The Cellular Concept

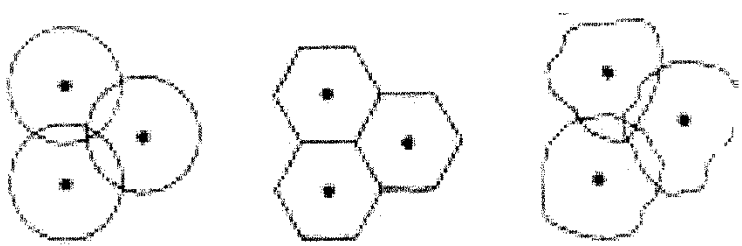
Introduction to Cellular Telephone Systems

<u>A cellular telephone system:</u>

1. Provides a wireless connection to the public switched telephone network (PSTN) for any user location within the radio range of the system.
2. Accommodates a large number of users over a large geographic area, within a limited frequency spectrum.
3. Provides high quality service that is often comparable to that of the landline telephone systems.

High capacity is achieved by limiting the coverage of each base station transmitter to a small geographic area called a *cell so* that the same radio channels may be reused by another base station located some distance away. A sophisticated switching technique called *handoff* enables a call to proceed uninterrupted when the user moves from one cell to another.

To design a cellular system a regular cell shape is needed for systematic system design and adaptation for future growth. Possible cell shapes are the circle where adjacent circles cannot be overlaid upon a map without leaving gaps or creating overlapping regions and the hexagon which closely approximates a circular radiation pattern which would occur for an omni-directional base station antenna and free space propagation. Real cell shapes are governed by propagation in the built environment, as illustrated in figure 1.



Ideal cell Fictitious cell Real cell

Figure 1 Possible cell shapes

Different cells are classified according to size as in figure 2: macrocells which can extend to several km's, microcells which extend up to a km, picocells and femtocells which are usually indoor cells.

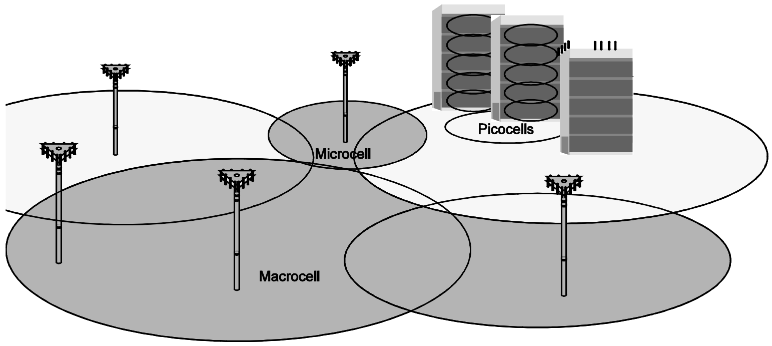


Figure 2 Illustration of cell sizes

The basic elements of a cellular network consist of *mobile stations*, *base stations* and a *mobile switching center (MSC)* as in figure 3 .

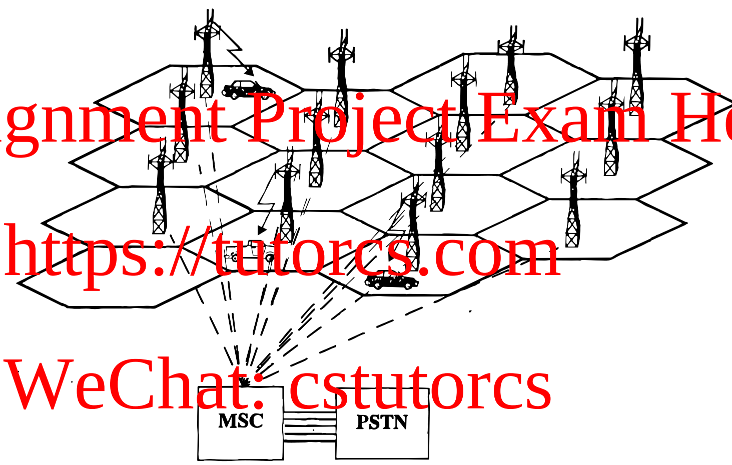


Figure 3 Elements of cellular network

Each mobile station has a transceiver and communicates with one of the base stations and may be handed-off to any number of base stations throughout the duration of a call. The base stations consist of several transmitters and receivers which simultaneously handle full duplex communications and generally have towers which support several transmitting and receiving antennas. The base station serves as a bridge between all mobile users in the cell and connects the simultaneous mobile calls via telephone lines or microwave links to the MSC. The MSC co-ordinates the activities of all the base stations and connects the entire cellular system to the PSTN. A typical MSC handles 100,000 cellular subscribers and 5,000 simultaneous conversations at a time, and accommodates all billing and system maintenance functions, as well.

When a mobile unit is engaged in transmitting or receiving voice signals, data, or fax information, the unit is *active*. A mobile unit, which is prepared to receive or place a call, but is not actively transmitting or receiving, is *idle*, as shown in Figure 4.

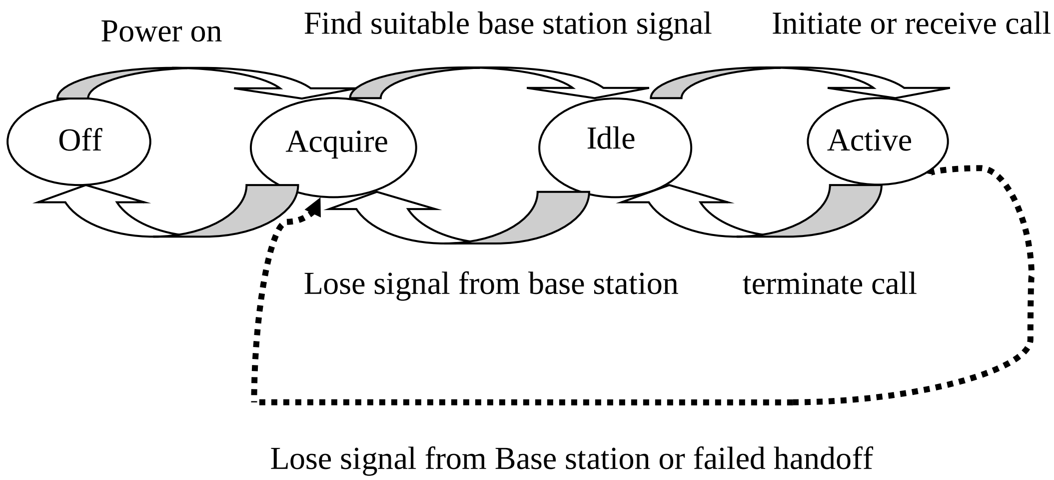


Figure 4 Typical state diagram for cellular subscriber units

The user communicates with the base station in each cell through a set of logical *channels*, which are used for paging, access, and traffic. A channel is allocated to a subscriber when it is active in a cell and is released when the portable unit terminates the call or hands-off to another cell.

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

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

The two channels responsible for initiating mobile calls are *the* ***forward control channels*** **(FCC)** and ***reverse control channels (RCC).*** Control channels transmit and receive data messages that carry call initiation and service requests, and are monitored by mobiles when they do not have a call in progress. Forward control channels also serve as beacons, which continually broadcast all of the traffic requests for all mobiles in the system.

Cellular systems rely on the frequency reuse concept, which requires that the forward control channels (FCCs) in neighbouring cells be different. By defining a relatively small number of FCCs as part of the common air interface, cellular phones can be manufactured by many companies, which can rapidly scan all of the possible FCCs to determine the strongest channel at any time. Once finding the strongest signal the cellular phone receiver stays "camped" to the particular FCC. By broadcasting the same set-up data on all FCCs at the same time, the MSC is able to signal all subscribers within the cellular system and can be certain that any mobile will be signalled when it receives a call via the PSTN.

Cellular system design fundamentals

The design objective of early mobile radio systems was to achieve a large coverage area by using a single, high-powered transmitter with an antenna mounted on a tall tower. This meant that it was impossible to reuse those same frequencies throughout the system due to interference. 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. To achieve high capacity with limited radio spectrum, while at the same time covering very large areas, the cellular concept was a major breakthrough. It offered very high capacity in a limited spectrum allocation without any major technological changes.

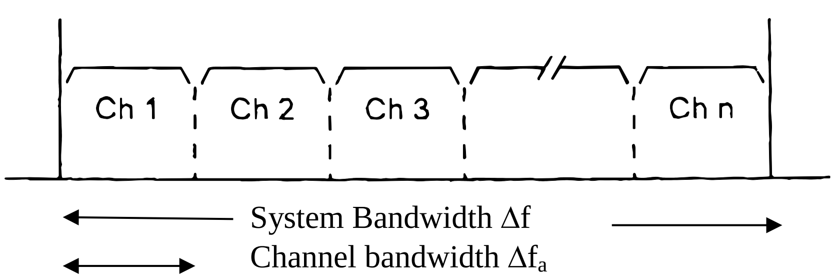
Each base station is allocated a portion of the total number of channels available to the entire system. Neighbouring base stations are assigned different groups of channels so that the interference between base stations (and the mobile users under their control) is minimised. By systematically spacing base stations and their channel groups, the available channels are distributed throughout the geographic region and may be reused as many times as necessary, so long as the interference between co-channel stations is kept below acceptable levels. The design process of selecting and allocating channel groups for all of the cellular base stations within a system is *called frequency reuse or frequency planning*

Frequency Reuse

Each base station is allocated a finite number, k, of the overall number of frequency channels S available in the system (see figure 5). This partitions the spectrum into clusters of size N, typically equal to 4, 7, or 12 where N= S / k. If a cluster is replicated M times within the system (see figure 6), the total number of duplex channels, C, can be used as a measure of capacity and is given by

$$C = M\,k\,N = M\,S$$

Thus the capacity of a cellular system is directly proportional to the number of times a cluster is replicated in a fixed service area.



Overall number of channels, S=Δf/Δfa , Number of channels per cell, k = S/N

Figure 5 Frequency division in cellular system to enhance capacity

Figure 6 shows a typical cluster structure (outlined in bold) where cells with the same letter use the same set of frequencies. 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. 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. A large cluster size indicates that the distance between co-channel cells, is large. Conversely, a small cluster size indicates that co-channel cells are located much closer together.

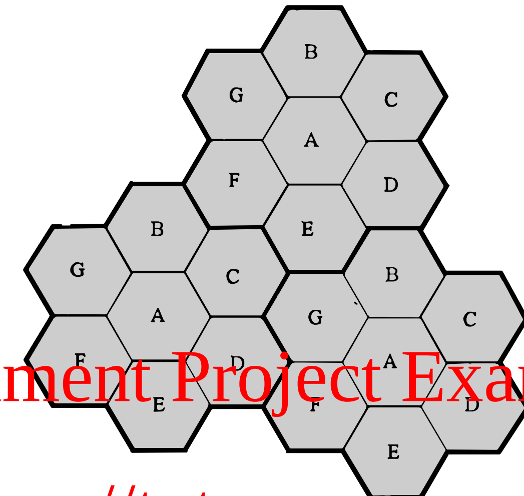


Figure 6 Example of a cell cluster

The value of 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. The concept of frequency reuse differs for different networks. For CDMA (3G systems) all stations use the same frequency band while in GSM they use different frequencies as illustrated in Figure 7.

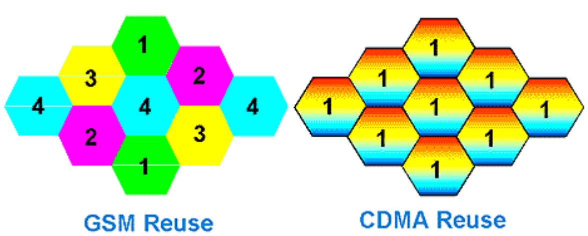


Figure 7 Frequency reuse in GSM and CDMA

Due to fact that the hexagonal geometry of a cell has exactly six equidistant neighbours and that the lines joining the centres of any cell and each of its neighbours are separated by multiples of 60 degrees, there are only certain cluster sizes and cell layouts, which are possible. The number of cells per cluster N, can only have values which satisfy the following equation:

$$N = i^2 + ij + j^2 \qquad (1)$$

where i and j are non-negative integers.

To find the nearest co-channel neighbours of a particular cell, one must do the following: (1) move i cells along any chain of hexagons and then; (2) turn 60^o counter clockwise and move j cells as illustrated in figure 8 for $i = 3$ and $j = 2$ (example, N = 19).

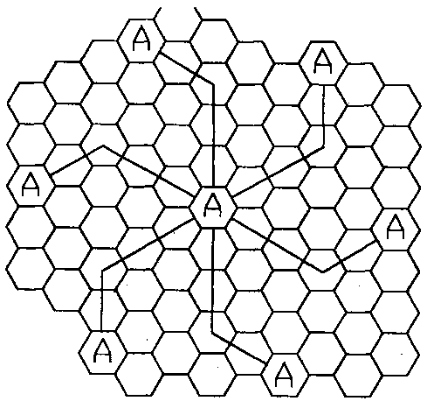


Figure 8: Finding neighbouring cells with the same frequency

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. If 1 MHz of the allocated spectrum is dedicated to control channels, determine an equitable distribution of control channels and voice channels in each cell for each of these three systems.

(a) 4-cell reuse, (b) 7-cell reuse, (c) 12-cell reuse.

Solution

Given total bandwidth = 33 MHz
Channel bandwidth = 25 kHz x 2 simplex channels = 50 kHz/duplex channel
Total available channels = 33000/50 = 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.

A 1 MHz spectrum for control channels implies that there are 1000/50 = 20 control channels out of the 660 channels. To evenly distribute the control and voice channels, simply allocate the same number of channels in each cell wherever possible. Here, the 660 channels must be evenly distributed to each cell within the cluster. In practice, only the 640 voice channels would be allocated, since the control channels are allocated separately as 1 per cell. Table 1 gives a possible distribution.

N	Control channel	**Voice channel**	In practice
4	Each cell with 5	**160**	1 Control and 160 voice per cell
7	4 with 3 2 with 3 1with 2	**92** **90** **92**	1 control per cell 4 with 91 voice 3 with 92 voice
12	8 with 2 4 with 1	**53** **54**	1 control per cell 8 with 53 voice 4 with 54 voice

Table 1 Distribution of channels for different cluster sizes

Channel Assignment Strategies

A variety of channel assignment strategies have been developed to increase capacity and minimising interference. Channel assignment strategies can be classified as either *fixed or dynamic*.

In a **fixed channel assignment** strategy, each cell is allocated a predetermined set of voice channels. Any call attempt within the cell can only be served by the unused channels in that particular cell. If all the channels in that cell are occupied, the call is blocked and the subscriber does not receive service. Several variations of the fixed assignment strategy exist such as the borrowing strategy, where a cell is allowed to borrow channels from a neighbouring cell if all of its own channels are already occupied. The mobile switching centre (MSC) supervises the procedure to ensure that the borrowing of a channel does not disrupt or interfere with any of the calls in progress in the donor cell.

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, and other cost functions.

Accordingly, the MSC only allocates a given frequency if that frequency is not presently in use in the cell or any other cell which falls within the minimum restricted distance of frequency reuse to avoid co-channel interference. Dynamic channel assignment reduces the likelihood of blocking, which increases the capacity of the system, since all the available channels in a market are accessible to all of the cells. However, it requires the MSC to collect real-time data on *channel occupancy, traffic distribution, and radio signal strength indication* (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 utilisation and decreased probability of a blocked call.

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 involves: (1) identifying a new base station, and (2) allocation of voice and control signals to channels associated with the new base station.

Handoffs must be performed *successfully* and as *infrequently* as possible, and be *imperceptible* to the users. In order to meet these requirements, system designers must specify an optimum signal level for acceptable voice quality at which to initiate a handoff. For example the minimum usable power level, P_r, at the base station receiver is normally taken as between -90 dBm and -100 dBm. Usually a slightly stronger signal level is used as a threshold at which a handoff is made. This margin, given by $\Delta = P_{r\ \mathrm{handoff}} - P_{r\ \mathrm{min.\ usable}}$, cannot be too large or too small.

If Δ is too large, unnecessary handoffs which burden the MSC may occur, and if Δ is too small, there may be insufficient time to complete a handoff before a call is lost due to weak signal conditions. Therefore Δ is chosen carefully to meet these conflicting requirements. Figure 9 shows examples of proper and improper handoff.

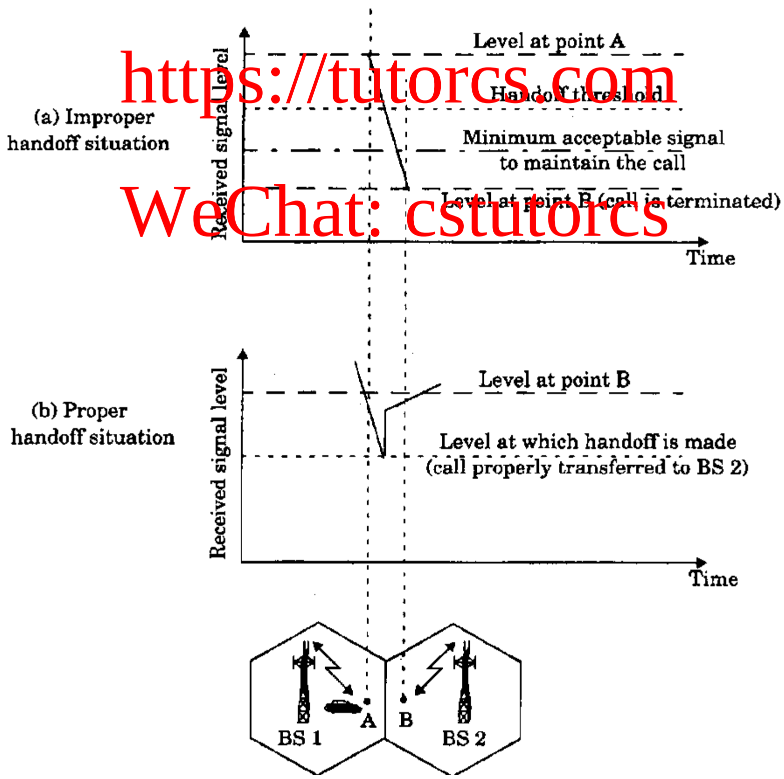


Figure 9 Examples of proper and improper handoff

Improper handoff results in dropped call event which can happen when there is an excessive delay by the MSC in assigning a handoff, or when the threshold 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 the unavailability of any of the nearby base stations.

In first generation analogue cellular systems, signal strength measurements are made by the base stations of all of its reverse voice channels to determine the relative location of each mobile user with respect to the base station tower. In addition to measuring the Received Signal Strength Indicator (RSSI) of calls in progress within the cell, a spare receiver in each base station, called the locator receiver, is used to determine signal strengths of mobile users which are in neighbouring cells. The locator receiver is used to monitor the signal strength of users in neighbouring cells which appear to be in need of handoff and reports to the MSC. Based on the locator receiver signal strength, and information from each base station, the MSC decides if a handoff is necessary or not.

In second generation systems that use digital TDMA technology, handoff decisions are mobile assisted. In 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 neighbouring cell begins to exceed the power received from the current base station by a certain level or for a certain period of time. This method enables the call to be handed over between base stations at a much faster rate than in first generation analogue systems since the handoff measurements are made by each mobile, and the MSC no longer constantly monitors signal strengths. MAHO is particularly suited for microcellular environments where handoffs are more frequent.

Prioritizing Handoffs

One method for giving priority to handoffs is called the guard channel concept, whereby a fraction of the total available channels in a cell is reserved exclusively for handoff requests. This reduces the total carried traffic, as fewer channels are allocated to originating calls. The number of guard channels, can be reduced with dynamic channel assignment strategies, which allocates channels on demand.

Practical Handoff Considerations

In practical cellular systems, several problems arise when attempting to design for a wide range of mobile velocities. Another practical limitation is the ability to obtain new cell sites. By using different antenna heights (often on the same building or tower) and different power levels, it is possible to provide "large" and "small" cells which are collocated. This technique is called the umbrella cell approach and is used to provide large area coverage to high-speed users while providing small area coverage to users travelling at low speeds as illustrated in figure 10.

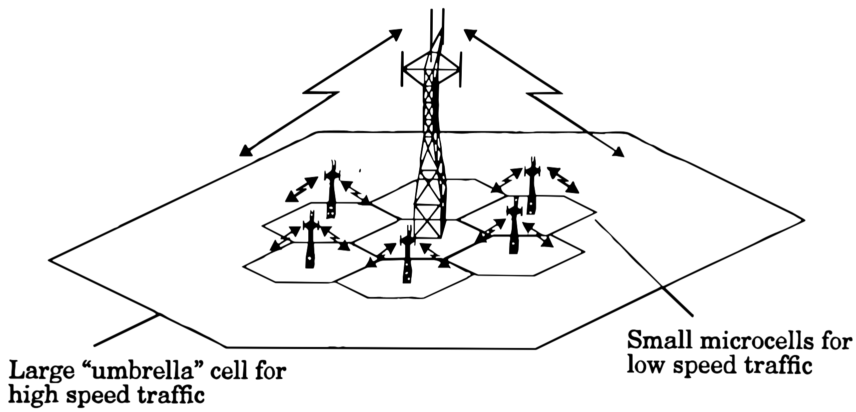


Figure 10. The umbrella approach to reduce handoff

The umbrella cell approach ensures that the number of handoffs is minimised for high-speed users and provides additional microcell channels for pedestrian users. The speed of each user may be estimated by the base station or MSC by evaluating how rapidly the short-term average signal strength on the Reverse Voice Channel changes over time, or more sophisticated algorithms may be used to evaluate and partition users. If a high speed user in the large umbrella cell is approaching the base station, and its velocity is rapidly decreasing, the base station may decide to hand the user into the collocated microcell, without MSC intervention.

Another practical handoff problem in microcell systems is known as cell dragging which results from pedestrian users that provide a very strong signal to the base station. Such a situation occurs in an urban environment when there is a line-of-sight (LOS) radio path between the subscriber and the base station. As the user travels away from the base station at a very slow speed, the average signal strength does not decay rapidly. Even when the user has travelled well beyond the designed range of the cell, the received signal at the base station may be above the handoff threshold, thus a handoff may not be made. This creates a potential interference and traffic management problem, since the user has meanwhile travelled deep within a neighbouring cell. To solve the cell dragging problem, handoff thresholds and radio coverage parameters must be adjusted carefully.

Hard and soft Handoff

Code division multiple access (CDMA) spread spectrum cellular systems such as IS-95 and 3G provide a unique handoff capability that cannot be provided with other wireless systems. Unlike systems that assign different radio channels during a handoff (called a hard handoff), spread spectrum mobiles share the same channel in every cell. Thus, the term handoff does not mean a physical change in the assigned channel, but rather that a different base station handles the radio communication task. By simultaneously evaluating the received signals from a single subscriber at several neighbouring base stations, the MSC may decide which version of the user's signal is best at any moment in time. This allows the MSC to make a soft decision as to which version of the user's signal to pass along to the PSTN. The ability to select between the instantaneous received signals from a variety of base stations is called soft handoff.

Interference and System Capacity

The two major types of cellular interference **are *co-channel interference and adjacent channel interference which*** 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.

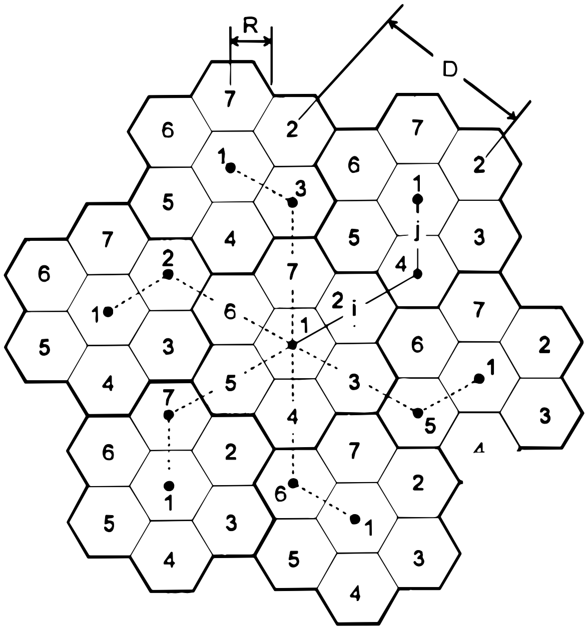
Co-channel Interference and System Capacity:

Frequency reuse implies that several cells 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*. Unlike thermal noise, which can be overcome by increasing the signal-to-noise ratio (SNR), co-channel interference cannot be combated by increasing the power of a transmitter. An increase in transmitted power increases the interference to neighbouring co-channel cells, which must be physically separated by a minimum distance to provide sufficient isolation (reduced interference) due to propagation.

In a cellular system, when the size of each cell is approximately the same, co-channel interference is independent of the transmitted power and becomes a function of the radius of the cell (R), and the distance to the centre of the nearest co-channel cell (D) as shown in figure 11. By increasing the ratio of D/R, the spatial separation between co-channel cells relative to the coverage distance is increased, thus reducing interference. The parameter Q, called the co-channel reuse ratio, is related to the cluster size. For a hexagonal geometry

$$Q = \frac{D}{R} = \sqrt{3N} \tag{2}$$

A small value of Q provides larger capacity since the cluster size N is small, whereas a large value of Q improves the transmission quality, due to a smaller level of co-channel interference. In actual cellular design, a trade-off is made between these two objectives. Table 2 gives values for Q for different cell sizes.



Cell Cluster with K= 7

Figure 11 Illustration of co-channel interference parameters

Co-channel Reuse Ratio for Some Values of N

	Cluster Size	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

To estimate the interference, let i_o be the number of co-channel interfering cells. Then, the signal-to-interference ratio (S/I or SIR) for a mobile receiver which monitors a forward channel can be expressed as

$$\frac{S}{I} = \frac{S}{\sum_{i=1}^{i_o} I_i} \qquad (3)$$

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. If the signal levels of co-channel cells are known, then the S/1 ratio for the forward link can be found using equation 3.

Propagation measurements in a mobile radio channel show that the average received signal strength at any point decays as a power law of the distance of separation between a transmitter and receiver. The average received power P, at a distance d from the transmitting antenna is approximated by

$$P_r = P_o\left(\frac{d}{d_o}\right)^{-n} \quad (4)$$

$$P_r(dBm) = P_o(dBm) - 10n\log\left(\frac{d}{d_o}\right)$$

where P_o is the power received at a close-in reference point in the far field region of the antenna at a small distance d_o from the transmitting antenna, and n is the path loss exponent which typically ranges between 2 and 4 in urban cellular systems.

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 $_i{}^{th}$ interferer, the received power at a given mobile due to this interfering cell will be proportional to $(D_i)^{-n}$.

When the transmitted power of each base station is equal and the path loss exponent is the same throughout the coverage area, S/I for a mobile can be approximated as

$$\frac{S}{I} = \frac{R^{-n}}{\sum_{i=1}^{i_o} D_i^{-n}} \quad (5)$$

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 centres, using equation 2 equation 5 simplifies to

$$\frac{S}{I} = \frac{(D/R)^n}{i_o} = \frac{\left(\sqrt{3N}\right)^n}{i_o} \quad (6)$$

Equation 6 relates S/I to the cluster size N, which determines the overall capacity of the system. For example, assume that the six closest cells create significant interference and that they are all approximately at equal distances from the desired base station. For the cellular system, which uses FM, subjective tests indicate that sufficient voice quality is provided when S/I is greater than or equal to 18 dB. Using equation 6 it can be shown in order to meet this requirement, the cluster size N should be at least 6.49, assuming a path loss exponent n = 4. Thus a minimum cluster size of 7 is required to meet the 18 dB S/I requirement.

Example

If a signal to interference ratio of 15 dB is 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 6 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 7-cell reuse pattern. Using the equation for Q the co-channel reuse ratio D/R = 4.583.

Using equation 6 the signal-to-noise interference ratio is equal to:

S/I = (1/6) x $(4.583)^4$ = 73.5, which is equivalent to 18.66 dB. Since this is greater than the minimum required S/I, N = 7 can be used.

b) $n = 3$

First, let us consider a 7-cell reuse pattern.
The signal-to-interference ratio is given by S/I = (1 /6) x $(4.583)^3$ =16.04 which is equivalent to 12.05 dB.

Since this is less than the minimum required S/I we need to use a larger N. Using equation 1, the next possible value of N is 12, ($i = j = 2$)

The corresponding co-channel ratio Q is D/R = 6.0, and the signal-to-interference ratio is given by
S/I = (1 /6) x $(6)^3$ = 36, = 15.56 dB.

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

Capacity Equation

In this analysis we express the capacity as a percentage of the population in a given service area that can be offered in a cellular service.

Let A denote the total service area in km^2, P the population in thousands, R the cell radius in km and k the number of channels per cell. We also introduce a multiplexing gain of 10π at the cell site. Then the effective number of subscribers per cell that can be supported equals $10\pi k$.

The number of cells in the total service area is

$$\frac{A}{\pi R^2}$$

Hence, the total number of subscribers supported throughout the service area is

$$10\pi k \frac{A}{\pi R^2} = \frac{10kA}{R^2}$$

The capacity expressed as a percentage of the population P is

$$C\% = \frac{10kA}{1000PR^2} X100 = \frac{kA}{PR^2}$$

However, $k = \frac{\Delta f}{N \Delta f_a}$ and $N = \frac{1}{3}\left(\frac{S}{I} i_o\right)^{2/n}$

Hence

$$C\% = \frac{3A\Delta f}{\Delta f_a PR^2 \left(\frac{S}{I} i_o\right)^{2/n}}$$

For a particular service area, both *A* and *P* are fixed parameters. Hence, to maximise the capacity we require a large Δf (i.e. system spectrum allocation) and small values of Δf_a, S/I and R.

Usually Δf is determined by internationally agreed standards. Δf_a is determined by the modulation scheme, for example in TACS FM modulation is used where Δf_a = 25 kHz. S/I is determined by the co-channel interference level and the capability of the receiver to operate at the lowest possible value of S/I while maintaining an acceptable quality of service.

Example

For the city of Leeds, P = 800 thousand and A=1 50 km^2. If R = 5 km, $\Delta f / \Delta f_a$ = 600 channels and S/I = 18 dB, determine the percentage capacity. Assume n=4 and number of interference channels is 6.

$$N = \frac{1}{3}\left(\frac{S}{I} i_o\right)^{2/n} = \sqrt{\frac{2S}{3I}} = 6.48$$

Hence we use K= 7 for an integer repeat pattern. Then:

C% = (150x600)/(800x25x7)=0.64%

which is very small!!