2.3 CAPACITY OF CELLULAR SYSTEMS

Channel capacity for a radio system can be defined as the maximum number of channels or users that can be provided in a fixed frequency band.
Radio capacity is a parameter which measures spectrum efficiency of a wireless system. This parameter is determined by the required carrier-to-interference ratio (C/I) and the channel bandwidth B_{Sc}.

In a cellular system the interference at a base station receiver will come from the subscriber units in the surrounding cells. This is called reverse channel interference.
For a particular subscriber unit, the desired base station will provide the desired forward channel while the surrounding co-channel base stations will provide the forward channel interference. Considering the forward channel interference problem, let D be the distance between two co-channel cells and R be the cell radius. Then the minimum ratio of D7R that is required to provide a tolerable level of co-channel interference is called the co-channel reuse ratio and is given by

$$Q = \frac{D}{R}$$

The radio propagation characteristics determine the carrier-to-interference ratio (C /1) at a given location, and models presented in Chapter 3 and Appendix B are used to find sensible C/I values. As shown in Figure 2.3.1, the M closest co-channel cells may be considered as first order interference in which case C/I is given by

$$\frac{C}{I} = \frac{D_0^{-n_0}}{\sum_{k=1}^{M} D_k^{-n_k}}$$

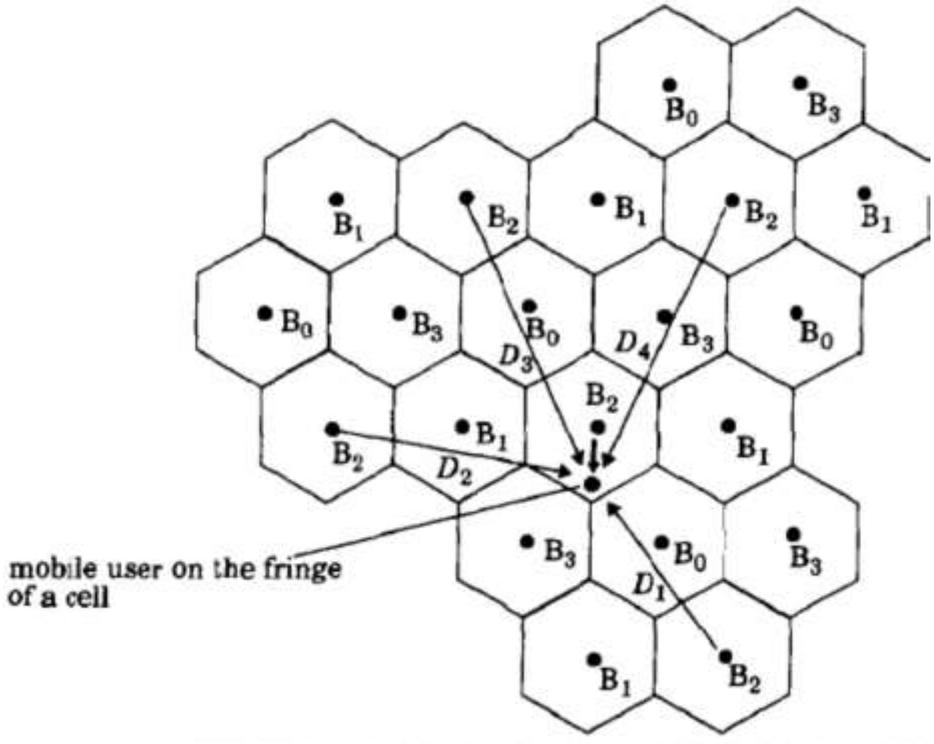


Fig 2.3.1: Illustration of forward channel interference for a cluster size of N = 4. Shown here are four co-channel base stations which interfere with the serving base station

[Source: "Wireless Communications" by Rappaport, Page-418.]

where n_o is the path loss exponent in the desired cell, D0 is the distance from the desired base station to the mobile, Do is the distance of the k the cell from the mobile, and n_o is the path loss exponent to the k the interfering base station. If only the six closest interfering cells are considered, and all are approximately at the same distance D and have similar path loss exponents equal to that in the desired cell, then C/I is given by

$$\frac{C}{I} = \frac{D_0^{-n}}{6D^{-n}}$$

If it is assumed that maximum interference occurs when the mobile is at the cell edge D0 = R, and if the C/I for each user is required to be greater than some minimum (C/I), which is the minimum carrier-to-interference ratio that still provides acceptable signal quality at the receiver, then the following equation must hold for acceptable performance:

$$\frac{1}{6}\left(\frac{R}{D}\right)^{-n} \geq \left(\frac{C}{I}\right)_{min}$$

The co-channel reuse factor is

$$Q = \left(6\left(\frac{C}{I}\right)_{min}\right)^{1/n}$$

The radio capacity of a cellular system is defined as

$$m = \frac{B_t}{B_c N} \text{ radio channels/cell}$$

Where m is the radio capacity metric, but is the total allocated spectrum for the system, B_{Sc} is the channel bandwidth, and N is the number of cells in a frequency reuse pattern. And N is related to Q. i.e.

$$Q = \sqrt{3N}$$

Therefore the radio capacity is given as

$$m = \frac{B_t}{B_c \frac{Q^2}{3}} = \frac{B_t}{B_c\left(\frac{6}{3^{n/2}}\left(\frac{C}{I}\right)_{min}\right)^{2/n}}$$

When n = 4, the radio capacity is given by

$$m = \frac{B_t}{B_c\sqrt{\frac{2}{3}\left(\frac{C}{I}\right)_{min}}} \text{ radio channels/cell}$$

2.2 Code Division Multiple Access (CDMA)

In CDMA, the narrowband message signal is multiplied by a very large bandwidth signal called the spreading signal.

The spreading signal is a pseudo-noise code sequence that has a chip rate which is orders of magnitudes greater than the data rate of the message.

All users use the same carrier frequency and may transmit simultaneously as shown in figure 2.2.1.

Each user has its own pseudorandom code word which is approximately orthogonal to all other code words.

The receiver performs a time correlation operation to detect only the specific desired code word. All other code words appear as noise due to decor relation. The receiver needs to know the code word used by the transmitter.

Each user operates independently with no knowledge of the other users.

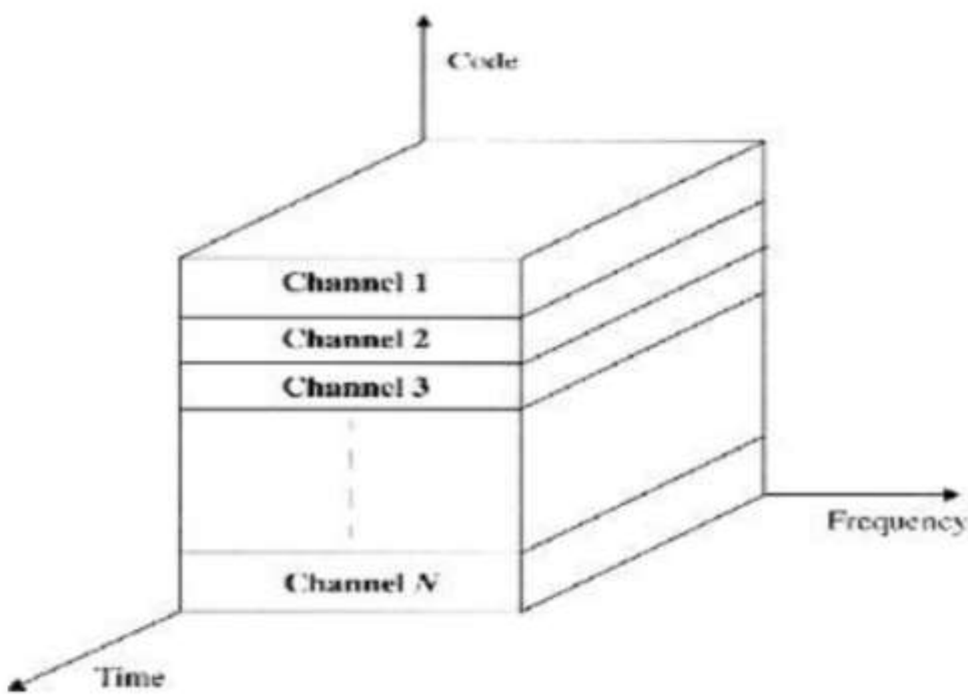


Fig 2.2.1: CDMA

[Source: "Wireless communications" by Theodore S. Rappaport, Page-406]

Near-far problem:

The near-far problem occurs when many mobile users share the same channel.

In general, the strongest received mobile signal will capture the demodulator at a base station.

In CDMA, stronger received signal levels raise the noise floor at the base station demodulators for the weaker signals, thereby decreasing the probability that weaker signals will be received.

The power of multiple users at a receiver determines the noise floor after decor relation.

Power control:

Provided by each base station in a cellular system and assures that each mobile within the base station coverage area provides the same signal level to the base station receiver. This solves the problem of a nearby subscriber.

Over powering the base station receiver and drowning out the signals of faraway subscribers.

Power control is implemented at the base station by rapidly sampling the radio signal strength indicator (RSSI) levels of each mobile and then sending a power change command over the forward radio link.

Features of CDMA:

Many users of a CDMA system share the same frequency. Either TDD or FDD may be used. Unlike TDMA or FDMA, CDMA has a soft capacity limit.

Increasing the number of users in a CDMA system raises the noise floor in a linear manner. Thus, there is no absolute limit on the number of users in CDMA.

Multipath fading may be substantially reduced because the signal is spread over a large spectrum. Channel data rates are very high in CDMA systems.

Consequently, the symbol (chip) duration is very short and usually much less than the channel delay spread. Since PN sequences have low autocorrelation, multipath which is delayed by more than a chip will appear as noise.

A RAKE receiver can be used to improve reception by collecting time delayed versions of the required signal.

Since CDMA uses co-channel cells, it can use macroscopic spatial diversity to provide soft handoff. Soft handoff is performed by the MSC, which can simultaneously monitor a particular user from two or more base stations.

The MSC may choose the best version of the signal at any time without switching frequencies.

Self-jamming is a problem in CDMA system.

Self-jamming arises from the fact that the spreading sequences of different users are not exactly orthogonal, hence in the dispreading of a particular PN code, non- zero contributions to the receiver decision statistic for a desired user arise from the transmissions of other users in the system.

The near-far problem occurs at a CDMA receiver if an undesired user has a high detected power as compared to the desired user.

2.5 CHANNEL ASSIGNMENT STRATEGIES

For efficient utilization of the radio spectrum, a frequency reuse scheme that is consistent with the objectives of increasing capacity and minimizing interference is required.

Types

Fixed channel assignment strategies and Dynamic channel assignment strategies.

Fixed channel assignment strategies

Each cell is allocated a predetermined set of 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.

Dynamic 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 fixture blocking within the cell, the frequency of use of the candidate channel, the reuse distance of the channel, and other cost functions.

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 is called handoff.

llustration of a handoff scenario at cell boundary is shown in Figure 2.5.1.

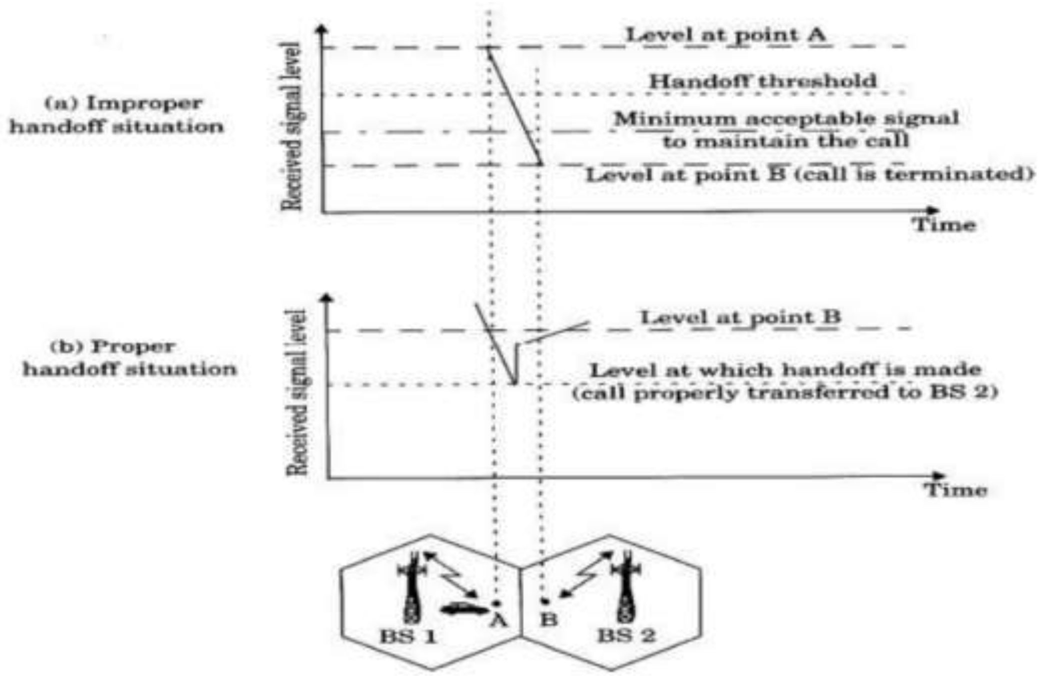


Fig 2.5.1: Handoff Scenario

[Source: "Wireless communications" by Theodore S. Rappaport, Page-31]

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

Many handoff strategies prioritize handoff requests over call initiation requests when allocating unused channels in a cell site.

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 at which to initiate a handoff.

Once a particular signal level is specified as the minimum usable signal for acceptable voice quality at the base station receiver (normally taken as between —90 dB and -100 dB), a slightly stronger signal level is used as a threshold at which a handoff is made.

This margin, given by $\Delta = P_{r\,handoff} - P_{r\,minimum\,usable}$ 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.

Figure (above) illustrates a handoff situation. It 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 z\ 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 momentary 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.
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, which include propagation, interference, distance between the subscriber and the base station, and other time varying effects. During the course of a call, if a mobile moves from one cellular system to a different cellular system controlled by a different MSC, an intersystem handoff becomes necessary.

Prioritizing Handoffs

One method for giving priority to handoffs is called the guard channel concept, here 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.
This method has the disadvantage of reducing the total carried traffic, as fewer channels are allocated to originating calls. Guard channels, however, offer efficient spectrum utilization when dynamic channel assignment strategies, which minimize the number of required guard channels by efficient demand based allocation, are used.

Practical Handoff Considerations

In practical cellular systems, several problems arise when attempting to design for a wide range of mobile velocities. High speed vehicles pass through the coverage region of a cell within a matter of seconds, whereas pedestrian users may never need a handoff during a call. Particularly with the addition of microcells to provide capacity, the MSC can quickly become burdened if high speed users are constantly being passed between very small cells. By using different antenna heights (often on the same building or tower) and different power levels, it is possible to provide "large" and "small" cells which are co-located at a single location. This technique is called the umbrella cell approach 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 (Fig: 2.5.2) ensures that the number of handoffs is minimized for high speed users and provides additional microcell channels for pedestrian users.

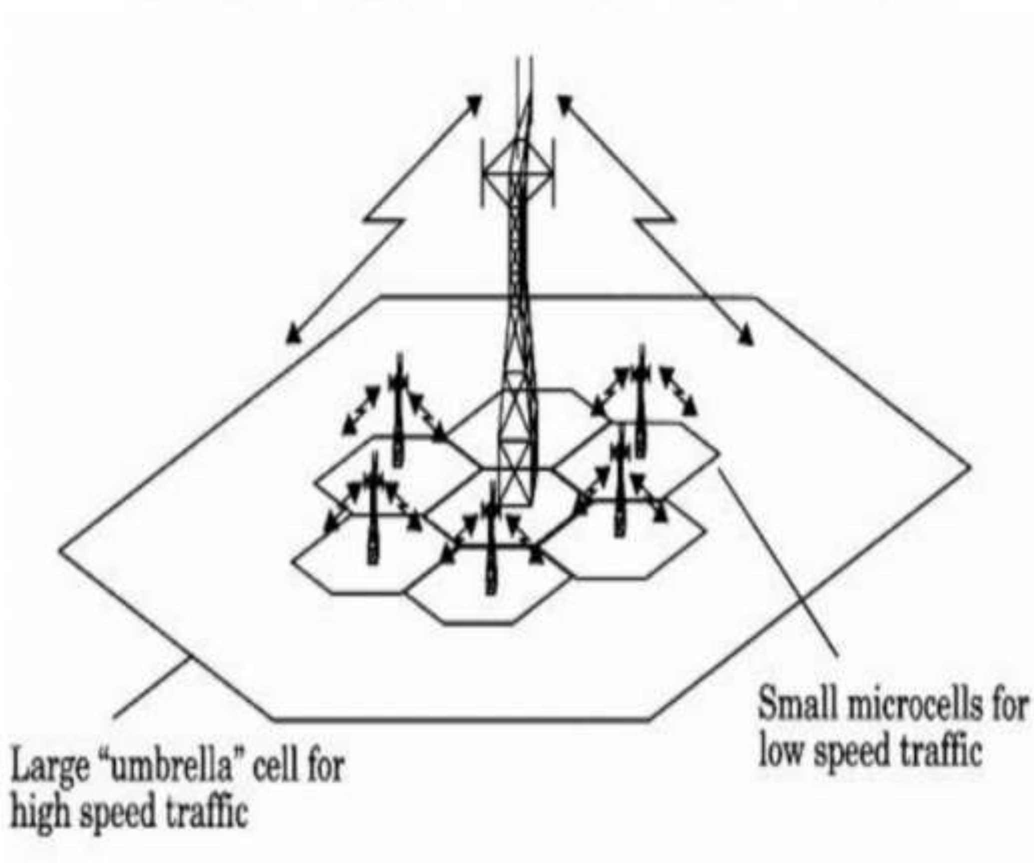


Fig 2.5.2: The umbrella cell approach

[Source: "Wireless communications" by Theodore S. Rappaport, Page-35]

The speed of each user may be estimated by the base station or MSC by evaluating how rapidly the short term average signal strength on the RVC changes over time, or more sophisticated algorithms may be used to evaluate and partition users.

If a high speed user in the large umbrella cell is approaching the base station, and its velocity is rapidly decreasing, the base station may decide to hand the user into

The co-located microcell, without MSC intervention.

In first generation analog cellular systems, the typical time to make a handoff, once the signal level is deemed to be below the handoff threshold, is about 10 seconds. This requires that the value for Δ be on the order of 6 dB to 12 db.

In GSM, the mobile assists with the handoff procedure by determining the best handoff candidates, and the handoff, once the decision is made, typically requires only 1 or 2 seconds. Consequently, Δ is usually between 0 dB and 6 dB in modem cellular systems.

In CDMA, by simultaneously evaluating the received signals from a single subscriber at several neighboring base stations, the MSC may actually decide which version of the user's signal is best at any moment in time. This technique exploits macroscopic space diversity provided by the different physical locations of the base stations and allows the MSC to make a "soft" decision as to which version of the user's signal to pass along to the PSTN at any instance.

The ability to select between the instantaneous received signals from a variety of base stations is called soft Handoff.

2.8 Coverage And Capacity Improvement

As the demand for wireless service increases, the number of channels assigned to a cell becomes insufficient to support the required number of users.

Techniques to expand the capacity of cellular systems:

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

Sectoring: relies on base station antenna placements to improve capacity by reducing co-

Coverage zone: distributes the coverage of a cell and extends the cell boundary to hard-to-reach places.

Cell Splitting

Cell splitting is the process of subdividing a congested cell into smaller cells as shown in figure 2.8.1, 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. Cells are split to add channels with no new spectrum usage.

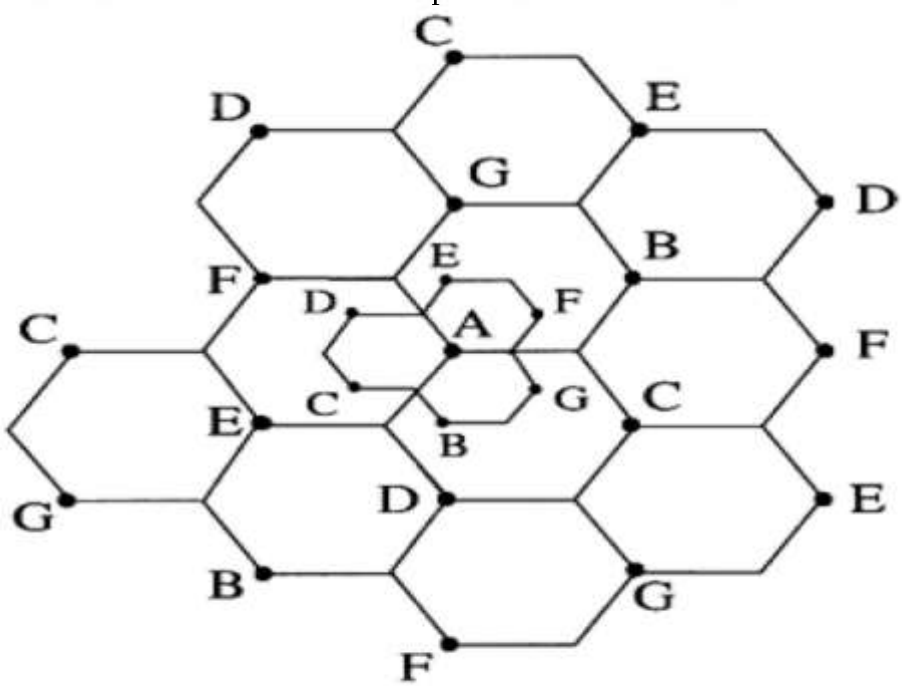


Fig 2.8.1: Cell splitting
[Source: "Wireless communications" by Theodore S. Rappaport, Page-55]

Sectoring

The technique for decreasing co-channel interference and thus increasing system capacity by using directional antennas is called sectoring.

The factor by which the co-channel interference is reduced depends on the amount of sectoring used. Sectoring improves Signal to Interference ratio.

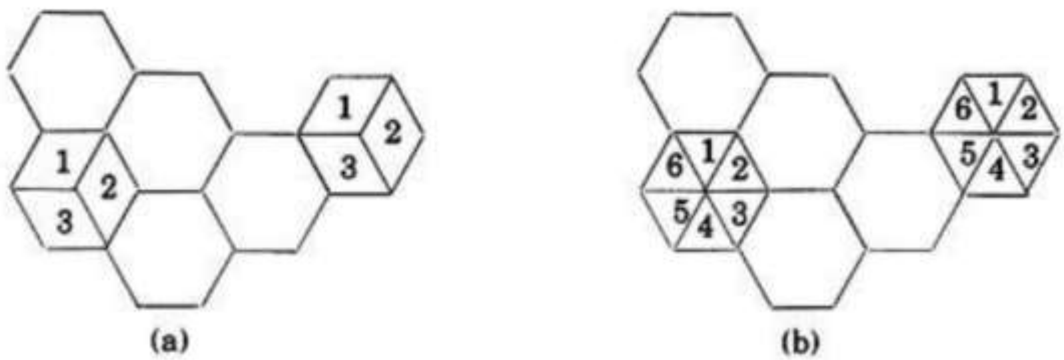


Fig 2.8.2: Cell Sectoring

[Source: "Wireless communications" by Theodore S. Rappaport, Page-59]

The technique for decreasing co-channel interference and thus increasing system capacity by using directional antennas is called sectoring. The factor by which the co-channel interference is reduced depends on the amount of sectoring used.

A cell is normally partitioned into three 120^0 degree sectors or six 60° sectors.

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 2.8.2. Assuming 7-cell reuse, for the case of 120° sectors, the number of interferers in the first tier is reduced from 6 to 2. This is because only 2 of the 6 co-channel cells receive interference with a particular sectored channel group.

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 un sectored case. Thus, sectoring reduces interference, which amounts to an increase in capacity by a factor of 12/7. or 1.714.

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 was proposed by Lee. This proposal is based on a microcell concept for 7 cell reuse, as shown in figure 2.8.3.

In this scheme, each of the three (or possibly more) zone sites are connected to a single base station and share the same radio equipment. The zones are connected by coaxial cable, fiber optic cable, or microwave link to the base station. Multiple zones and a single base station Make up a cell

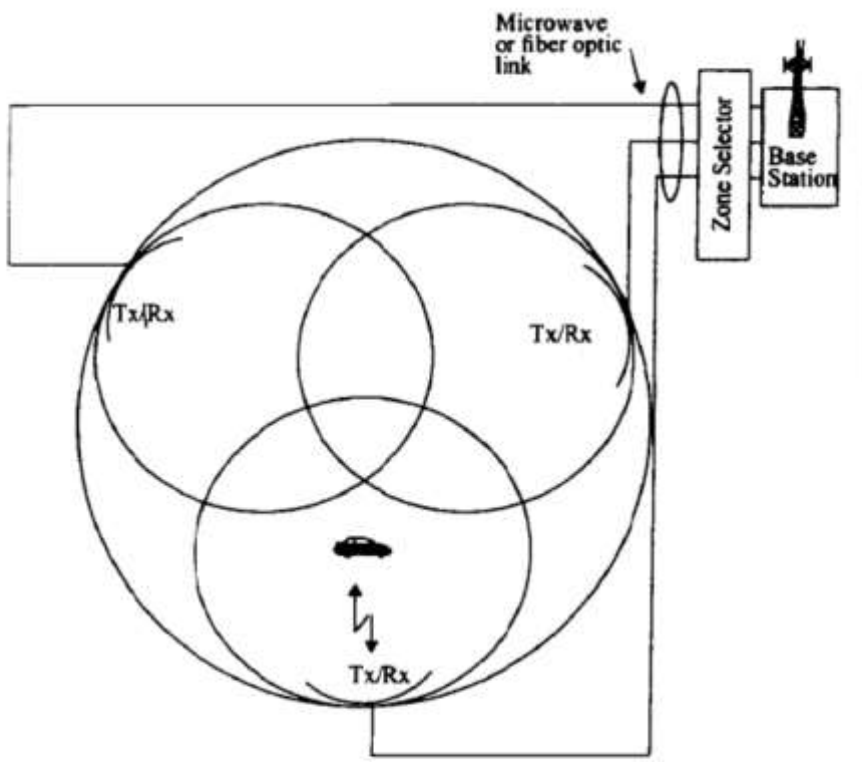


Fig 2.8.3: Micro Cell Concept

[Source: "Wireless communications" by Theodore S. Rappaport, Page-62]

As a mobile travels within the cell, it is served by the zone with the strongest signal. This approach is superior to sectoring since antennas are placed at the outer edges of the cell, and any base station channel may be assigned to any zone by the base station.

As a mobile travels from one zone to another within the cell, it retains the same channel. Thus, unlike in sectoring, a handoff is not required at the MSC when the mobile travels between zones within the cell.

The base station simply switches the channel to a different zone site. In this way, a given channel is active only in the particular zone in which the mobile is traveling, and hence the base station radiation is localized and interference is reduced.

The co-channel interference in the cellular system 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

UNIT II CELLULAR ARCHITECTURE

2.1 MULTIPLE ACCESS TECHNIQUES

Multiple access schemes are used to allow many mobile users to share simultaneously a finite amount of radio spectrum.

High capacity is required.

Must be done without severe degradation in the performance.

Duplexing is needed to allow subscribers send and receive information simultaneously.

Example- Telephone systems

Frequency division duplexing (FDD)

Provides two distinct bands of frequencies for every user.

Forward band - from the base station to the mobile. (Referred in figure 2.1.1.)

Reverse band - from the mobile to the base station.

Consists of two simplex channels. The frequency split between the forward and reverse channel is constant.

Time division duplexing (TDD)

Uses time to provide both a forward and reverse link. (Referred in figure 2.1.1.)

If the time split between the forward and reverse time slot is small, then the transmission and reception of data appears simultaneous.

Allows communication on a single channel and simplifies the subscriber equipment since a duplexer is not required.

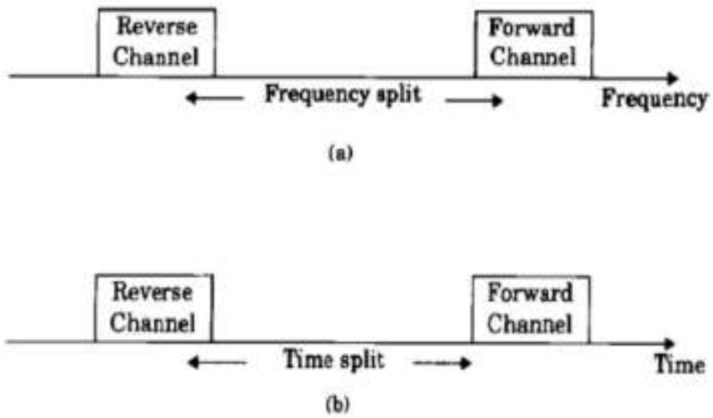


Fig 2.1.1: Duplexing

[Source:" Wireless Communications "by Theodore S. Rappaport, Page-396]

Trade-offs between FDD and TDD:

FDD

Each transceiver simultaneously transmits and receives radio signals which vary by more than **100 dB**, the frequency allocation used for the forward and reverse channels must be carefully coordinated with out-of-band users that occupy spectrum between these two bands. The frequency separation must be coordinated to permit the use of inexpensive RF technology.

TDD

Eliminate the need for separate forward and reverse frequency bands.

There is a time latency due to the fact that communications is not full duplex in the truest sense.

Three major techniques:

Frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA) are the three major access techniques used to share the available bandwidth in a wireless communication system.

These techniques can be grouped as narrowband and wideband systems, depending upon how the available bandwidth is allocated to the users.

The duplexing technique of a multiple access system is usually described along with the particular multiple access scheme.

Narrowband Systems

The available radio spectrum is divided into a large number of narrowband channels.

Each channel is relatively narrow compared with the coherence bandwidth. The channels are usually operated using FDD.

To minimize interference between forward and reverse links, the frequency split is made as great as possible allowing inexpensive duplexers.

Narrowband FDMA-- a user is assigned a particular channel which is not shared by other users in the vicinity.

If FDD is used, the system is called FDMA/FDD.

Narrowband TDMA -- allows users to share the same channel but allocates a unique time slot to each user.

For narrowband TDMA, generally a large number of channels allocated using either FDD or TDD, and each channel is shared using TDMA.

Wideband systems

The transmission bandwidth of a single channel is much larger than the coherence bandwidth.

Multipath fading does not greatly affect the received signal, frequency selective fades occur in only a small fraction of the bandwidth.

A large number of transmitters are allowed to transmit on the same channel.

Wideband TDMA - allocates time slots to many transmitters on the same channel and allows only one transmitter to access the channel at any instant of time,

TDMA/FDD, TDMA/TDD

Wideband CDMA- allows all of the transmitters to access the channel at the same time.

Frequency Division Multiple Access (FDMA)

Each user is allocated a unique frequency band or channel. These channels are assigned on demand, and cannot be shared a shown in figure 2.1.2.

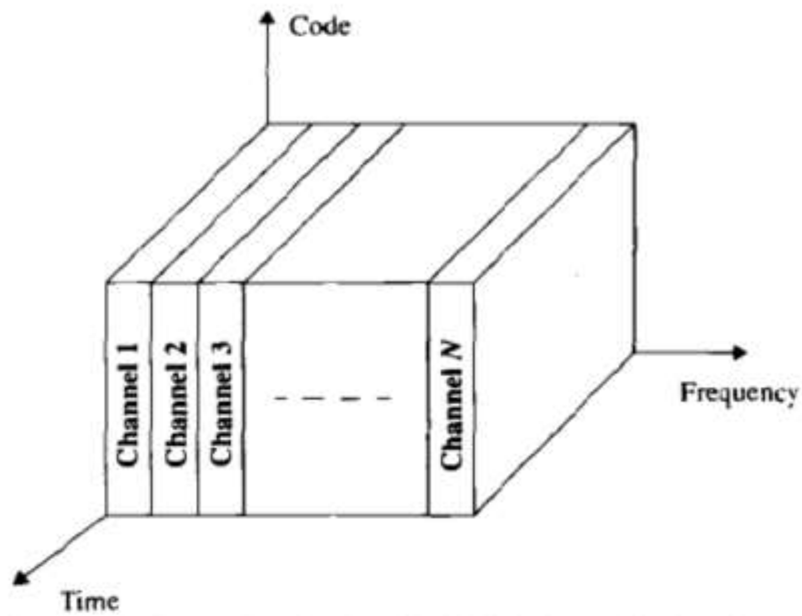


Fig 2.1.2: FDMA

[Source: "Wireless Communications" by Theodore S. Rappaport, Page-400]

The Features of FDMA:

The FDMA channel carries only one phone circuit at a time.

If an FDMA channel is not in use, then it is idle and cannot be used by other users to increase or share capacity. It is essentially a wasted resource.

After the assignment of a voice channel, the base station and the mobile transmit simultaneously and continuously.

The bandwidths of FDMA channels are relatively narrow (30 kHz) as each channel supports only one circuit per carrier.

That is, FDMA is usually implemented in narrowband systems. The symbol time is large as compared to the average delay spread. This implies that the amount of inter symbol interference is low and, thus, little or no equalization is required in FDMA narrowband systems.

Since FDMA is a continuous transmission scheme, fewer bits are needed for overhead purposes (such as synchronization and framing bits) as compared to TDMA.

FDMA systems have higher cell site system costs as compared to TDMA systems, because of the single channel per carrier design, and the need to use costly band pass filters to eliminate spurious radiation at the base station.

The FDMA mobile unit uses duplexers since both the transmitter and receiver operate at the same time.

This results in an increase in the cost of FDMA subscriber units and base stations.

FDMA requires tight RF filtering to minimize adjacent channel interference.

Nonlinear Effects in FDMA:

In FDMA, Many channels share the same antenna at the base station.

The power amplifiers or the power combiners, when operated at or near saturation for maximum power efficiency, are nonlinear.

The nonlinearities because signal spreading in the frequency domain and generate inter modulation (IM) frequencies. i.e., interfere adjacent-channels, or adjacent services.

The first U.S. analog cellular system, the Advanced Mobile Phone System (AMPS), is based on FDMA/ FDD. A single user occupies a single channel while the call is in progress, and the single channel is actually two simplex channels which are frequency duplexed with a 45 MHz split.

When a call is completed, or when a handoff occurs, the channel is vacated so that another mobile subscriber may use it.

The number of channels that can be simultaneously supported in a FDMA system is given by

$$N = \frac{B_t - 2B_{guard}}{B_c}$$

Where B_{ut} is the total spectrum allocation. Guard is the guard band allocated at the edge of the allocated spectrum, and B_c is the channel bandwidth.

Time Division Multiple Access (TDMA)

Time Division Multiple Access (TDMA) systems divide the radio spectrum into time slots, and in each slot only one user is allowed to either transmit or receive as shown in figure 2.1.3.

Each user occupies a cyclically repeating time slot.

A channel may be thought of as particular time slot that re occurs every frame, where N time slots comprise a frame.

TDMA systems transmit data in a buffer-and-burst method, the transmission for any user is non continuous.

Digital data and digital modulation must be used with TDMA.

Frame consists of a number of slots (information message), together with a preamble, and tail bits as shown in figure 2.1.4.

Preamble contains the address and synchronization information that both the base station and the subscribers use to identify each other.

Guard times allow synchronization of the receivers between different slots and frames.

In TDMA/ TDD, half of the time slots in the frame information message would be used for the forward link channels and half would be used for reverse link channels.

In TDMA/ FDD systems, an identical or similar frame structure would be used solely for either forward or reverse transmission, but the carrier frequencies would be different for the forward and reverse links.

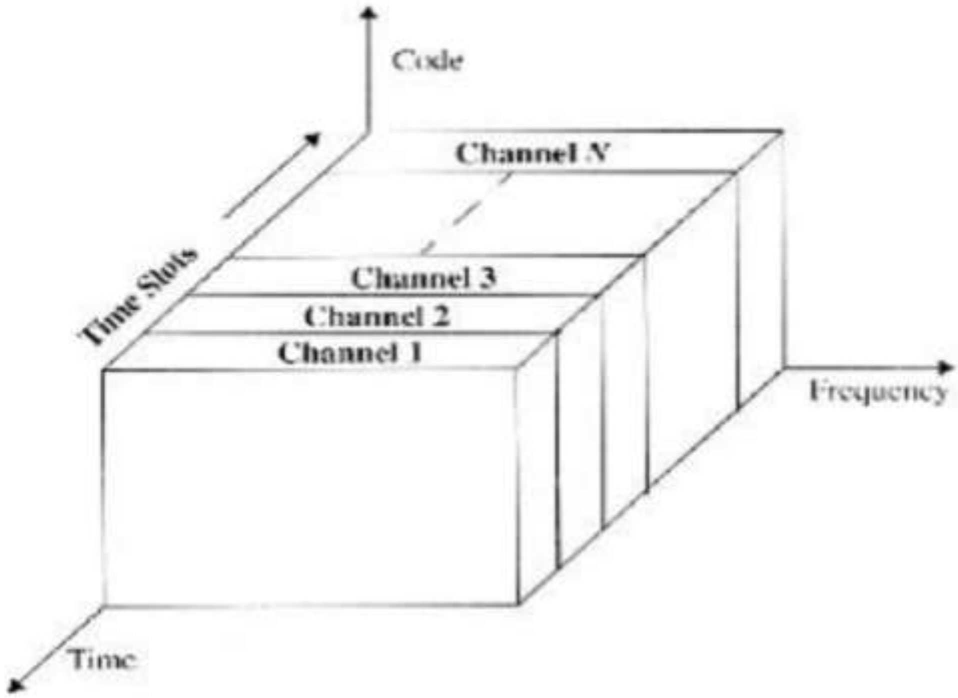


Fig 2.1.3: TDMA

[Source : "Wireless communications" by Theodore S. Rappaport,Page-401]

Features of TDMA:

TDMA shares a single carrier frequency with several users, where each user makes use of non-overlapping time slots.

The number of time slots per frame depends on several factors, such as modulation technique, available bandwidth, etc.

Data transmission for users of a TDMA system is not continuous, but occurs in bursts. This results in low battery consumption, since the subscriber transmitter can be turned off when not in use (which is most of the time).

Because of discontinuous transmissions in TDMA, the handoff process is much simpler for a subscriber unit, since it is able to listen for other base stations during idle time slots.

An enhanced link control, such as that provided by mobile assisted handoff (MAHO) can be carried out by a subscriber by listening on an idle slot on the TDMA frame.

TDMA uses different time slots for transmission and reception, thus duplexers are not required.

Even if FDD is used, a switch rather than a duplexer inside the subscriber unit is all that is required to switch between transmitter and receiver using TDMA.

Adaptive equalization is usually necessary in TDMA systems, since the transmission rates are generally very high as compared to FDMA channels.

In TDMA, the guard time should be minimized. If the transmitted signal at the edges of a time slot are suppressed sharply in order to shorten the guard time, the transmitted spectrum will expand and cause interference to adjacent channels.

TDMA has an advantage in that it is possible to allocate different numbers of time slots per frame to different users.

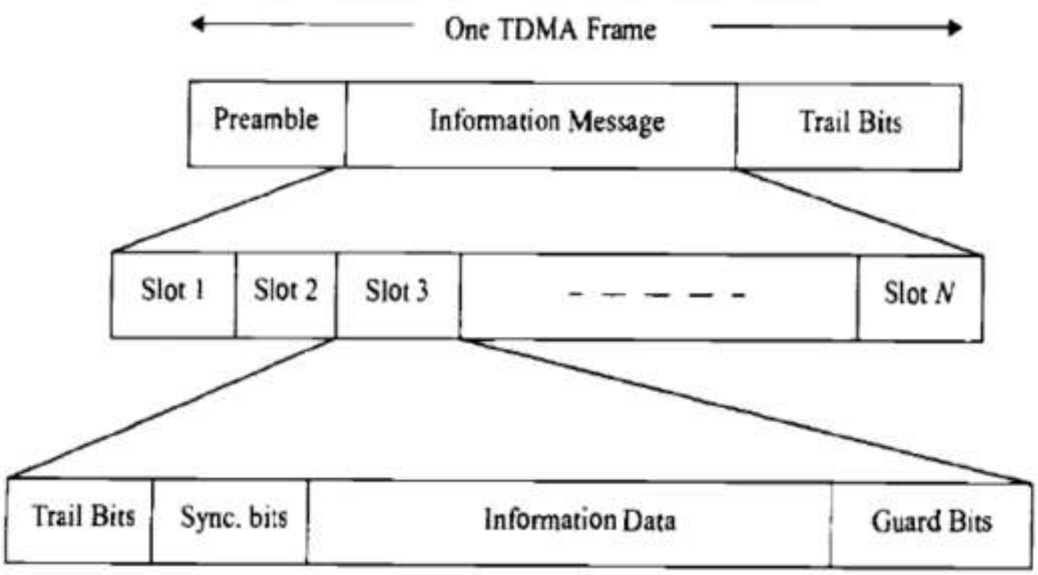


Fig 2.1.4: TDMA Frame structure

[Source: "Wireless communications" by Theodore S. Rappaport, Page-402]

Efficiency of TDMA:

The frame efficiency, is the percentage of bits per frame which contain transmitted data.

$$\eta_f = \left(1 - \frac{b_{OH}}{b_T}\right) \times 100\%$$

The number of overhead bits per frame is

$$Both = N_r b_r + N_t b_p + N_t b_g + N_r B_g$$

The total number of bits per frame, B_t, is $B_t = T_f R$

It is a measure of the percentage of transmitted data that contains information as opposed to providing overhead for the access scheme.

The transmitted data may include source and channel coding bits, so the raw end- user efficiency of a system is generally less than frame efficiency.

Number of channels in TDMA system:

Can be found by multiplying the number of TDMA slots per channel by the number of channels available. m is the maximum number of TDMA users supported on each radio channel.

$$N = \frac{m(B_{tot} - 2B_{guard})}{B_c}$$

2.6 INTERFERENCE AND SYSTEM CAPACITY

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

Interference has been recognized as a major bottleneck in increasing capacity and also responsible for dropped calls.

The two major types of system-generated cellular interference are:

Co-channel interference

Adjacent channel interference

Power Control for reducing interference

1. Co-channel Interference and System Capacity

Co-channel Interference

Cells using the same set of frequencies 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 simply increasing the carrier power of a trans matter.

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.

The co-channel interference ratio is 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.

Co channel reuse ratio

The parameter Q=D/R, called the co-channel reuse ratio, is related to the cluster size N.

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

From Figure 2.6.1, it can be seen for a 7-cell cluster, with the mobile unit is at the cell boundary, the mobile is a distance D- R. From the two nearest co-channel interfering cells and approximately D + R/2, D, D- R/2, and D + R from the other interfering cells in the first tier and n=4. The signal-to-interference ratio for the worst case can be closely approximated as

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

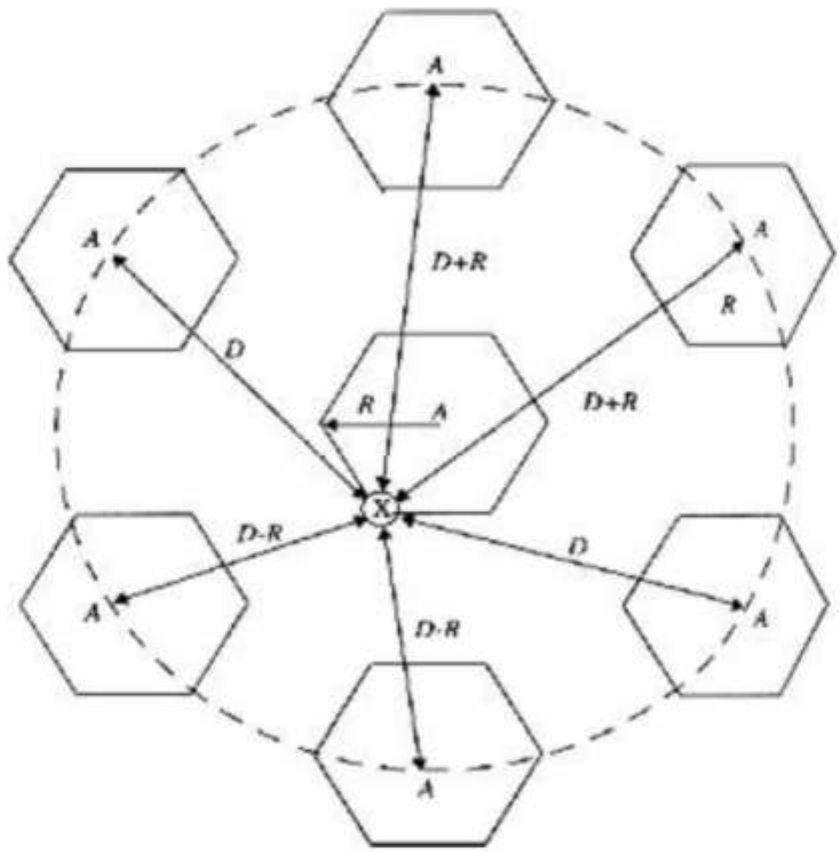


Fig 2.6.1: Co-channel cells for 7-cell reuse

[Source: "Wireless communications" by Theodore S. Rappaport, Page-41]

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).

When the size of each cell is approximately the same, and the base stations transmit the same power, we have 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.

A trade-off must be made between these two objectives in actual cellular design.

Signal-to-interference ratio (SIR)

$$SIR = \frac{S}{\sum_{i=0}^{i_0} I_i}$$

S denotes the desired signal power;

Ii is the interference power caused by the itch interfering co-channel cell base station;

I**0** is the number of co-channel interfering cells.

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

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

If all base stations transmit at the same power level, the SIR can be given as

$$SIR = \frac{R^{-n}}{\sum_{i=0}^{i_0} D_i^{-n}}$$

The path loss exponent typically ranges between 2 and 4 in urban cellular systems.

In practice, measures should be taken to keep the SIR on a acceptable level.

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 pass band. The problem can be particularly serious if an adjacent channel user is transmitting in very close range to a subscriber's receiver, while the receiver attempts to receive a base station on the desired channel. This is referred to as the near-far effect.

The near-far effect occurs when a mobile close to a base station transmits on a channel close to one being used by a weak mobile. The base station may have difficulty in discriminating the desired mobile user from the "bleed over" caused by the close adjacent channel mobile. Adjacent channel interference can be minimized through careful filtering and channel assignments. Since each cell is given only a fraction of the available channels, a cell need not be assigned channels which are all adjacent in frequency.

By keeping the frequency separation between each channel in a given cell as large as possible, the adjacent channel interference may be reduced considerably.

For example, if a mobile is 20 times as close to the base station as another mobile and has energy spill out of its pass band, the signal-to interference ratio for the weak mobile (before receiver filtering) is given by,

$$\frac{S}{I} = (20)^{-n}$$

2.4 THE 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.

The cellular concept is a system-level idea which calls for replacing 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.

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

Channels so that all the available channels are assigned to a relatively small number of neighboring base stations.

Neighboring base stations are assigned different groups of channels so that the interference between base stations (and the mobile users under their control) is minimized.

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.

This fundamental principle is the foundation for all modern wireless communication systems, since it enables a fixed number of channels to serve an arbitrarily large number of subscribers by reusing the channels throughout the coverage region.

Frequency Reuse

Cellular radio systems rely on an intelligent allocation and reuse of channels throughout a coverage region.

Each cellular base station is allocated a group of radio channels to be used within a small geographic area called a cell.

Base stations in adjacent cells are assigned channel groups which contain completely different channels than neighboring cells. The base station antennas are designed to achieve the desired coverage within the particular ce

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 distances large enough to keep interference levels within tolerable limits.

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.

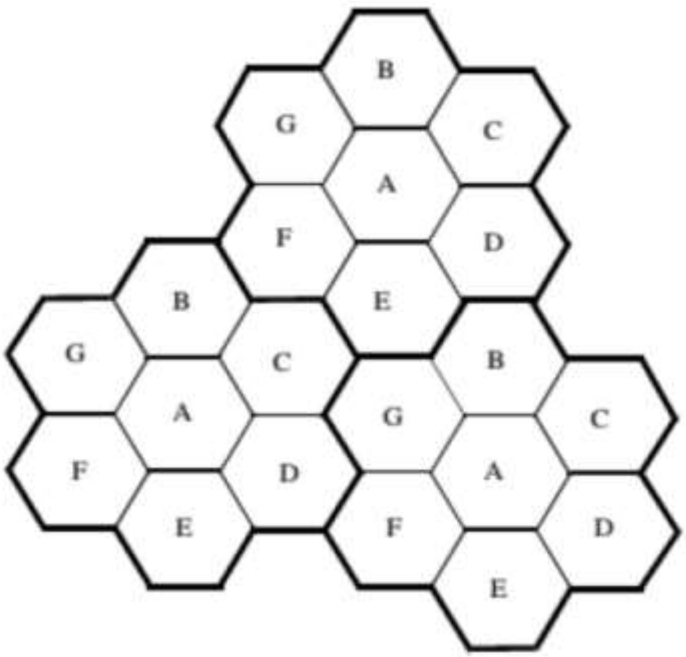


Fig 2.4.1: Frequency reuse concept

[Source: "Wireless communications" by Theodore S. Rappaport, Page-27]

The hexagonal cell shape shown in figure 2.4.1. Is conceptual and is a simplistic model of the radio coverage for each base station, but it has been universally adopted since the hexagon permits easy and manageable analysis of a cellular system.

The actual radio coverage of a cell is known as the footprint and is determined from field measurements or propagation prediction models.

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.

Normally, Omni directional antennas are used in center-excited cells and sectored directional antennas are used in corner-excited cells.

Practical considerations usually do not allow base stations to be placed exactly as they appear in the hexagonal layout.

To understand the frequency reuse concept, consider a cellular system which has a total of S duplex channels available for use.

If each cell is allocated a group of k channels (k< S), and if the S channels are divided among N cells into unique and disjoint channel groups which each have the same number of channels, the total number of 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 a cluster is replicated M times within the system, the total number of duplex channels, can be used as a measure of capacity and is given by

$$C=MN=MS$$

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

The factor N is called the cluster size and is typically equal to 4, 7, or 12. If the cluster size Nis 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.

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.

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

Where I and j are non-negative integers.

To find the nearest co-channel neighbors of a particular cell, one must do the following:

(1) move cells along any chain of hexagons as in figure 2.4.2 and then

(2) Turn 60 degrees counter-clockwise and move j cells.

19- Cell reuse example (N=19)

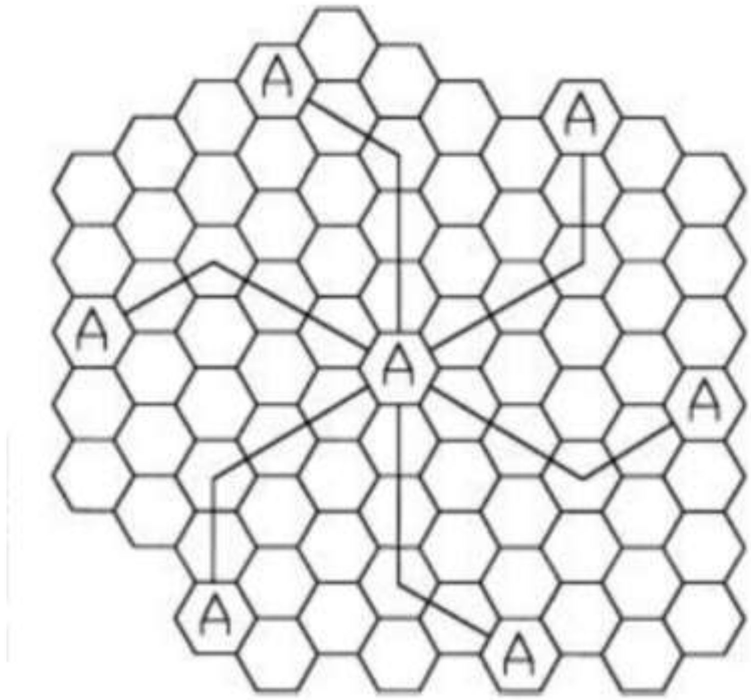


Fig 2.4.2: Method of locating co-channel cells in a cellular system.

[Source: "Wireless communications "by Theodore S. Rappaport, Page-29]

Method of locating co-channel cells in a cellular system is shown above. In this example, N= 19 (i.e., i =3, j = 2).

2.7 TRUNKING AND GRADE OF SERVICE

Cellular radio systems rely on trucking to accommodate a large number of users in a limited radio spectrum. The concept of trucking 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 telephone company uses trucking theory to determine the number of telephone circuits that need to be allocated for office buildings with hundreds of telephones, and this principle is used in designing cellular radio systems.

In a trunked mobile radio system, when a particular user requests service and all of the radio channels are already in use, the user is blocked, or denied access to the system. The fundamentals of trucking theory were developed by Erlangen, a Danish mathematician, in the late 19th century.

One Erlangen represents the amount of traffic intensity carried by a channel that is completely occupied (i.e. 1 call-hour per hour or 1 call-minute per minute). For example, a radio channel that is occupied for thirty minutes during an hour carries 0.5 Elands of traffic.

The grade of service (GOS) is a measure of the ability of a user to access a trunked system during the busiest hour. The busy hour is based upon customer demand at the busiest hour during a week, month, or year. The busy hours for cellular radio systems typically occur during rush hours, between 4 p.m. and 6 p.m. on a Thursday or Friday evening. The grade of service is used to define the desired performance of a particular trunked system by specifying a desired likelihood of a user obtaining channel access given a specific number of channels available in the system.

GOS is given as the likelihood that a call is blocked, or the likelihood of a call experiencing a delay greater than a certain queuing time. The traffic. Intensity offered by

Each user is equal to the call request rate multiplied by the holding time. That is, each user generates a traffic intensity of Au Elands given by

$$A_u = FIH$$

Where H is the average duration of a call and k is the average number of call requests per unit time. For a system containing U users and an unspecified number of channels, the total offered traffic intensity A, is given as

$$A = UAU$$

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 Elands. 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 Elands. Grade of Service (005): A measure of congestion which is specified as the probability of a call being blocked (for Erlangen B), or the probability of a call being delayed beyond a certain amount of time (for Erlangen C).

Request Rate: The average number of call requests per unit time. Denoted by A seconds1. In a C channel trunked system, if the traffic is equally distributed among the channels, then the traffic intensity per channel Ac, is given as

$$A_c = UA_u/C$$

When the offered traffic exceeds the maximum capacity of the system, the carried traffic becomes limited due to the limited capacity (i.e. limited number of channels). The maximum possible carried traffic is the total number of channels, C, in Elands.

The AMPS cellular system is designed for a GOS of 2% blocking. This implies that the channel allocations for cell sites are designed so that 2 out of 100 calls will be blocked due to channel occupancy during the busiest hour.

There are two types of trunked systems which are commonly used.

The first type offers no queuing for call requests. That is, for every user who requests service, it is assumed there is no setup time and the user is given immediate access to a channel if one is available. If no channels are available, the requesting user is blocked without access and is free to try again later. This type of trucking is called blocked calls cleared and assumes that calls arrive as determined by a Poisson distribution. There are an infinite number of users as well as the following:

(a) there are memory less arrivals of requests, implying that all users, including block users, may request a channel at any time;

(b) the probability of a user occupying a channel is exponentially distributed, so that longer calls are less likely to occur as described by an exponential distribution; and

(c) There are a finite number of channels available in the trucking pool. This is known as an M/M/m queue, and leads to the derivation of the Erlangen B formula (also known As the blocked calls cleared formula).

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

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

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

The second type of trunked system is one in which a queue is provided to hold calls which are blocked. If a channel is not available immediately, the call request may be delayed until a channel becomes available. This type of trucking is called Blocked Calls Delayed, and its measure of GOS is defined as the probability that a call is blocked after

Waiting a specific length of time in the queue. To find the GOS, it is first necessary to find the likelihood that a call is initially denied access to the system.

The likelihood of a call not having immediate access to a channel is determined by the Erlangen C formula and is given as

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

If no channels are immediately available the call is delayed, and the probability that the delayed call is forced to wait more than t seconds is given by the probability that a call is delayed, multiplied by the conditional probability that the delay is greater than t seconds.

The GOS of a trunked system where blocked calls are delayed is hence given by

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

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

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

Where the average delay for those calls which are queued is given by H/(C—A).

The Erlangen B and Erlangen C Chart is shown in figure 2.7.1 and 2.7.2.

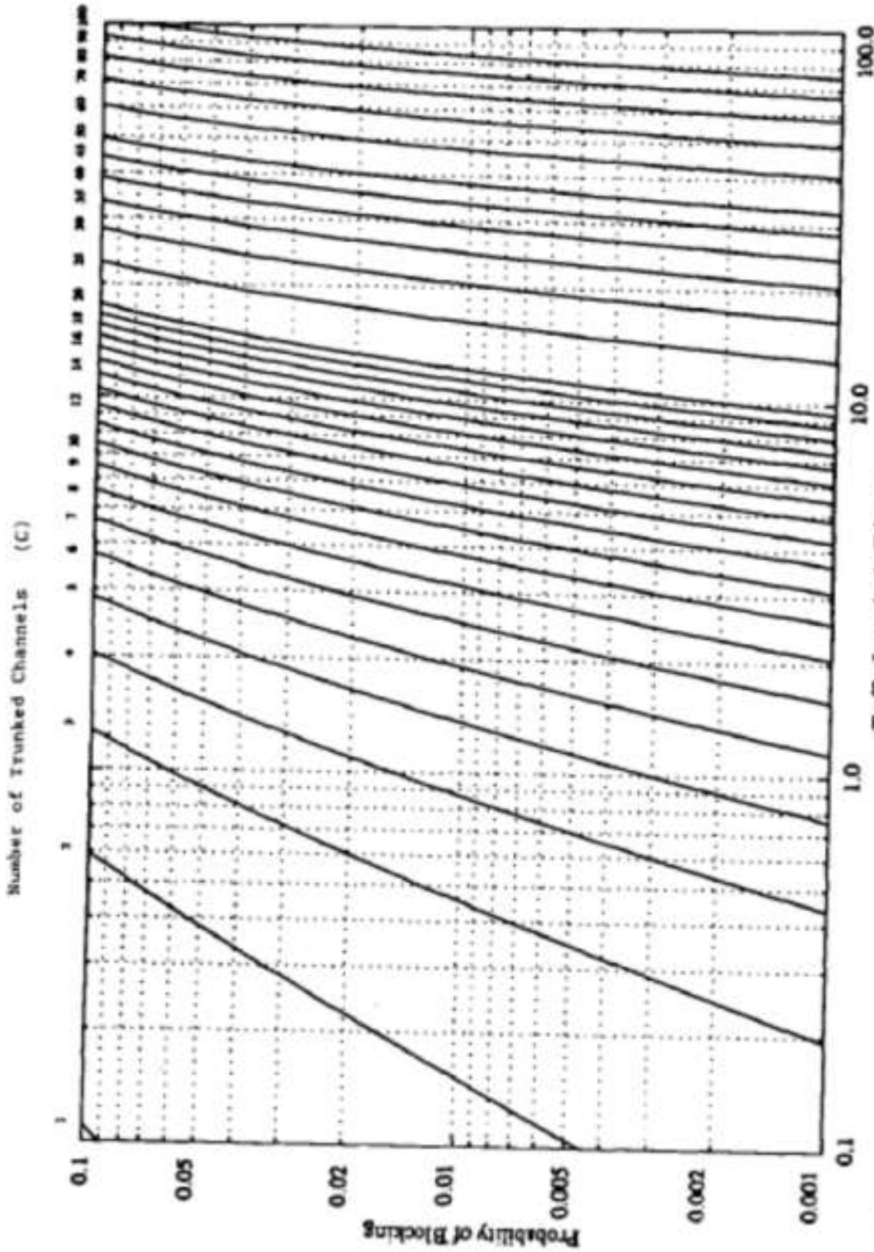
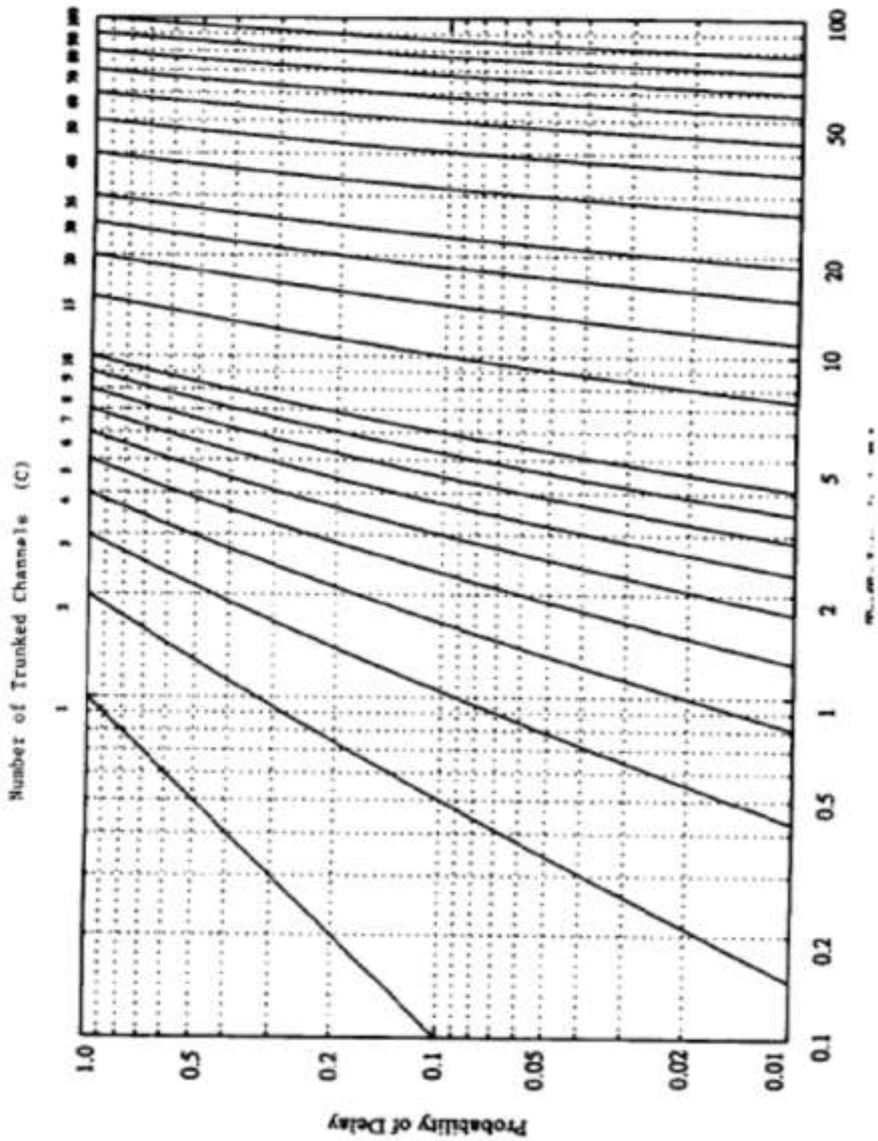


Figure 2.6
The Erlang B chart showing the probability of blocking as functions of the number of channels and traffic intensity in Erlangs.



Number of Trunked Channels (C)
Probability of Delay
1.0
0.5
0.2
0.1
0.05
0.02
0.01
0.1
0.2
0.5
1
2
5
10
20
50
100