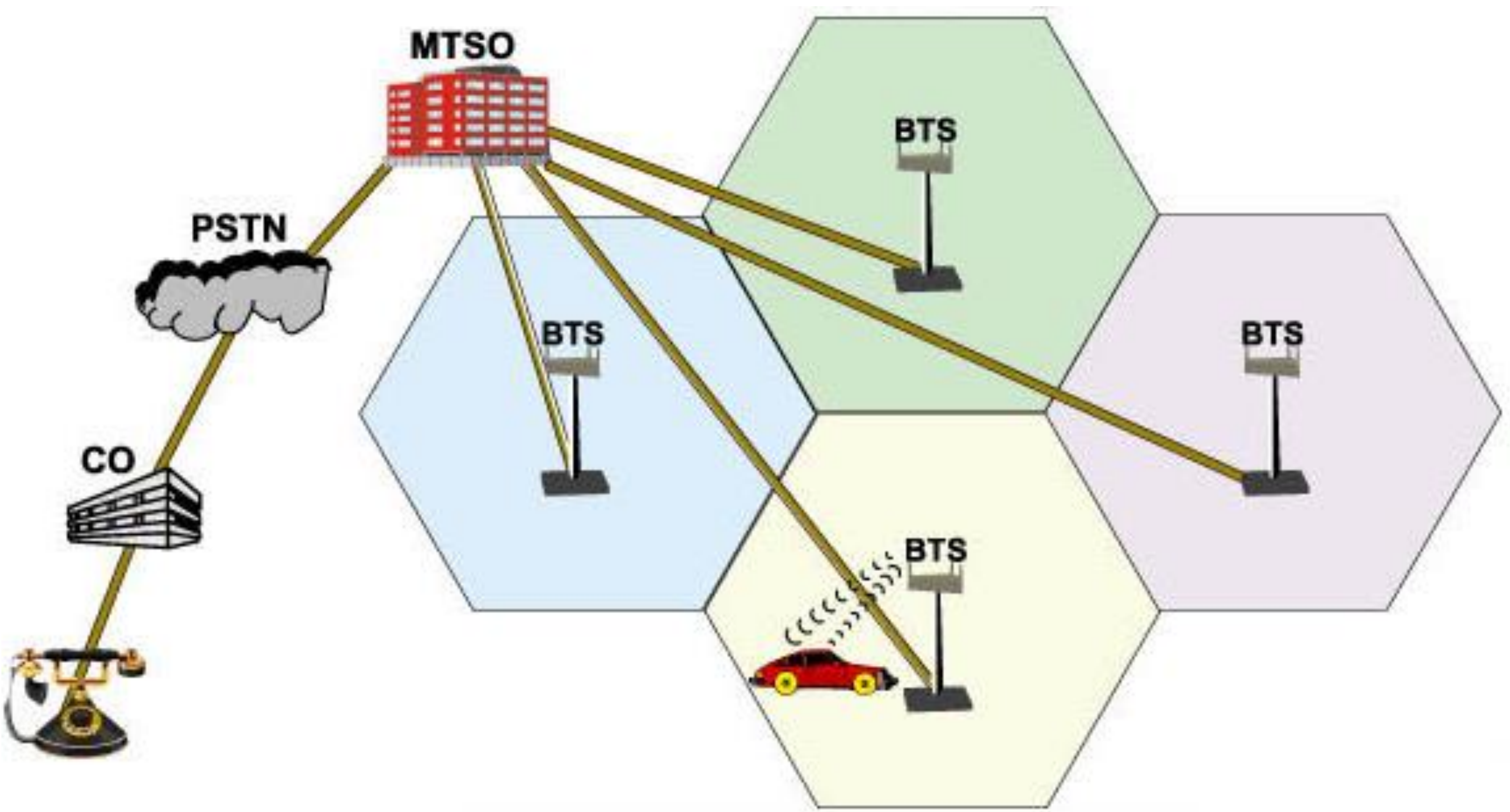
Cellular System Design Fundamentals

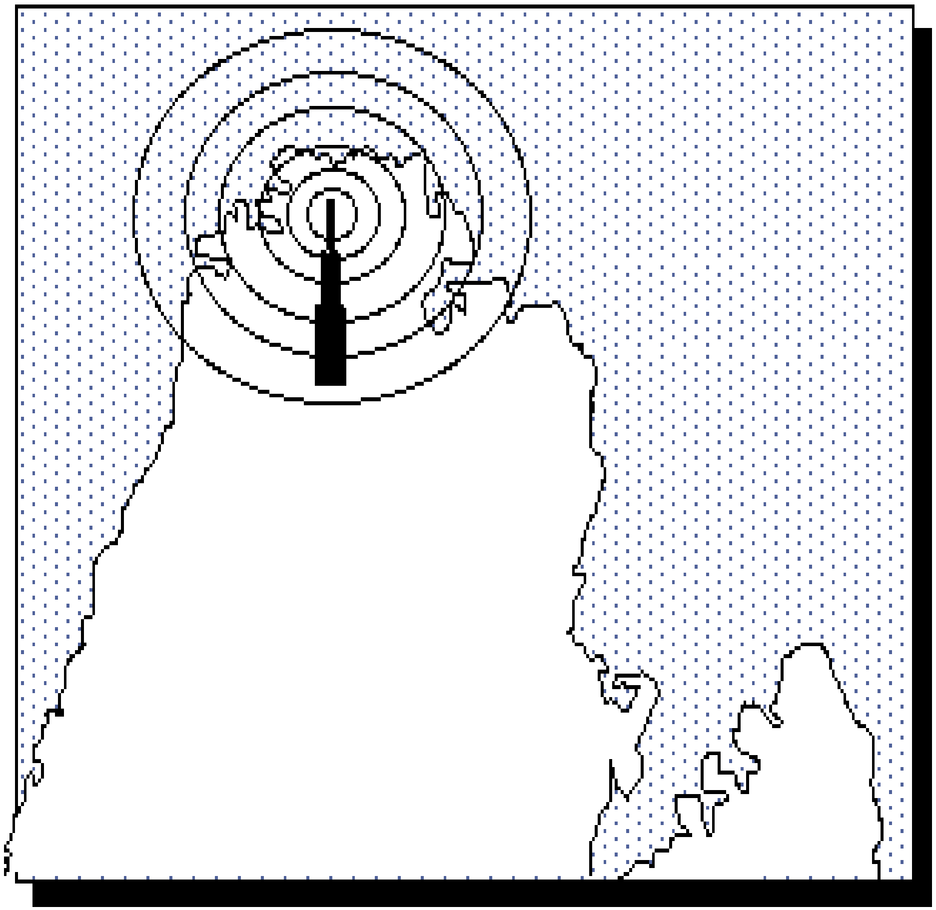
Chapter 3, Wireless communications, 2/e, T. S. Rappaport



Topics

- Cellular Concept
- Frequency reuse
- Channel Assignment Strategies
- Handoff Strategies
- Interference and System Capacity
- Co-channel Interference
- Adjacent Channel Interference
- Power Control for Reducing Interference
- Trunking
- Improving Capacity in Cellular Systems

Traditional mobile service was structured in a fashion similar to television broadcasting: One very powerful transmitter located at the highest spot in an area would broadcast in a radius of up to 50 kilometers.

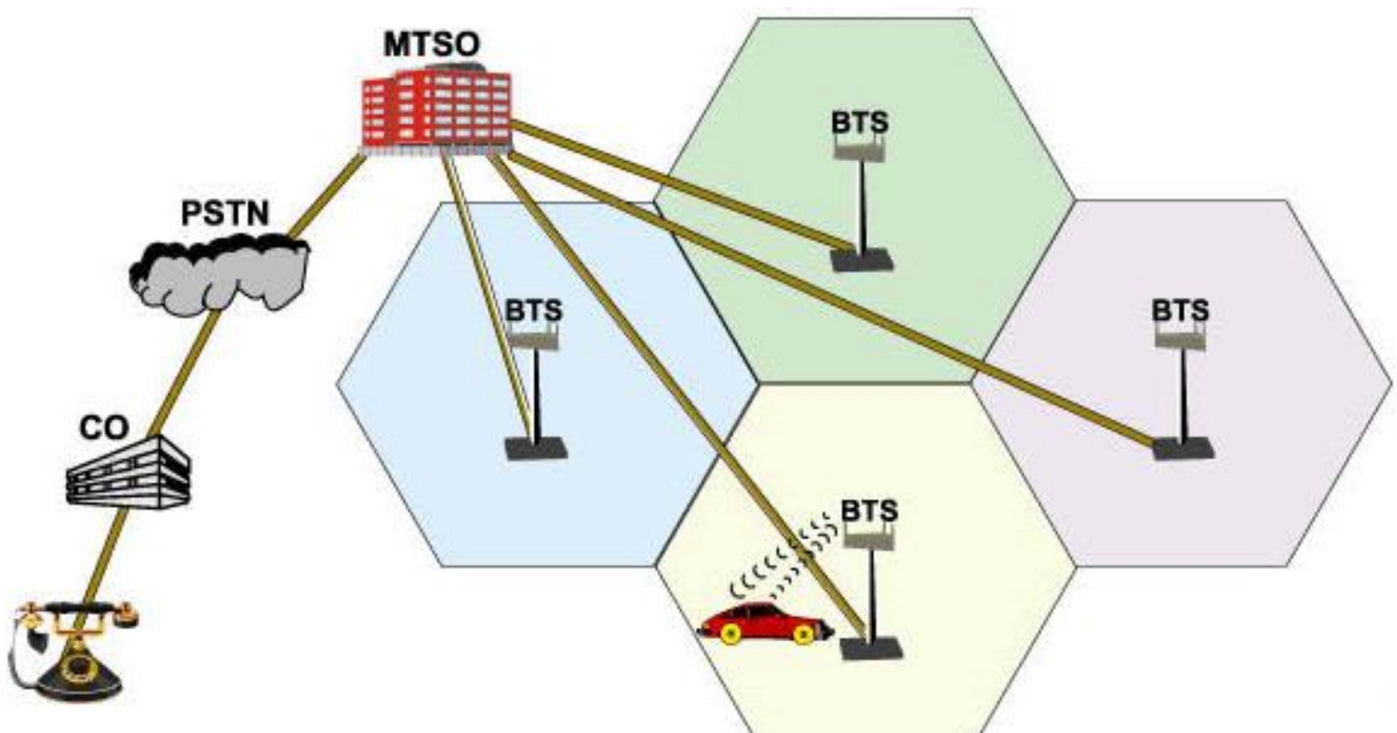


Drawbacks:

- High power consumption
- Large size of the mobile
- Low capacity

Cellular Concept:

The Cellular concept is a system level idea which calls for replacing,a single,high power transmitter with many low power transmitters,each providing coverage to only small portion of the service area.

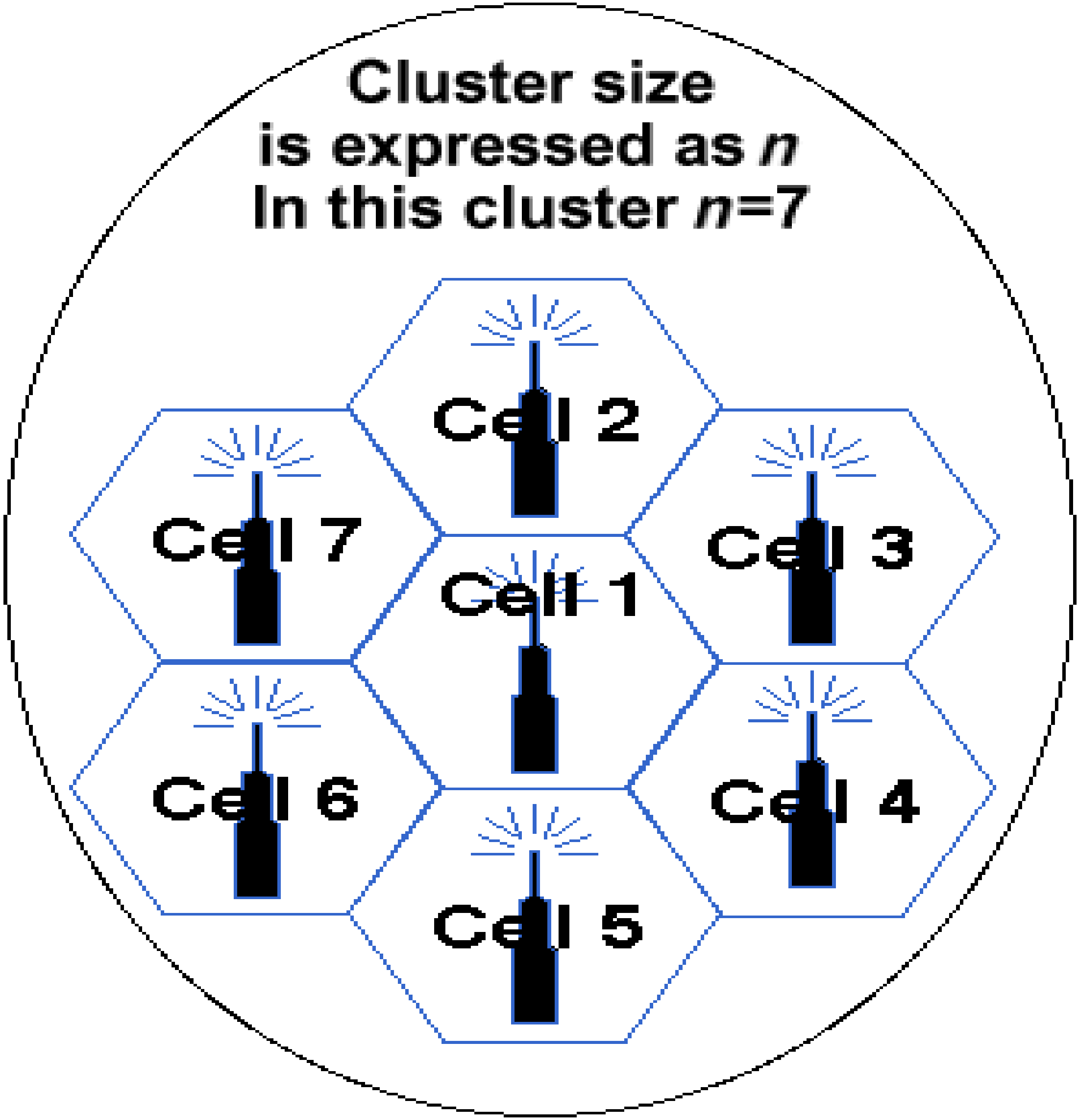


Allocation of channels

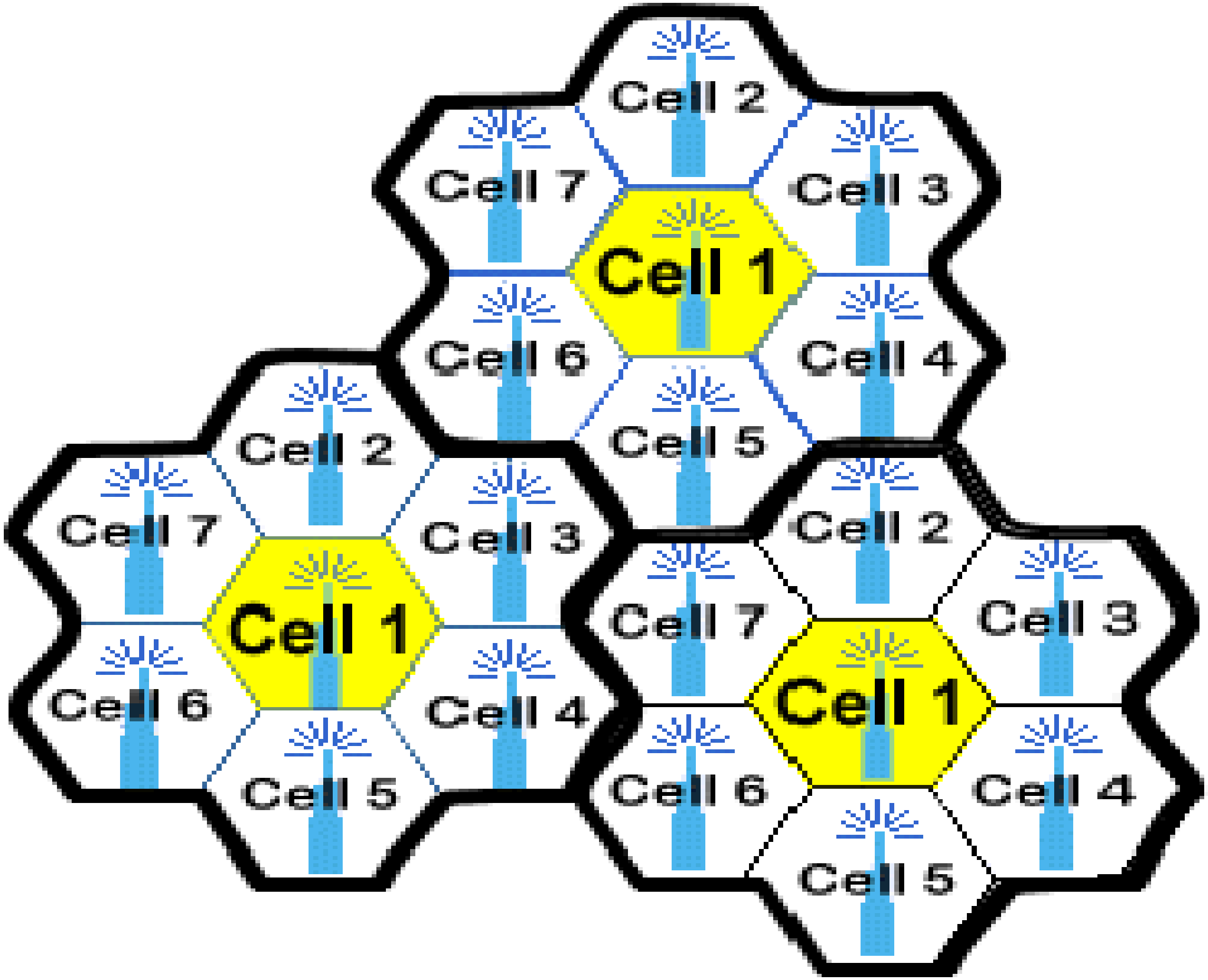
Each Base station is allocated a portion of total number of channels available to the entire system, and nearby base stations are assigned ***different*** groups of channels to minimize the interference between base stations.

Frequency Reuse

The design process of selecting and allocating channel groups for all the cellular base stations within a system is called frequency reuse.


Cluster size
is expressed as *n*
In this cluster *n*=7
Cell 2
Cell 7
Cell 3
Cell 1
Cell 6
Cell 4
Cell 5

The Cellular Concept



Frequency reuse concept

Consider cellular system with S duplex channels available,let each cell be allocated a group of k channels(k<s) and if the S channels are divided among N cells.

Available radio channels can be expressed as

$$S = KN$$

The N cells which collectively use the complete set of available frequencies is called a cluster.

If it is replicated M times within the system, total no.of duplex channels:

C, can be used as a measure of capacity and is given by

$$C = MKN$$
$$= MS$$

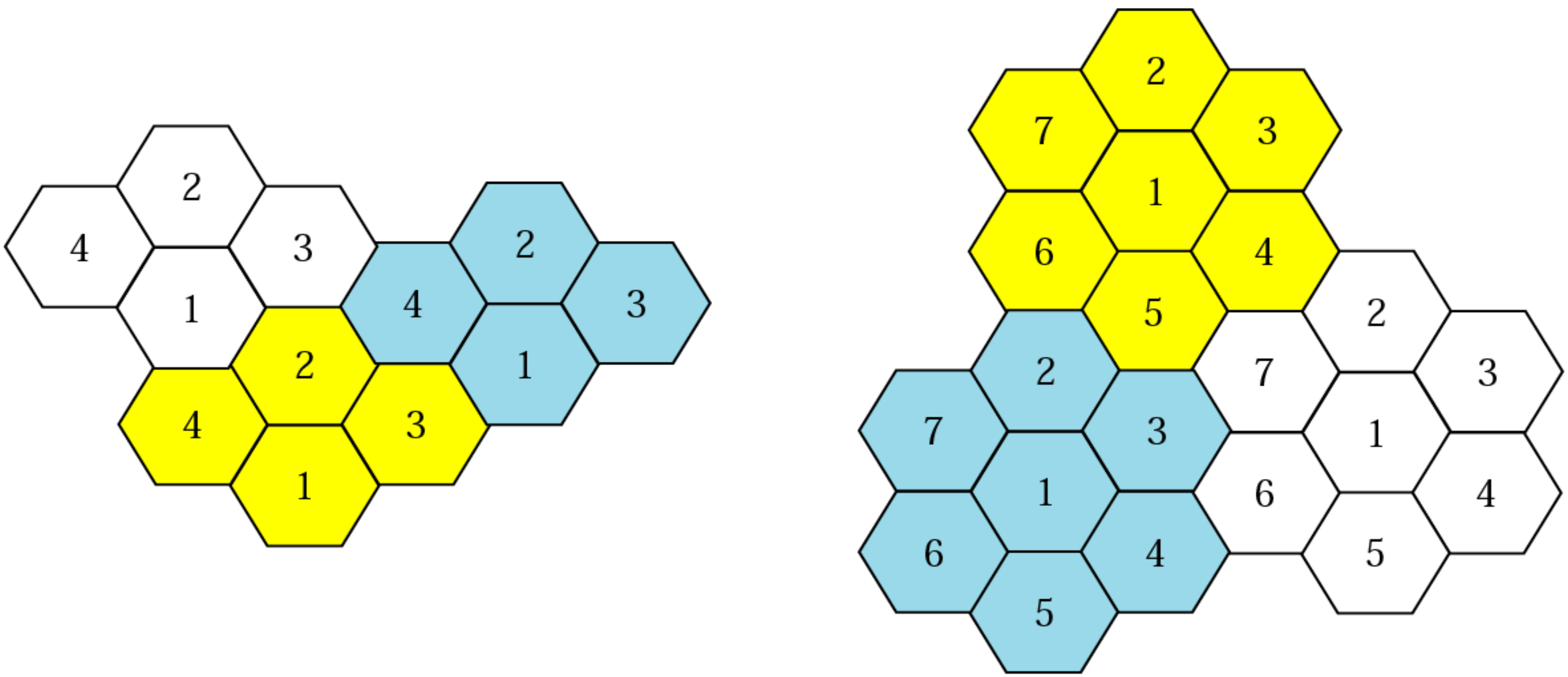
N = Cluster size and typically equal to 4,7,12.

From geometry of hexagons is such that the number of cells per Cluster, N, can only have the values which satisfy equation

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

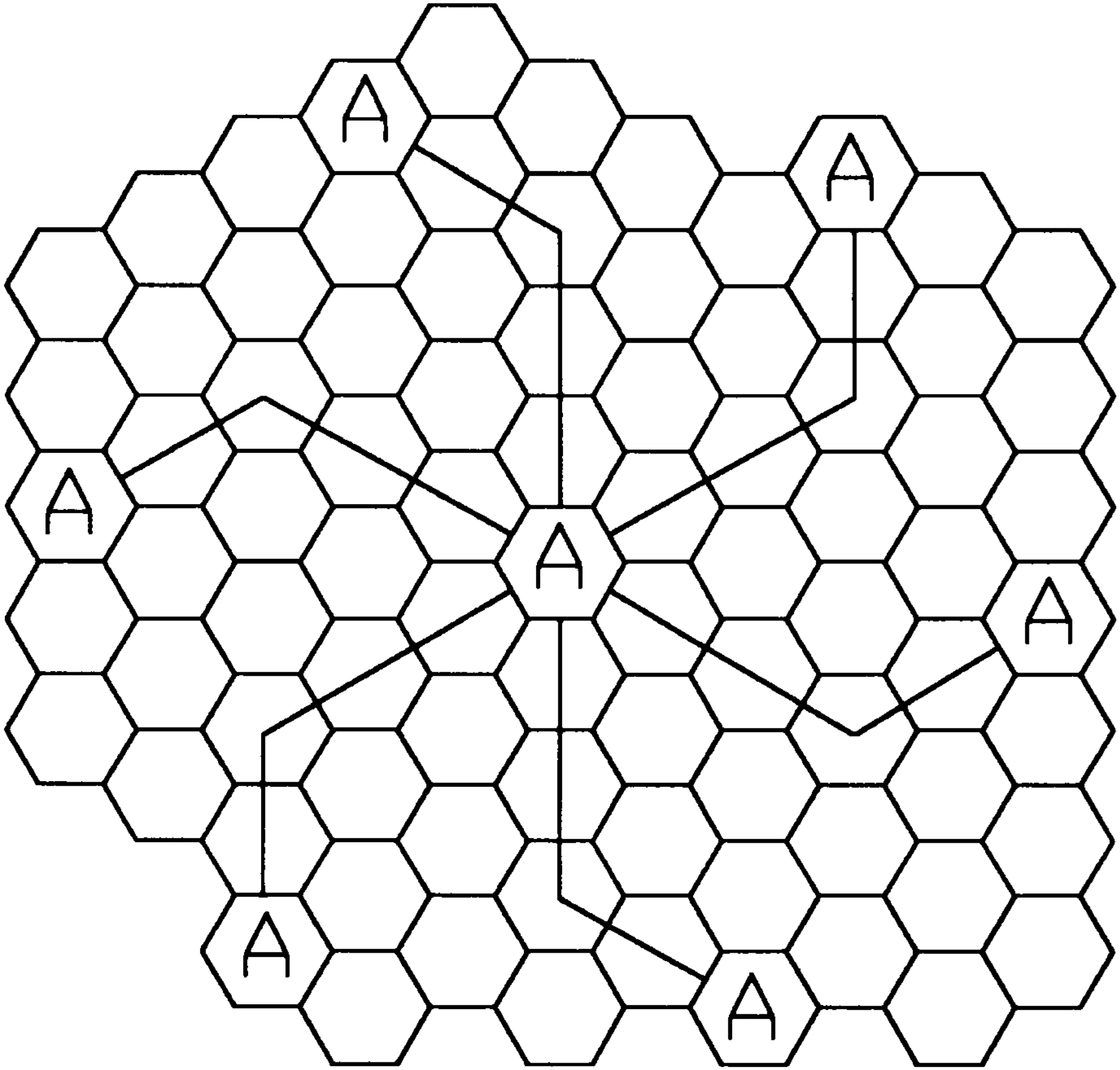
i and j are non-negative integers.

N can have the values of 3, 4, 7, 9, 12, 13,19,…



a. Reuse factor of 4 b. Reuse factor of 7

19-cell reuse example (N=19)



To find the nearest co-channel of a neighboring cell:

1. Move i cells along any chain of hexagons.
2. Turn 60 degrees counter clockwise.
3. Move j cell.

Figure 3.2 Method of locating co-channel cells in a cellular system. In this example, N = 19 (i.e., I = 3, j = 2). (Adapted from [Oet83] © IEEE.)

Channel assignment strategies

Fixed channel assignment

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

Fixed assignment with borrowing

Before a call is blocked, a BS might try to “borrow" a channel from a neighbouring BS.

Dynamic channel assignment

The voice channels are not allocated to different cells permanently, instead each time a call request is made, the serving base station request a channel from the mobile switching center.

Handoff 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.

This handoff operation not only involves identifying a new base station, but also requires that the voice and control signals be allocated to channels associated with the new base station.

Handoffs – the basics

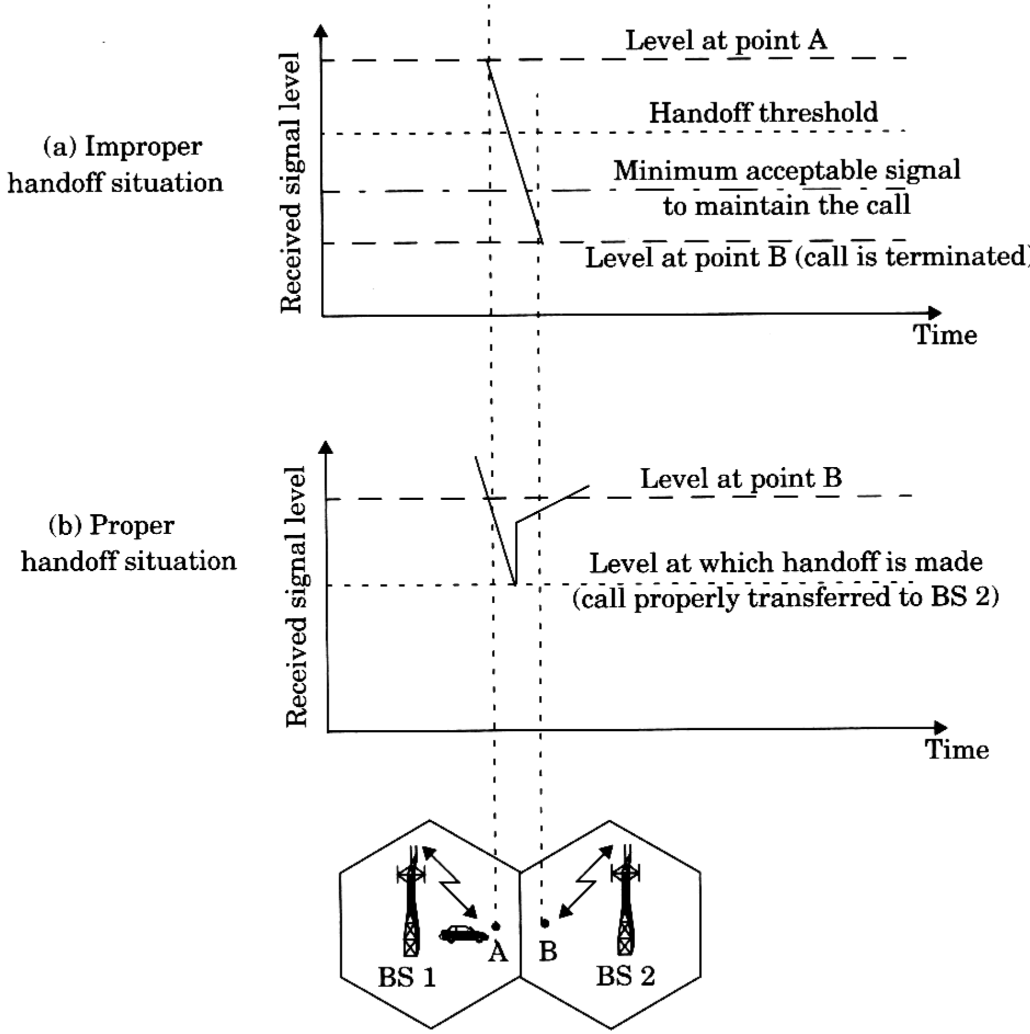


Figure 3.3 Illustration of a handoff scenario at cell boundary.

- In the first generation analog cellular systems, Signal strength Measurements are made by the base station to determine the relative location of each mobile user with respect to the base station.

- In second generation systems that use digital TDMA technology,handoff decisions are made mobile assisted handoff (MAHO). 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.

Prioritizing handoffs

- Guard channel concept

  In this a fraction of total available channels in a cell is reserved exclusively for handoff requests from ongoing calls which may be handed off into the cell.

- Queuing of handoff requests is another method

  to decrease the probability of forced termination of a call due to lack of available channels.

Practical handoff considerations

•Using different antenna heights 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 umbrella cell approach and is 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 in minimized for high speed users and provides additional microcell channels for pedestrian users.

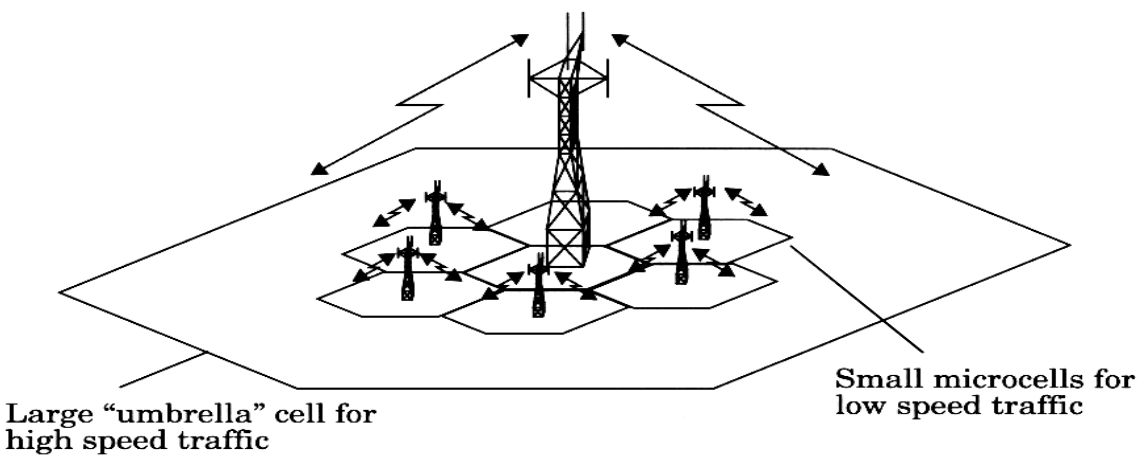


Figure 3.4 The umbrella cell approach.

Hard handoff and soft handoff

- **Hard handoff:** When the signal strength of a neighboring cell exceeds that of the current cell, plus a threshold, the mobile station is instructed to switch to a new frequency band that is within the allocation of the new cell.
- **Soft handoff**: a mobile station is temporarily connected to more than one base station simultaneously. A mobile unit may start out assigned to a single cell. If the unit enters a region in which the transmissions from two base stations are comparable (within some threshold of each other), the mobile unit enters the soft handoff state in which it is connected to the two base stations. The mobile unit remains in this state until one base station clearly predominates, at which time it is assigned exclusively to that cell.

Co-channel reuse ratio

Assuming *same cell size* and that the base stations transmit the *same power*

The Co-channel interference ratio becomes independent of the Transmitted power and becomes function of Radius of the cell (R) and Distance between centers of the nearest co-channel cells (D)

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

I	J	Cluster Size (N)	Co-Channel Reuse Ratio (Q)
1	1	3	3
1	2	7	4.58
2	2	12	6
1	3	13	6.24

You are trying to design a cellular network that will cover an area of at least 2800 km^2. There are K=300 available voice channels. Your design is required to support at least 100 concurrent calls in each cell. If the co-channel cell centre distance is required to be 9 km, how many base stations will you need in this network?

- If 100 concurrent voice calls must be supported in each cell, each cell must be allocated 100 voice channels.
- This necessitates the frequency re-use factor, N, to be 300/100=3.
- The distance between co-channel cell centres D is related to R and N via the formula:
- $$\frac{D}{R} = \sqrt{3 \cdot N}$$
- D = 9 km, then, R = 3 km
- cell area is $\frac{3 \cdot \sqrt{3}}{2} \cdot R^2 = 23.38$
- 2800/23.38 = 120 base stations are required

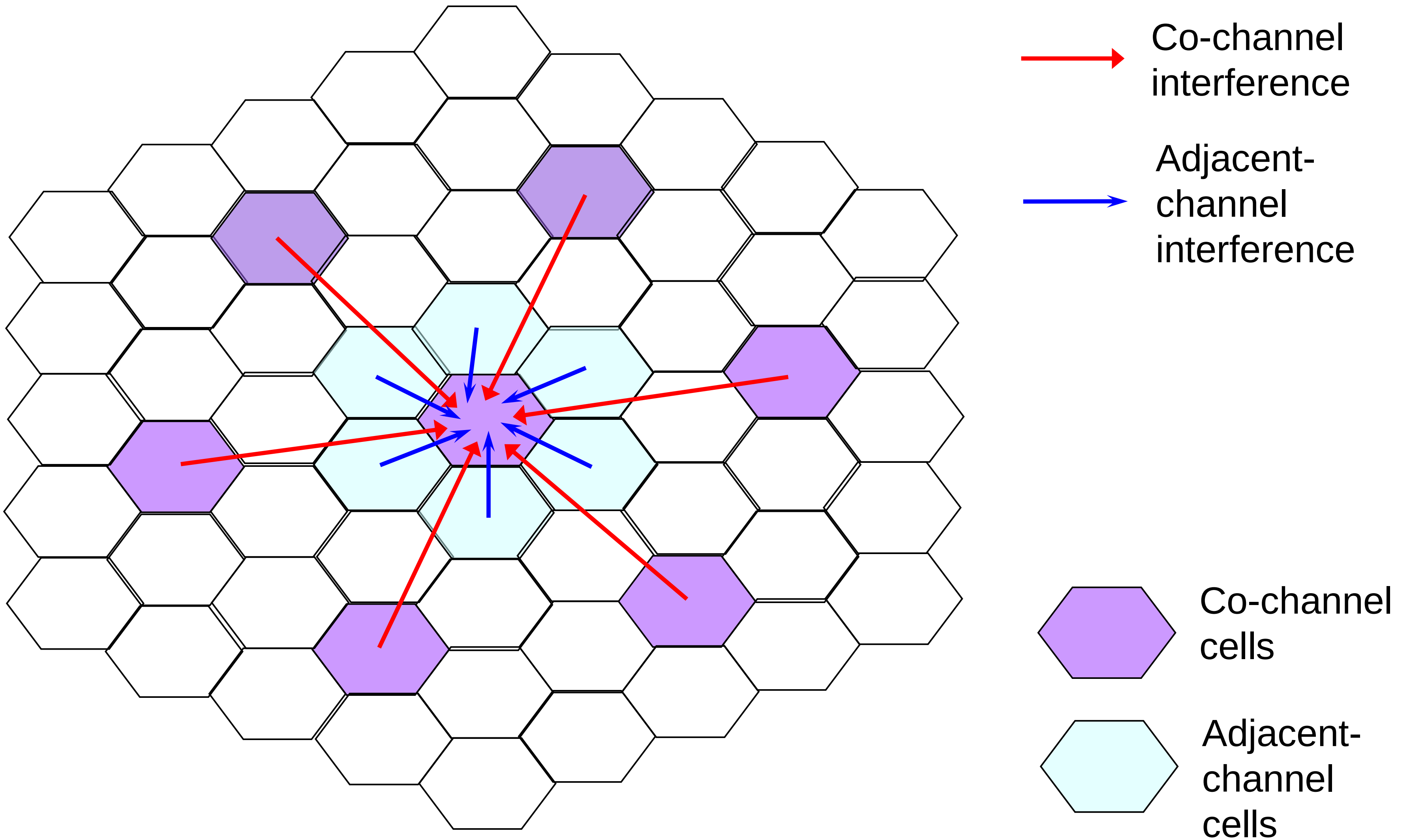
Interference

- Interference is a major limiting factor in the performance of cellular radio system
- Sources of Interference
  - 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 non cellular system which inadvertently leaks energy into the cellular frequency band

The two major types of system generated interferences are

- **Co-channel interference**
- **Adjacent channel interference**

Co-channel & Adjacent channel Interference



Co-channel cells for 7-cell reuse

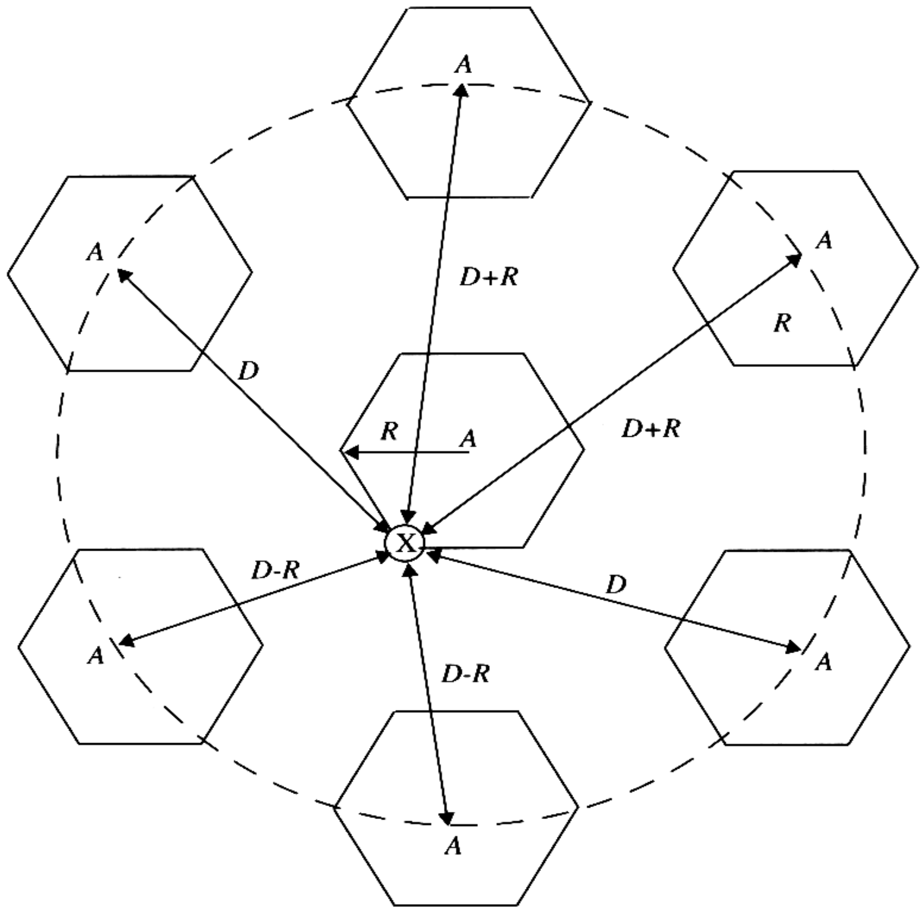


Figure 3.5 Illustration of the first tier of co-channel cells for a cluster size of $N = 7$. An approximation of the exact geometry is shown here, whereas the exact geometry is given in [Lee86]. When the mobile is at the cell boundary (point X), it experiences worst case co-channel interference on the forward channel. The marked distances between the mobile and different co-channel cells are based on approximations made for easy analysis.

Signal to Interference Ratio (SIR)

$$\frac{S}{I} = \frac{S}{\sum_{i=1}^{i_O} I_i}$$

where S – desired signal power

I_i – Interference power caused by the ith interfering co-channel cell base station

Assuming that the transmitting power of each base station is equal and the path loss exponent same through out the coverage area

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

i_o – The number of Co-channel interfering cells and
S/I – Signal to interference ratio at the desired mobile receiver

Considering first layer of interfering cells. If all the interfering base stations are equidistant from the desired base station (by D between cell centers)

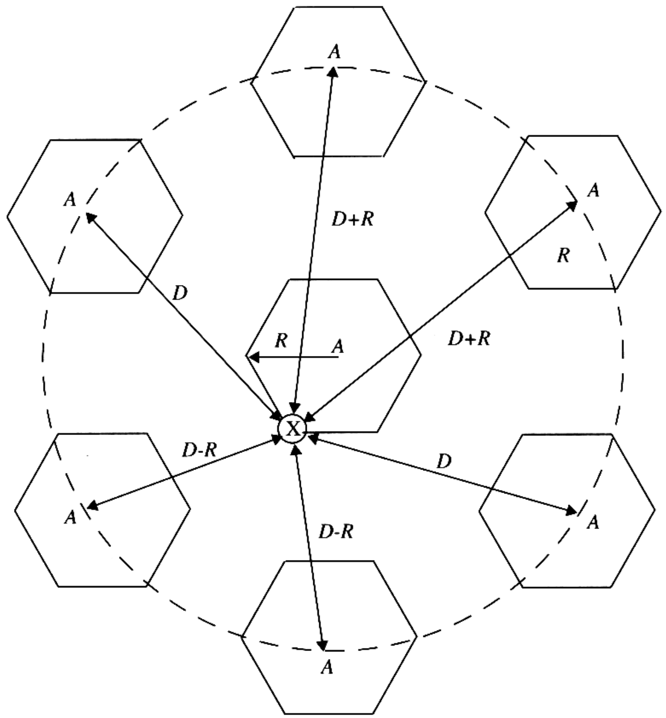
$$\frac{S}{I} = \frac{(D/R)^n}{i_0} = \frac{(\sqrt{3N})^n}{i_0}$$

For the case where the mobile unit is at the cell boundary in a 7-cell cluster (the worst case). The distances from the co-channel interfering cells are approximated to

D-R, D and D+R .

Assuming n= 4

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



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the worst case SIR

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

For N=7 , Q= 4.58 from

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

From

(worst case)

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

S/I = 49.56 (17 dB)

But by using

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

S/I = 17.8 dB

(average)

Hence for a 7-cell cluster, the S/I ratio is slightly less that 18 dB in the worst case.

Adjacent Channel Interference

1. What is adjacent channel interference?

   Interference resulting from signals which are adjacent in frequency to desired signal.

2. Why does it occur?

   This results from imperfect receiver filters which allow nearby frequencies to leak into the pass band.

3. How can adjacent channel interference be reduced?

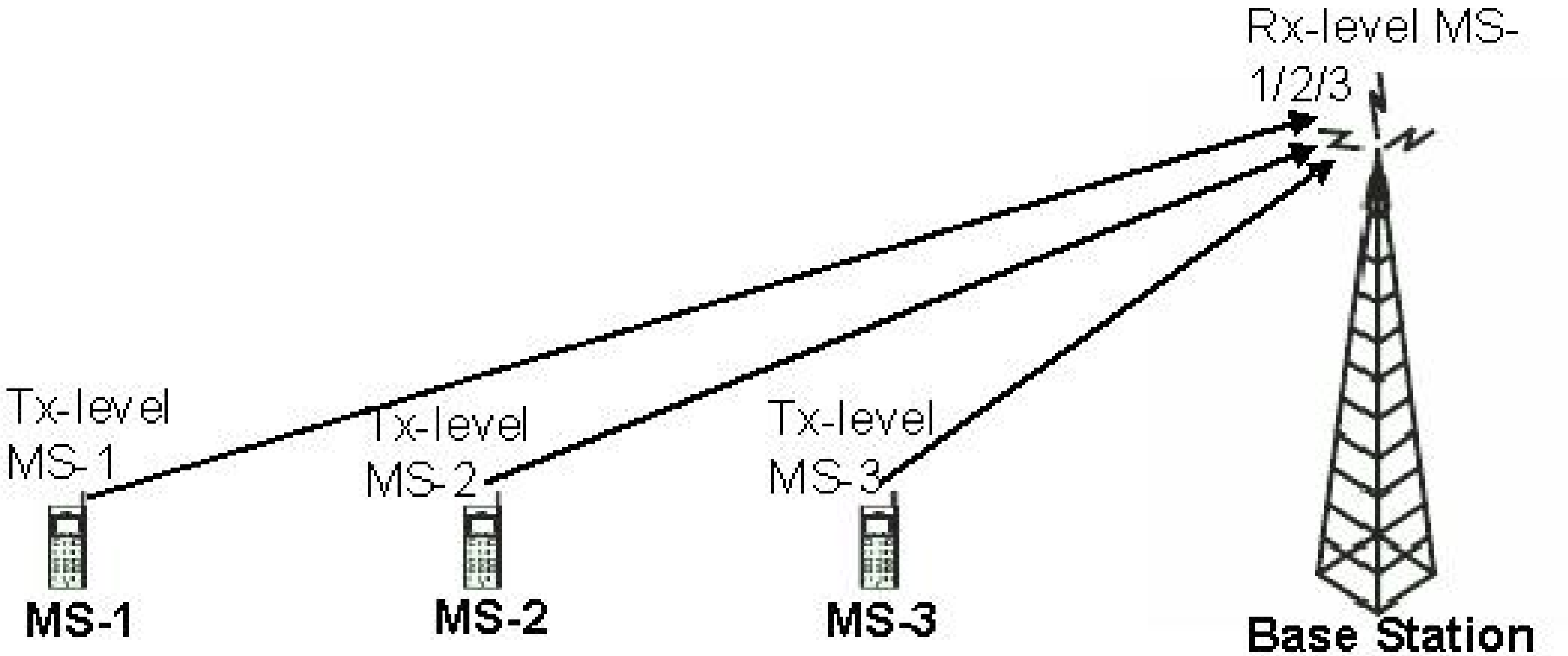
- careful filtering and channel assignment
- By keeping the frequency separation between each channel in a given cell as large as possible
- By sequentially assigning successive channels in the frequency band to different cells

Power Control For Reducing Interference

In practical cellular radio and personal communication systems the power levels transmitted by every subscriber unit are controlled by the serving base stations

Need for Power Control:

- Received power must be sufficiently above the background noise for effective communication
- Desirable to minimize power in the transmitted signal from the mobile. Reduce co-channel interference, alleviate health concerns, save battery power
- In Spread Spectrum systems using CDMA, it's desirable to equalize the received power level from all mobile units at the Base station.



Without Power Control:

Tx level MS-1 = Tx level MS-2 = Tx level MS-3 →

Rx level MS-1 < Rx level MS-2 < Rx level MS-3

With Power Control:

Tx level MS-1 > Tx level MS-2 > Tx level MS-3 →

Rx level MS-1 = Rx level MS-2 = Rx level MS-3

Power Control

- **Power control** enable the transmitter side to adapt its output power according to pilot signal's strength.
- Aims to solve the '**near-far**' problem with the goal to achieve uniform signal to interference ratio (SIR) for all the active users.
- Two methods:

    a) open-loop Power Control

    b) closed-loop Power Control.

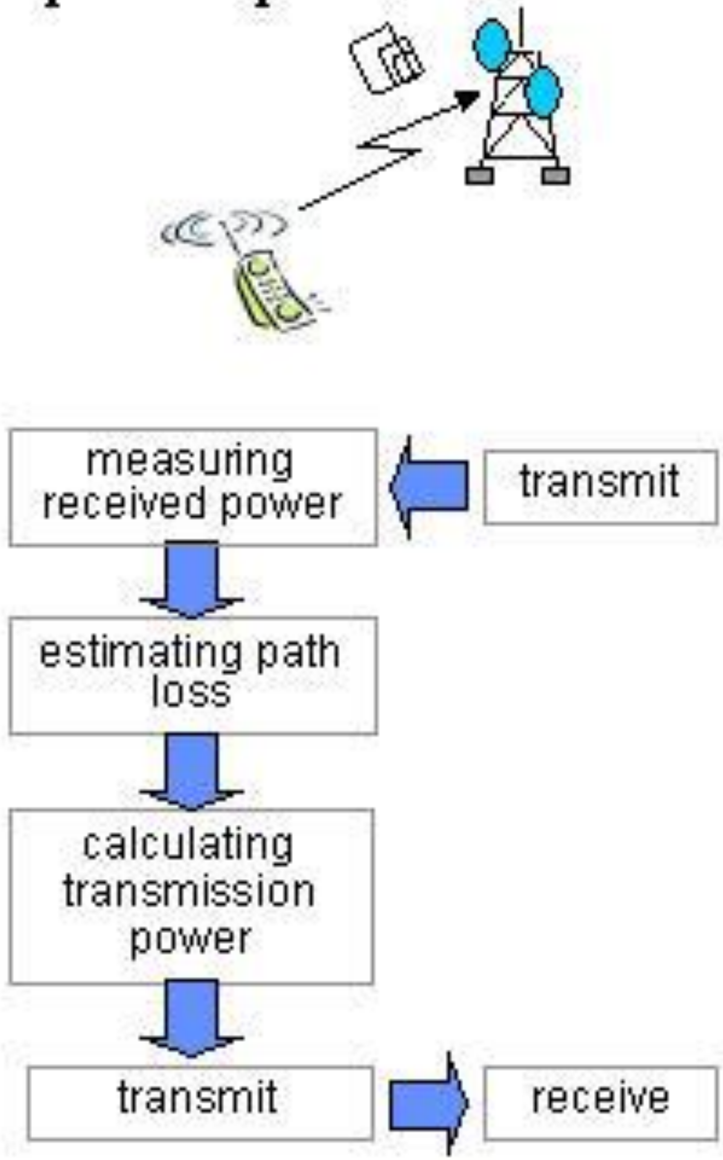
Open-loop Power Control

- In **open-loop PC**, the **mobile** measures the pilot strength (continuously transmitted by the BS) which is related to path loss. If the pilot gets weak it powers-up, when the pilot gets strong it powers down.
- It assumes that the forward and reverse link are similar.--- not accurately (incase of FDD).
- Quickly react. – e.g. mobile emerges from a behind a large building.
- It gives quite results with the TDD mode.
- It is used in WCDMA-FDD mode but only to provide initial power setting of the mobile station at the beginning of the connection.

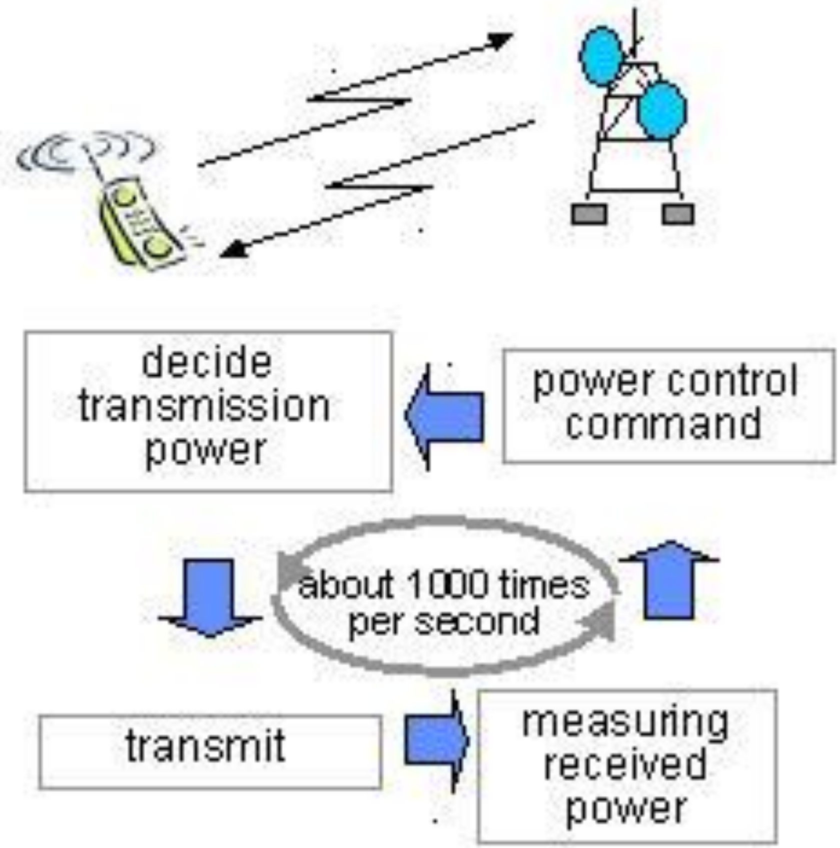
Closed-loop Power Control

- In **closed-loop PC**, feedback is used whereby the **base-station** measures the signal-quality of mobile; e.g. frame error rate (FER) and commands each mobile to power up and down accordingly in order to keep the overall FER at desired level. – reverse link.
- The mobile provides information about received signal quality to the BS, which then adjusts transmitted power. – forward link.
- The UTRA-FDD mode uses **fast closed-loop power control** technique both in uplink and downlink.

Open Loop Power Control



Closed Loop Power Control



GSM 900M transmitter classes

Power Class	Base station power (watts)	Mobile station power (watts)
1	320	20
2	160	8
3	80	5
4	40	2
5	20	0.8
6	10	
7	5	
8	2.5	

The transmission power in the handset is limited to a maximum of 2 watts in GSM850/900 and 1 watt in GSM1800/1900.

Low-height high-power mobile phone base station (under 10m)

			Equivalent isotropically radiated power (dBW)		
Network	**Frequency**	**Base Stations**	**Minimum**	**Average**	**Maximum**
Vodafone	900 MHz	23	7.1	7.1	7.4
O2	900 MHz	21	0.3	7.3	11.7
Orange	1800 MHz	22	12.9	15.2	19.4
T-Mobile	1800 MHz	25	4.0	9.3	11.0
T-Mobile	2100 MHz	3	9.0	10.0	11.0

7 dBW represents 5 watts radiated power per channel. 15 dBW (the Orange average) represents 32 watts radiated power per channel

Traffic Engineering

Developed in PSTN, but equally apply to cellular networks.

Ideally, Num of channels = Num of total subscribers (could be active at any time).

It is not practicable to have the capacity to handle any possible load **at all time**. And not all subscribes place calls at the same time.---- share the channels.

Key Definitions for Trunked Radio

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}.

1 Erlang :

Represents the amount of traffic intensity carried by a channel that is completely occupied : 1 call hour per hour

Ex: a radio channel that is occupied for 30 min during an hour carries 0.5 Erlangs of traffic.

Grade of Service :

- Measure of the ability of a user to access a trunked system during the busiest hour.
- The busy hour is based on customer demand at the busiest hour during a week, month or year.
- For cellular radio systems : rush hour is between 4pm-6pm, Thurs-Fri.

Formulas and derivation

Traffic intensity generated by each user : A_u Erlangs

$$A_u = \lambda H$$

H : average duration of the call

λ : average number of call requests per unit time

For a system containing U users and unspecified number of channels,

Total offered traffic intensity : A Erlangs

$$A = U A_u$$

In C channel trunked system, if the traffic is equally distributed among the channels,

Traffic intensity per channel : A_c Erlangs

$$A_c = U A_u / C$$

Types of trunked system

- No queuing for call requests

  " Blocked Calls Cleared "

- Queue is provided to hold calls

  " Blocked Calls Delayed "

Assumption :

- calls arrive as determined by Poisson distribution
- infinite number of users
- memoryless arrivals of requests : all users can request channel at any time
- probability of user occupying a channel is exponentially distributed
- finite number of channels available in the trunking pool

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

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

Erlang C formula : if offered call cannot be assigned a channel, it is placed in a queue which has a finite length, each call is then serviced in the order of its arrival.

Probability that an arriving call occurs when all C channels are busy and thus has to wait is

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

If no channels are immediately available the call is delayed, and the probability that the delayed call is forced to wait more than ‘t’ secs is

$$\begin{aligned} Pr[delay > t] &= Pr[delay > 0]\, Pr[delay > t \mid delay > 0] \\ &= Pr[delay > 0] \exp(-(C-A)t/H) \end{aligned}$$

The average delay D for all calls in a queued system is given by

$$D = Pr[delay > 0] \frac{H}{C-A}$$

Trunking efficiency :

Measure of the number of users which can be offered a particular GOS with a particular configuration of fixed channels.

Allocation of channels in a trunked radio system has a major impact on overall system capacity.

Erlang B Trunking GOS

Table 3.4 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	0.900	0.762
10	4.46	3.96	3.43	3.09
20	12.0	11.1	10.1	9.41
24	15.3	14.2	13.0	12.2
40	29.0	27.3	25.7	24.5
70	56.1	53.7	51.0	49.2
100	84.1	80.9	77.4	75.2

Erlang B

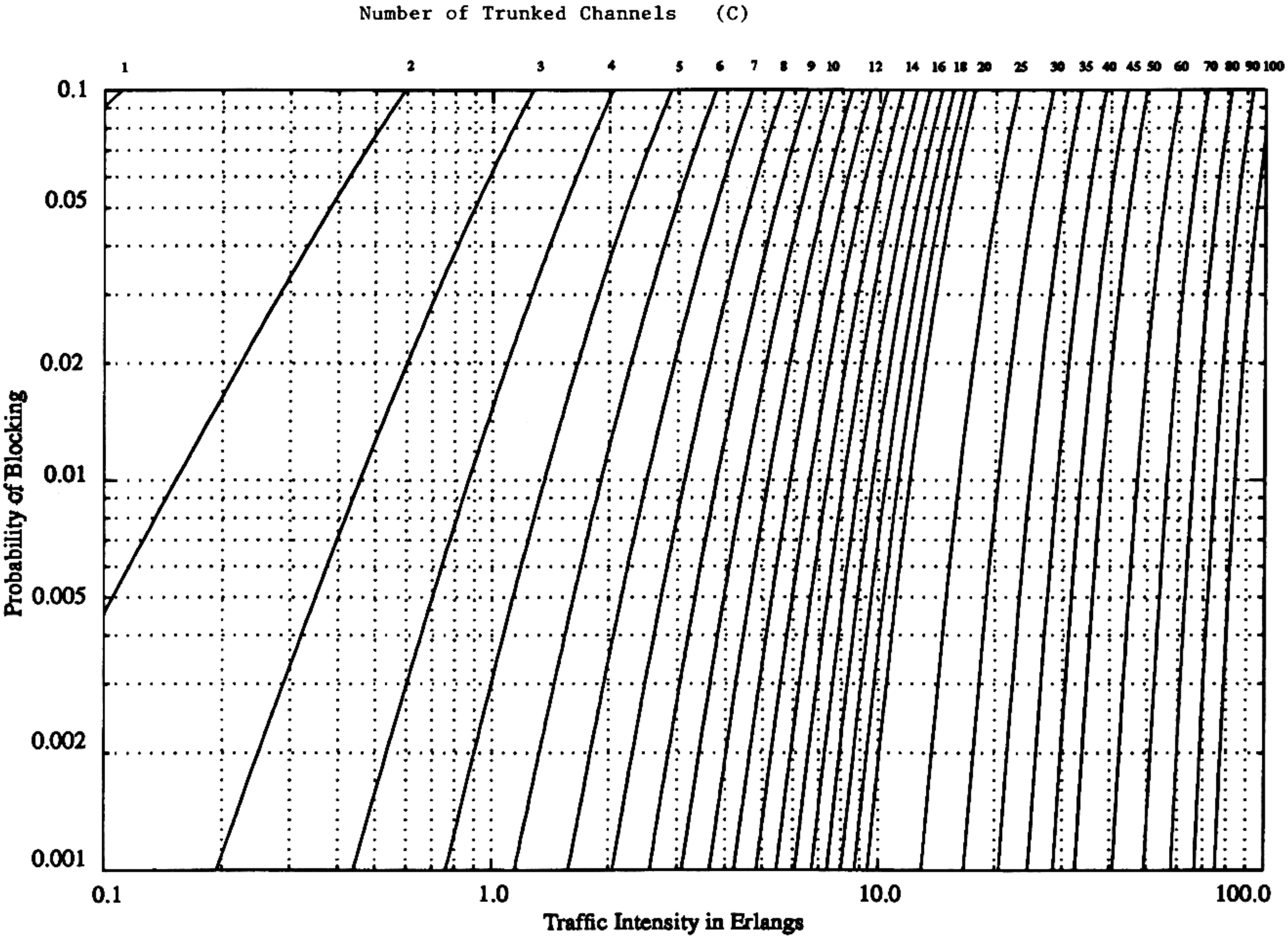


Figure 3.6 The Erlang B chart showing the probability of blocking as functions of the number of channels and traffic intensity in Erlangs.

Erlang C

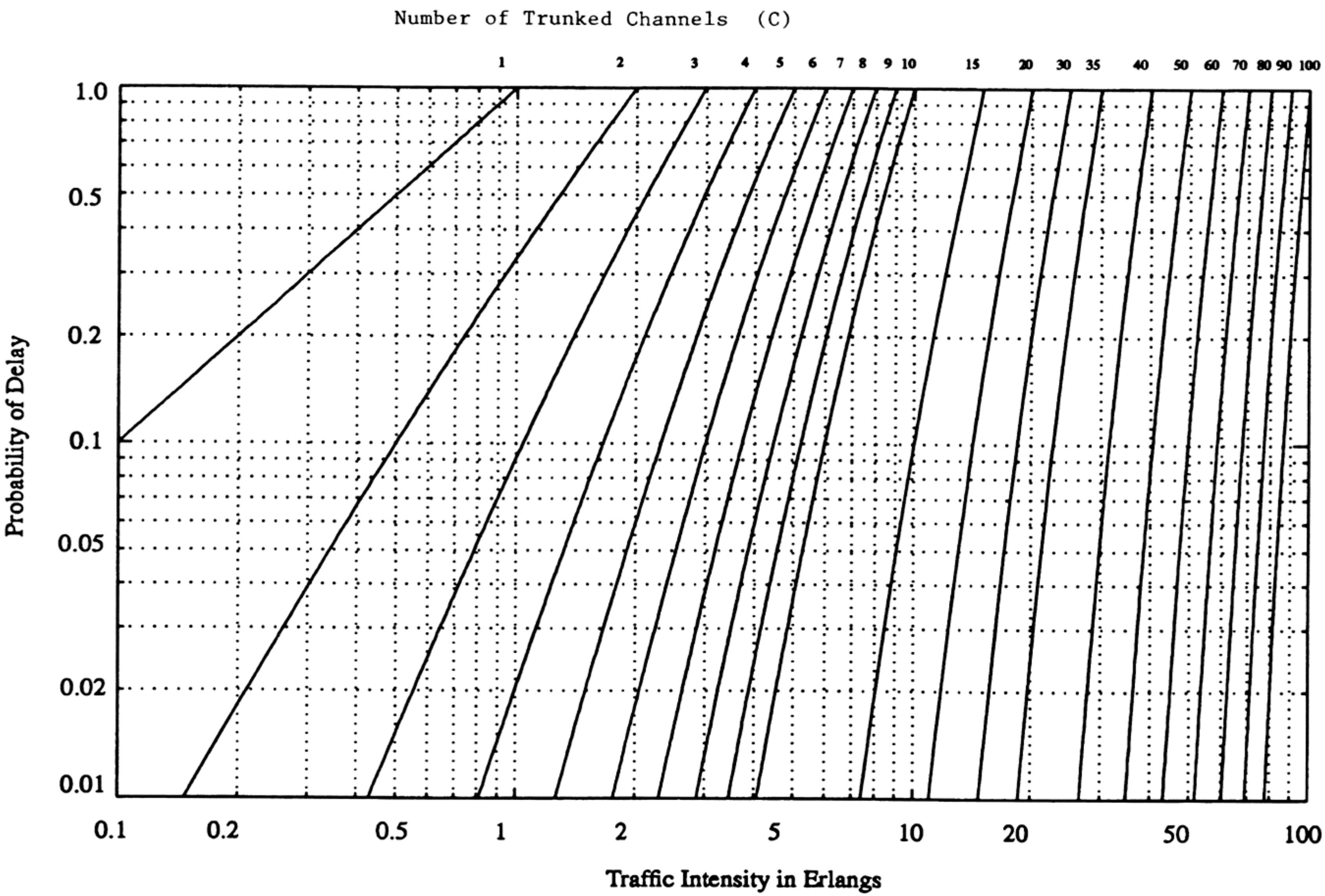


Figure 3.7 The Erlang C chart showing the probability of a call being delayed as a function of the number of channels and traffic intensity in Erlangs.

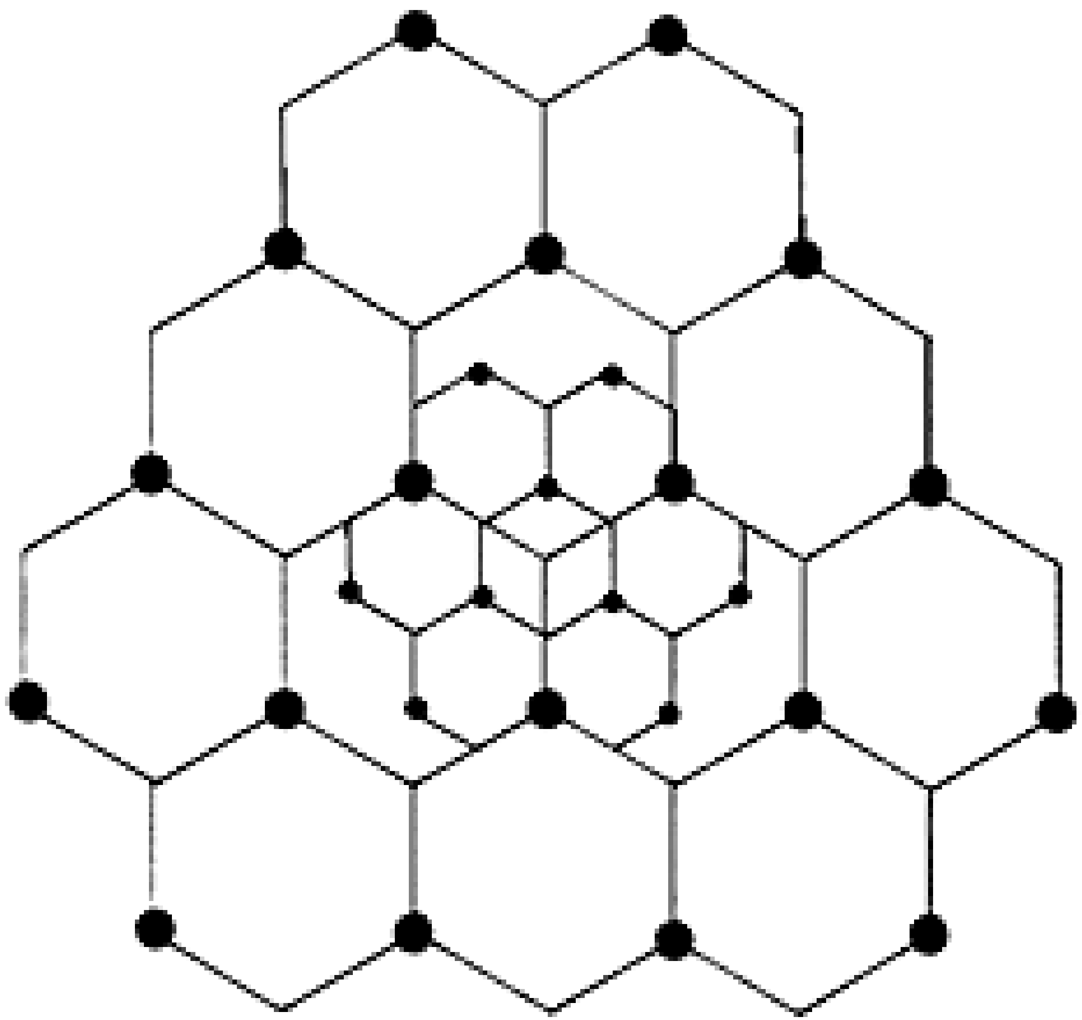
Improve Capacity

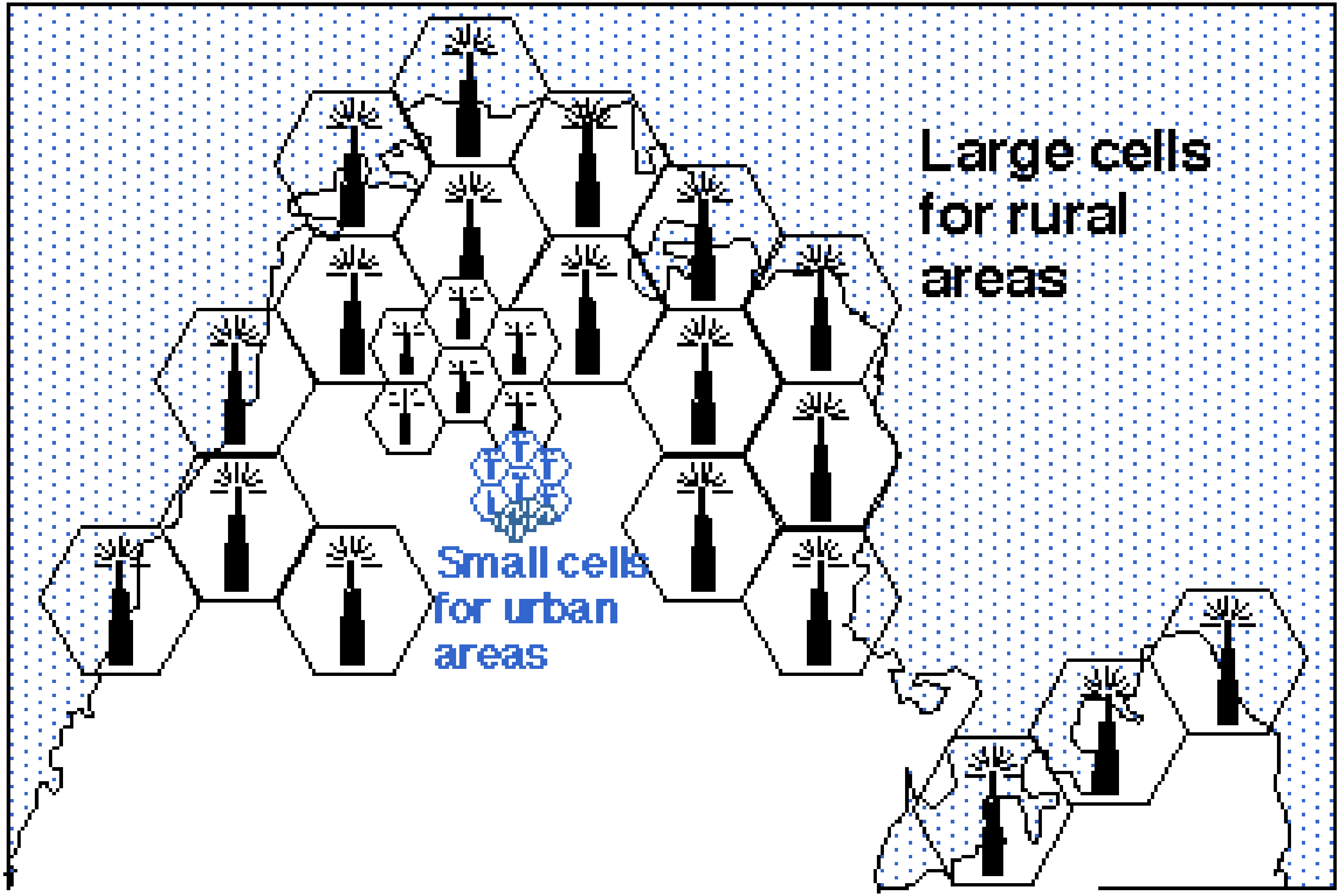
- Cell Splitting : It allows an orderly growth of the cellular system
- Sectoring : It uses Directional antennas to control the interference and frequency reuse of channels.
- Zone Microcell: It distributes the coverage of the Cell.
- More bandwidth
- Borrow channel from nearby cells

CELL SPLITTING

- Cell Splitting : It is the process of subdividing the congested cell into smaller cells.
- Each of the smaller cells will have their own base station with a reduction in antenna height and transmitted power.
- The smaller cells are known as Microcells.
- Cell Splitting increases the capacity of the cellular system as it increases the number of times the channels are reused
- The increased number of cells would increase the number of clusters over the coverage region,which in turn increase the number of channels,and thus capacity in the coverage area
- Cell Splitting allows the system to grow by replacing large cells with smaller cells without changing the co-channel re-use ratio Q

Cells are split to add channels with no new spectrum usage

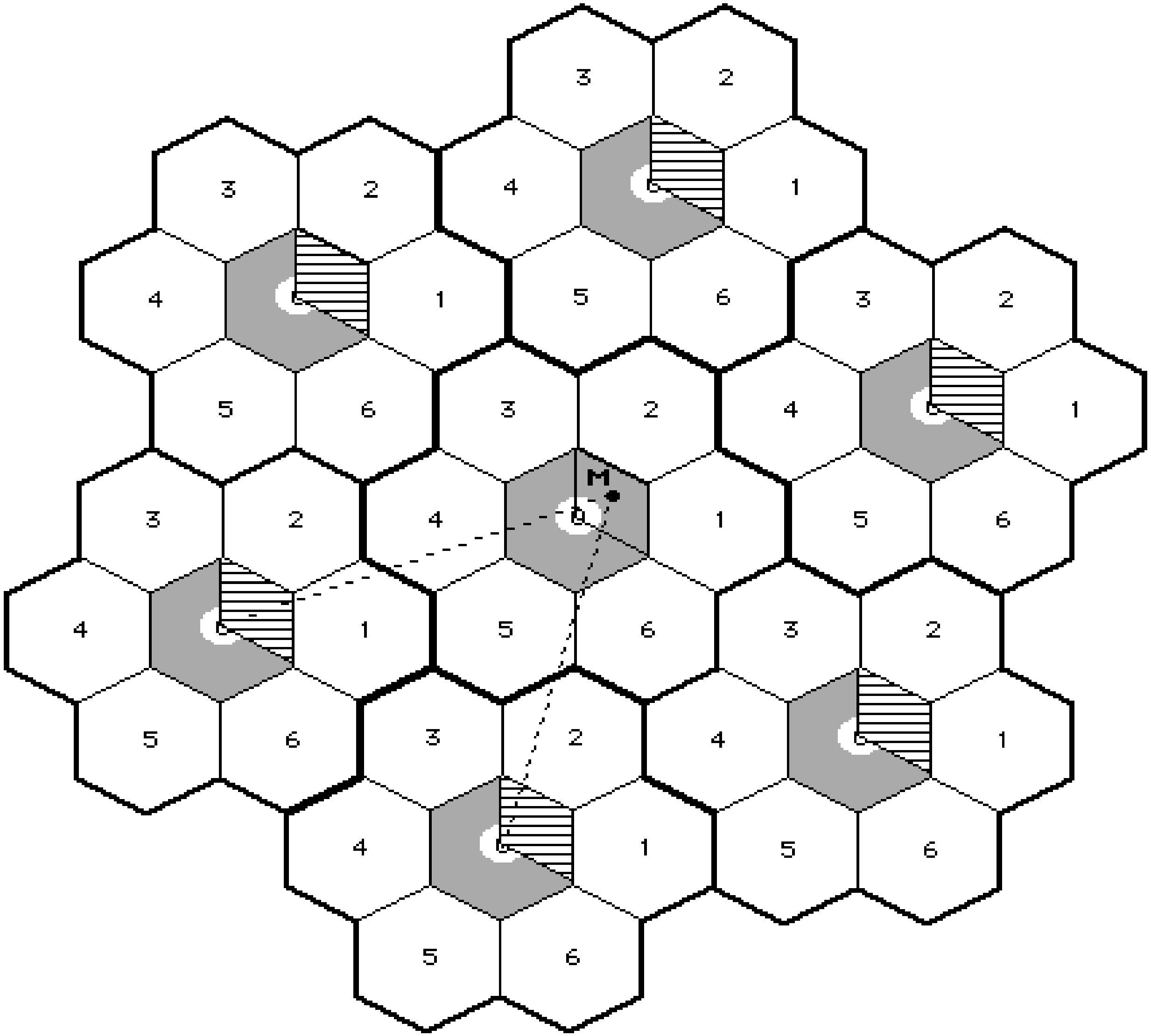



Large cells
for rural
areas
Small cells
for urban
areas

Sectoring:

- The co-channel interference in a cellular system can be decreased by replacing the omni directional antenna at the base station by several directional antennas, each radiating within a specified sector.
- The process of reducing the co-channel interference and thus increasing the capacity of the system by using directional antennas is known as ***Sectoring.***
- In general a cell is partitioned into three 120 degree sectors or six 60 degree sectors.
- When sectoring is employed, the channels used in a particular cell are broken down into sectored groups and are used only in a particular sector.

Sectoring improves S/I






1
2
3

- The Improvement in ***(S/I)*** suggests that the minimum required ***(S/I)*** of 18 dB can be easily achieved with 7-cell reuse by employing 120 degree sector technique when compared to 12-cell reuse
- Therefore Sectoring reduces interference and increases the capacity by an amount of ***(12/7)*** i.e ***1.714***
- In general, the reduction in interference by sectoring enables planners to reduce the cluster size N, and provides an additional freedom in assigning channels

Disadvantages:

- Increased number of ***antennas*** at each base station
- Decrease in ***trunking efficiency*** due to channel sectoring at each base station
- As sectoring reduces the coverage area of a particular group of channels, the number of handoffs increase.

The Microcell Zone Concept

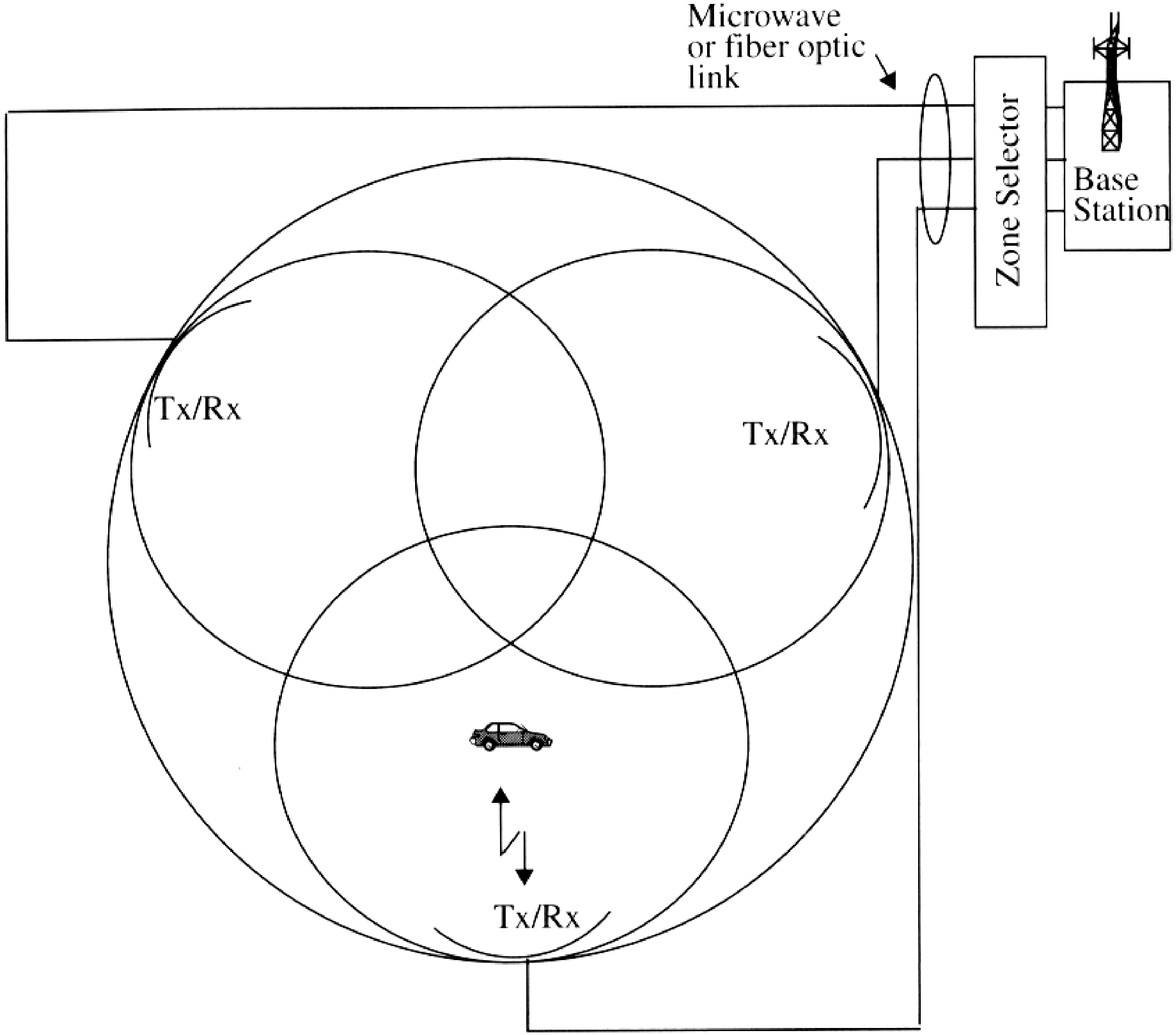


Figure 3.13 The microcell concept [adapted from [Lee91b] © IEEE].

ADVANTAGES OVER SECTORING

- As the mobile travels from one zone to another within the cell, it retains the same channel.Thus, a handoff is not required at the MSC
- A given channel is active only in the particular zone in which the mobile is traveling and hence the base station radiation is localised and interference is reduced
- The co-channel interference is also reduced as a large base station is replaced by several lower powered transmitters on the edges of the cell

Summary

- In this chapter,concepts like handoff,frequency reuse,trunking efficiency have been studied
- The capacity of a cellular system,it's dependence on several factors and the methods to increase the capacity have also been studied
- The main objective of these points is to increase the number of users in the system