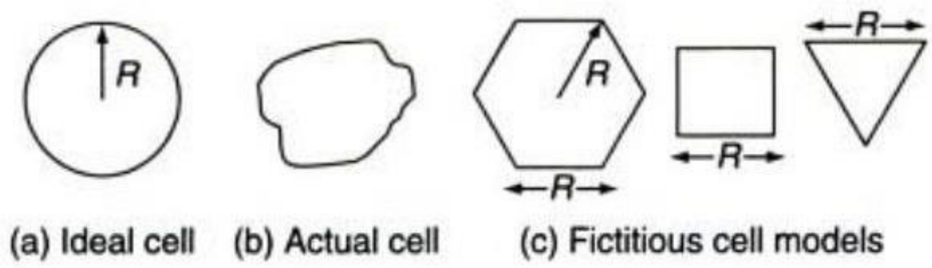
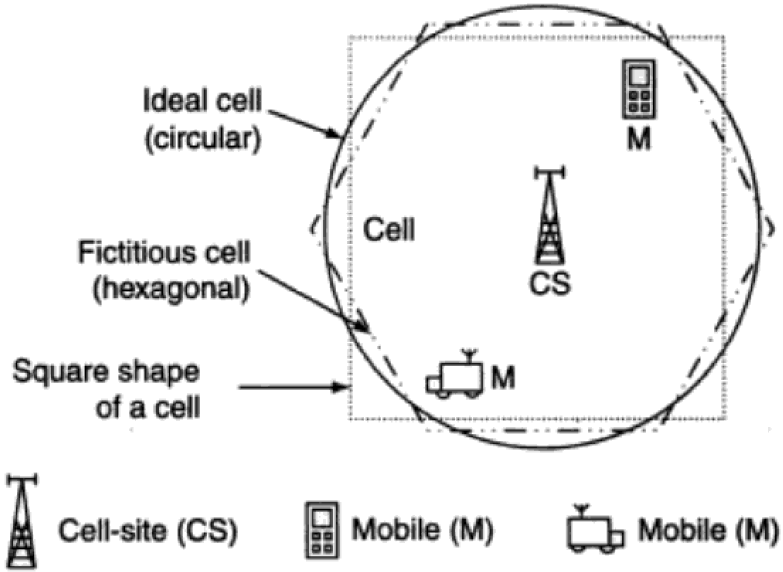
Cellular Systems

“Cell”ular Structure





Significance of cellular topology: Example 1

Consider a single high-power transmitter that can support 40 voice channels over an area of 140 km² with the available spectrum. If this area is equally divided into seven smaller areas (cells), each supported by lower power transmitters so that each cell supports 30% of the channels, then determine

(a) coverage area of each cell

(b) total number of voice channels available in cellular system

Comment on the results obtained.

Solution

Total service area to be covered = 140 km^2 (given)

Total number of channels available = 40 (given)

Number of cells = 7 (given)

(a) *To determine coverage area of each cell*

Step 1. *Coverage area of a cell = Total service area / Number of cells*

Hence, coverage area of a cell = 140 km^2 / 7 = 20 km^2

(b) *To determine total number of voice channels available in the cellular system*

Step 2. *Number of voice channels per cell = 30% of original channels (given)*

Number of voice channels per cell = $0.3 \times 40 = 12$ channels/cell

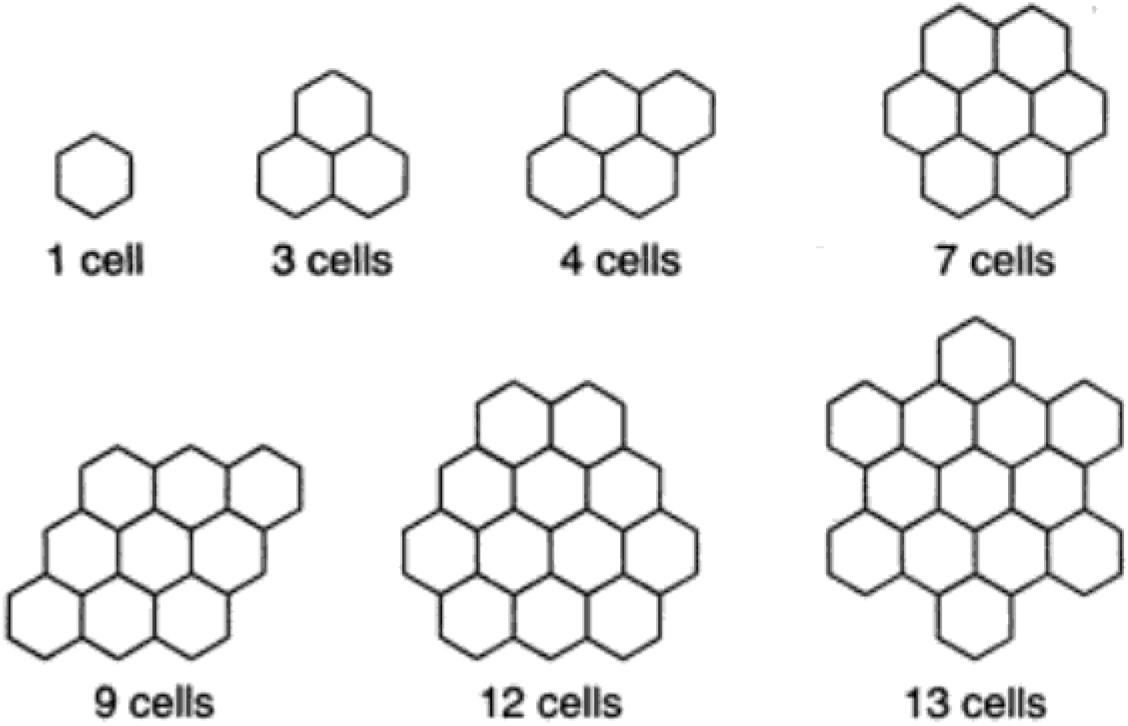
Total number of voice channels available in cellular system is given by the number of channels per cell multiplied by the number of cells in the service area.

Hence, total number of voice channels = $12 \times 7 = 84$ channels

Comment on the results

- Thus, there is a significant increase in the number of available channels (84 channels as calculated above) in a given cellular system as compared to a non-cellular system (40 channels as given).
- This means the system capacity is increased.
- However, care has to be taken in allocation of channels to various cells in such a way so as to prevent interference between the channels of one cell and that of another cell.
- Adjacent cells should not be allocated the same channels, whereas cells located far apart can be allocated the same channels using frequency reuse scheme.

“Cluster”



Frequency Reuse Concept

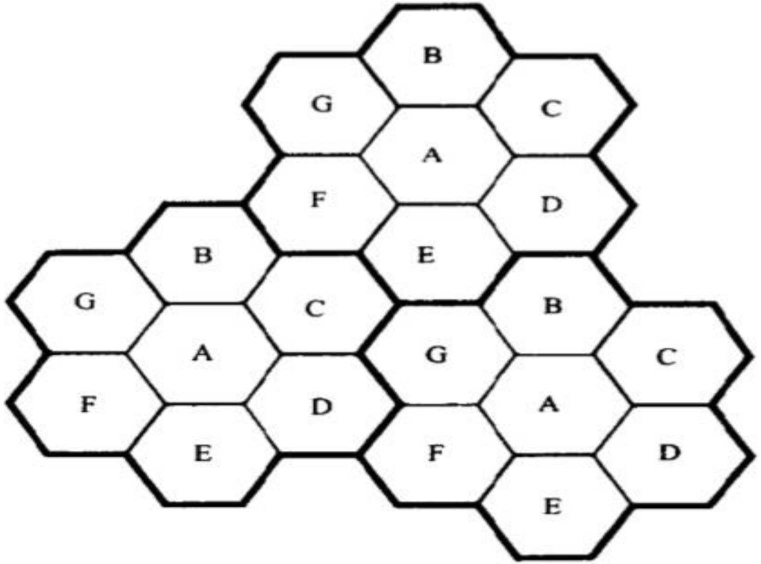


Illustration of the cellular frequency reuse concept. Cells with the same letter use the same set of frequencies. A cell cluster is outlined in bold and replicated over the coverage area. In this example, the cluster size, N, is equal to seven, and the frequency reuse factor is 1/7 since each cell contains one-seventh of the total number of available channels.

Number of Cluster replication: Example 2

Calculate the number of times the cluster of size 4 have to be replicated in order to approximately cover the entire service area of 1765 km² with the adequate number of uniform-sized cells of 7 km² each.

Solution

Size of the cluster, $K = 4$ (given)

Area of a cell, $A_{cell} = 7 \text{ km}^2$ (given)

Step 1. *To determine area of the cluster*

Area of a cluster, $A_{cluster} = K \times A_{cell}$

Therefore, $\boxed{A_{cluster} = 4 \times 7 \text{ km}^2 = 28 \text{ km}^2}$

Step 2. *To determine number of clusters in the service area*

Total service area, $A_{system} = 1765 \text{ km}^2$ (given)

Number of clusters in service area $= A_{system} / A_{cluster}$

Number of clusters in service area $= 1765 \text{ km}^2 / 28 \text{ km}^2 = 63$

Hence, the number of times the cluster of size 4 has to be replicated is 63.

Cell Size and System Capacity: Example 3

(a) *Assume a cellular system of 32 cells with a cell radius of 1.6 km, a total spectrum allocation that supports 336 traffic channels, and a reuse pattern of 7. Calculate the total service area covered with this configuration, the number of channels per cell, and a total system capacity. Assume regular hexagonal cellular topology.*

(b) *Let the cell size be reduced to the extent that the same area as covered in Part (a) with 128 cells. Find the radius of the new cell, and new system capacity.*

Comment on the results obtained.

Solution

(a) *To calculate total service area, number of channels per cell, and system capacity*

Total number of cells in service area = 32 (given)

Radius of a cell, R = 1.6 km (given)

Step 1. *To calculate area of a regular hexagonal cell*

$$\text{Area of a regular hexagonal cell, } A_{cell} = 3\sqrt{3}/2 \times R^2 = 3\sqrt{3}/2 \times (1.6 \text{ km})^2 = 6.65 \text{ km}^2$$

Step 2. *To calculate total service area*

Total service area covered = no. of cells in total area × Area of a cell

Hence, total service area covered $= 32 \times 6.65 = 213 \text{ km}^2$

Step 3. *To calculate number of channels per cell*

Total number of available traffic channels $= 336$ (given)

Frequency reuse pattern (cluster size) $= 7$ (given)

Hence, number of channels per cell $= 336/7 = 48$

Step 4. *To calculate total system capacity*

Total system capacity = number of channels per cell × number of cells

Hence, total system capacity $= 48 \times 32 = 1536$ channels

(b) *Total number of available cells = 128 (given)*

Total service area $= 213\ \text{km}^2$ (as calculated in Step 2)

Step 5. *To determine area of new regular hexagonal cell*

Area of a regular hexagonal cell = total service area / number of cells

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

Step 6. *To find radius of new smaller cell, R*

Area of a regular hexagonal cell $= 3\sqrt{3}/2 \times R^2$

But, $3\sqrt{3}/2 \times R^2 = 1.66\ \text{km}^2$ (as calculated in Step 5)

Or, $R = 0.8$ km

Hence, radius of new smaller cell $R = 0.8$ km

Step 7. *To find new system capacity*

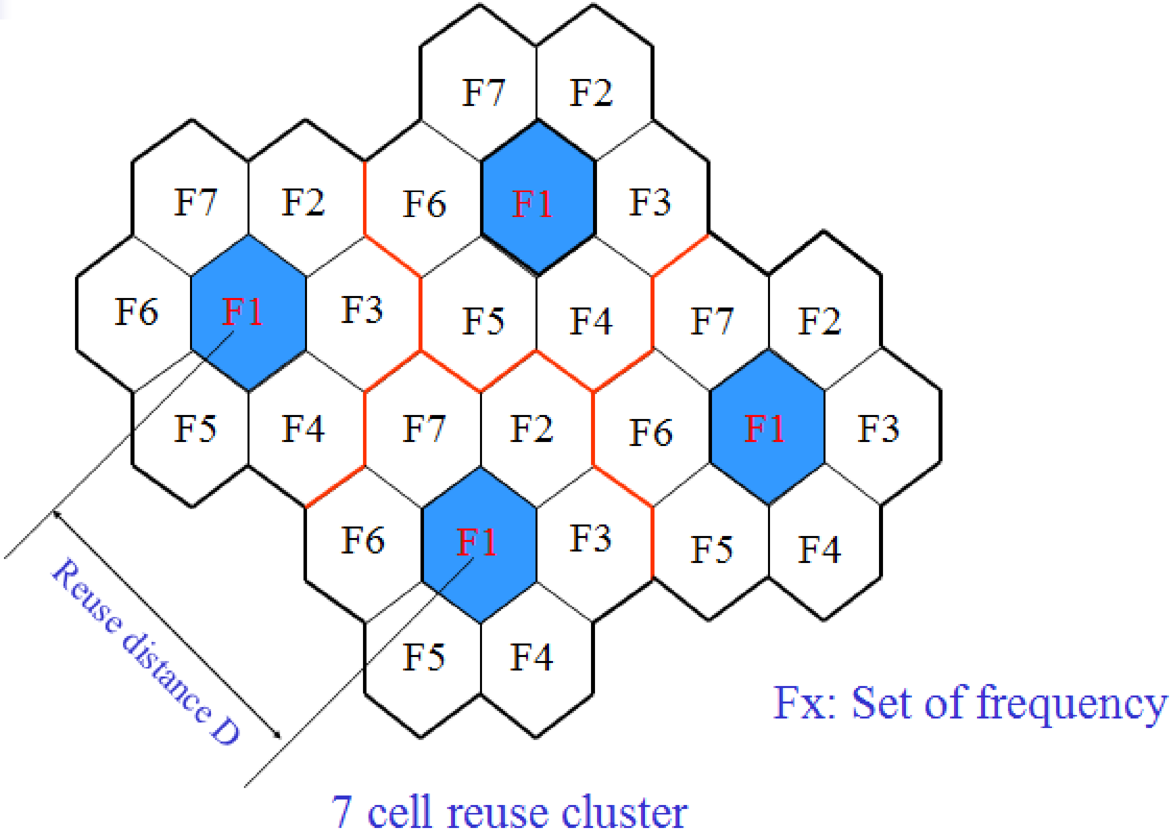
$$\text{New system capacity} = \text{number of channels per cell} \times \text{number of cells}$$

$$\text{New system capacity} = 48 \times 128$$

Hence, new system capacity = 6144 channels

Comment on the results It is observed that as the number of cells are increased from 32 to 128 to cover the same service area (213 km^2), the size of the cell (in terms of radius R) is decreased from 1.6 km to 0.8 km. Keeping the identical number of channels (48) per cell, total system capacity is significantly increased from 1536 channels to 6144 channels. Hence, cell size is one of the major factors to determine the system capacity for a given number of frequency channels allocated to serve the designated area.

Frequency Reuse and Co-channel Distance



Cluster Size and System Capacity

- K = No. of cells per cluster
- N = No. of channels available in a cluster.
- Then number of channels per cell are = $J = N / K$
- ***The cluster is replicating many times to cover the given geographical area. Total number of clusters = M***
- ***Overall System Capacity = C = M N = M J K***

Frequency Reuse and System Capacity

If K $\downarrow$ ***and then J*** $\uparrow$ ***provided N*** = No. of channels available are kept constant. In this case, it is necessary to replicate the smaller cluster more times in order to cover the same geographical service area.

This means the value of ***M*** has to be increased.

Since, $\boldsymbol{J \times K\ (= N)}$ remains constant and ***M*** is increased, it shows that the system capacity ***C*** is increased.

That is, when ***K*** is minimized, ***C*** is maximized.

But minimizing ***K*** will increase **cochannel interference.**

Frequency reuse and spectrum efficiency: Example 4

Consider a single high-power transmitter that can support 100 voice channels covering a given service area. Let the service area be divided into seven smaller areas (cells) as shown in Fig. below, each supported by lower power transmitters. The available spectrum of 100 voice channels is divided into 4 groups of 25 channels each. The cells (1, 7), (2, 4), (3, 5), and 6 are assigned distinct channel groups. Show that the total number of channels that can be supported is enhanced to 175 to cover the same service area. Comment on the results obtained.

Solution

Total number of channels available, $N = 100$ (given)

Case 1. *When a single high-power transmitter is used to cover the given service area*

This implies that it is a non-cellular system.

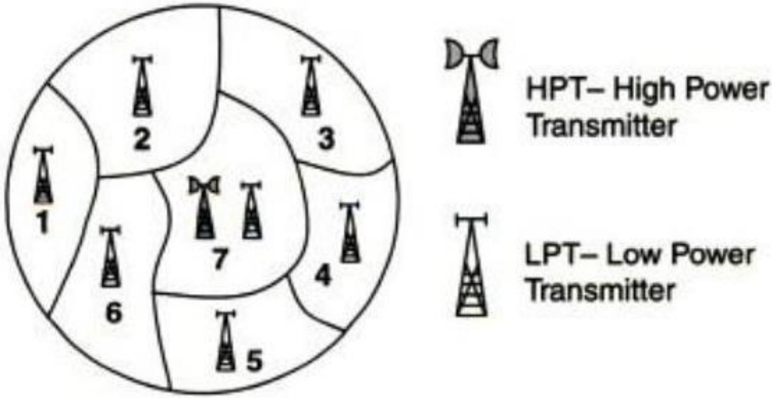
Hence, total number of channels in the system are limited to 100 only.

Case 2. *When the service area is divided into seven cells*

Number of distinct cells $= 7$ (given)

Number of channel groups $= 4$ (given)

Number of channels per channel group $= 25$ (given)



Step 1. *Allocation of channel groups to cells*

Let channel group 1 be allocated to cells 1 as well as 7; channel group 2 be allocated to cells 2 as well as 4; channel group 3 be allocated to cells 3 as well as 5; and channel group 4 be allocated to cell 6 (refer given Fig. 4.7).

Step 2. *Total number of channels available in the specified cellular system*

Total number of channels allocated to all cells is equal to the number of channels per channel group multiplied by the number of distinct cells. That is,

Total number of channels allocated to all cells $= 25 \times 7$

Hence, total number of channels available $= 175$ channels

Comment on the results It is seen from the above example that the total number of channels that can be supported by the given cellular system is increased to 175 from 100 in a non-cellular system to cover the same service area. Hence, it can be concluded that

> 'The theoretical coverage range and capacity of a cellular communication system are unlimited, with optimum use of RF spectrum utilisation.'
>
> 'The frequency reuse can drastically increase the spectrum efficiency, thereby increasing the system capacity.'

Method of Locating Co-Channel Cells

Cells, which use the same set of frequencies or channels, are referred to as cochannel cells.

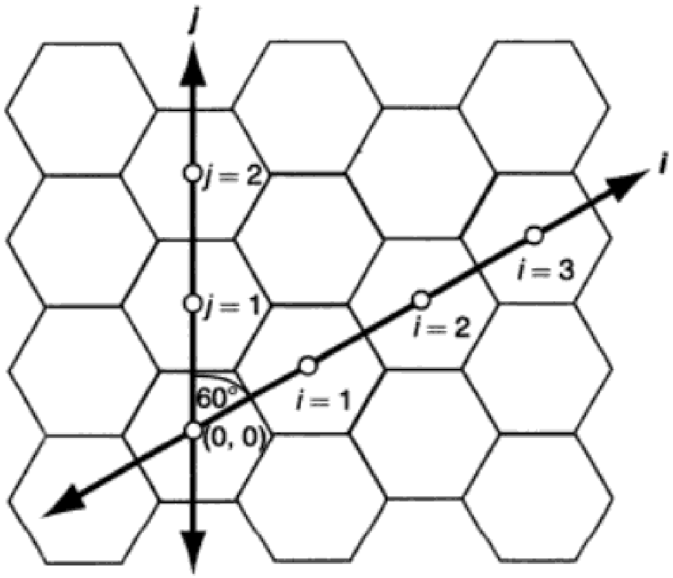
The two shift parameters i and j can be used to determine the location of the nearest cochannel cell in a hexagonal geometry where i and j are separated by 60 degrees. The shift parameters i and j can have any integer value 0, 1, 2, 3, and so on.

To locate the nearest cochannel cells (neighboring cells or cells in the first tier), mark the centre of the cell as (0, 0) for which cochannel cells are required to be located. Define the unit distance as the distance of centres of two adjacent cells. Now follow the two steps mentioned below:

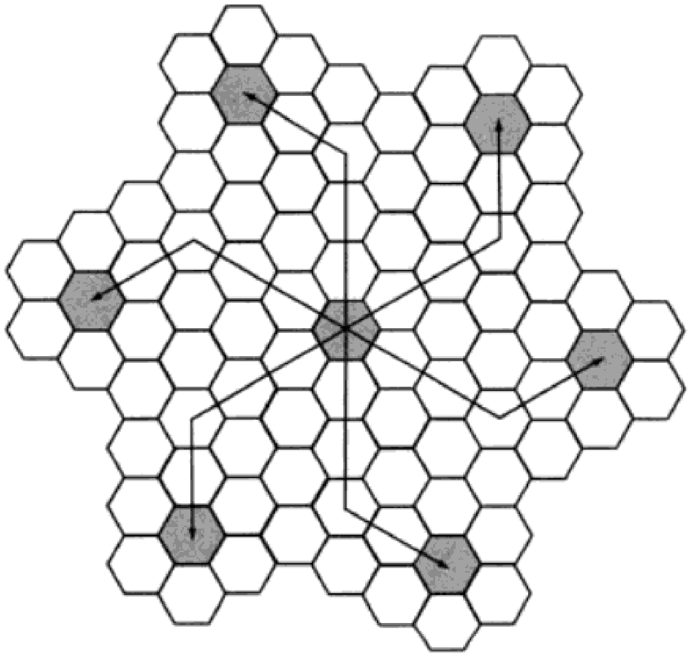
Step 1 Move i number of cells along any chain of hexagons.
Step 2 Turn 60 degrees counterclockwise and move j number of cells.

The method of locating cochannel cells in a cellular system using the preceding procedure is shown in Figure for i = 3 and j = 2, where cochannel cells are shaded. The parameters i and j measure the number of nearest neighboring cells between cochannel cells.

Relationship between cluster size *K* and shift parameters i, j



Shift parameters i and j in a hexagonal geometry



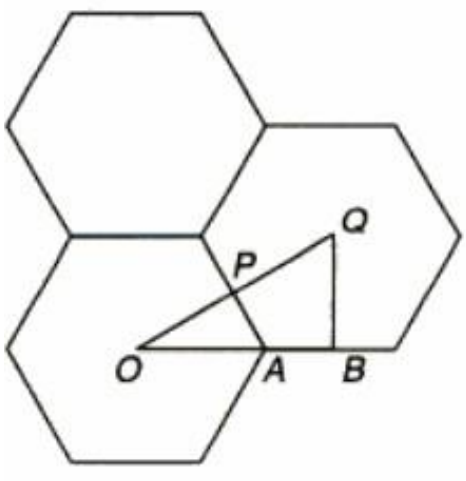
Locating cochannel cells in a cellular system for i = 3, j = 2. Shaded cells are cochannel cells

$$K = i^2 + j^2 + i \times j$$

where K = number of cells per cluster or cluster size
i = number of cells (centre to centre) along any chain of hexagon
j = number of cells (centre to centre) in 60° counterclockwise of i

Relationship between cluster size *K* and shift parameters i, j

Refer Figure below, Let '***R***' be the distance from the centre of a regular hexagon and any of its vertex. A regular hexagon is one whose sides are also equal to '***R***'. Let '***d*** ' be the distance between the centres of two adjacent regular hexagons.



Distance between two adjacent cells

Step 1. *To show that* $d = \sqrt{3}R$

From the geometry of the figure, $OA = R$ and $AB = R/2$.

Then, $OB = OA + AB = R + R/2 = 3\,R/2$.

Then, in right-angled $\Delta\ OAP$,

$OP = OA \sin 60° = (\sqrt{3}/2)R$

Let the distance between the centres of two adjacent hexagonal cells, OQ, be denoted by 'd'. Then,

$OQ = OP + PQ$ (where $OP = PQ$)

Therefore, $d = (\sqrt{3}/2)R + (\sqrt{3}/2)R$

Hence, $d = \sqrt{3}R$ (4.4)

Step 2. *Area of a small hexagon,* $A_{small hexagon}$ *W*

The area of a cell (the small hexagon) with radius R is given as

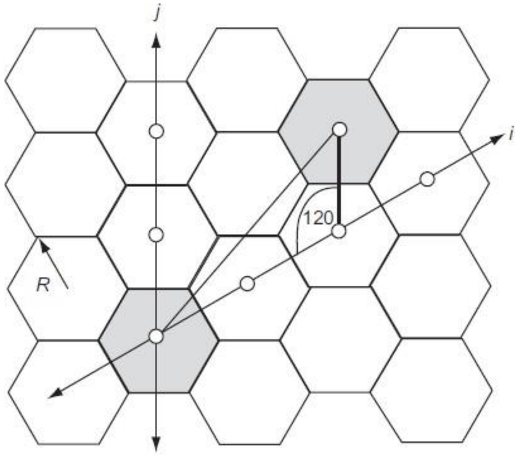
$A_{small\ hexagon} = (3\sqrt{3}/2) \times R^2$ (4.5)

Relationship between cluster size *K* and shift parameters i, j

Step 3. *Procedure of locating cochannel cells*

A cell has exactly six equidistant neighbouring (nearest or first tier) cells, formed by following the procedure of locating cochannel cells, corresponding to six sides of the hexagon. That is,

- firstly moving *i* number of cells along *i* axis,
- secondly, turning 60 degrees counterclockwise, and
- then moving *j* number of cells along *j* axis, as shown in Fig.



Relationship between K and shift parameters i, j

Step 4. *To establish relation between D, d and shift parameters*

Let '*d*' be the distance between two adjacent cells and '*D*' be the distance from the centre of the cell under consideration to the centre of a nearest cochannel cell.

Using cosine formula to Δ *XYZ* in Fig. 4.11, we have

$$XZ^2 = XY^2 + YZ^2 - 2 \times XY \times YZ \cos 120°$$

Or, $D^2 = (i \times d)^2 + (j \times d)^2 - 2 \times (i \times d) \times (j \times d) \cos 120°$

Or, $D^2 = (i \times d)^2 + (j \times d)^2 - 2 \times (i \times d) \times (j \times d) \times (-½)$

Or, $D^2 = (i \times d)^2 + (j \times d)^2 + (i \times d) \times (j \times \mathrm{d})$

Or, $D^2 = d^2\,(i^2 + j^2 + i \times j)$ (4.6)

Step 5. *To establish relation between D, R and shift parameters*

Using Eqs. (4.4) and (4.6),

$$D^2 = 3 \times R^2 \times (i^2 + j^2 + i \times j) \qquad (4.7)$$

Relationship between cluster size *K* and shift parameters i, j

Step 6. *Area of a large hexagon, $A_{large\ hexagon}$*

By joining the centres of the six nearest neighbouring cochannel cells, a large hexagon is formed with radius equal to D, which is also the cochannel cell separation. Refer Fig. 4.12. The area of the large hexagon with radius D can be given as

$$A_{large\ hexagon} = (3\sqrt{3} / 2) \times D^2 \tag{4.8}$$

Using Eq. (4.7),

$$A_{large\ hexagon} = (3\sqrt{3} / 2) \times 3 \times R^2 \times (i^2 + j^2 + i \times j) \tag{4.9}$$

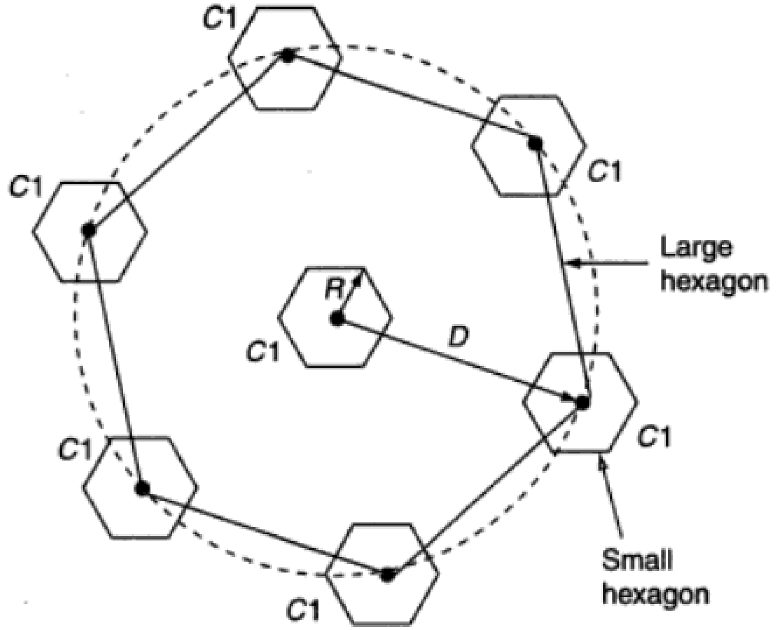
Step 7. *To determine number of cells in the large hexagon, L*

Number of cells in large hexagon,

$$L = A_{large\ hexagon} \quad A_{small\ hexagon} \tag{4.10}$$

Using Eqs. (4.9) and (4.5) in Eq. (4.10), we get

$$L = 3 \times (i^2 + j^2 + i \times j) \tag{4.11}$$



Relationship between cluster size *K* and shift parameters i, j

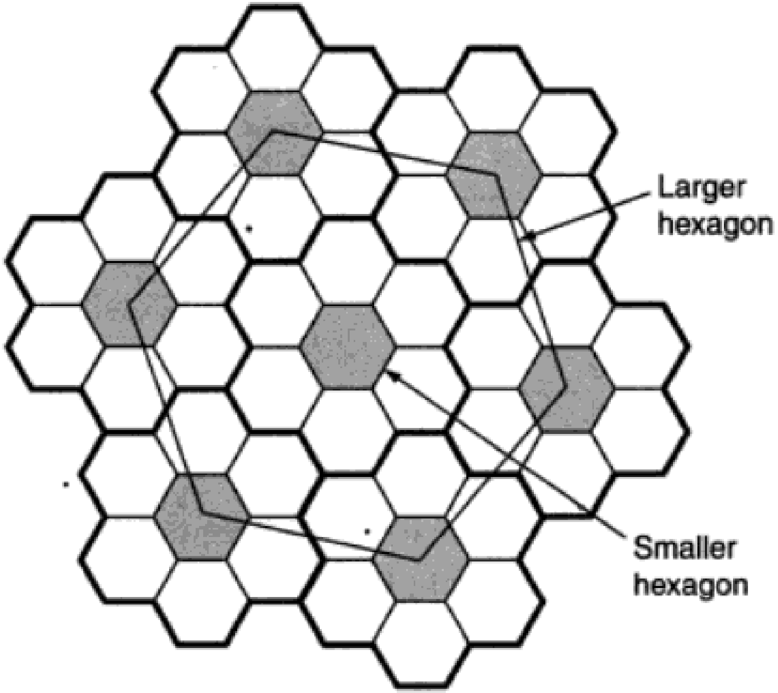
Step 8. *Relationship between L and cluster size K*

On the other hand, from the geometry as given in Fig. 4.13 for cluster size 7, as an example, it can be easily seen that the larger hexagon formed by joining the centers of cochannel cells in the first tier encloses 7 cells of the middle cluster plus 1/3rd of the number of 7 cells of all surrounding six neighbouring clusters. In general, it can be computed that the larger hexagon encloses the centre cluster of K cells plus 1/3rd the number of the cells associated with six other peripheral clusters in the first tier.

Hence, the total number of cells enclosed by the larger hexagon is

$$L = K + 6 \times \;(1\;\;3) \times K$$

Or, $$L = 3 \times K \qquad (4.12)$$



Step 9. *To establish relation between K and shift parameters*

From Eq. (4.11) and (4.12), we get

$$3 \times K = 3 \times (i^2 + j^2 + i \times j)$$

Or, $$K = i^2 + j^2 + i \times j \qquad (4.13)$$

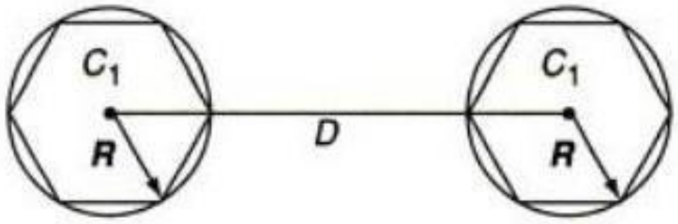
Thus, the cluster size K (i.e., the number of cells per cluster) can be determined from the shift parameters i, j using the above mathematical expression, where i and j can have any integer values such as 0, 1, 2, 3, . so on.

Frequency Reuse Distance = *D*

It is desirable to find the minimum frequency reuse distance ***D*** in order to reduce this cochannel interference.

It depend on many factors such as:

- the number of cochannel cells in the vicinity of the centre cell,
- the type of geographic terrain contour,
- the antenna height, and
- the transmitted power at each cell-site.



Cochannel interference is a function of a parameter known as **frequency reuse ratio, q**,

$$q = D / R$$

where D is the distance between two nearest cochannel cells

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Frequency Reuse Distance = *D*: Example 5

Determine the distance from the nearest cochannel cell for a cell having a radius of 0.64 km and a cochannel reuse factor of 12.

Solution

The radius of a cell, $R = 0.64$ km (given)

The cochannel reuse factor, $q = 12$ (given)

To determine the distance from the nearest cochannel cell, D

We know that $q = D \quad R,$

Or, $D = q \times R$

Therefore, $D = 12 \times 0.64 \text{ km} = 7.68 \text{ km}$

Hence, the distance from the nearest cochannel cell $D = 7.68$ km

Thus, the important parameters of the network designed on cellular approach are

- Reuse pattern, K
- Reuse distance, D
- Frequency reuse factor, q

Cellular System Capacity: Example 6

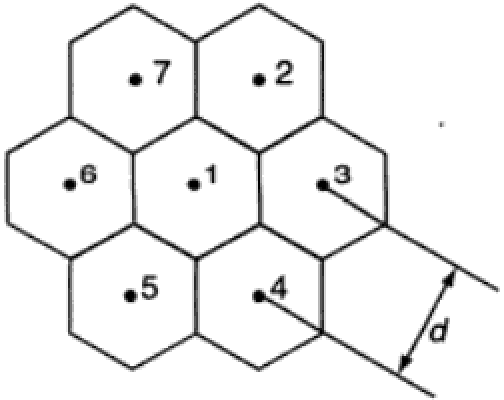
Consider that a geographical service area of a cellular system is 4200 km^2. A total of 1001 radio channels are available for handling traffic. Suppose the area of a cell is 12 km^2.

(a) How many times would the cluster of size 7 have to be replicated in order to cover the entire service area? Calculate the number of channels per cell and the system capacity.

(b) If the cluster size is decreased from 7 to 4, then does it result into increase in system capacity? Comment on the results obtained.

Relationship between frequency reuse ratio q and cluster size K

$q = (3K)^{0.5}$

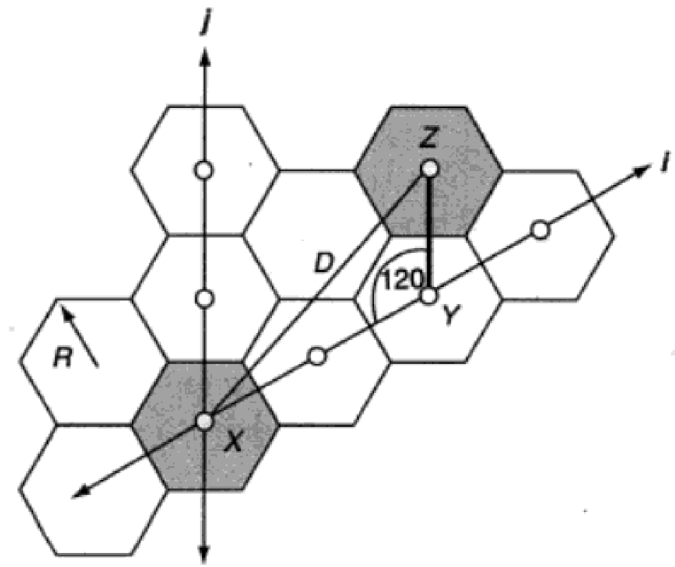


The geometry of an array of regular hexagonal cells is depicted in Fig. below, where ***R*** is the radius of the hexagonal cell (from its centre to one of its vertex). A hexagon has exactly six equidistant neighboring hexagons corresponding to six sides of the hexagon.

Step 1. Relation between ***d*** and ***R*** Let the distance between the centres of two adjacent hexagonal cells be denoted by ***d***. Then, using the trigonometry, it can be seen that $d = R\sqrt{3}$

Relationship between frequency reuse ratio *q* and cluster size *K*

$q = (3K)^{0.5}$



Step 2. Procedure of locating a cochannel cell:

The procedure is as follows:

- Firstly, move i number of cells along the i axis from the centre of the hexagonal cell under consideration (say point X to point Y) along one side of hexagon.
- Secondly, turn 60 degrees counterclockwise.
- Then move j number of cells along j axis (point Y to point Z) to locate the centre of the nearest cochannel cell.

Let D be the distance from the centre of the cell under consideration to the centre of a nearest cochannel cell (that is, XZ).

Relationship between frequency reuse ratio q and cluster size K

$q = (3K)^{0.5}$

Step 3*. To derive the relation between *D*. *d* and *shift parameters

Applying cosine formula to Δ XYZ , we have,

$$D^2 = (i \times d)^2 + (j \times d)^2 - 2 \times (i \times d) \times (j \times d) \cos 120°$$

Or, $D^2 = (i \times d)^2 + (j \times d)^2 - 2 \times (i \times d) \times (j \times d) \times (-½)$

Or, $D^2 = (i \times d)^2 + (j \times d)^2 + (i \times d) \times (j \times d)$

Or, $D^2 = d^2 (i^2 + j^2 + i \times j)$

Using Eq. (4.16),

$$D^2 = 3 \times R^2 \times (i^2 + j^2 + i \times j)$$

Step 4. *To establish relationship between K and shift parameters*

$$K = i^2 + j^2 + i \times j \quad \text{(given)}$$

Substituting it in Eq. (4.18), we get

$$D^2 = 3 \times R^2 \times K$$

Or, $D^2 / R^2 = 3 \times K$

Or, $D/R = \sqrt{3K}$

By definition $q = D/R$; therefore, we get

$$q = \sqrt{3K}$$

Channel Assignment Strategies

Channel assignment strategies can be classified as either **fixed** or **dynamic**.

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

Several variations of the fixed assignment strategy exist.

In one approach, called the borrowing strategy, a cell is allowed **to borrow channels from a neighboring cell** if all of its own channels are already occupied.

The mobile switching center (MSC) supervises such borrowing procedures and ensures that the borrowing of a channel does not disrupt or interfere with any of the calls in progress in the donor cell.

Channel Assignment Strategies

In a **dynamic channel assignment strategy**, voice channels are **not allocated to different cells permanently**.

Instead, each time a **call request is made**, the serving base station requests a channel from the MSC.

The switch then allocates a channel to the requested cell following an algorithm that takes into account

- the likelihood of future blocking within the cell,
- the frequency of use of the candidate channel,
- the reuse distance of the channel,
- other cost functions.

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.**

Channel Assignment Strategies

Advantages of Dynamic Strategy

Dynamic channel assignment reduce the likelihood of blocking, which increases the trunking capacity of the system, since all the available channels in a market are accessible to all of the cells.

Dynamic channel assignment strategies require the MSC to collect real-time data on channel occupancy, traffic distribution, and *radio signal strength indications* (RSSI) of all channels on a continuous basis.

This increases the storage and computational load on the system but provides the advantage of increased **channel utilization** and **decreased probability of a blocked call**.

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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 inadvertently 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. Interference is more severe in urban areas, due to the greater RF noise floor and the large number of base stations and mobiles. Interference has been recognized as a major bottleneck in increasing capacity and is often responsible for dropped calls.

Types of Interference

The two major types of system-generated cellular interference are *co-channel interference* and *adjacent channel interference*. Even though interfering signals are often generated within the cellular system, they are difficult to control in practice (due to random propagation effects). Even more difficult to control is interference due to out-of-band users, which arises without warning due to front end overload of subscriber equipment or intermittent intermodulation products. In practice, the transmitters from competing cellular carriers are often a significant source of out-of-band interference, since competitors often locate their base stations in close proximity to one another in order to provide comparable coverage to customers.

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*, and the interference between signals from these cells is called *co-channel interference*.

When the size of each cell is approximately the same, and the base stations transmit the same power, 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). By increasing the ratio of D/R, the spatial separation between co-channel cells relative to the coverage distance of a cell is increased. Thus interference is reduced from improved isolation of RF energy from the co-channel cell. The parameter Q, called the *co-channel reuse ratio*, is related to the cluster size. For a hexagonal geometry

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