Mobile Communications

The Cellular Concept-System Design Fundamentals

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Wireless Communications

Principles and Practice

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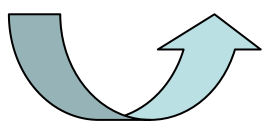
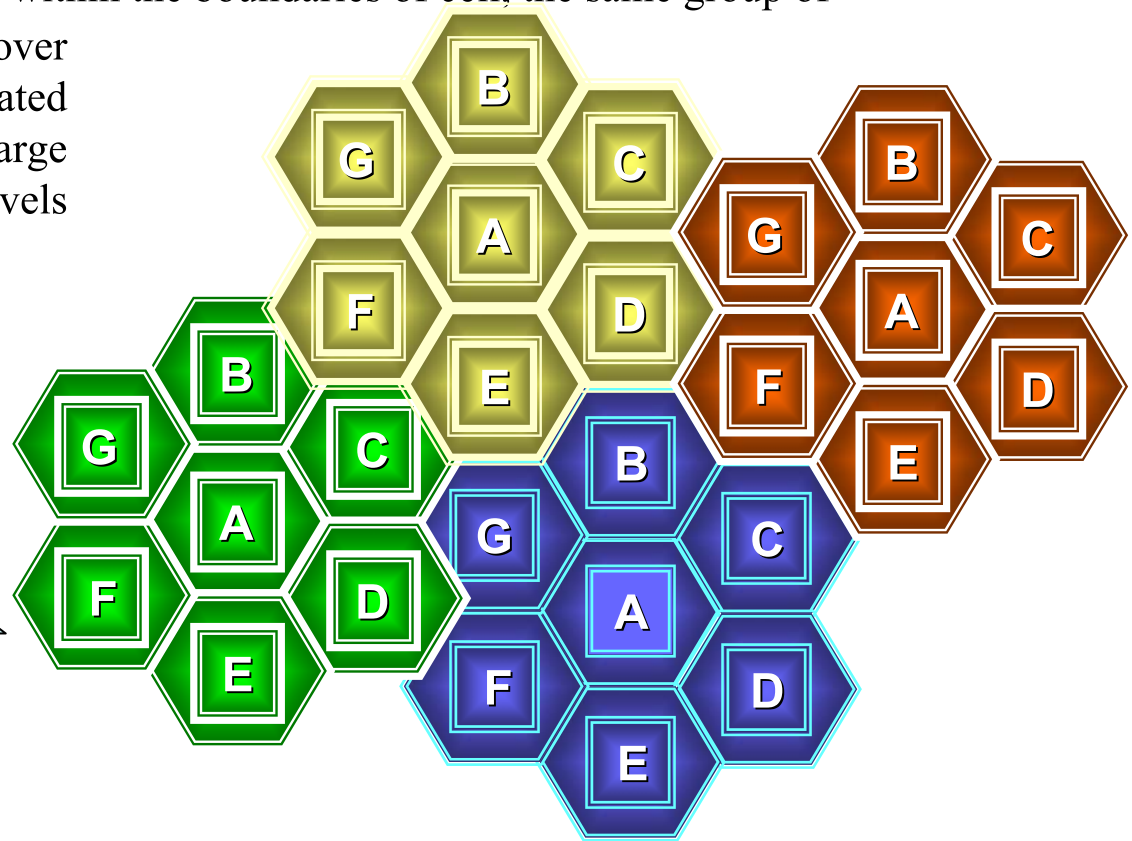
FREQUENCY REUSE

- Each Cellular base station is allocated a group of radio channels to be used within a small geographic area called a *cell*
- By limiting the coverage area to within the boundaries of 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.

Hexagonal Shape





FREQUENCY REUSE

- The actual radio coverage of a cell is known as the *footprint* and is determined from field measurements or propagation prediction models.
- By using the *hexagon* geometry , the fewest number of cells can cover a geographic region and the hexagon closely approximates a circular radiation pattern which would occur for omnidirectional base station antenna and free space propagation.
- Base station transmitter depicted:

1. Center-Excited Cells: in the center of the cell. (omnidirectional antenna)
2. Edge-Excited Cells: on three of the six cell vertices. (sectored directional antenna)

FREQUENCY REUSE

- The total number of available radio channels

$$S = kN$$

Cluster is the complete set of available frequencies used by *N* cells.

S: Total Number of duplex channels in a cellular system

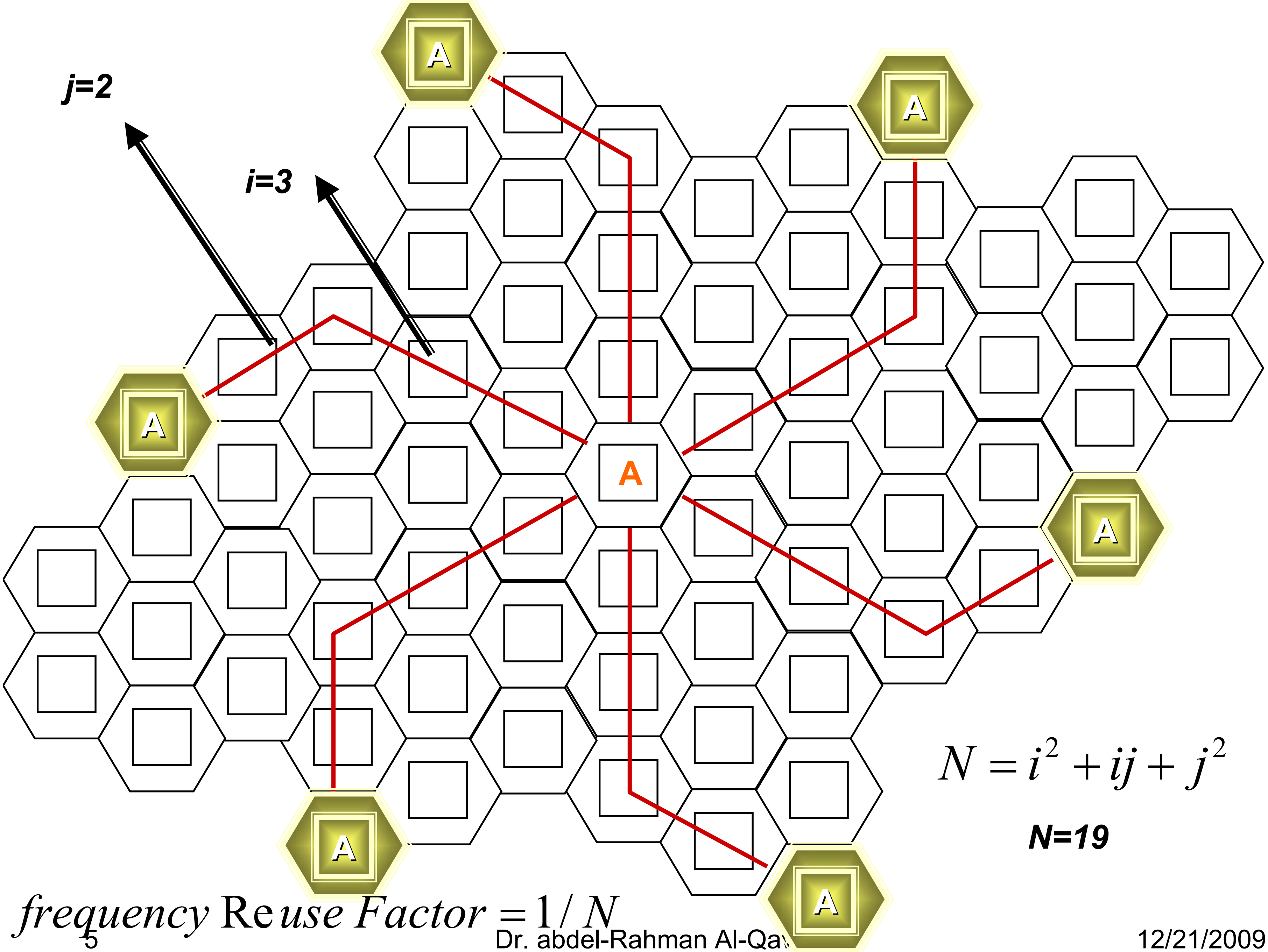
k: Number of Channels

N: Number of Cells (Cluster size=4,7 or 12)

The total number of duplex channels, *C* (Capacity):

$$C = MkN = MS$$

M: Number of replication of cluster



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

N=19

$$frequency\ Reuse\ Factor = 1/N$$

FREQUENCY REUSE Example

Channel Assignment Strategies

The objectives of Frequency Reuse are:

1- Increasing Capacity 2- Minimizing Interference

Channel Assignment Strategies:

Fixed: each cell is allocated a predetermined set of voice channels. Borrowing is used to borrow channels from neighboring cell supervised by MSC (no interference)

Dynamic: Voice channels are not allocated to cells permanently. MSC allocates a channel to the requested cell. MSC collects real-time data, traffic distribution and *radio signal strength indications* (RSSI)

Handoff Strategies

•When mobile moves into a different cell while a conversation is in progress, the MSC automatically transfers the call into a new channel belonging to the new base station.

•Handoffs must be infrequently and imperceptible.

•The minimum usable for acceptable voice quality at the base station receiver given by

$$\Delta = P_{rHandoff} - P_{rMinimumUsable}$$

$$P_{rMinimumUsable} = -90dBm \text{ to } -100dBm$$

If Δ too large then unnecessary handoffs and if Δ is small then insufficient time to complete a handoff before a call is lost due to weak signal conditions

Handoff Strategies

•The base station monitors the signal level for a certain time of period before handoff is initiated to ensure that the mobile is moving away and the drop in the measured signal level is not due to momentary fading. (Time depends on vehicle speed).

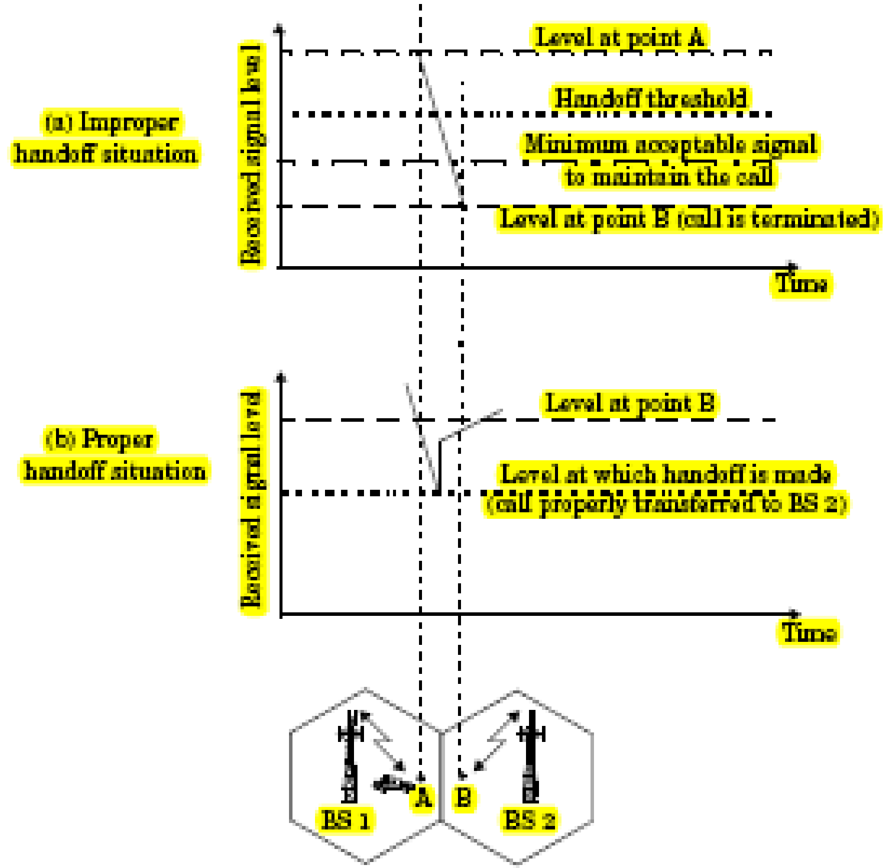
•The time over which a call may be maintained within a cell, without handoff is called the dwell time.

•Dwell time depends on the speed of user and the type of radio coverage.

•First Generation: Signal strength measurements are made by the base station and supervised by MSC.

•Second Generation: handoff decisions are mobile assisted (mobile assisted handoff MAHO) [good for microcells with frequently handoffs.

•If a mobile moves from one cellular sytem to a different cellular system controlled by a different MSC, then an intersystem handoff becomes necessary.



Prioritizing Handoff

Guard Channel Concept: a fraction of the total available channels in a cell is reserved for handoffs from ongoing calls which may be handed off into a cell.

(Low carried traffic but efficient spectrum for dynamic channel assignment strategies.

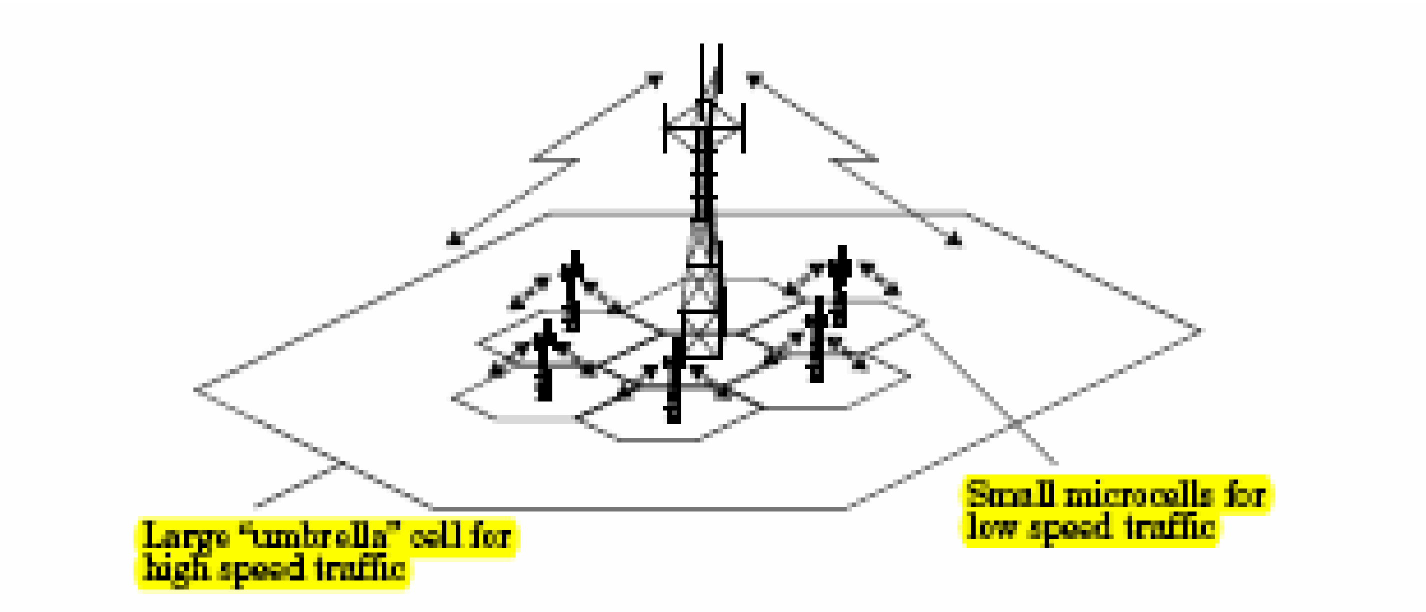
Queuing of handoffs requests: due to the fact that there is a finite time interval between the time the received signal level drops below the handoff threshold and the time the call is terminated due to insufficient signal level.

Practical Handoff Considerations

Problem:

- High speed vehicles need more handoffs than pedestrians.

•**Solution** : Microcells are added to Main cell for pedestrians.



Interference and System capacity

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

1. Another mobile in the cell
2. A call in progress in neighboring cell
3. Other base stations operating in the same frequency band

- Interference on voice channels causes cross talk {subscriber hears interference in the background due to undesired transmission}
- The two major types of interference:

1. Co-Channel interference
2. Adjacent channel interference.

Co-Channel Interference and System Capacity

- The cells that use the frequency reuse are called co-channel cells and the interference between their signals is called co-channel interference.
- Co-channel interference can be reduced by separating the cells by a minimum distance to provide sufficient isolation due to propagation (Not by increasing power).
- For same size of cells and the same power transmitted from base stations , the interference becomes a function of radius R and the distances between centers of nearest co-channel cells D.[by increasing D, more isolation].
- For hexagonal geometry:

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

Q- Co-channel reuse ration

- If Q small then large capacity (N is small)
- If Q large then small level of co-channel interference.
- We need trade-off to be made between these two objectives.

Co-Channel Interference and System Capacity

Example:

For i=2 and j=2, compute the co-channel reuse ratio (Q):

Solution:

$$Q = \sqrt{3N} = \sqrt{3(i^2 + ij + j^2)} = 6$$

To find the signal-to-interference ratio (SIR):

$$S/I = \frac{S}{\sum_{i=1}^{i_0} I_i}$$

S is desired signal power from the desired base station and I_i is the interference power caused by the *ith* interfering co-channel cell base station

Co-Channel Interference and System Capacity

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

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

or

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

n is the path loss exponent and

.

P_0 is a reference power at a distance d_0

Co-Channel Interference and System Capacity

The S/I for a mobile

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

R is the cell radius and D_i is the distance of *ith* interferer from the mobile. For hexagonal cell geometry and all the interfering cells are equidistant

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

S/I relates to the cluster size N, which in turn determines the overall capacity of the system. (Example).

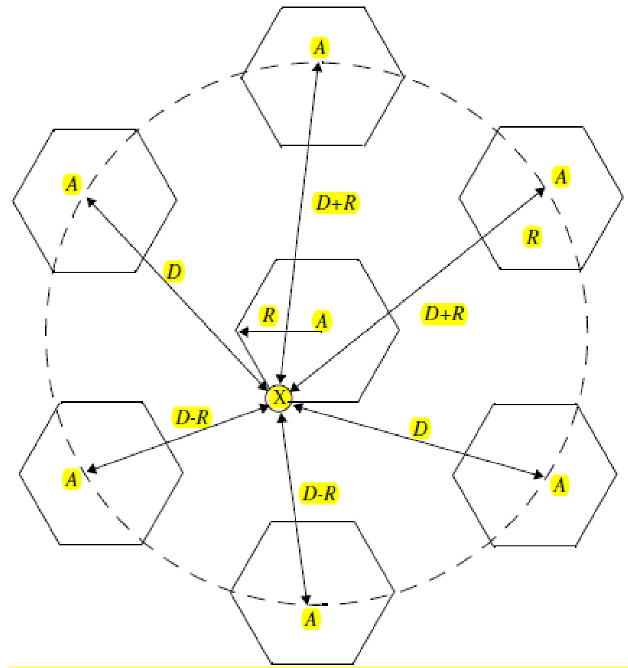
Example

Equation (3.9) relates S/I to the cluster size N, which in turn determines the overall capacity of the system from Equation (3.2). For example, assume that the six closest cells are close enough to create significant interference and that they are all approximately equidistant from the desired base station. For the U.S. AMPS cellular system which uses FM and 30 kHz channels, subjective tests indicate that sufficient voice quality is provided when S/I is greater than or equal to 18 dB. Using Equation (3.9), 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 seven is required to meet an S/I requirement of 18 dB. It should be noted that Equation (3.9) is based on the hexagonal cell geometry where all the interfering cells are equidistant from the base station receiver, and hence provides an optimistic result in many cases. For some frequency reuse plans (e.g., $N = 4$), the closest interfering cells vary widely in their distances from the desired cell.

Co-Channel Interference and System Capacity

For N=7 (n=4)

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



or

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

where $Q = D/R$

The co-channel interference determines link performance, which in turn dictates the frequency reuse plan and the overall capacity of a cellular system.

Example

Example 3.2

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 six co-channel cells in the first tier, and all of them are at the same distance from the mobile. Use suitable approximations.

Solution

(a) $n = 4$

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

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

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

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

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

(b) $n = 3$

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

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

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

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

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

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

$$D/R = 6.0$$

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

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

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

Channel planning in Wireless systems

In practical systems, the air-interface standard ensures a distinction between voice and control channels.
The frequency reuse applied to control channel is different and generally more conservative (More S/I) than the voice channels

- In CDMA the cluster size=1. In CDMA we use soft handoff.
- Because interference can occurred in some of CDMA applications and the most popular approach is to use f_1/f_2 cell planning , where the nearest neighbor cells use radio channels that are different from its closest neighbor in particular locations (Hard handoffs)
- See practical example page 73.

Adjacent channel interference

- Adjacent channel interference: interference resulting from signals which are adjacent in frequency to the desired signal because if imperfect receiver filters.
- The near-far-effect: where a nearby transmitter captures the receiver of the subscriber.
- Adjacent channel interference can be minimized through careful filtering , channel assignment, and keeping the frequency separation between each channel in a given cell as large as possible.
- If the frequency reuse is large (N is small), the adjacent channel interference will be high.

able limits. For example, if a close-in mobile is 20 times as close to the base station as another mobile and has energy spillout of its passband, the signal-to-interference ratio at the base station for the weak mobile (before receiver filtering) is approximately

$$\frac{S}{I} = (20)^{-n} \qquad (3.12)$$

For a path loss exponent $n = 4$, this is equal to –52 dB. If the intermediate frequency (IF) filter of the base station receiver has a slope of 20 dB/octave, then an adjacent channel interferer must be displaced by at least six times the passband bandwidth from the center of the receiver frequency passband to achieve 52 dB attenuation. Here, a separation of approximately six channel bandwidths is required for typical filters in order to provide 0 dB SIR from a close-in adjacent channel user. This implies more than six channel separations are needed to bring the adjacent channel interference to an acceptable level. Tight base station filters are needed when close-in and distant users share the same cell. In practice, base station receivers are preceded by a high Q cavity filter in order to reject adjacent channel interference.

Example

AMPS Original 1983 Channels **666**

New Service 10MHz *(1989)* Channels **166**

Total number of Channels **832**

First Channel	**666th** Channel	
Forward **870.03 MHz**	Forward **889.98 MHz**	**667** through **799**
Reversed **825.03MHz**	Reversed **844.98MHz**	**990** through **1023**

Block **A**
Nonwireline operators

Block **B**
wireline operators

21 Control Channels used over **21** cells and reuse scheme used over three clusters (**7**-cell reuse system)

Power Control for Reducing interference

- The power levels transmitted by every subscriber unit are under constant control by the serving base stations to ensure that mobile transmits the smallest power necessary to maintain a good quality link. (reverse channel).
- Power control helps :

1. Prolong battery life.
2. Reducing the reverse channel S/I.

Trunking and Grade Services

- The accommodation of larger number of users in a limited radio spectrum denoted by *trunking*

- Trade off between the number of available telephone circuits (in the telephony system) and the likelihood of a particular users finding that no circuits on the peak time

- The Grade of Service (GOS) is a measure of the ability of a user to access a trunked system during the busiest hour
- By specifying a desired likelihood of a user obtaining channel access given a specific number of channels available in the system (It's the benchmark used to design the performance of a particular trunked system)
- It's the designer's job to estimate the max required capacity to allocate the proper number of channels to meet the GOS

Table 3.3 Definitions of Common Terms Used in Trunking Theory

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

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

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

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

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

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

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

Trunking and GOS

- GOS is typically given as the likelihood that a call is blocked or experiencing a delay greater than a certain queuing delay time
- A_u is defined as a traffic intensity and is given by

  $A_u = \lambda H$ *where λ is the average number of call requests per unit time for each user, H is the average duration of a call*

- The total offered traffic intensity for U users is

  $A = A_u U$

- In a C channel trucked system, the traffic intensity per channel, A_c, is given by

  $A_c = A/C$

- The max possible carried traffic is the total number of channels, C, in Erlangs

Trunking and GOS

- AMPS system is designed for a GOS of 2% blocking
- Tow types of trunked systems

- offers no queuing for call requests (*no set up time and given immediate access to a channel if one is available or blocked if no available ones*)

* assume infinite number of users
* memoryless arrivals of requests
* exponentially distributed probability of a user occupying a channel (longer calls are less to happened)
* a finite number of channels are available in the pool

Trunking and GOS

- Erlang B formula determine the probability that a call is blocked and is a measure of the GoS for a trunked system (which provides no queuing for blocked call)

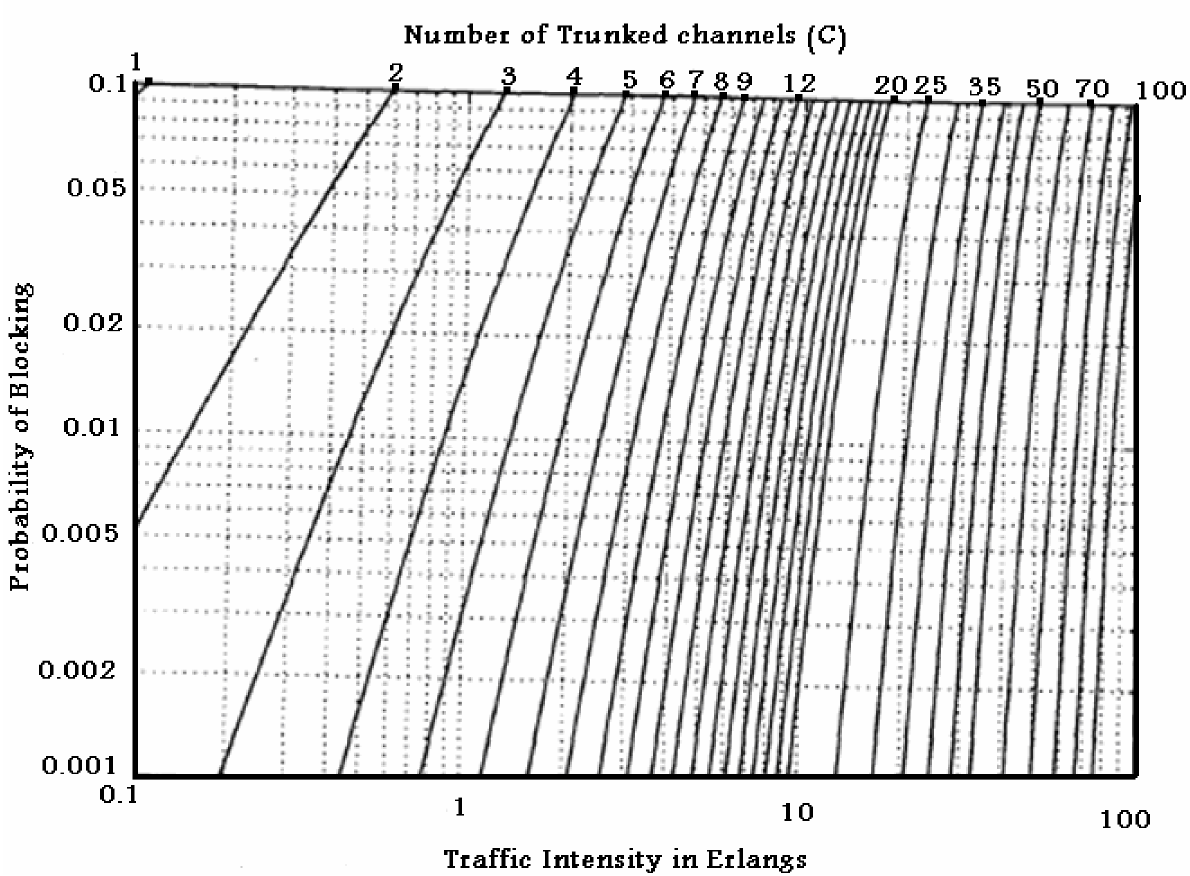
$$\Pr(Blocking) = GoS = \frac{\left(A^C / C!\right)}{\sum_{k=0}^{C-1}\left(A^k / k!\right)}$$

where **C** is the number of trunked channels offered by a radio system

A is the total offered traffic

Trunking and GOS

- Erlang B chart



Trunking and GOS

•Tow types of trunked systems

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

$$\Pr(delay > t) = \Pr(delay > 0) \times e^{\left(-\left(\frac{(C-A)t}{H}\right)\right)}$$

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

D = Pr(delay>0) [$H/(C-A)$]

Trunking and GOS

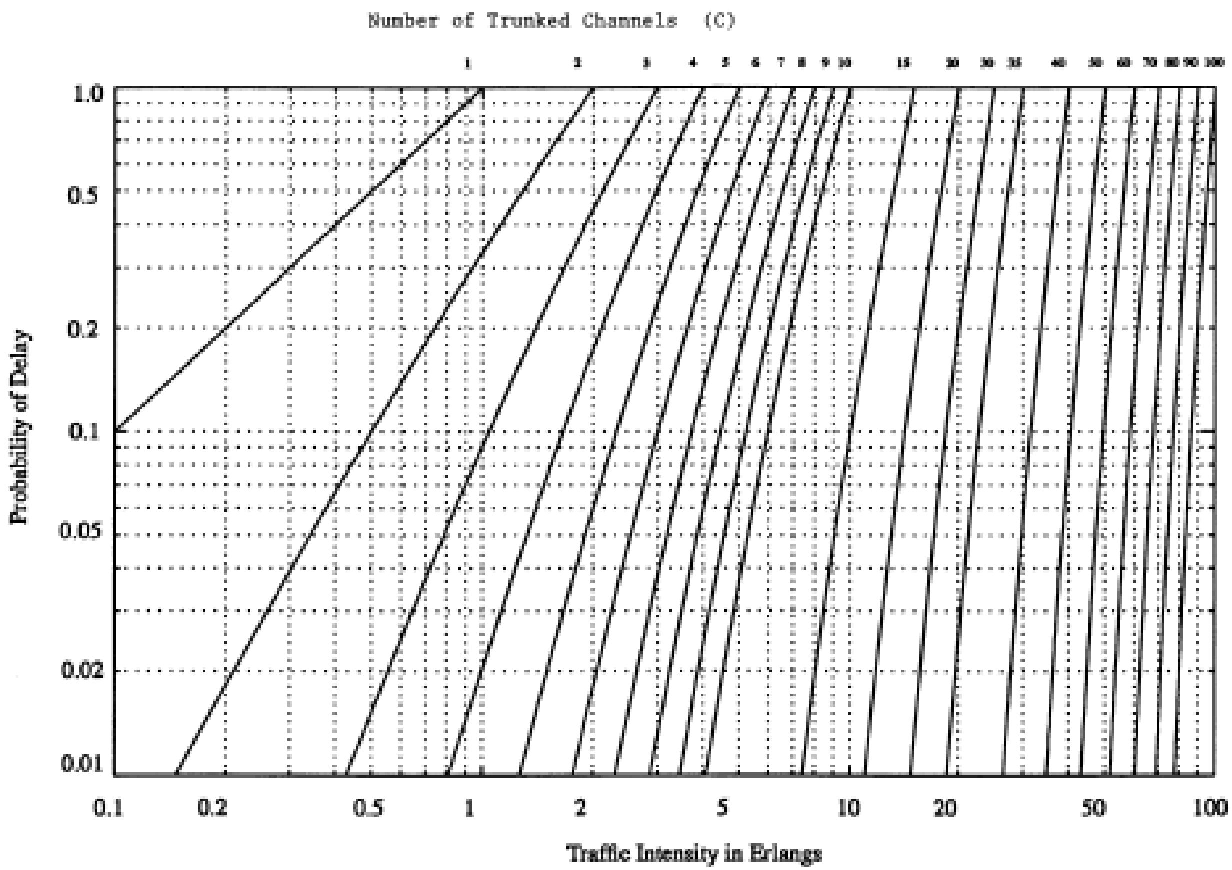


Figure 3.7 The Erlang C chart showing the probability of a call being delayed as a function of the number of channels and traffic intensity in Erlangs.

Improving Coverage and Capacity in Cellular Systems

Different techniques are used to expand the capacity of cellular systems:

1- **Cell Splitting**:

• is the process of subdividing a congested cell into a small cells, each with its base station and a corresponding reduction in an antenna height and transmitter power (using microcells increases the number of times that channels are reused).

•Cell splitting allows a system to grow by replacing a large cells with smaller cells.

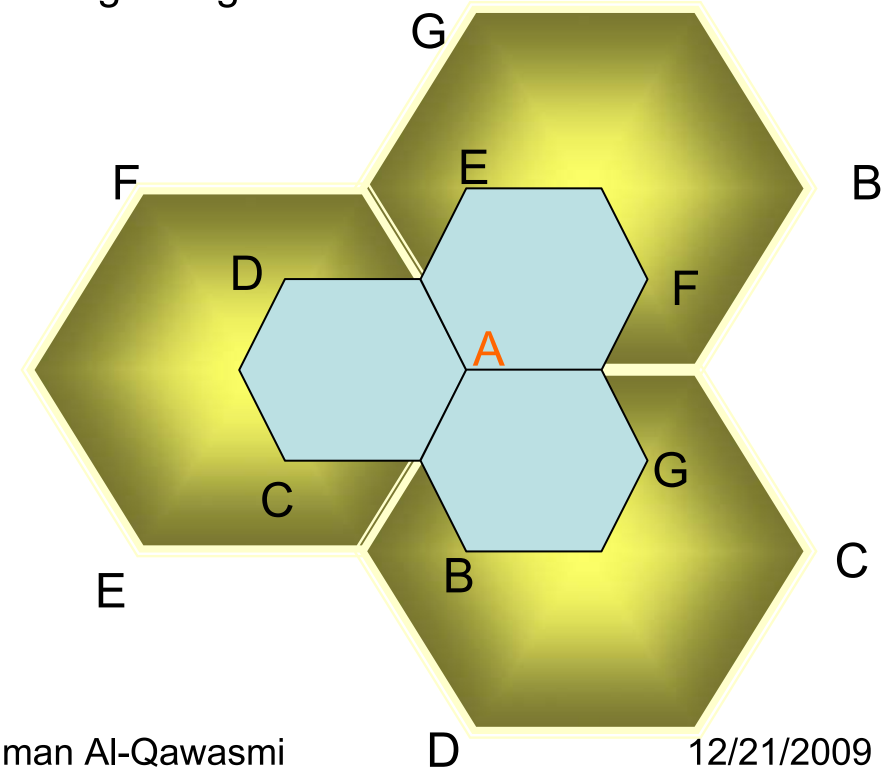
The transmit power of new cells must be reduced

P_r (at old cell boundary) $\alpha\ P_{t1}\ (R)^{-n}$,

P_r (at new cell boundary) $\alpha\ P_{t2}\ (R/2)^{-n}$

, where n is the path loss exponent, P_{t2} and P_{t1} are the transmit power of the larger and smaller cell BSs, respectively.

If the received powers are equal and n =4, then $P_{t2} = P_{t1}/16$



Improving Coverage and Capacity

2-Sectoring

- By rescaling the system the capacity can be achieved

The cell radius is kept R by sectoring try to reduce the co-channel reuse ratio D/R, thus will increase the frequency reuse

The co-channel interference increases (it can be reduced by replacing the omnidirectional antennas by directional antennas, each radiated within a specific area)

The factor by which the co-channel interference is reduced by using directional antennas depends on the amount of sectoring used

The channels used are broken down into sectored group and are used only within a particular sector

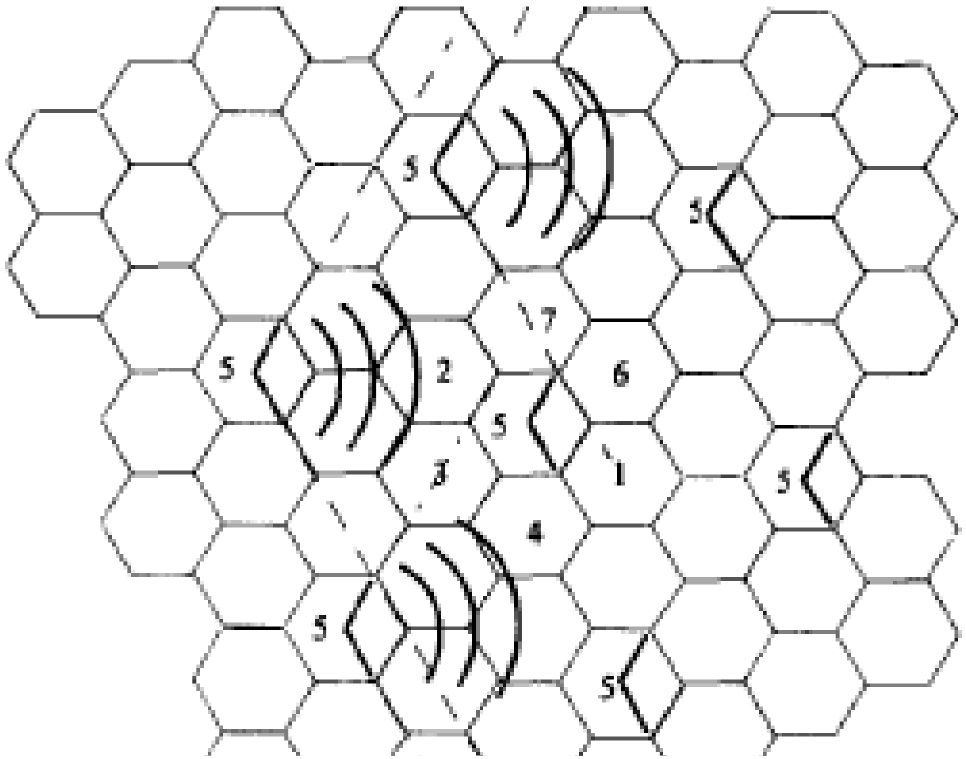
Consider the interference experienced by a mobile located in the right-most sector in the center cell labeled by 5

Out of the three in right, two have sectors radiate to interfere the sector labeled 5 in the center cell

Find S/I. its 24.4 dB which has a significant improvement over the omindirectional antenna (*worst case 17 dB*)

If N decreased, the frequency reuse is improved and thus the system capacity

Improving Coverage and Capacity



Improving Coverage and Capacity

3-Repeaters

Radio retransmitters are needed to provide dedicated coverage for hard-to-reach areas

They simultaneously send signals and received signal from a serving BS (*bidirectional*)

Doesn't add capacity to the system, but serves to radiate signals to required areas

Microcell Zone Concept

Sectoring increases the number of handoffs (results in an increased load on switching and control link elements)

As an example; shown below; each of the three zone sites are connected to a single BS and share the same radio equipment

The antennas are placed at the outer edge of the cell

As a mobile travels in this zone, it will be served by the strongest signal

Improving Coverage and Capacity

4- Microcell Zone Concept

The handoff is not required ???? (MS retains the same frequency channel, BS simply switches the channel into a different zone site)
Co-channel interference reduced (large central BS replaced by several low powered transmitters), and thus improves the signal quality