Chapter 3

The Cellular Concept

Dr. Salam A. Zummo
Associate Professor, EE

Topics

- Basics of cellular structure
- Handoff
- Interference
- Trunking
- Coverage and Capacity

The Evolution of Cellular Concept

- 1st generation mobile systems consisted of one high power transmitter covering the service area.
- The allocated spectrum was divided into a number of duplex channels.
- With time, the system was not able to accommodate more users over the same allocated spectrum.
- The *cellular* concept provides the solution for the capacity problem.
- Theoretically speaking, "cellularity" can provide as much capacity as needed (more and more channels) over a limited allocated spectrum.

The Basic Concept of Cellularity

- Replace the single, high-power transmitter covering a large area by many low-power transmitters covering smaller areas (cells).
- The available frequencies will be *re-used*.
- This way, the number of available channels over the service area equals the number of licensed channels multiplied by the number of transmitters.

The Cellular Advantage

- Cluster patterns and the corresponding frequencies are re-used in a regular pattern over the entire service area
- System Capacity (number of users that system can serve simultaneously) can be increased if C is made smaller
- Capacity can be increased by reducing the size of the cells and increasing their number

Cell Design Requirements

- **Large capacity and coverage area:**
  Accommodates a large number of mobile users who are free to move within a large geographic area.
- **Efficient resource allocation:** Fits within the limited radio spectrum for this type of service.
- System capacity depends on the number of cells and how the available spectrum is partitioned.

Cellular Systems Essential Elements

- Low power transmitters: cover small areas (cells)
- Spectrum (frequency) reuse
- Handoff:
  - Switching ongoing calls between cells (channels)

Cell Design Problem

- How to allocate frequencies so that:
  - Calls do not interfere with each other
  - Users have low probability of blocking
  - A large user pool can be accommodated given the limited spectrum

Components of Cellular Systems

- A cellular system consists mainly of:
  - Mobile station (MS)
  - Base station (BS)
  - Mobile Switching Center (MSC)

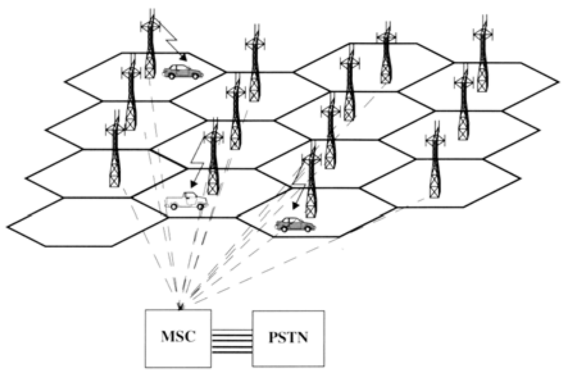


Figure 1.5 A cellular system. The towers represent base stations which provide radio access between mobile users and the mobile switching center (MSC).

Base Station (BS)

- A transmitter and receiver that relays signals (control and information - voice or data) from the mobile station (MS) to the MSC and vice versa.
- The BS is the bridge between the MS and the MSC

Mobile Switching Center (MSC)

- Controls a cluster of cells.
- Base stations are connected to the MSC via wireline or microwave links.
- The MSC is the bridge between the cellular system and the PSTN.

Forward vs. Reverse Links

- **Forward Link (Downlink):**
  The transmission path from the BS to the MS.

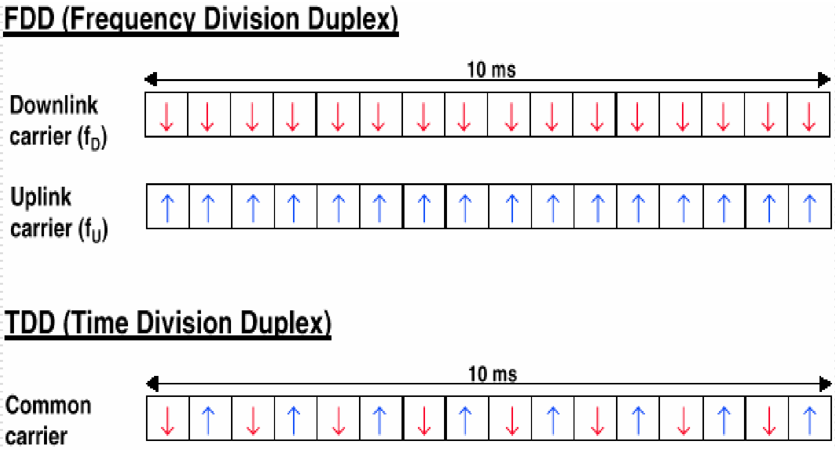
- **Reverse Link (Uplink):**
  The transmission path from the MS to the BS.

Sending and Receiving Types/Techniques

- **Types:**
  - **Simplex:** one-way communication
  - **Half-Duplex:** two-way **but** one-way at a time
  - **Full Duplex:** two-way simultaneously

- **Techniques:**
  - Frequency Division Duplex (FDD)
  - Time Division Duplex (TDD)

FDD vs. TDD



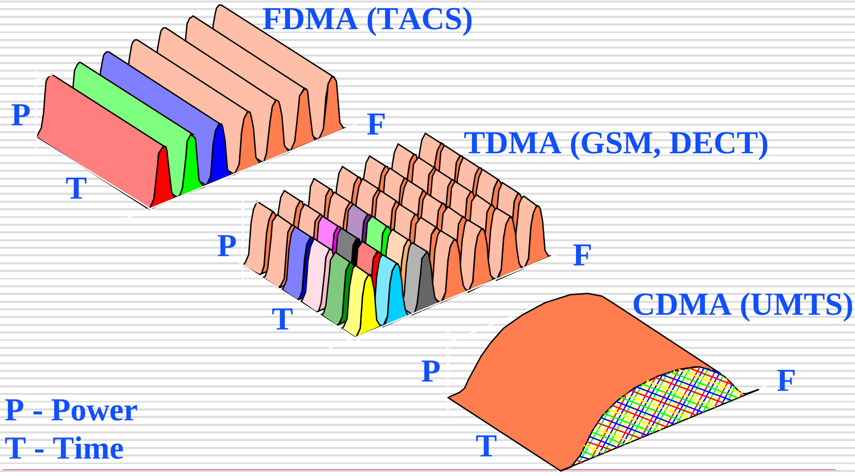
Basic Multiple Access Techniques

Used to simultaneously share a finite amount of the radio spectrum

Basic Types:

- Frequency Division Multiple Access (FDMA)
- Time Division Multiple Access (TDMA)
- Code Division Multiple Access (CDMA)

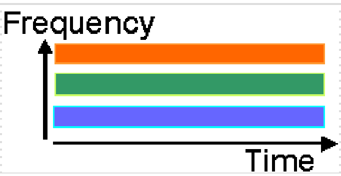
Access Techniques for Mobile Systems



P - Power
T - Time
F - Frequency

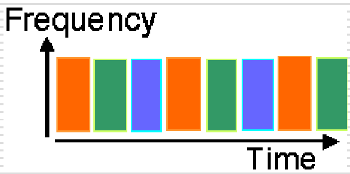
FDMA

- Each user is given a frequency slot
- He uses this frequency all the time
- Can be used in analog and digital systems
- Drawbacks:
  - Very limited capacity
  - No flexibility



TDMA

- Each user is allocated a time slot.
- Can be used only in digital systems.
- Better capacity and more flexibility than FDMA



- Drawbacks:
  - Synchronization
  - Higher peak power > short battery life
  - Need for equalization for high data rate transmission (small bit duration)

CDMA

- It is a "spread spectrum" technology.
- All users share the same range of the radio spectrum.
- All user send at the same time over the same frequency band.
- Uses unique digital codes, rather than separate RF frequencies or channels to differentiate subscribers.
- The codes are called "Pseudo-Noise" (PN) code sequences.

The Implications of Cellularity

- Interference between re-used channels

- Mobility management issues
  - Locating the users to initiate calls
  - Call handover to maintain active calls.
  - Management and billing issues.

Handling the Interference Issue

- Each transmitter (BS) is allocated a subset of the total available channels.
- Neighboring cells are allocated different sets of channels.
- Those sets of frequencies will be re-used only far enough to minimize interference level.
- This process is called *frequency reuse* or *frequency planning*.

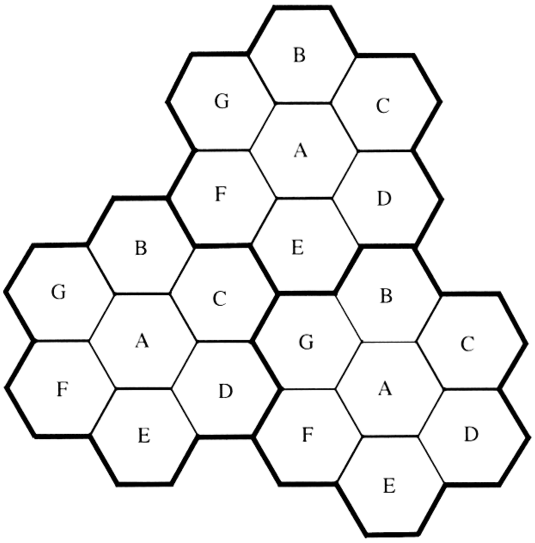


Figure 3.1 Illustration of the cellular frequency reuse concept. Cells with the same letter use the same set of frequencies. A cell cluster is outlined in bold and replicated over the coverage area. In this example, the cluster size, *N*, is equal to seven, and the frequency reuse factor is 1/7 since each cell contains one-seventh of the total number of available channels.

The Hexagon Shape?

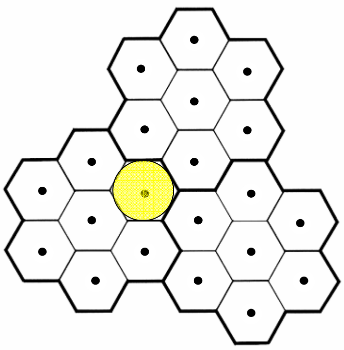
- A cell is an area over which a base station (BS) has a "good" coverage.
- Actual cell footprint is irregular.
- An intuitive regular shape of a cell would be circular.
- Circles do not lend themselves easily for coverage analysis. They will either overlap or leave uncovered areas.
- The only shapes that can be stacked perfectly are the square, triangle and Hexagon.
- Hexagon is closest to circle, in addition to some other useful features.

Cellular Definitions and Notations

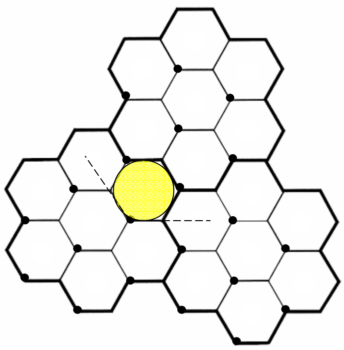
- **Cluster**: set of neighboring cells that use the available channels distinctively and exhaustively.
- **Co-channel cells**: cells in different clusters that use the same group of frequencies.
- N = the cluster size (in cells)
- $1/N$ = frequency re-use factor (*Fraction of channels used by each cell*).
- R = cell radius (distance from hexagon center to corner).
- D = distance between centers of nearest co-channel cells.

Antenna Positions

- Center-excited cells: Omnidirectional



- Edge-excited cells: Directional antennas



Cellular System Capacity

- Let the total number of channels available in the system be K,
- The number of clusters in the service area be M.
- Then:
  The system capacity $C = M \times K$ channels

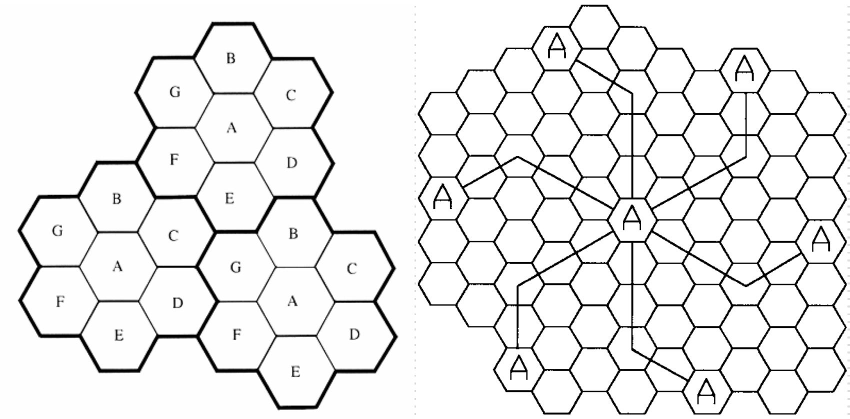
Capacity = # possible simultaneous calls

Cluster Size

- For hexagon cells, to have a uniform co-channel distance D for all cells in the system, N must obey the relation:
  $N = i^2 + i \times j + j^2 \qquad i \geq j \geq 0$
- **Regardless of the cluster size, each cell has 6 first tier co-channel cells.**
- Co-channel cells are identified from (i,j)

i	j	N
1	0	1
1	1	3
2	0	4
2	1	7
2	2	12

Co-channel cells for *N*=7 (2,1) and *N*=19 (3,2)



- *C* is proportional to *M* (since *S* is constant)
- Small cluster size results in:
  - Larger capacity (larger *M*)
  - Larger co-channel interference
- Large cluster size results in:
  - Smaller capacity (smaller *M*)
  - Less co-channel interference
- *C* is maximized by minimizing *N*

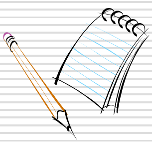
Channel Categories

- **Voice channels:**

  Carry voice traffic (~ 95%)

- **Control channels:**

  Carry data about call setup, handoff, power control and other management data (~ 5%)



Example 1

- Determine the number of channels per cell for the following cellular system for $N = 4$ and $N=7$:
  - A total of 33 MHz bandwidth is allocated to the system.
  - It is divided into 50-kHz (voice/control) channels.
  - One control channel per cell.
  - Frequency re-use factor of control channels is 3 times less than voice channels.
- Solution:
  - Total number of channels = 33000/50 = 660
  - $N = 4$:
    - 12 channels reserved for control.
    - Every cell has 648/4 = 162 voice channels and one control channel
  - $N = 7$
    - 21 channels reserved for control
    - 639/7 = 91.3. Two cells have 92 + control, five have 91 + control.

Channels Assignment Strategies

- Fixed Allocation: As in the previous example
  - Simple
  - Less efficient (higher blocking probability)
  - Can be improved by implementing a borrowing strategy
- Dynamic Allocation: All channels requested by MSC.
  - Less blockage
  - More processing

Dynamic Channel Assignment

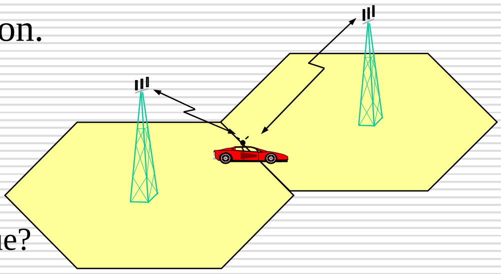
- MSC assigns a vacant channel to a BS upon request
- Takes into account interference and frequency reuse distance
- Offers higher overall capacity (smaller blocking probability)
- Harder to configure

Channel Assignment in CDMA Systems

- In CDMA systems the cluster size is N=1.
- A single 1.25 MHz channel carries the simultaneous transmission of a single control channel and up to 64 voice channels.
- In some ill-behaved propagation conditions a simple f_1/f_2 planning scheme is used:
  - Nearest neighbor cells use a frequency channel that is different from its closest neighbor in *particular* location/direction.

Handoff

- Passing an active call from one BS to another without disconnection.



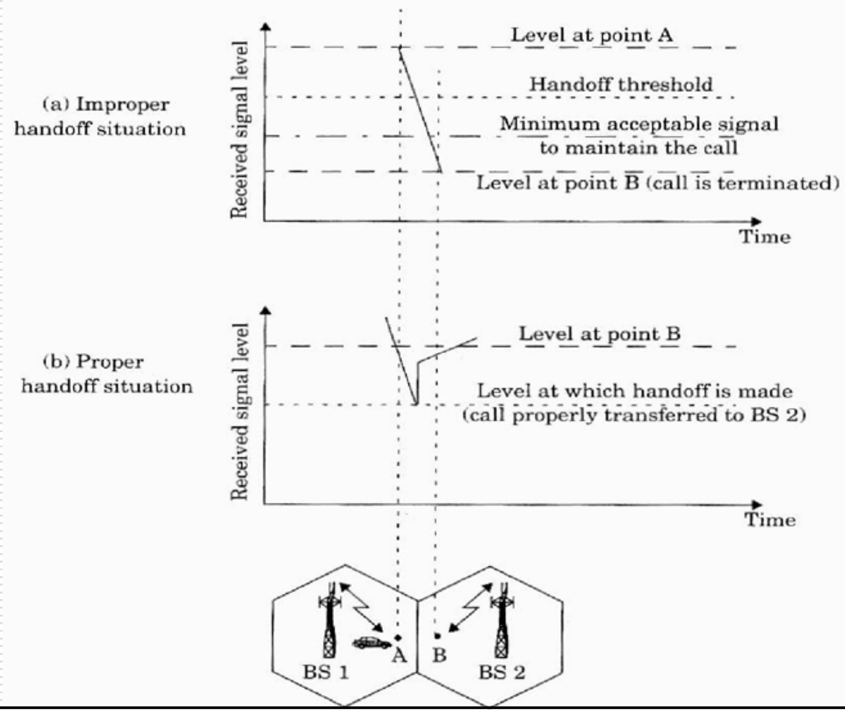
- Basic concerns:
  - When handoff is due?
  - Where to handoff?
  - How to handoff transparently?
  - Management and billing

Soft and Hard Handoffs

- **Hard Handoff:**
  - Handoff involves moving a call to another channel and another BS. (FDMA/TDMA systems)
  - MS switches to a new channel after leaving the old one (The old BS drops the MS before the new one acquires it).
- **Soft Handoff:**
  - A call is moved to a different BS (CDMA).
  - MS communicates with two BSs until handover is made.

Handoff Criterion

- The criterion for handoff is based primarily on the received signal level at the MS, Received Signal Strength Information (RSSI) (inferred from the reverse channel measurement).
- Two levels are defined: the minimum acceptable signal level to maintain a call, and the handoff threshold
  - $P_{r,\,handoff} = P_{r,minimum} + \Delta$
- Optimum signal level for handoff initiation has to be designed
  - If Δ is too large, unnecessary handoffs occur
  - If Δ is too small, insufficient time to complete the handoff
- Dwell time: the time over which a call may be maintained without handoff. It is a random time that depends on the motion of the user as well as motion in the environment.



Who does the Measurement for Handoff?

- In 1st generation cellular systems, signal measurements are done by BS and supervised by MSC.
- BS measures RSSI of calls in progress within the cell and reports to MSC
- A dedicated receiver in every BS measures RSSI in neighboring cells and reports to MSC.
- The MSC finds out that a call on frequency f_0 is getting weaker in a cell and stronger in a neighboring cell. Then, a handoff process is initiated.
- The handoff process takes around 10 seconds. Δ is in the range 6 – 12 dB.

- In 2nd Generation cellular systems, handoff decisions are mobile assisted (MAHO).
- Each MS measures received power from surrounding BSs and reports to the serving BS.
- A handoff is initiated if the power received for a neighboring BS exceeds the power received from the serving BS (i) by certain threshold or (ii) over certain period of time.
- MAHO systems are faster. The handoff process takes 1-2 seconds. Δ is usually less than 6 dB.

Prioritizing Handoffs

- A fraction of total channels is reserved for handoff requests. (More efficient with dynamic channel assignment).
- Queuing, with handoff requests given priority over new calls.

Practical Issues: False Handoffs

- Problem:
  - Sometimes the drop in signal level is momentary (fading) and does not require handoff.
- Solution:
  - Monitor the signal level for some time to detect moving-away pattern.
  - Averaging the measurements over some period may be useful as well.

Practical Issues: High Speed Users

- Problem:
  - frequent handoffs.
- Solution: Umbrella cell.
  - Large and Small cells co-located.
  - High-speed users are served by umbrella cell, while slow users are served by the microcells.
  - Sophisticated algorithms are used to evaluate and partition users according to their speeds

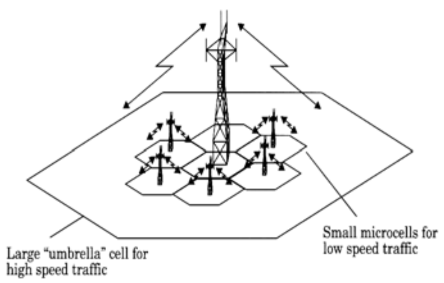


Figure 3.4 The umbrella cell approach.

Practical Issues: Cell Dragging

- Problem:
  - The signal stays strong even outside cell boarders.
  - Creates potential interference and management problems.
- Solution:
  - Handoff thresholds and coverage parameters must be adjusted.
- Note: Handoff is not required to rescue calls only. It is also required for proper overall system operation.

Intra-system and Inter-system Handoffs

- Intra-system: A handoff between BSs that are controlled by the same MSC.
- Inter-system: A handoff between BSc controlled by different MSCs.
- While Intra-system handoff are essential in any cellular system, Inter-system are not because they are not very frequent. It is acceptable that the call be disconnected while trans-crossing systems (or operators).

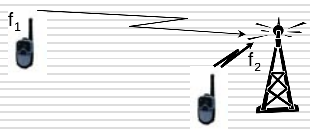
Interference

- There are many source of interference, but mainly two:
  - Co-channel Interference (from users in other cells operating at the same frequency)
  - Adjacent-channel interference (from users within cell).
- For voice channels, interference results in cross talk and background noise.
- For control channels, interference results in missed or blocked calls.

Adjacent Channel Interference (ACI)

- Results from imperfect filters which allow nearby frequencies to leak into the working passband.

- Near-far effect, due to:
  - f_1 and f_2 being near in band
  - One signal being orders of magnitude stronger than the other
  - It results in f_2 capturing the receiver of f_1.

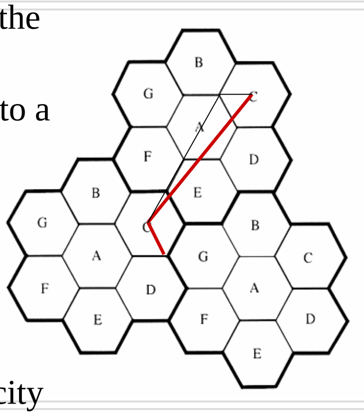


Solutions to ACI

- Filtering: High quality filters.
- Channel assignment: Channels assigned to a cell are maximally separated.
  - Sequential assignment: Guarantees N channel separation.
  - We can even prevent second tier interference by not assigning adjacent frequencies to adjacent cells (feasible for large N).
  - More efficient when N is large.
- Power Control:
  - Reduces interference
  - Prolongs battery life.

Co-Channel Interference (CCI) and Capacity

- Assumption: All BSs transmit at the same power.
- Worst case analysis: CCI caused to a user on the edge of the cell.
- CCI is a decreasing function of $Q = D/R$ (Co-channel reuse ratio)
- For a hexagon, $Q = (3N)^{1/2}$
- Small N ➔ small Q ➔ high CCI
- Small N ➔ large M ➔ high capacity



Co-channel Reuse Ratio

- **If *Q* is large,** there is:
  - A lower interference level (co-channel cells are far apart since the cluster size is large)
  - Smaller capacity
- **If *Q* is small,** the system has:
  - A higher interference level
  - A larger capacity (since the cluster size is small)

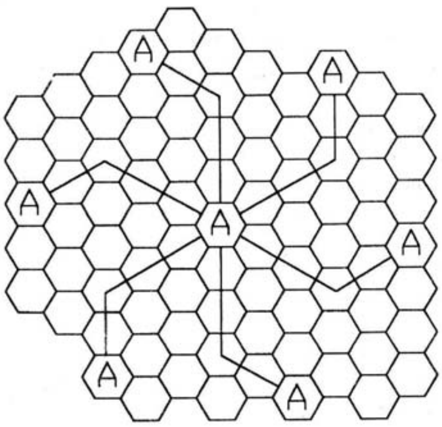
System design needs to trade off capacity and interference levels

Co-Channel Cells

$i = 3, j = 2 \Rightarrow N = 19$

To find the co-channel cells:

- Move *i* cells along any direction
- Rotate 60^o counter-clockwise and move *j* cells



Interfering Cells

- **First-tier cells:** The closest cells which use the same channels (1st-layer)
- For simplicity we only take the first tier of cells into account for co-channel interference
- 2nd, 3rd, etc. tiers, cause negligible interference (larger distances)

Model Assumptions

- The signal strength has a power law decay with distance
- Only relatively close co-channel cells will cause interference (i_o will be small)
- The forward link power level is the source of the interference

Rough *SIR* Calculations

$$SIR = S / I = \frac{S}{\sum_{i=1}^{i_0} I_i} \quad \text{(forward channel)}$$

- S = Signal power from desired BS
- I_i= CCI power from the i^{th} co-channel BS
- i_0 = the number of interferers
- As a rough calculation $P_r(d) = P_0 \left(\frac{d}{d_0} \right)^{-n}$
- P_r = received power at distance d from transmitter.
- P_0 = power at a reference point d_0 from transmitter.
- n = path loss exponent

- Substituting for S and I

$$SIR = \frac{R^{-n}}{\sum_{i=1}^{i_0} D_i^{-n}}$$

- Assuming same distance D from MS to the interferer BSs, and considering only first tier CCI (i_0 = 6)

$$SIR = \frac{(D/R)^n}{i_0} = \frac{\left(\sqrt{3N}\right)^n}{6}$$

Example 2: Draft Design

- If the minimum *SIR* for acceptable operation of a cellular system is 18 dB. Find the frequency reuse factor. Assume $n = 4$.
- $(1/6)(3N)^{n/2} > 10^{1.8}$
  $N > 6.5$. Choose $N = 7$.
  Frequency re-use factor is 1/7.
- If $n = 3$:
  Results in an SIR = 12 dB => $N = 7$ is not good
  => find higher value of N.

SIR: Better Approximation

$$SIR = \frac{1}{2(Q-1)^{-n} + 2(Q+1)^{-n} + 2Q^{-n}}$$

- For $N = 7$, $n = 4$
  Q =4.58, SIR = 17 dB
  (Exact solution = 17.8 dB)
- If SIR is to be increased, take N=9 (i=3, j=0).
  Q =5.2 , SIR = 20 dB
- This makes a reduction in capacity by 7/9.

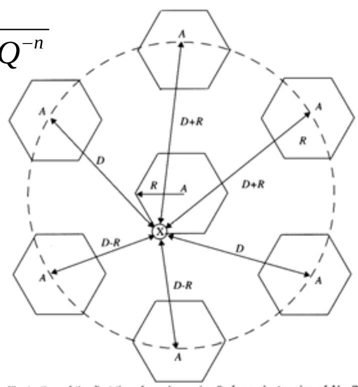


Figure 3.5 Illustration of the first tier of co-channel cells for a cluster size of $N = 7$. An approximation of the exact geometry is shown here, whereas the exact geometry is given in [Lee86]. When the mobile is at the cell boundary (point X), it experiences worst case co-channel interference on the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

Voice vs. Control Channels

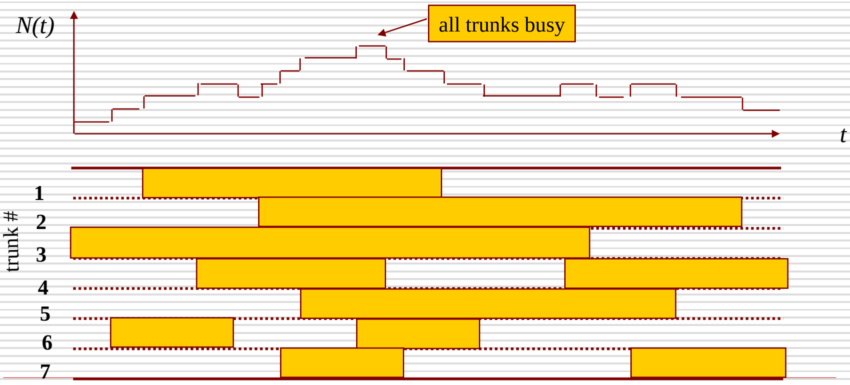
- Frequency-reuse factor is set different for voice and control channels
- Control channels are more vital
- Control channels are protected more from interference (high SIR and large Q)
- Voice channels are protected less (lower SIR and small Q)

Interference in CDMA Systems

- CCI interference is coming from other users in the same cell.
- The level of interference is a function of number of active users.
- The coverage range is dynamic/time varying
  ➔ *Breathing* cell effect.
- Power levels and thresholds have to be adjusted according to the traffic intensity.

Trunking

- A technique where a pool of channels are used to serve larger number of users on demand.



Traffic Terminology

- **Blocking**: A call is denied service due to lack of channels.
- **Traffic intensity**: measure of channel time utilization. Measured in Erlangs (E).
  - One Erlang of traffic occupies one trunk 100% of the time .
  - 0.5 Erlang = amount of traffic that is carried by a channel that is 50% of the time occupied on the average.
- **GoS**: A measure of congestion. Specified by either:
  - Blocking probability, P_B , at the Busy Hour (BH).
  - Probability a call is delayed beyond a certain amount of time.
- **Holding time**: Average duration of a typical call (H) seconds.
- **Request rate**: average number of call requests /time (λ calls/sec)

Traffic Modeling

- Offered traffic = $A_{offered} = \lambda \times H$
- Carried Traffic = $A_{carried} = \{1 - P_B\} \times A_{offered}$
- General Assumptions:
  - Memoryless arrivals of requests
  - Calls arrive according to Poisson Distribution
    - $P[N(t)=k] = \{(\lambda t)^k/k!\}e^{-\lambda t}$
  - Call duration follows an exponential distribution.
  - Infinite number of users (or much greater than number of trunks)

Models of Trunking Systems

- Blocked Calls Cleared (BCC)
  - Erlang's B Formula: probability a call is blocked
    $P_B = (A^C/C!)/(\sum_{k=0}^{C} A^k/k!)$;
    A=offered load at BH; C =# trunks
- Blocked Calls Delayed (BCD)
  - Erlang's C formula: Prob. a call is queued.

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

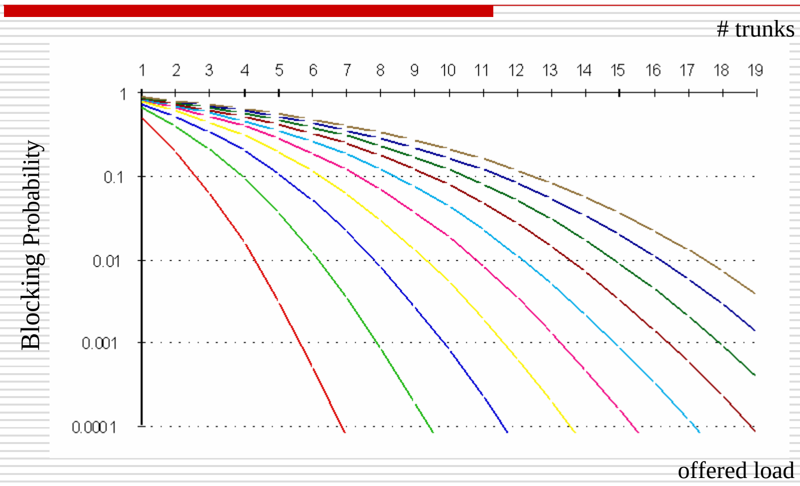
  - $P_D[\tau > t] = \Pr[\tau > 0] \times \Pr[\tau > t | \tau > 0]$
    $= \Pr[\tau > 0] \times \exp((A-C)t/H)$
  - Average delay of all calls = $\Pr[\tau > 0] \times (H/(C-A))$

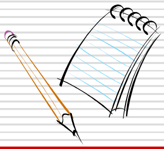
Erlang B Trunking GOS

Table 3.4 Capacity of an Erlang B System

Number of Channels *C*	Capacity (Erlangs) for GOS = 0.01	= 0.005	= 0.002	= 0.001
2	0.153	0.105	0.065	0.046
4	0.869	0.701	0.535	0.439
5	1.36	1.13	0.900	0.762
10	4.46	3.96	3.43	3.09
20	12.0	11.1	10.1	9.41
24	15.3	14.2	13.0	12.2
40	29.0	27.3	25.7	24.5
70	56.1	53.7	51.0	49.2
100	84.1	80.9	77.4	75.2

Blocking Probability Curves





Example 3

- A cell has 19 channels. Find the number of users that can be supported at 2% blocking probability, if each user makes two calls per hour on the average, and the average call duration is 3 minutes.
- For GoS = 0.02 and C = 19 ➔ A = 12 E.
  Traffic intensity per user = 2×(3/60) = 0.1 E
  Number of users supported in a cell = 120

System Capacity

- System capacity can be defined as:
  - The maximum number of channels
  - The maximum number of subscribers

Example 4

- Service Area = 1,250 sq miles.
- $N = 7$; $R = 4$ miles
- Total system BW = 40 MHz
- Full duplex channel BW = 50 kHz
- One control channel per cell. No frequency re-use.
- Traffic per user = $A_u = 0.03$ E
- Required GoS = 0.01 (Erlang B)
- Find:
  - Maximum number of users that can be served at one time.
  - Maximum number of subscribers that can be supported within this GOS?
  - Discuss the case of a CDMA system

- Cell Area = $2.589 \times R^2 = 41.57$ sq. mi.
- Number of cells = 1250/41.57 = 30
- Number of channels = 800
- Total voice channels = 770
- Number of voice ch. per cell = 110
- Ans. to first question: 110x30=3,300
- Traffic intensity/cell = A(110, 0.01) = 90 E
- Max. # of subscribers in a cell = 90/0.03 = 3,000
- Maximum number of system subscribers assuming uniformly distributed over the cells = 3000 × 30 = 90,000
- Max. % of active users = 3,300/90,000 = 3.6% of total subscribers.
- # of subscribers / channel = 90,000/770 = 117

Example on Erlang C

- $N = 4$; $R = 1.387$ km
- Total voice channels = 60
- $A_u = 0.029$ E; $\lambda = 1$ call/hour
- GoS = 5% probability delay
- Find:
  - How many users/km² the system supports?
  - Probability a delayed call will wait more than 10 sec.
  - Probability a call will be delayed more than 10 sec.

- Area of cell = 5 km^2
- Number of channels/cell = 15
- From Erlang C curves, A (15, %5 delay) = 9 E
- Supported Number of users in a cell = 9/0.029 = 310
- Number of users/km^2 = 62
- For λ=1, H = 0.029 hour =104.4 s.
- Pr[delay >10|delay] = $\exp(A-C)\times 10/H)$=56%
- Pr[delay >10] = 0.05×0.56 = 2.8%

Trunk Utilization

- $U = (1 - P_B)(A/C)$
- Table produced at 1% blockage.
- Observations:
  - The larger the offered load the better the utilization (to some extent)
  - Increased efficiency in sharing resources

Load (E)	# Trunks	*U*
1	5	0.20
2	7	0.29
4	10	0.40
8	15	0.53
10	18	0.56
30	42	0.71
50	64	0.78
60	75	0.80
90	106	0.85
100	117	0.85

- Which is favorable from capacity prospective:
  - Send 10 E over 16 trunks, or
  - Send 20 E over 32 trunks?
- From Erlang-B Table:
  - P_B (10E,16 trunks) = 2%
  - P_B (20E,32 trunks) = 0.5%
  - For 32 trunks and 2%, you can carry 23.7 E (18% more users)
- For a given service area, and a given cell area (transmitted power), it is favorable form capacity prospective to have small cluster size *N* for two reasons:
  - Each channel is used more number of times (More number of clusters)
  - More channels (trunks) per cell (higher supported traffic).

However, small *N* results in higher CCI.

Improving Coverage and Capacity

- Cell Splitting: Increase the number of BSs
- Sectoring: Antenna direction adjustment to reduce CCI.
- Zone Microcell: Antenna power adjustment to reduce CCI.

Cell Splitting

- Subdivide congested cells into smaller cells (microcells), each with its own BS, by:
  - Reduction in antenna height
  - Reduction in transmitted power.
- Capacity is increased by increasing the number of times the (channel) frequency is used (more clusters for the same service area).

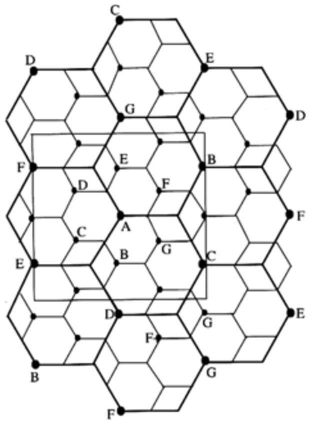


Figure 3.9 Illustration of cell splitting within a 3 km by 3 km square centered around base station A.

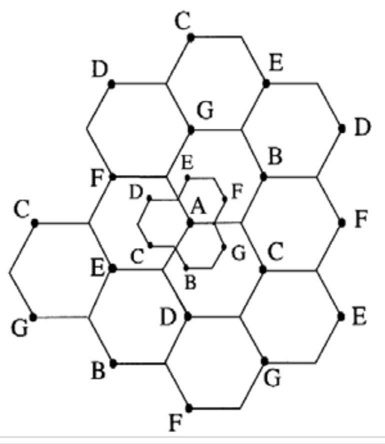
- Both R and D are reduced at the same rate. Q is not changed. *SIR* not changed.
- Depending on the new designed cell radius, the transmitted power should be re-adjusted such that:
  P_r[at new cell boundary] = P_r[at old cell boundary]
- P_r is proportional to $P_t R^{-n}$
- If the cell radius is reduced to αR, the transmitted power should be reduced by α^n
  That is $P_{t,2} / P_{t,1} = \alpha^n$
- Example: R reduced by half, n=4 ➔ $P_{t,2} / P_{t,1}$ = 1/16

How much Capacity Enhancement is Achieved?

- For reducing the radius by half, we are reducing cell area by 4; multiplying the number of clusters in the service area by 4.
- Therefore, capacity (number of channels) is quadrupled.
- At what cost?
  - Increasing the numbers of BSs (by a factor of 4).
  - More handoffs (sophistication and processing)

Different-cell-size Systems

- Not all cells have (or need) to be split.
- In this case, different-size cells exists (different transmitter powers).
- Channel assignments becomes complicated.



Sectoring

- Using directional antennas.
- Common sectoring patterns: 120^0 and 60^0
- The channels assigned to a cell are divided between the sectors.

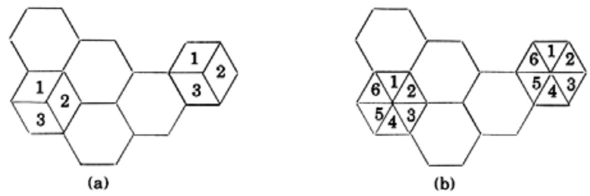


Figure 3.10 (a) 120° sectoring; (b) 60° sectoring.

Sectoring

- By using directional antennas, we reduce the number of co-channel interferers.
- For 120^0 sectoring, 1st tier interferers reduced from 6 to 2.

$$SIR = \frac{(D/R)^n}{i_0} = \frac{\left(\sqrt{3N}\right)^n}{2}$$

- Improvement of 10log3 ≈ 5 dB (using better approx. ≈ 6.4 dB).
- 60° sectoring reduces them by a factor of 6
- Improves *SIR* => can use small cluster size *N* => increase capacity

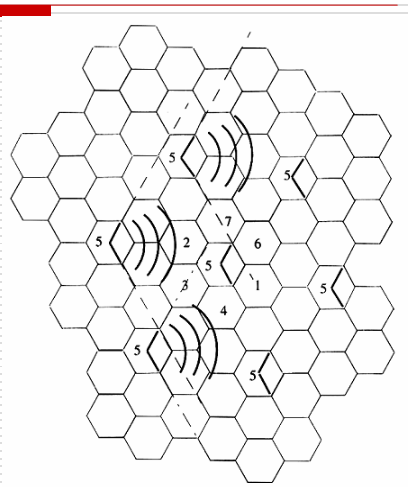
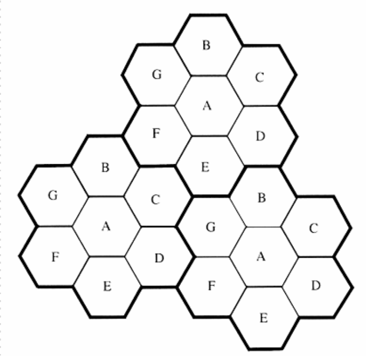
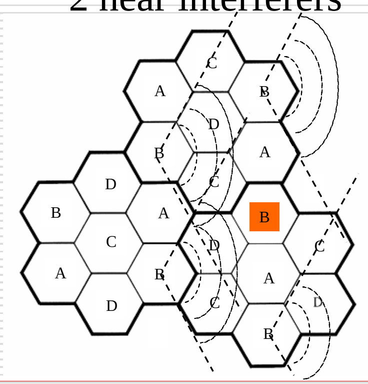


Illustration of Same CCI Scenarios

Omnidirectional
6 distant interferers

Directional
2 near interferers





Example

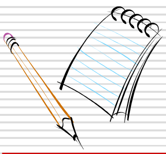
To achieve minimum SIR of 18 dB:

- **No Sectoring:**
  - Smallest cluster size is $N = 12$
- **120º Sectoring:**
  - Smallest cluster size is $N = 7$

=> 12/7 increase in capacity

How much capacity enhancement is achieved?

- For $n = 4$, we can reduce N by a factor of sqrt($10^{0.64}$)= 2.09. For example, from N=7 to N=4.
- We enhanced the capacity (number of channels) by 1.75 times, BUT ...
- Capacity (number of users) is not enhanced by the same ratio.
  - The number of channels per cell is increased (due to smaller N)
  - The three sectors will divide the cell channels among them.
  - The number of channels per sector is less than the number of channels in a cell before sectorization.
  - This results in a decrease in trunking efficiency, which leads to lowering the number of subscribers to keep the same GoS.



Example

- Given:
  - number of available voice channels = 400, n = 4, N = 7, A_u = 0.03 E. We require GoS=0.01.
- Unsectorized design:
  - number of channel/cell = 57
  - For GoS = 1% blocking, A = 44.2 Erlangs
  - For A_u = 0.03 E, number of users/cell = 1473
- For the sectored system, N = 4.
  - Number of channel/cell = 100.
  - Number of channels/sector = 33.
  - For GoS = 1%, A = 22 E. Number of users/sector = 733, per cell = 2199
- Capacity enhancement in terms of number of users = 2199/1473 = 1.5
- While Capacity enhancement in terms of number of channels = 7/4 = 1.75
- Note that in this example the sectored system still provides marginal *SIR* Over the un-sectored system.
- If we decide to utilize sectorization for the sole purpose of increasing *SIR*, then the sectored system will result in reduction in number of subscribers.

Cell Sectoring: Pros and Cons

- **Advantages:**
  - Improves the *SIR* of the system
  - A gain of ~ 7 dB is achieved over omni-directional systems when 120° sectoring is used
- **Problems:**
  - Increased handoff requirements
  - Multiple antennas are required in a BS
  - Decreased trunking efficiency (less # channel per sector)

Microcell Zone Concept

- The high-power single cell transmitter is replaced by several lower power transmitters.
- Each transmitter defines a microcell.
- All microcell transmitters are connected to the cell BS (via fiber, coax, or microwave).
- A mobile in a cell is served by one zone at any instant of time.
- Cell channels are in a pool for all zones (no sub-trunking).
- Once a channel is assigned to a zone, it is not assigned to any other zone.
- A mobile user traveling from one zone to another in the cell retains the same frequency.
- Handoff is not required by MSC when crossing zones; the BS simply hands the mobile from one transmitter to the other without changing the frequency.

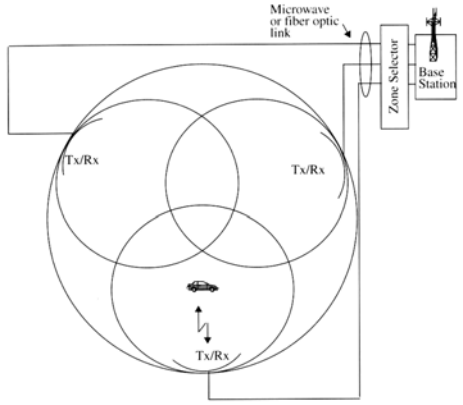


Figure 3.13 The microcell concept [adapted from [Lee91b] © IEEE].

Why Capacity Enhancement is achieved?

- Because a frequency is used in one zone only (part of the cell) at any instant of time at a lower power, the co-channel interference is generally reduced.
- Put it differently, for the same *SIR* of the normal system we can have smaller cluster size, i.e. more frequency re-use, leading to increased capacity.
- Unlike sectoring, no sub-trunking is done within the cell. Therefore the gain from reducing cluster size is intact.

Example

- The minimum required SIR for system operation is 18 dB.
- Consider a 7-cell structure.

$$SIR = \frac{1}{2(Q-1)^{-n} + 2(Q+1)^{-n} + 2Q^{-n}}$$

- $Q = D/R = 4.6$
- If we maintain $D_z / R_z = 4.6$, we maintain 18 dB.
- Let's approximate circles by hexagons in the following skecth.

- $R_z = R/2$
- For $D_z/R_z = 4.6$
  $D/R \approx 3$ (show)
- So, $N = 3$
- N reduces from 7 to 3.
- Channel expansion= 7/3
- User Expansion = 7/3
- Cost: Smarter BSs.

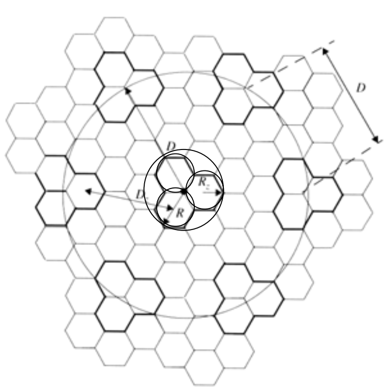


Figure 3.14 Define D, D_z, R, and R_z for a microcell architecture with $N = 7$. The smaller hexagons form zones and three hexagons (outlined in bold) together form a cell. Six nearest co-channel cells are shown.

Repeaters

- Used to extend coverage of a BS in covered or shadowed areas
- A repeater can be used for the whole spectrum
- Distributed Antenna System (DAS):
  - Provides directional coverage at input/output of a repeater (Rx/Tx)
- Do not add capacity to system
- Usually used in buildings

Power Control

- Use of power control is to reduce:
  - Power consumption => long battery life
  - Interference => higher capacity
- Both MS's and BS's operate at the lowest power level that will maintain an acceptable signal quality
- Vital for the operation of CDMA systems
- Done through steps of power levels
- Two types: **Open-loop** and **Closed-loop**

Open-Loop Power Control

- Depends solely on MS; no feedback from BS
- BS continuously sends a pilot signal for phase and channel estimation
- MS monitors the received power level
- MS adjusts its uplink power level accordingly
- **Assumption:** uplink and downlink channels are highly correlated
- Not as accurate as closed-loop
- Quick reaction to rapid signal fluctuations
- Essential in CDMA systems to make received signals of users equal in power

Closed-Loop Power Control

- MS measures signal strength or quality and passes the information to the BS.
- BS decides on adjusting power levels based on different metrics such as:
  - Rx signal power level or Rx SNR
  - Rx bit error rate
- BS sends command to MS via a control channel to adjust its power level
- Used in GSM with 8 power levels
- More accurate
- Slow and more complex to implement