assignment strategy**

- 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

Fixed Channel Assignment

1. Each cell is allocated a predetermined set of voice channels permanently.
2. Any call attempt within the cell can only be served by the unused channels in that particular cell.
3. If all the channels in that cell are occupied, then call is *blocked* and the subscriber does not receive service.

Variations fixed assignment strategy:

Ex: ***Borrowing strategy:***

- In this, 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.

Dynamic Channel Assignment

1. Voice channels are not allocated permanently to cells.
2. Each time, when a call request is made, the serving base station requests a channel from the MSC.
3. The MSC then allocates a channel to the requested call, based on a decision algorithm taking into account different factors - frequency re-use of candidate channel, cost factors.
4. 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.

Dynamic channel assignment strategy

Limitations:

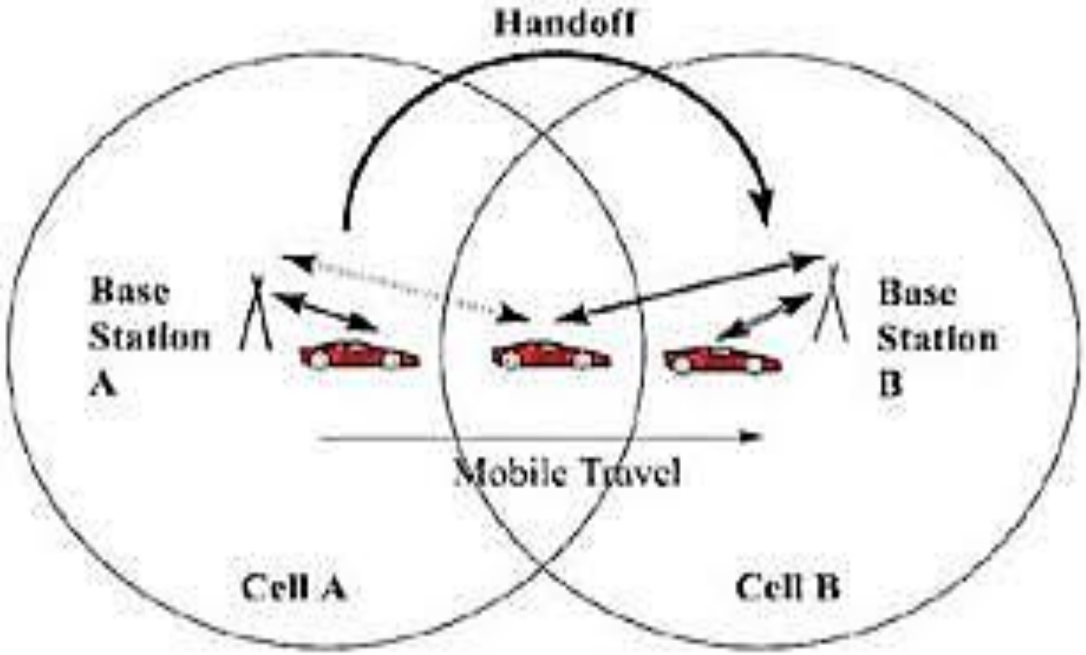
1. It require the MSC to collect real-time data on channel occupancy, traffic distribution, and *radio signal strength indications* (RSSI) of all channels on a continuous basis.
2. This increases the storage and computational load on the system.

Advantages:

1. It provides increased channel utilization and
2. Decreased probability of a blocked call.

6. 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. (Or)
- A handoff refers to the process of transferring an active call or data session from one cell in a cellular network to another or from one channel in a cell to another.



- Handoff operation includes
  - identifying a new base station
  - re-allocating the voice and control channels with the new base station.

- Processing handoffs is an important task in any cellular radio system.

- System designers must specify an optimum signal level at which to initiate a handoff.

- **Selection of Handoff threshold:**
  - In general, the minimum usable signal level for acceptable voice quality at the base station receiver is -90dBm to -100dBm.
  - A slightly stronger signal level which is more than the minimum usable signal level is used as a **threshold** at which a handoff is made.
  - The **Handoff margin** is given:

$$\Delta = P_{r,handoff} - P_{r,minimum\,usable}$$

  - **Handoff margin cannot be too large or too small**.
  - If Handoff margin (Δ) is **too large**, unnecessary handoffs occurs which burden the MSC.
  - If Handoff margin (Δ) is **too small**, there may be insufficient time to complete handoff before a call is lost due to weak signal conditions.

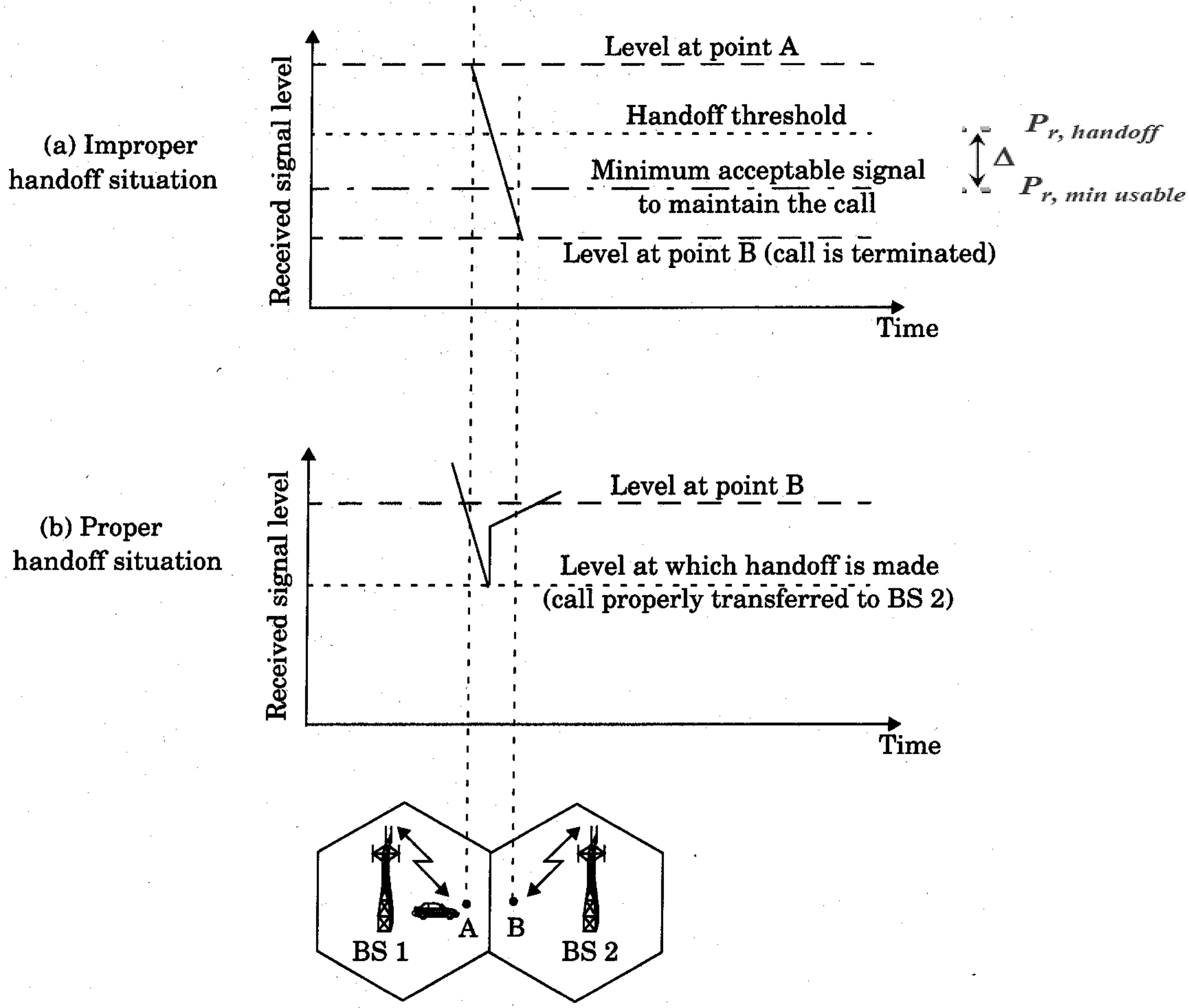


Figure 3.3(a) demonstrates the case where a handoff is not made and the signal drops below the minimum acceptable level to keep the channel active.

- This dropped call event can happen
  - when there is an excessive delay by the MSC in assigning a handoff or
  - when the threshold Δ is set too small for the handoff time in the system.

- Excessive delays may occur during high traffic conditions due to:
  - computational loading at the MSC or
  - due to the fact that no channels are available on any of the nearby base stations (thus forcing the MSC to wait until a channel in a nearby cell becomes free).

- In deciding when to handoff, it is important to ensure that the drop in the measured signal level is not due to fading and that the mobile is actually moving away from the serving base station.

- In order to ensure this, the base station monitors the signal level for a certain period of time before a handoff is initiated.

- This running average measurement of signal strength should be optimized so that unnecessary handoffs are avoided, while ensuring that necessary handoffs are completed before a call is terminated due to poor signal level.

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

- The time over which a call may be maintained within a cell, without handoff, is called the *dwell time.*

- The dwell time of a particular user is governed by a number of factors, including propagation, interference, distance between the subscriber and the base station, and other time varying effects.

- Dwell time vary greatly, depending on the speed of the user and the type of radio coverage.

6.1. Types of Handoffs:

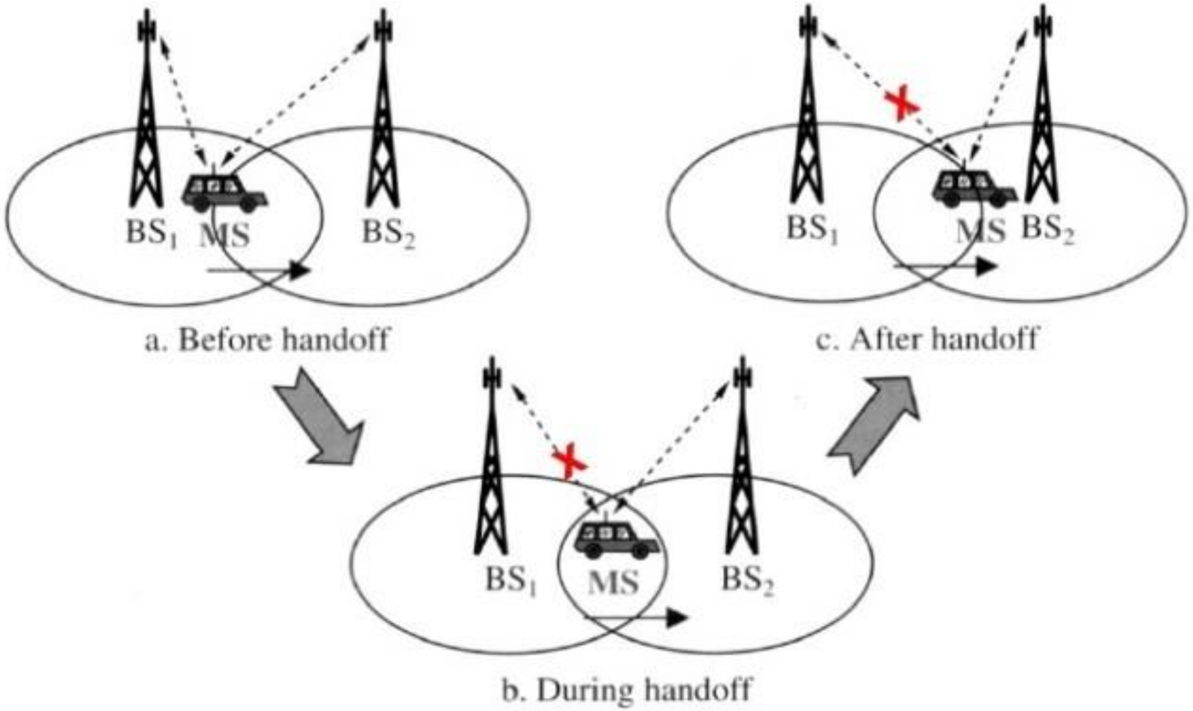
- When a mobile moves into a different cell while a conversation is in progress, the MSC automatically transfers the call to a new channel belonging to the new base station. This procedure is called handoff.
- The handoffs are of following types:
  1. Hard Handoff
  2. Soft Handoff
  3. Queued Handoff
  4. Delayed Handoff
  5. Intersystem Handoff
  6. Intrasystem Handoff
  7. Network controlled Handoff (NCHO)
  8. Mobile Assisted Handoff (MAHO)

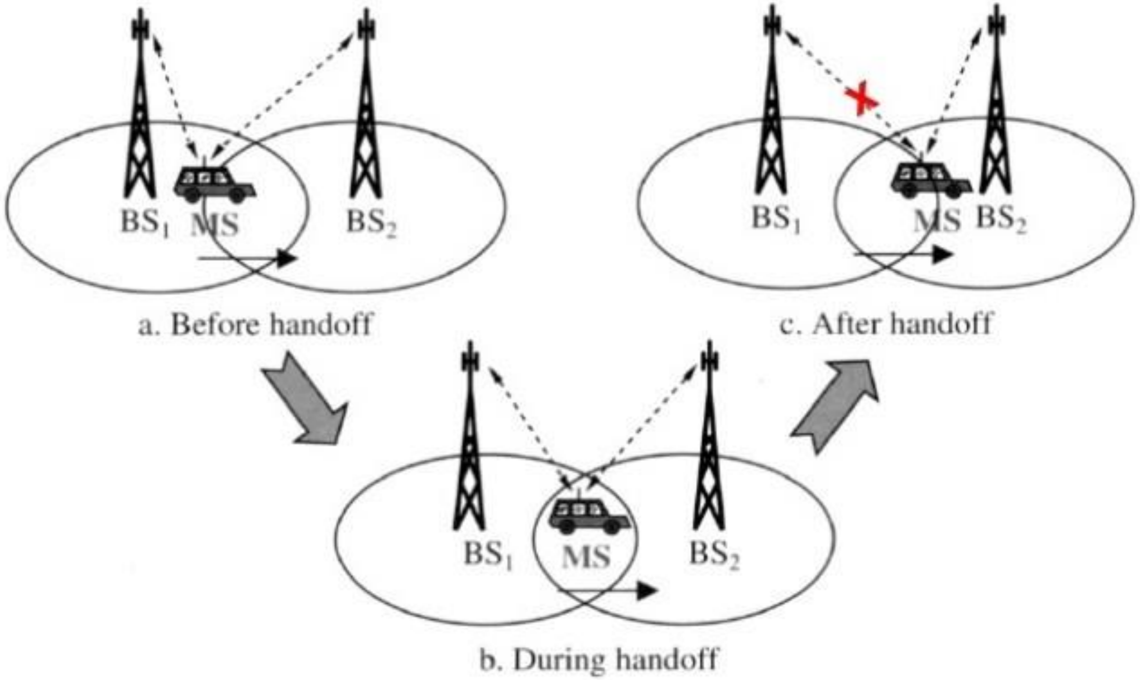
6.1.1. Hard Handoff:

- It is defined as a hard handoff where an existing connection must be broken before the new one is established.
- It allocate different frequency of user.
- In this, a handset always communicates with one BS at any given time.
- It is typically used in TDMA and FDMA systems.

6.1.2. Soft handoff:

- It is defined as a soft handoff where a new connection is established before the old one is released.
- It allocate same frequency.
- In this, a handset may connect up to three or four radio links at the same time.
- It is used in CDMA and some TDMA systems.
- Soft handoff is more complicated than hard handoff.
- On the other hand, soft handoff degrades channel availability because a handset may consume multiple radio channels.


BS1
MS
BS2
a. Before handoff
BS1
MS
BS2
c. After handoff
BS1
MS
BS2
b. During handoff


BS1
MS
BS2
a. Before handoff
BS1
MS
BS2
c. After handoff
BS1
MS
BS2
b. During handoff

6.1.3. Delayed handoff

- A Delayed handoff is a two-handoff level algorithm. It provides more opportunity for a successful hand off.
- The MTSO always handles the handoff first and the originating calls second. If no neighboring cells are available after the second handoff level is reached, the call continues until the signal strength drops below the threshold level then the call is dropped.
- It makes the handoff occur at the proper location and eliminates possible interference in the system.

6.1.4. Queued handoff:

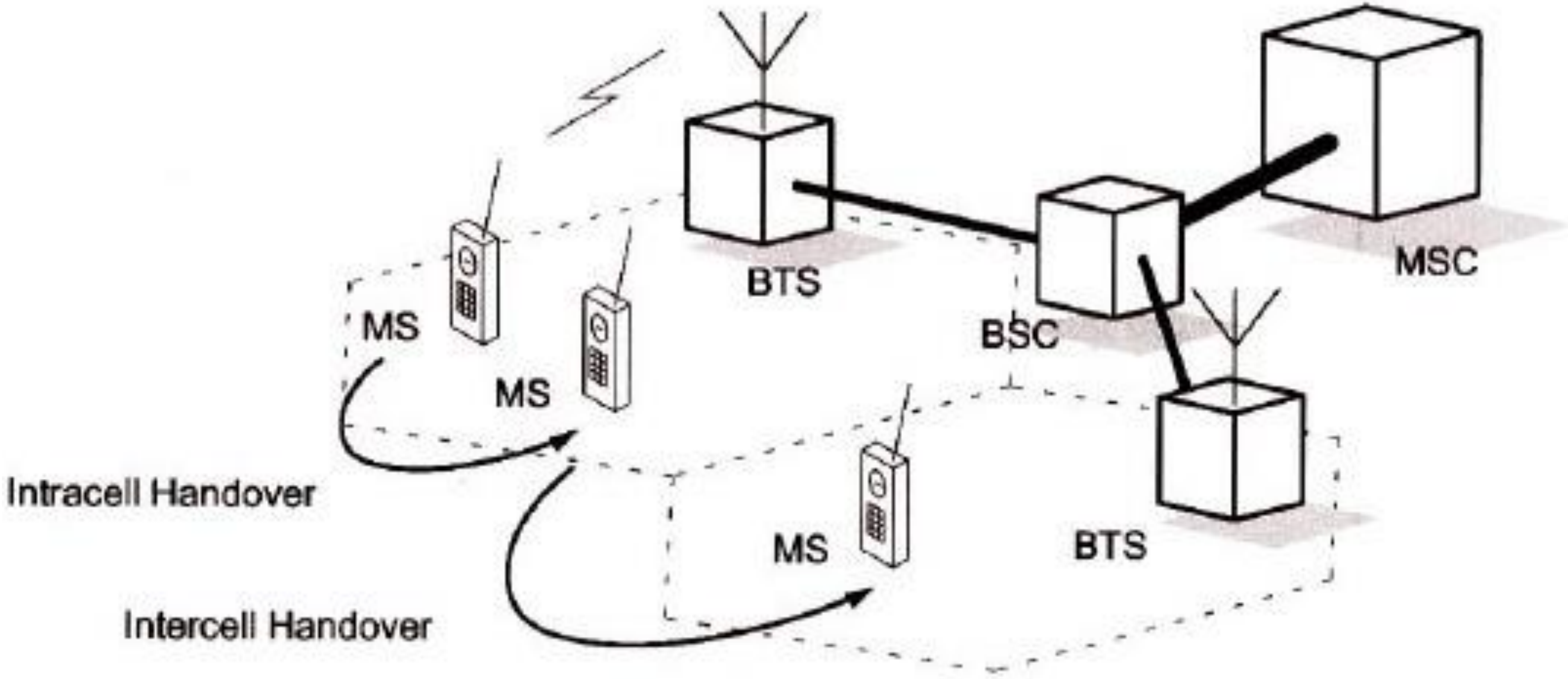
- Queued handoff is more effective than two threshold level handoffs.
- The MTSO will queue the requests of handoff calls instead of rejecting them if the new cell sites are busy.
- With Queuing of originating calls only, the probability of blocking is reduced.
- It is effective when implementing a simple queue for handoff calls which reduces call drops.

6.1.5. Intersystem Handoff:

- If during an ongoing call a mobile unit moves from one cellular system to a different cellular system which is controlled by different MTSO, a handoff procedure which is used to avoid dropping of call referred as Intersystem Handoff.
- An MTSO engages in this handoff system when a mobile signal becomes weak in a given cell and MTSO cannot find another cell within its system to which it can transfer the call then in progress.
- Before implementation of Intersystem Handoff, the MTSO compatibility must be checked and in an Intersystem Handoff a local call may become a long distance call as the mobile moves out of its home system and becomes a roamer in a neighboring system.

6.1.6. Intrasystem Handoff:

- If during an ongoing call a mobile unit moves from one cellular system to an adjacent cellular system which is controlled by the same MTSO, a handoff procedure which is used to avoid dropping of call referred to as Intra System Handoff.
- An MTSO engages in this handoff system when a mobile signal becomes weak in a given cell and the MTSO finds another cell within its system to which it can transfer the call in progress.
- In Intra System Handoff local calls always remain local calls only since after handoff also the call is handled by the same MTSO. In first generation analog cellular systems, signal strength measurements are made by the base stations and supervised by the MSC.
- Each base station constantly monitors the signal strengths of all of its reverse voice channels to determine the relative location of each mobile user with respect to the base station tower.


BTS
MSC
MS
BSC
MS
Intracell Handover
MS
BTS
Intercell Handover

6.1.7. Mobile Assisted Handoff (MAHO)

- In this, every mobile station measures the received power from surrounding base stations and continually reports the results of these measurements to the serving base station.
- A handoff is initiated, when the power received from the base station of a neighboring cell begins to exceed the power received from the current base station by a certain level or for a certain period of time.
- In MAHO method call handed over between base stations is much faster than first generation analog systems since handoff measurements are made by each mobile, MSC no longer constantly monitors signal strengths.
- MAHO is particularly suited for microcellular environments where handoffs are more frequent.

6.2. Prioritizing Handoffs

- Methods for giving priority to handoffs:

1. **Guard channel concept**: a fraction of the total available channels in a cell is reserved exclusively for handoff requests from ongoing calls which may be handed off into the cell.
    - Disadvantage: reducing the total carried traffic, as fewer channels are allocated to originating calls.
    - Advantage: offer efficient spectrum utilization when dynamic channel assignment strategies are used.
2. **Queuing of handoff requests**:
    - Advantage: decrease the probability of forced termination of a call due to lack of available channels.
    - queuing does not guarantee a zero probability of forced termination, since large delays will cause the received signal level to drop below the minimum required level to maintain communication and hence lead to forced termination.

6.3. Practical Handoff considerations

7. Interference and System Capacity

- Interference is the major limiting factor in the performance of cellular radio systems.

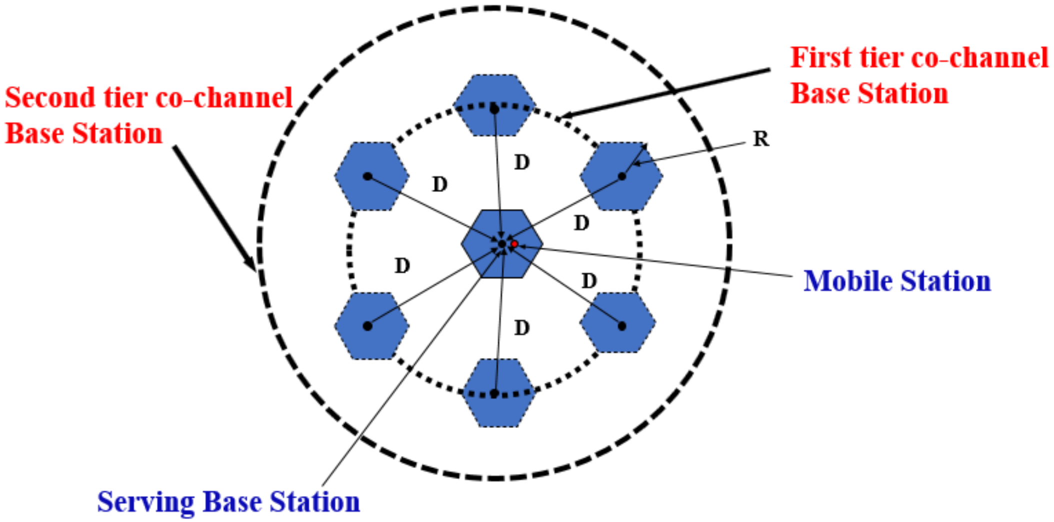
- Sources of interference include:
  - Another mobile in the same cell,
  - A call in progress in a neighboring cell,
  - Other base stations operating in the same frequency band, or
  - Any noncellular system which unintentionally leaks energy into the cellular frequency band.

- Interference on:
  - Voice channels causes **cross talk**, where the subscriber hears interference in the background due to an undesired transmission.
  - On control channels, interference leads to **missed and blocked calls** due to errors in the digital signaling.

- The two major types of system-generated cellular interference are:
  1. *Co-channel interference* and
  2. *Adjacent channel interference (*Intra-Cell Type and Inter-Cell Type)

7.1. Co-channel Interference and System Capacity

- Frequency reuse implies that in a given coverage area there are several cells that use the same set of frequencies. These cells are called ***co-channel cells.***
- The interference between signals from co-channel cells is called ***co-channel interference*.**
- Unlike thermal noise which can be overcome by increasing the signal-to-noise ratio (SNR), **co-channel interference cannot be suppressed by simply increasing the carrier power of a transmitter**.
- This is because an increase in carrier transmit power increases the interference to neighboring co-channel cells.
- To reduce co-channel interference, **co-channel cells must be physically separated by a minimum distance** to provide sufficient isolation due to propagation.



co-channel interference depends on:

i. Distance (D) between co-channel cells
ii. Radius (R) of the cell
iii. Transmitted power from the base station

7.1.1. Co-channel reuse ratio

- When:
  - the size of each cell is approximately the same and
  - the base stations transmit the same power,
- Then the **co-channel interference ratio** is independent of the transmitted power and becomes a **function** of the **radius of the cell (*R*)** and the **distance between centers of the nearest co-channel cells (*D*).**
- The parameter ***Q***, called the ***co-channel reuse ratio***, is related to the cluster size. For a hexagonal geometry

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

Reuse Distance $D = \sqrt{3N}\,R$ (3.4)

- A **small value of *Q*** provides **larger capacity** since the cluster size *N* is small.
- A **large value of *Q*** improves the transmission quality, due to a **smaller co-channel interference.**
- A trade-off must be made between these two objectives in actual cellular design.

	Cluster Size (N)	Co-channel Reuse Ratio (Q)
$i = 1,\ j = 1$	3	3
$i = 1,\ j = 2$	7	4.58
$i = 2,\ j = 2$	12	6
$i = 1,\ j = 3$	13	6.24

6.1.2. Signal-to-interference ratio (S/I or SIR)

- Let i_0 be the number of **co-channel interfering cells**.
- Then, the signal-to-interference ratio **(*S/I* or *SIR*)** for a mobile receiver can be written as

$$\frac{S}{I} = \frac{S}{\sum_{i=1}^{i_0} I_i} \qquad (3.5)$$

where

S is the desired signal power from the desired base station and

I_i is the interference power caused by the *i*th interfering co-channel cell base station.

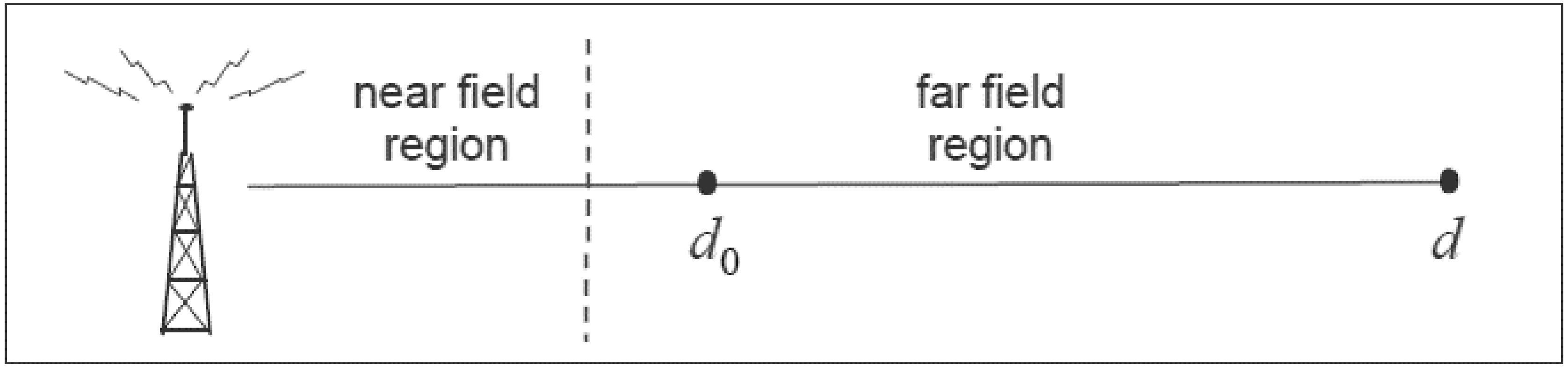
- The average received power P_r at a distance d from the transmitting antenna is approximated by

$$P_r = P_0\left(\frac{d}{d_0}\right)^{-n} \tag{3.6}$$

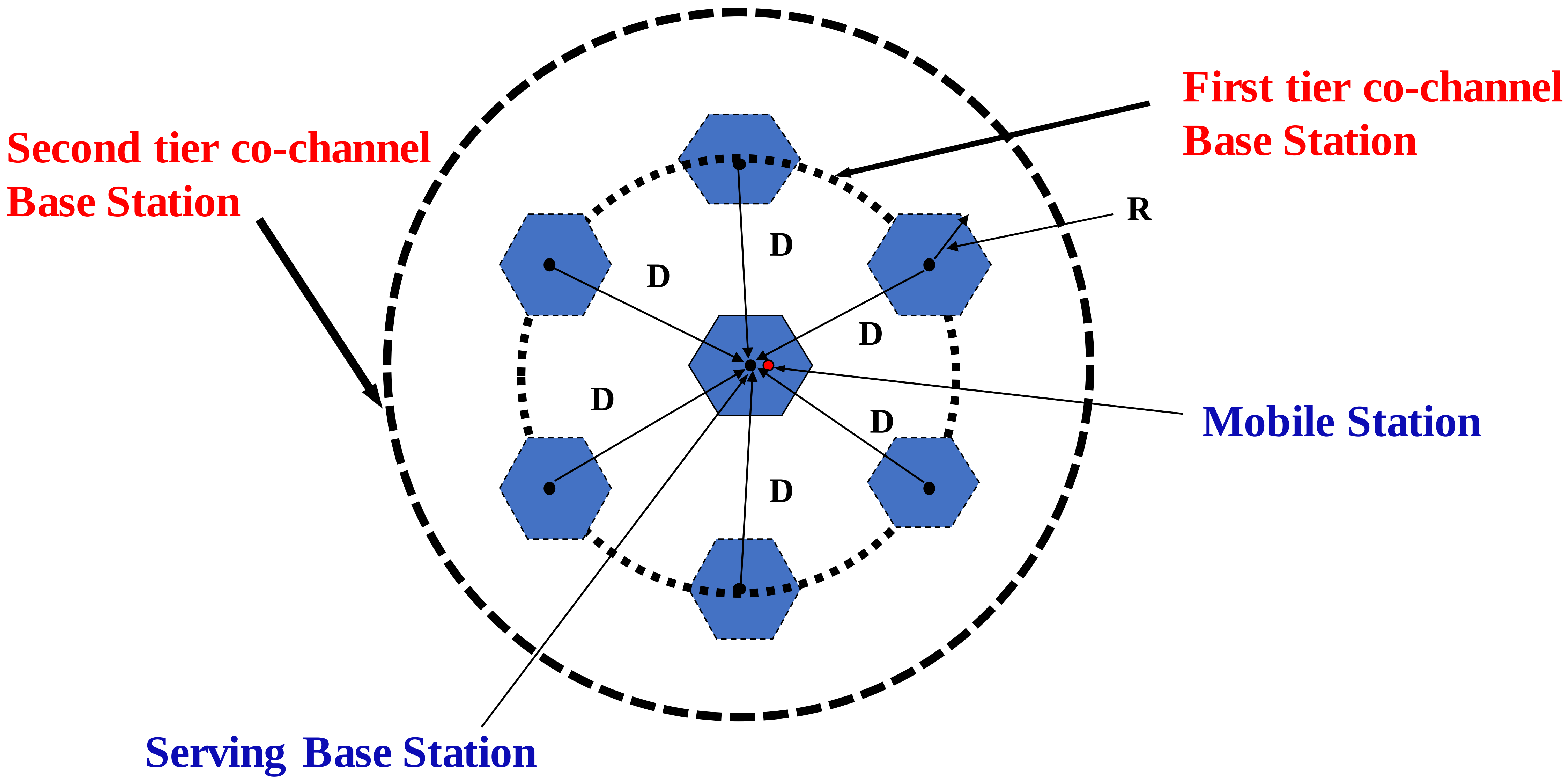
$$P_r(\text{dBm}) = P_0(\text{dBm}) - 10n\log\left(\frac{d}{d_0}\right) \tag{3.7}$$

where

P_0 is the power received at a close-in reference point in the far field region of the antenna at a small distance d_0 from the transmitting antenna and n is the path loss exponent.



Best case Co-channel Interference



- Now consider the forward link where the desired signal is the serving base station and where the interference is due to co-channel base stations.
- If D_i is the distance of the ith interferer from the mobile,
- the received power P_r at a given mobile due to the ith interfering cell will be proportional to $(D_i)^{-n}$.
- The path loss exponent n typically ranges between **two and four** in urban cellular systems.

$$\frac{S}{I} = \frac{S}{\sum_{i=1}^{i_o} \left(\frac{D_i}{R}\right)^{-n}}$$

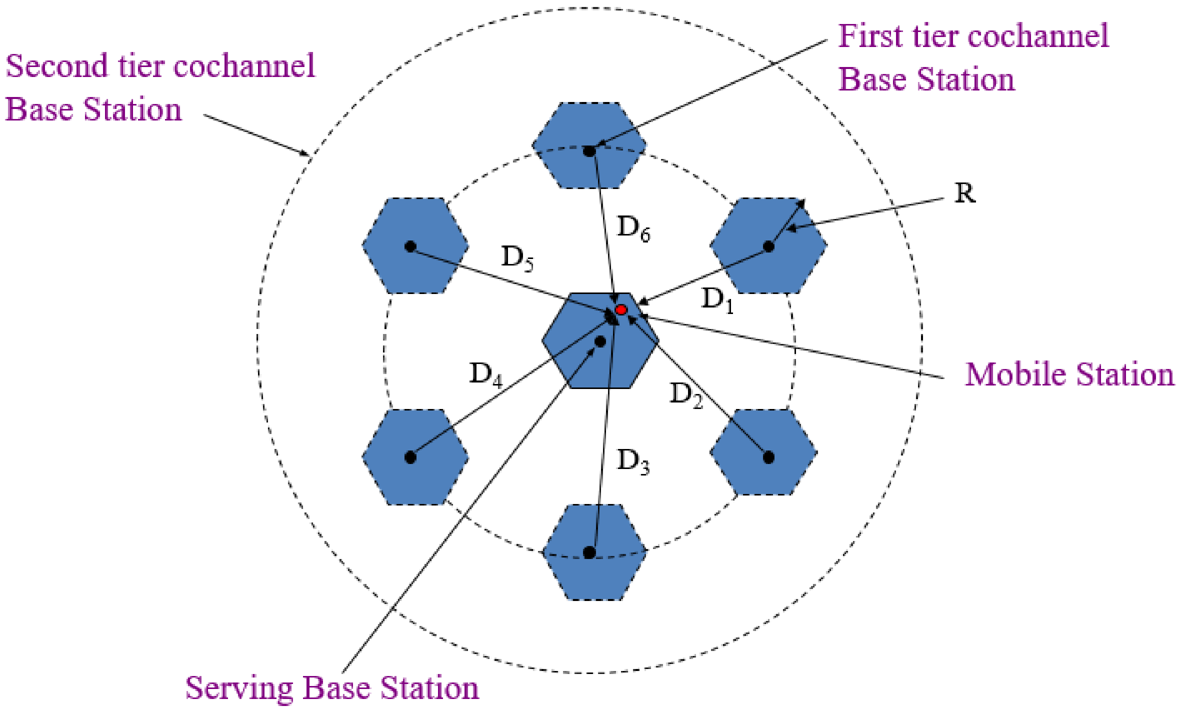
- When the

  -transmit power of each base station is equal and

  -the path loss exponent ***n*** is same throughout the coverage area, then *S*/*I* can be approximated as:

$$\frac{S}{I} = \frac{S}{\sum_{i=1}^{i_o} \left(\frac{D_i}{R}\right)^{-n}} \qquad \frac{S}{I} = \frac{R^{-n}}{\sum_{i=1}^{i_0} (D_i)^{-n}} \qquad (3.8)$$

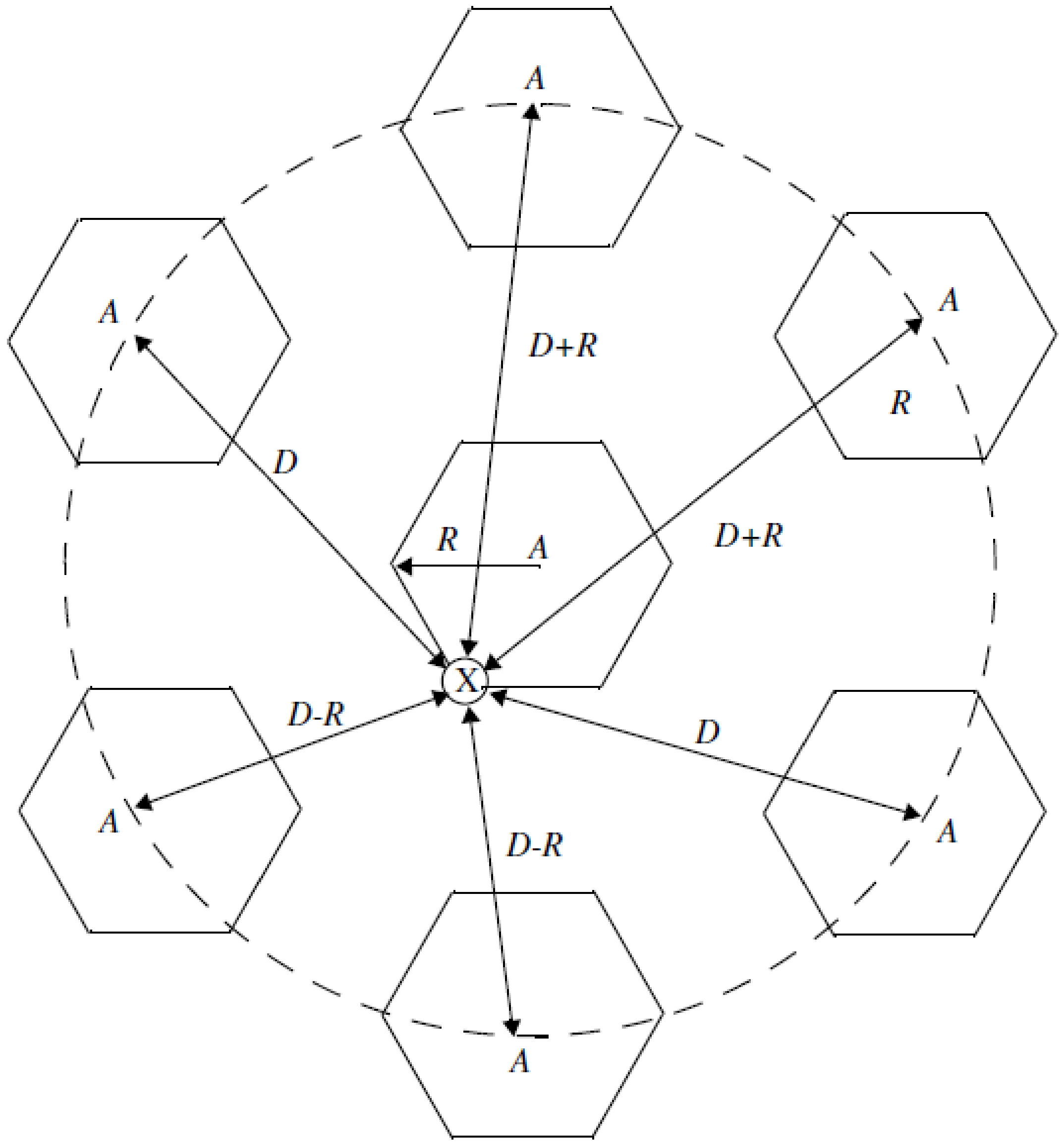
- Considering only the **first layer of interfering cells**, if all the interfering base stations are **equidistant** from the desired base station and if this **distance is equal to the distance *D* between cell centers**, then



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

$$\frac{S}{I} = \frac{(D/R)^n}{i_0} = \frac{(\sqrt{3N})^n}{i_0} \qquad (3.9)$$

- Using an exact cell geometry layout:
  - A seven-cell cluster, with the mobile unit at the cell boundary:
    - ***D − R****: is the distance* from the two nearest co-channel interfering cells to the mobile
    - ***D + R:*** *is the distance* from the two farthest co-channel interfering cells to the mobile.



- Assuming ***n* = 4**, the signal-to-interference ratio for the worst case can be closely approximated as:

$$\frac{S}{I} = \frac{R^{-n}}{\sum_{i=1}^{i_0} (D_i)^{-n}}$$

$$\frac{S}{I} = \frac{R^{-4}}{2(D-R)^{-4} + 2(D+R)^{-4} + 2D^{-4}} \quad (3.10)$$

- Above equation *(S/I)* can be rewritten in terms of the co-channel reuse ratio *Q*, as

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

$$\frac{S}{I} = \frac{1}{2(Q-1)^{-4} + 2(Q+1)^{-4} + 2Q^{-4}} \quad (3.11)$$

- For $N = 7$, the co-channel reuse ratio Q is 4.6, and the worst case S/I is approximated as 49.56 (17 dB) using Equation (3.11), whereas an exact solution using Equation (3.8) yields 17.8 dB.
- Hence for a seven-cell cluster, the S/I ratio is slightly less than 18 dB for the worst case.

Example 6: If a signal-to-interference ratio of 15 dB is minimum required for satisfactory forward channel performance of a cellular system, what is the frequency reuse factor and cluster size that should be used for maximum capacity if the path loss exponent is (a) $n = 4$, (b) $n = 3$? Assume that there are six co-channel cells in the first tier, and all of them are at the same distance from the mobile. Use suitable approximations.

Solution

(a) $n = 4$

First, let us consider a seven-cell reuse pattern.

Using Equation (3.4), the co-channel reuse ratio $D/R = 4.583$.

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

Using Equation (3.9), the signal-to-noise interference ratio is given by

$$S/I = (1/6) \times (4.583)^4 = 75.3 = 18.66 \text{ dB}$$

Since this is greater than the minimum required S/I, $N = 7$ can be used.

$$\frac{S}{I} = \frac{(D/R)^n}{i_0} = \frac{(\sqrt{3N})^n}{i_0}$$

(b) $n = 3$

First, let us consider a seven-cell reuse pattern.

Using Equation (3.9), the signal-to-interference ratio is given by

$$S/I = (1/6) \times (4.583)^3 = 16.04 = 12.05 \text{ dB}$$

Since this is less than the minimum required S/I, we need to use a larger N.

Using Equation (3.3), the next possible value of N is 12, ($i = j = 2$).

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

The corresponding co-channel ratio is given by Equation (3.4) as

$$D/R = 6.0$$

Using Equation (3.3), the signal-to-interference ratio is given by

$$S/I = (1/6) \times (6)^3 = 36 = 15.56 \text{ dB}$$

$$\frac{S}{I} = \frac{(D/R)^n}{i_0} = \frac{(\sqrt{3N})^n}{i_0}$$

Since this is greater than the minimum required S/I, $N = 12$ is used.

Example 6:

Determine the S/I ratio at the mobile receiver located at boundary of its omnidirectional cell under the influence of interfering signal from six co channel cells for N = 7, N = 9 and N = 12. Given $\eta = 4$ and permissible S/I threshold is 19 dB

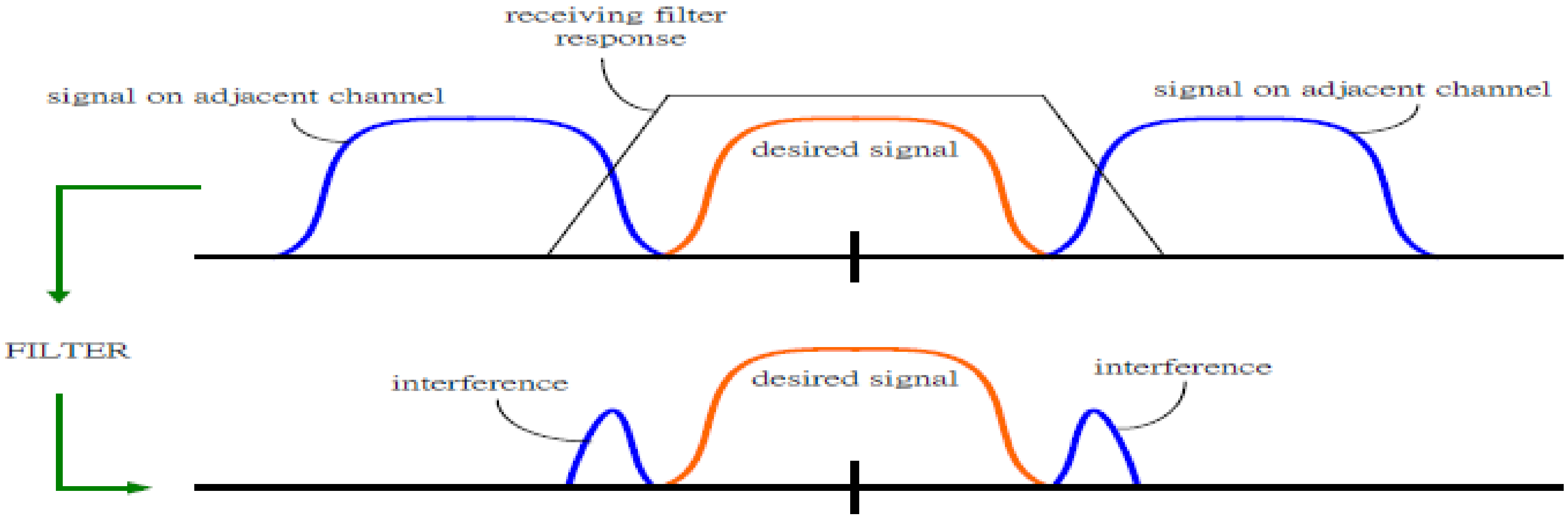
$N = 7 \rightarrow \quad S/I = 17\ dB$

$N = 9 \rightarrow \quad S/I = 20\ dB$

$N = 12 \rightarrow \quad S/I = 23\ dB$

7.2.Adjacent channel interference

- Interference resulting from ***signals which are adjacent in frequency*** to the desired signal is called adjacent channel interference.
- Adjacent channel interference results from ***imperfect receiver filters*** which allow nearby frequencies to leak into the passband and **improper channel assignments**.
- Adjacent channel interference can be ***minimized through careful filtering and channel assignments.***
- If the frequency reuse factor is large (e.g., small N), the separation between adjacent channels at the base station may not be sufficient to keep the adjacent channel interference level within tolerable limits.
- By ***keeping the frequency separation between each channel in a given cell as large as possible***, the adjacent channel interference may be reduced considerably.


receiving filter response
signal on adjacent channel
signal on adjacent channel
desired signal
FILTER
interference
desired signal
interference


BS as Rx
Weaker signal
Strong "bleed over"
Desired Mobile Tx
Adjacent Channel Mobile Tx

7.3. Power Control for Reducing Interference

- In practical cellular radio and personal communication systems, the ***power levels transmitted by every subscriber unit are under constant control by the serving base stations***.

- Power control is to ensure that each mobile transmits the smallest power necessary to maintain a good quality link on the reverse channel.

- Power control not only helps ***prolong battery life*** for the subscriber unit, but also dramatically ***reduces the reverse channel S/I*** in the system.

8. Trunking and Grade of Service

- Cellular radio systems rely on Trunking to accommodate a large number of users in a limited radio spectrum.
- 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 a pool of 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 fundamentals of trunking theory were developed by Erlang a Danish mathematician in the late 19th century.
- One Erlang represents the amount of traffic intensity carried by a channel that is completely occupied

Table 3.3 Definitions of Common Terms Used in Trunking Theory

Set-up Time: The time required to allocate a trunked radio channel to a requesting user.

Blocked Call: Call which cannot be completed at time of request, due to congestion. Also referred to as a *lost call*.

Holding Time: Average duration of a typical call. Denoted by H (in seconds).

Traffic Intensity: Measure of channel time utilization, which is the average channel occupancy measured in Erlangs. This is a dimensionless quantity and may be used to measure the time utilization of single or multiple channels. Denoted by A.

Load: Traffic intensity across the entire trunked radio system, measured in Erlangs.

Grade of Service (GOS): A measure of congestion which is specified as the probability of a call being blocked (for Erlang B), or the probability of a call being delayed beyond a certain amount of time (for Erlang C).

Request Rate: The average number of call requests per unit time. Denoted by λ seconds^{-1}.

- 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.

9. Improving Coverage and 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.

- Solution: cellular design techniques are needed to provide more channels per unit coverage area (cell).

- Techniques used in practice to improve the capacity of cellular systems.
  1. *Cell splitting,*
  2. *Sectoring*, and
  3. *Coverage zone or Microcell Zone concept*

- **Cell splitting** increases the number of base stations in order to increase the capacity.

- **Sectoring** uses directional antennas to further control the interference and frequency reuse of channels.

- ***Microcell-zone*** concept distributes the coverage of a cell and extends the cell boundary to hard to-reach places.

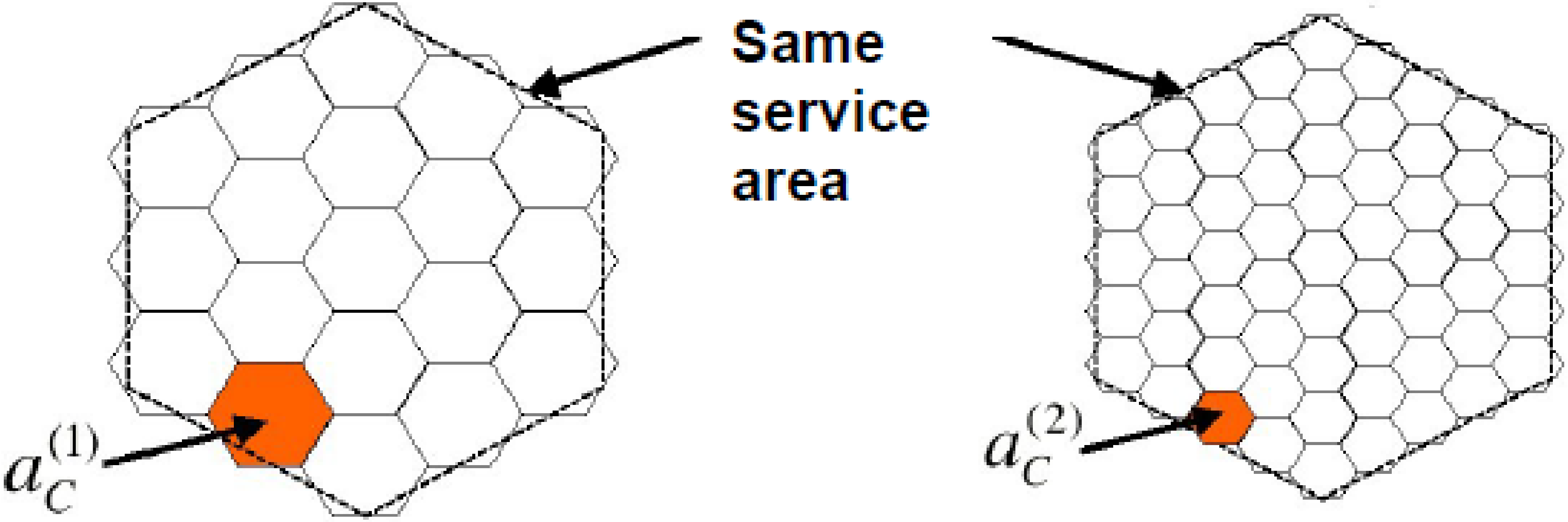
The objective in all of these methods is to
increase the number of users within the system.

9.1. Cell Splitting

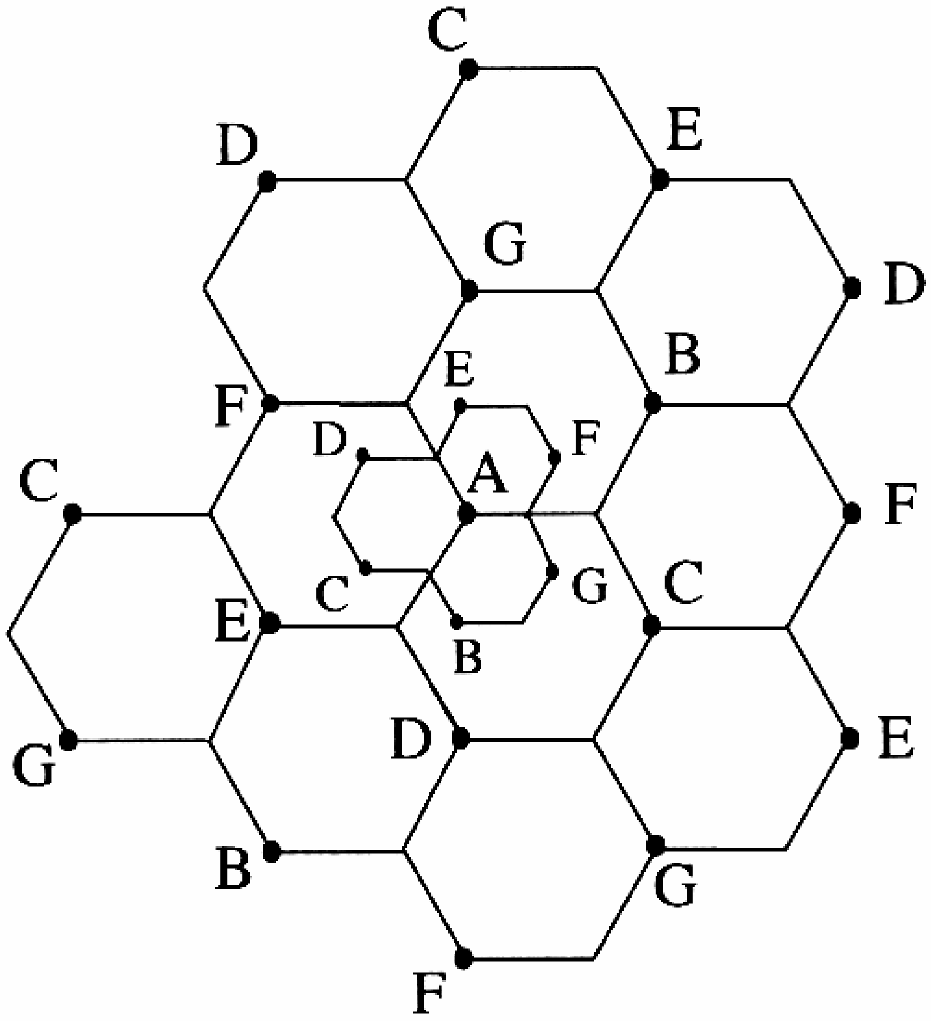
- **Cell splitting** is the process of **subdividing a congested cell into smaller cells**, each with its own base station and a corresponding reduction in antenna height and transmitter power.

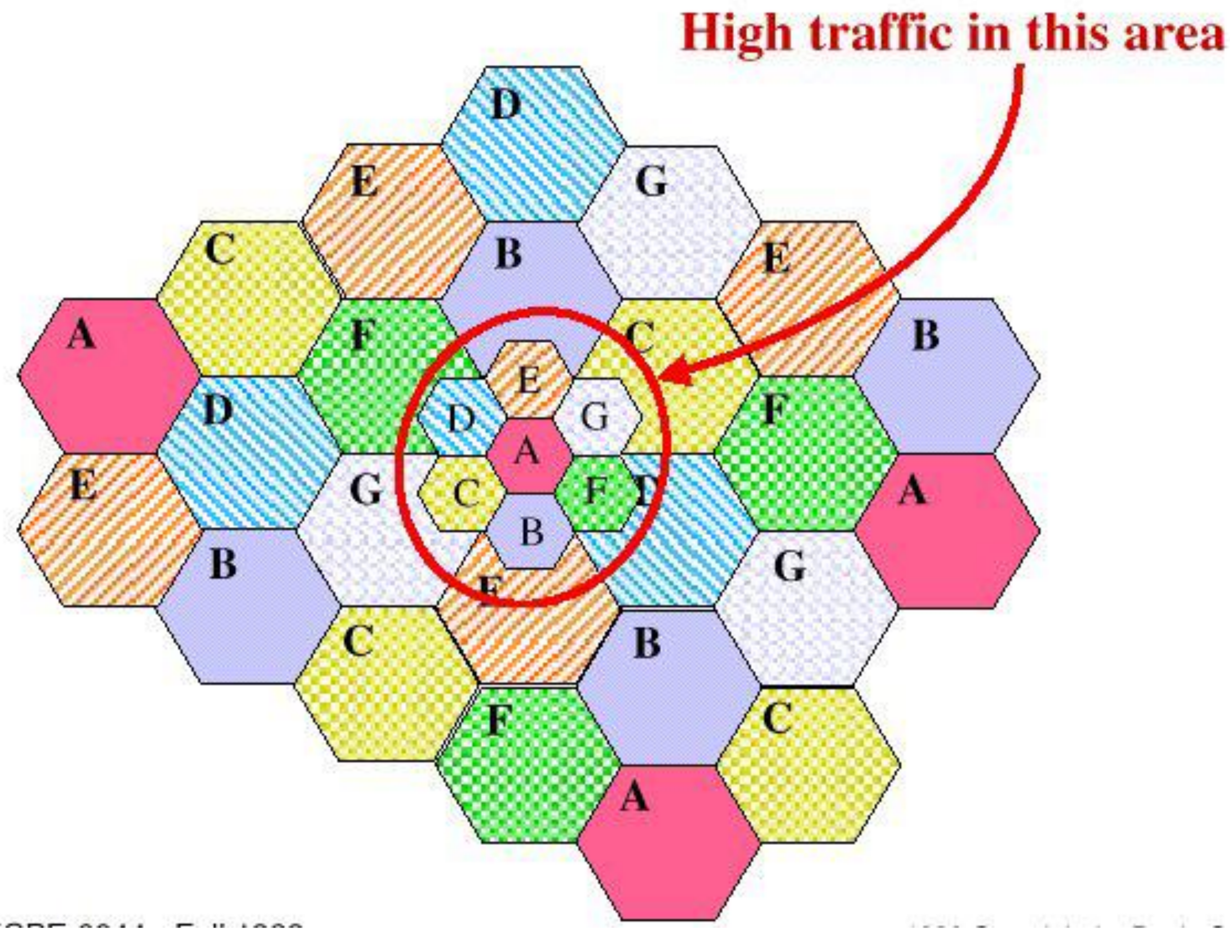
- Cell splitting increases the capacity of a cellular system since it increases the **number of times that channels are reused**.

- 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.



More cells in the service area, more capacity.





In Figure 3.8, 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.
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 microcells.

- In order to cover the entire service area with smaller cells, approximately four times as many cells would be required.

- ***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 *Q* between co-channel cells.

Conclusion:

- Cell splitting achieves capacity improvement by *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.

- 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 ***Pr*** at the new and old cell boundaries and setting them equal to each other.

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

$$P_r[\text{at new cell boundary}] \propto P_{t2} (R/2)^{-n}$$

where $\boldsymbol{P_{t1}}$ and $\boldsymbol{P_{t2}}$ are the transmit powers of the larger and smaller cell base stations, respectively, and ***n*** is the path loss exponent.

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

$$P_r[\text{at new cell boundary}] = P_r[\text{at old cell boundary}]$$

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

- 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.

9.2. Sectoring

- Sectoring is another way to increase capacity. In this method, keep the cell radius *R* unchanged and decrease the *D*/*R* ratio.
- *Sectoring increases SIR so that the cluster size may be reduced* and hence number of channels are increased.
- In this approach, first the SIR is improved using directional antennas, then capacity improvement is achieved by reducing the number of cells in a cluster, thus increasing the frequency reuse.
- However, it is necessary to reduce the 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.
- The technique for decreasing co-channel interference and thus increasing system performance by using directional antennas is called *sectoring*.

- By using directional antennas, a given cell will receive interference and transmit with only a fraction of the available co-channel cells.
- ***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 Figure 3.10(a) and (b).

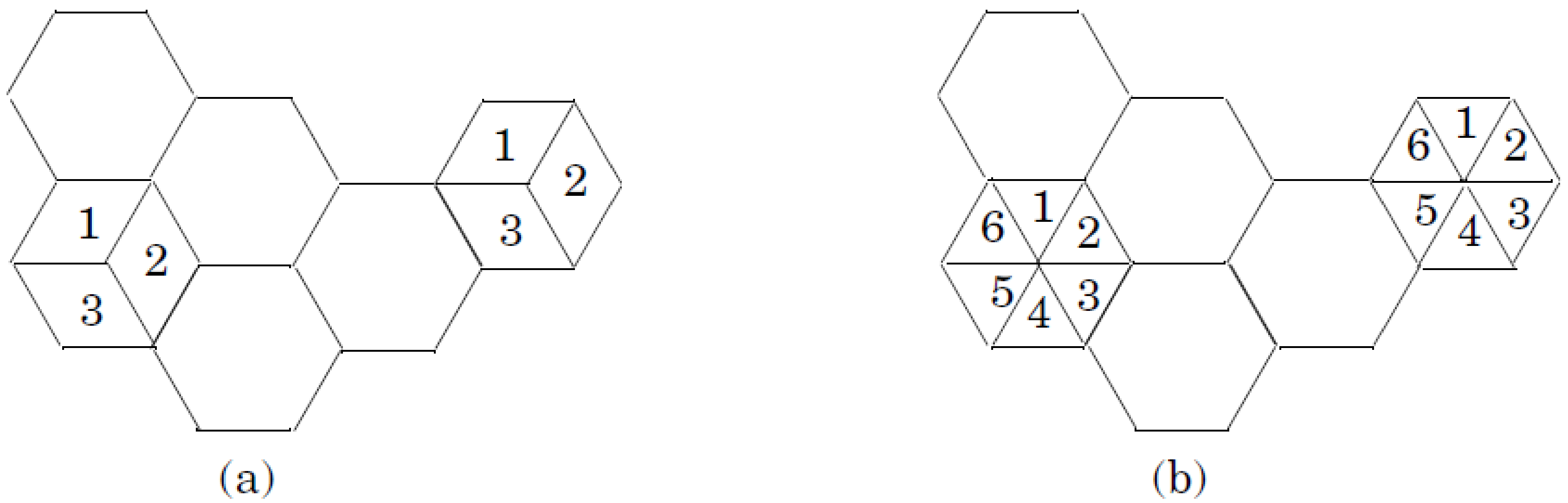


Figure 3.10 (a) 120° sectoring; (b) 60° sectoring.

- 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, as illustrated in Figure 3.10(a) and (b).
- Assuming seven-cell reuse, for the case of 120° sectors, the number of interferers in the first tier is reduced from six to two. This is because only two of the six co-channel cells receive interference with a particular sectored channel group.

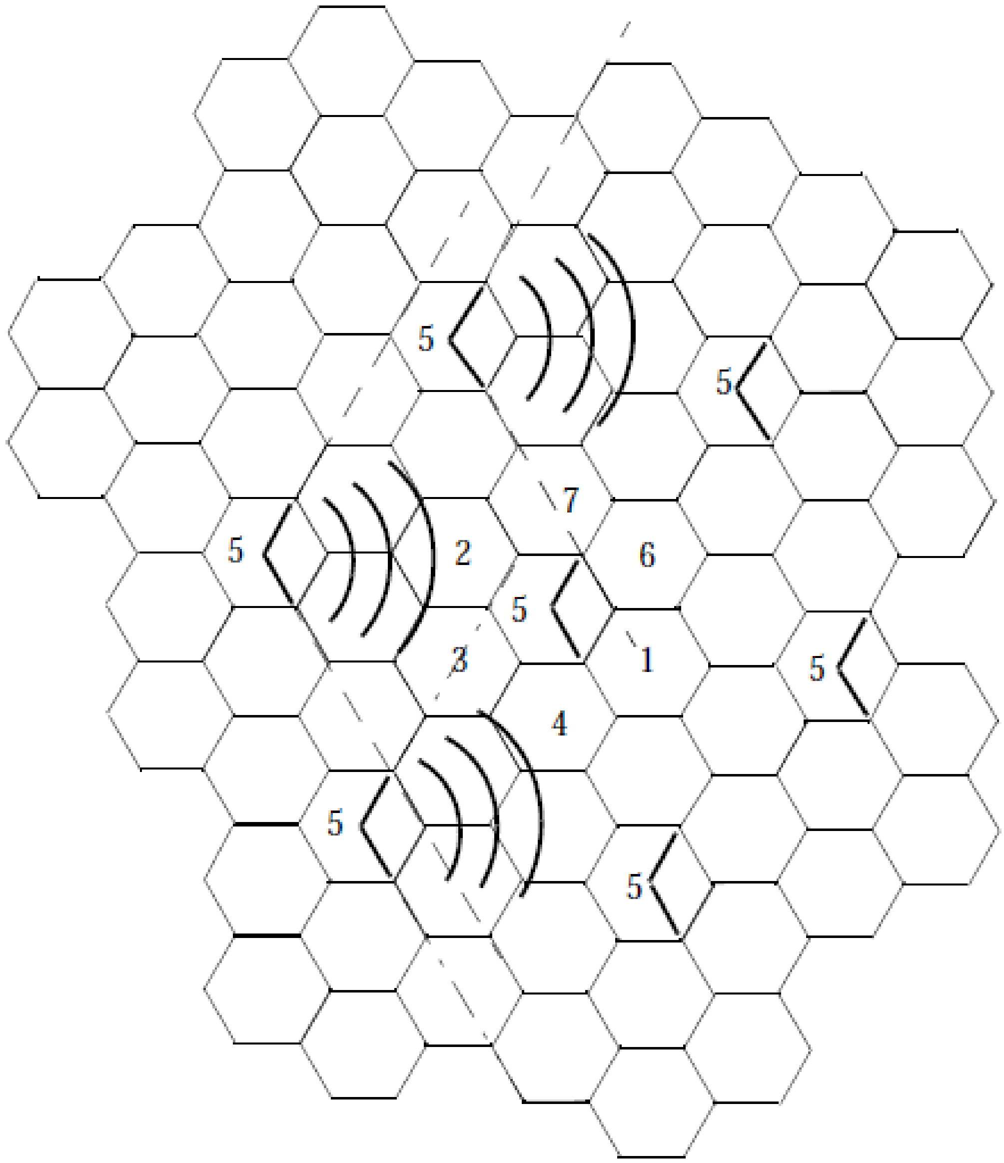


Figure 3.11 Illustration of how 120° sectoring reduces interference from co-channel cells. Out of the 6 co-channel cells in the first tier, only two of them interfere with the center cell. If omnidirectional antennas were used at each base station, all six co-channel cells would interfere with the center cell.

- The resulting *S/I* for this case can be found using Equation (3.8) to be 24.2 dB, which is a significant improvement over the omnidirectional case, where the worst case *S/I* was shown to be 17 dB.
- This *S/I* improvement allows the wireless engineer to then decrease the cluster size *N* in order to improve the frequency reuse, and thus the system capacity.
- 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 results to an increase in capacity by a factor of 12/7, or 1.714.

Limitations:

- Increased number of antennas at each base station, and a decrease in trunking efficiency.
- Reduces the coverage area of a particular group of channels, the number of handoffs increases.

9.3. Repeaters for Range Extension

- Wireless operator needs to provide dedicated coverage for hard-to-reach areas, such as within buildings, or in valleys or tunnels.
- *Radio retransmitters*, known as repeaters, are used to provide such range extension capabilities.
- Repeaters are bidirectional that means they simultaneously send signals to and receive signals from a serving base station.
- Upon receiving signals from a base station on forward link, the repeater amplifies and reradiates the base station signals to the specific coverage region.
- Unfortunately, the received noise and interference is also reradiated by the repeater on both the forward and reverse link.
- So care must be taken to properly place the repeaters, and to adjust the various forward and reverse link amplifier levels and antenna patterns.
- The repeater does not add capacity to the system—it simply serves to reradiate the base station signal into specific locations.
- Repeaters are increasingly being used to provide coverage into and around buildings, where coverage has been traditionally weak.

9.4. A Microcell Zone Concept

- The increased number of handoffs required when sectoring is employed results in an increased load on the switching and control link elements of the mobile system.
- A solution to this problem is a microcell concept.
- Figure 3.13 is an example of microcell concept for 7-cell reuse.

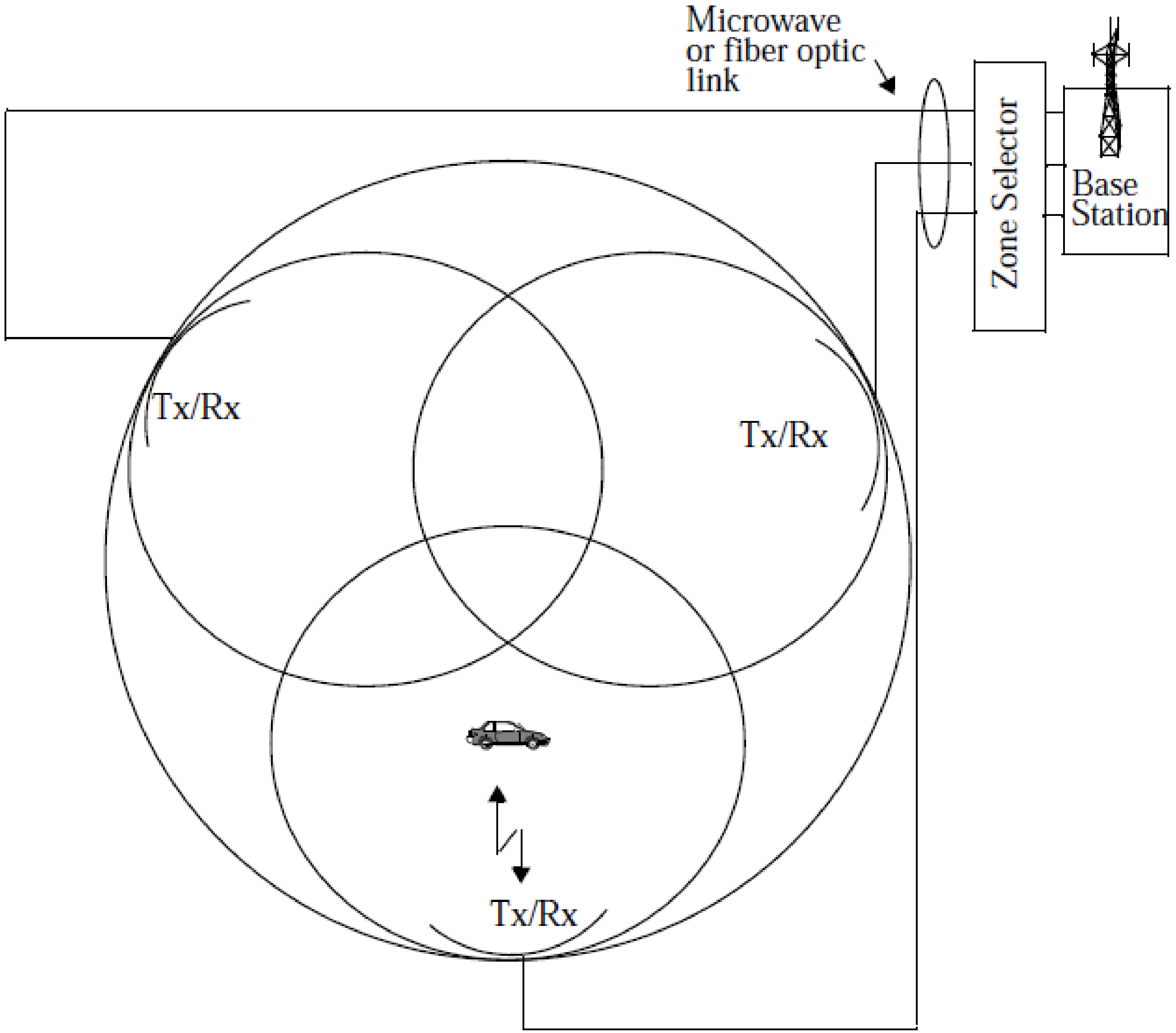


Figure 3.13 The microcell concept [adapted from [Lee91b] © IEEE].

- In this scheme, each of the three zone sites (represented as Tx/Rx in Figure 3.13) are connected to a single base station and share the same radio equipment.
- The zones are connected by coaxial cable, fiberoptic cable, or microwave link to the base station.
- Multiple zones and a single base station make up a cell. As a mobile travels within the cell, it is served by the zone with the strongest signal.
- As a mobile travels from one zone to another within the cell, it retains the same channel. The base station simply switches the channel to a different zone site.
- Thus, unlike in sectoring, a handoff is not required at the MSC when the mobile travels between zones within the cell.

- The channels are distributed in time and space by all three zones and are also reused in co-channel cells.

- This technique is particularly useful along highways or along urban traffic corridors.

- Advantage:
    - The co-channel interference is reduced since a large central base station is replaced by several lower powered transmitters (zone transmitters) on the edges of the cell.
    - Decreased co-channel interference improves the signal quality and also leads to an increase in capacity without the degradation in trunking efficiency caused by sectoring.
    - A handoff is not required at the MSC when the mobile travels between zones within the cell.

- In Figure 3.14, let each individual hexagon represents a zone, while each group of three hexagons represents a cell.
- The zone radius ***R_z*** is approximately equal to one hexagon radius.
- Now, the capacity of the zone microcell system is directly related to the distance ***D*** between co-channel cells, and not zones.

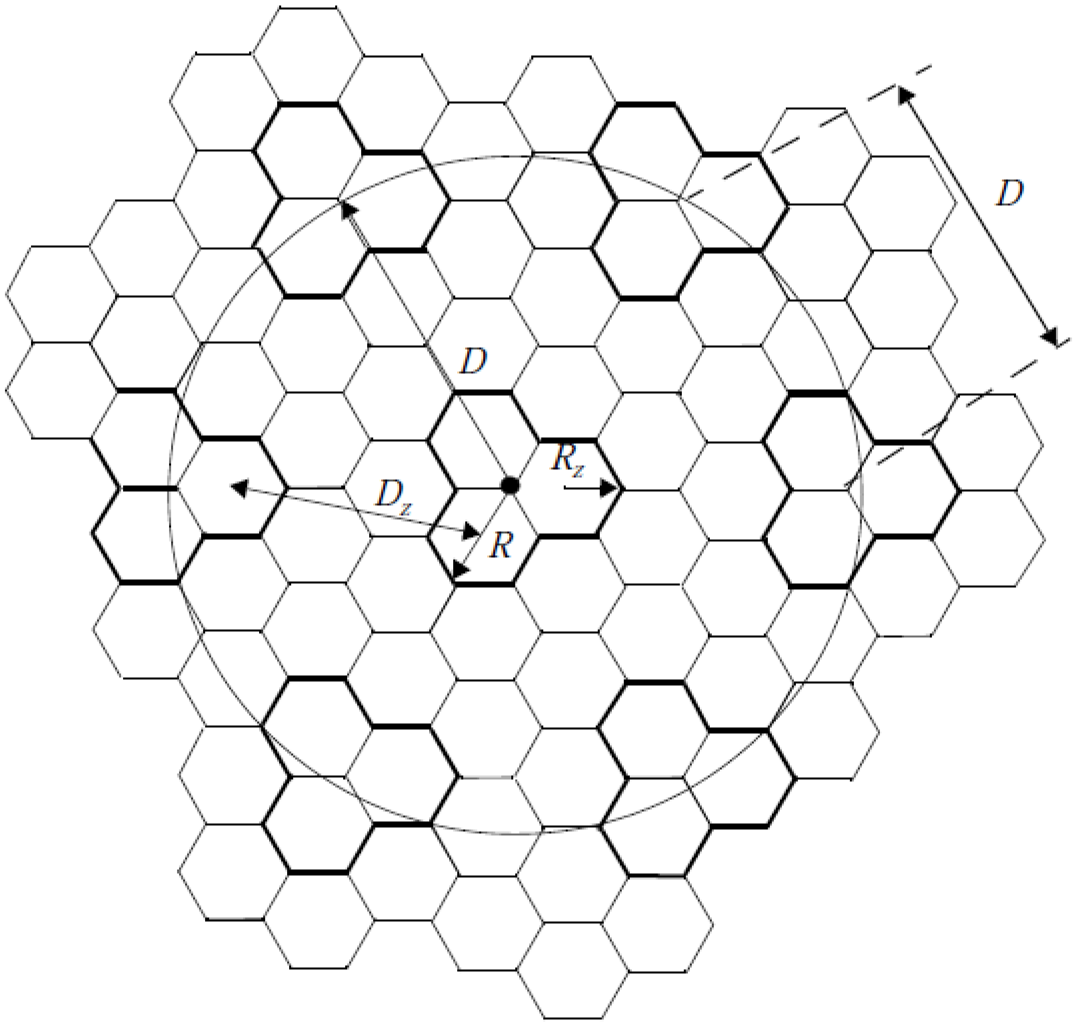


Figure 3.14 Define D, D_z, R, and R_z for a microcell architecture with $N = 7$. The smaller hexagons form zones and three hexagons (outlined in bold) together form a cell. Six nearest co-channel cells are shown.

Ex: To achieve *S/I* of 18 dB:

- Normal system requires D/R ratio of 4.6 with N=7.
- Microcell system requires D/R ratio of 3 with N=3.

- This reduction in the cluster size from N = 7 to N = 3 results to a 2.33 times increase in capacity for a system using microcell zone concept.

- Hence for the same S/I requirement of 18 dB, this system provides a significant increase in capacity over conventional cellular planning.