Cellular Communication

Technical Challenges of Wireless Comm.

- Wired and wireless communications
  - Medium
  - Capacity
  - Communication range
  - Delay in transmission
  - BER
  - Quality
  - Interference and crosstalk
  - Energy consumption

- Wireless and mobile communications
  - A, f, and Φ are fixed with time. In mobile any of three, or all of three are time dependent – accounts for Doppler shift

Technical Challenges contd…

- Multipath propagation
- Spectrum limitations
- Energy limitations
- User mobility
- Noise and interference limited systems

Cellular Concept–

System Design Fundamentals

Cellular telephone system

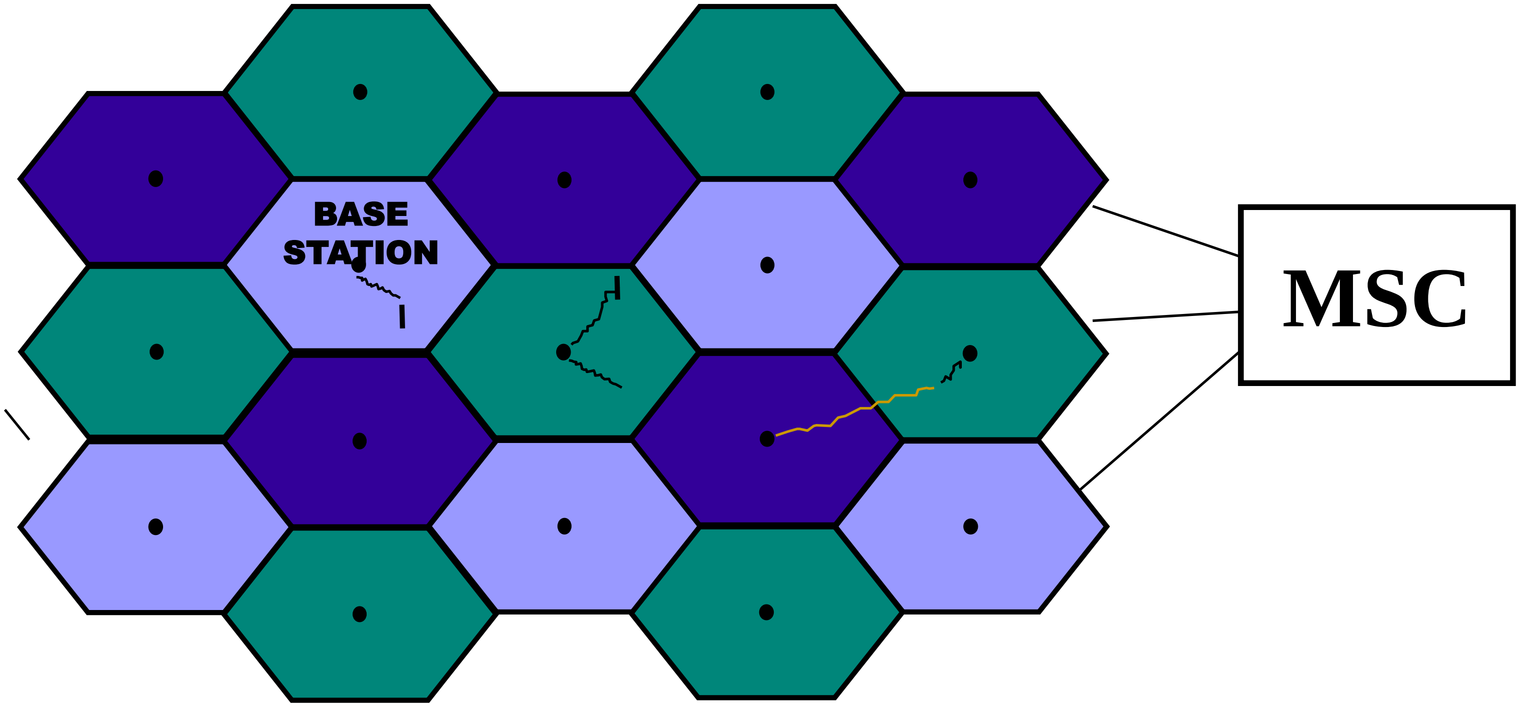
- Limitations in conventional mobile phone system

1. Limited service capability (handoff)
2. Poor service performance (33 channels to MTS / 50 mi dia) – high blocking probability
3. Inefficient frequency spectrum utilization (each channel can serve only one user at a time in whole area)

- Cellular came into picture (1971) – spectrally efficient
- AMPS (1983-Bell labs) – first installed system in U.S.
- Many low power Txs, each to serve only a small area called "Cell"
- Each cell is assigned a portion of the available spectrum called "channels"
- Same channels could be reused in different cells with sufficient distance

Cellular principles

- Low power Txs. and small coverage zones
- Frequency reused at spatially-separated locations



Introduction

- Underlying technology for mobile phones, personal communication systems, wireless networking etc.

- Developed for mobile radio telephone
  - Replace high power transmitter/receiver systems

  - Use lower power, shorter range, more transmitters

Cellular Network Organization

- Multiple low power transmitters
  - 100w or less
- Area divided into cells
  - Each with own antenna
  - Each with own range of frequencies
  - Served by base station
    - Transmitter, receiver, control unit
  - Adjacent cells on different frequencies to avoid interference or crosstalk

The Cellular Concept

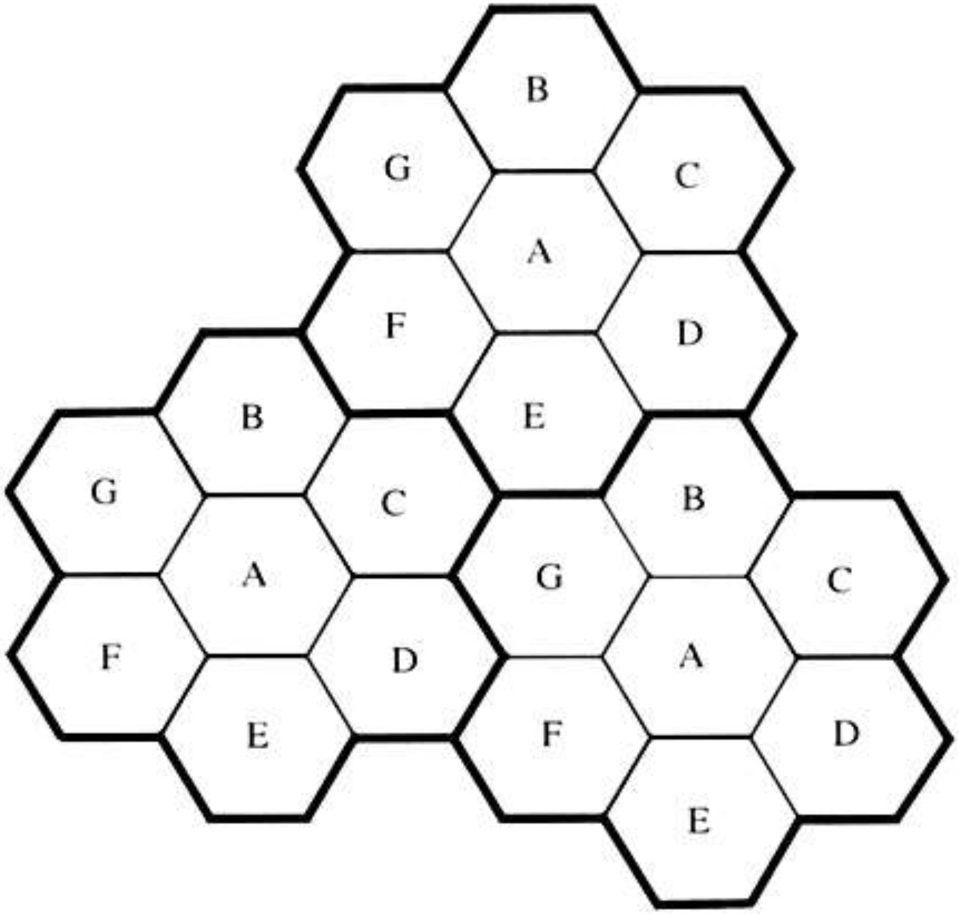


Illustration of the cellular frequency reuse concept. Cells with the same letter use the same set of frequencies. A cell cluster is outlined in bold and replicated over the coverage area. In this example, the cluster size, *N*, is equal to seven, and the frequency reuse factor is 1/7 since each cell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

Shape of Cells (1)

-Hexagonal shape of a cell is a conceptual model.

-Hexagon permits easy and manageable analysis of a cellular system.

-Choices of coverage as per radiation:

+Circle

+Square

+Equilateral triangle

+Hexagon

Requirement:

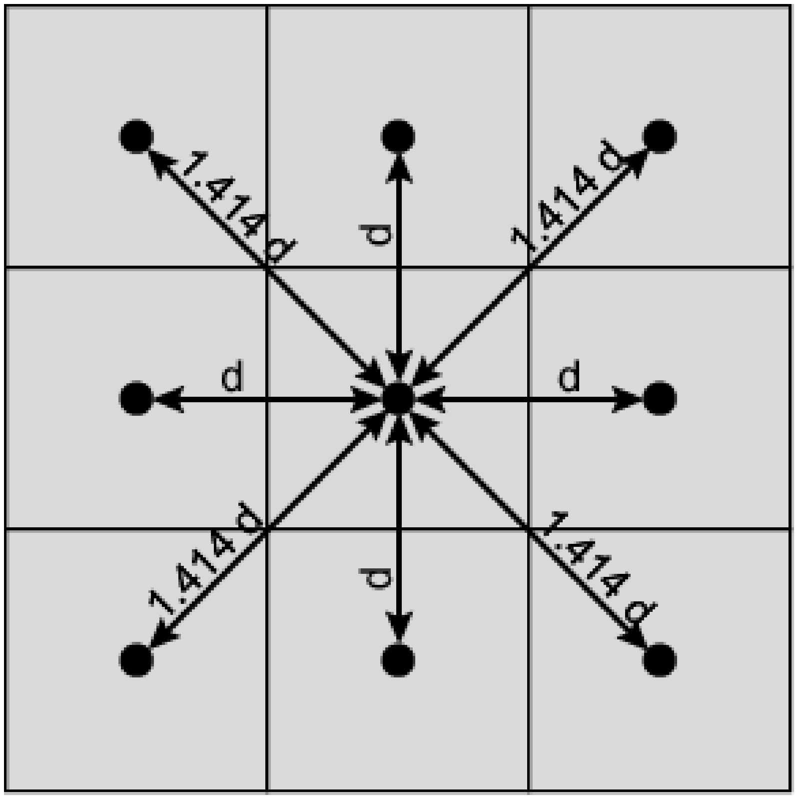
-Large coverage area without overlapping and leaving space,

-Service to weakest mobiles within the footprint.

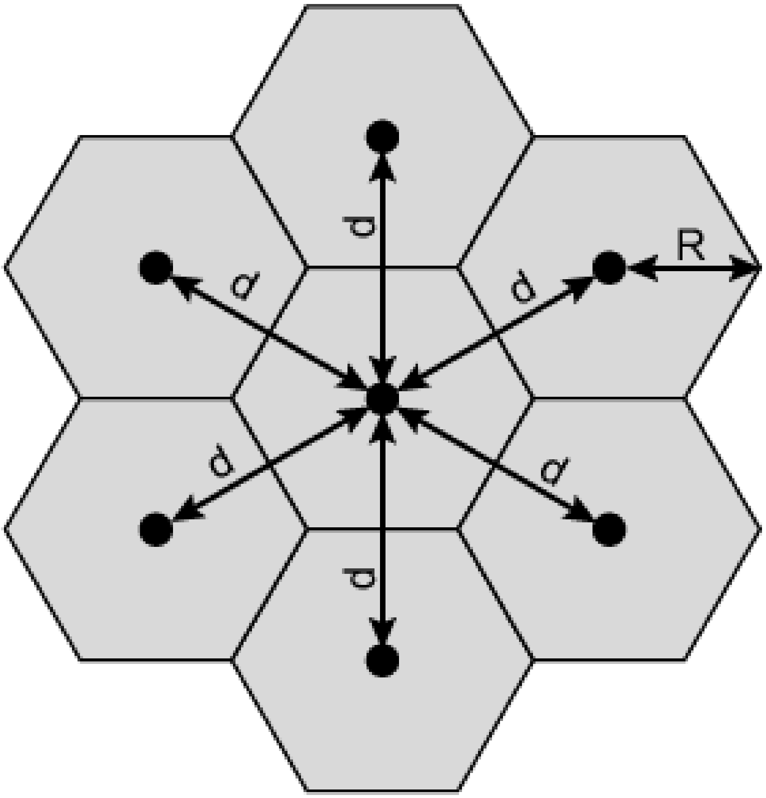
Shape of Cells (2)

- Square
  - Width d, cell has four neighbours at distance d and four at distance $\sqrt{2}\ d$
  - Better if all adjacent antennas equidistant
    - Simplifies choosing and switching to new antenna
- Hexagon
  - Provides equidistant antennas
  - Radius defined as radius of circum-circle
    - Distance from centre to vertex equals length of side
  - Distance between centres of cells radius d is $\sqrt{3}\ R$
  - Not always precise hexagons
    - Topographical limitations
    - Local signal propagation conditions
    - Location of antennas

Cellular Geometries



(a) Square pattern



(b) Hexagonal pattern

Solution:

-For a given distance between the centre of a polygon and its farthest perimeter points, the hexagon has the largest area out of three. (Square, Triangle & Hexagon)

-With hexagon fewest number of cells can cover a geographical region.

-Hexagonal cell can be approximated as circle

→ Omni-directional base station antenna.

Frequency Reuse & Cluster Size

Cellular system with

$S \longrightarrow$ Duplex channels available

$k \longrightarrow$ Group of channels allocated for each cell

$N \longrightarrow$ Number of cells

so, $S = kN$

$N \longrightarrow$ Cluster size

$M \longrightarrow$ No. of times cluster is repeated

so, Total No. of duplex channels

Capacity $(C) = MkN = MS$

Typical cluster size $\longrightarrow$ 4,7, or 12

As per geometry of hexagon No. of cells per cluster, N, can have only such values which satisfies

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

$i, j, \longrightarrow$ non negative integers

$i=j=1$	$N=03$
$i=1, j=2$	$N=07$
$i=2, j=2$	$N=12$

Interference & System Capacity

Interference: A major limiting factor in the performance of cellular radio system.

Sources
- Mobile in same cell
- Call in progress in neighbouring cell
- Other base station operating at same frequency
- Non cellular systems that leaks energy in cellular

Types

Co-channel → Physical Distance Should be large enough To isolate

Adjacent Channel → Proper Filtering & channel assignment

Co-channel Interference

- Cells using the same set of frequencies are called co-channel cells

- Co-channel cells are separated with distance to reduce interference

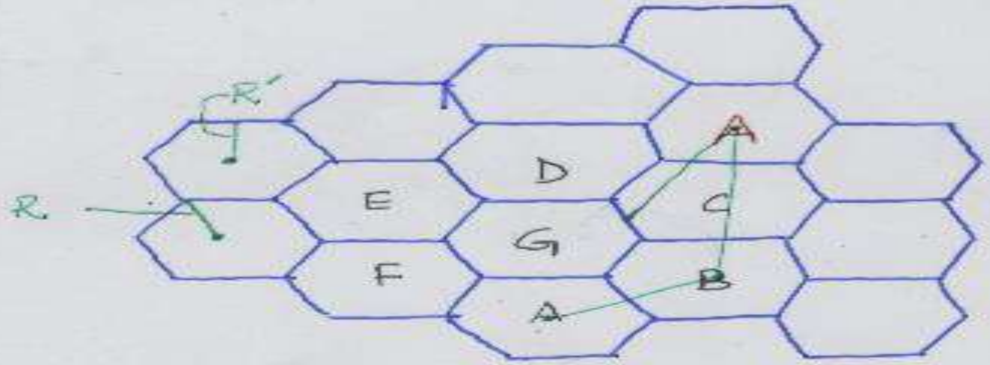
- Cell radius = R; Distance b/w centres of co-channel cells = D

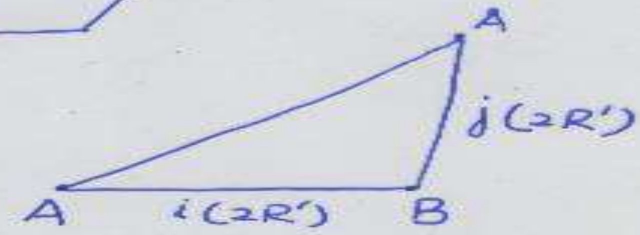
- Increasing D/R=Q (Co channel reuse ratio)
  $\longrightarrow$ Reduction in interference (Isolation in RF energy)

- For hexagon geometry,

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

Find nearest Co-channel neighbors of a particular cell.





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

(i) Move i cells along any chain of hexagons & then
(ii) turn to 60° counter clockwise and move j cells.

Using Cosine law:

$$D^2 = [i(2R')]^2 + [j \cdot (2R')]^2 - 2i(2R') \cdot j(2R') \cdot \cos 120^\circ$$

where $R' = \frac{\sqrt{3}}{2} R$

$$\therefore \quad D = \sqrt{3i^2R^2 + 3j^2R^2 + ij\,3R^2} = \sqrt{3N} \cdot R$$

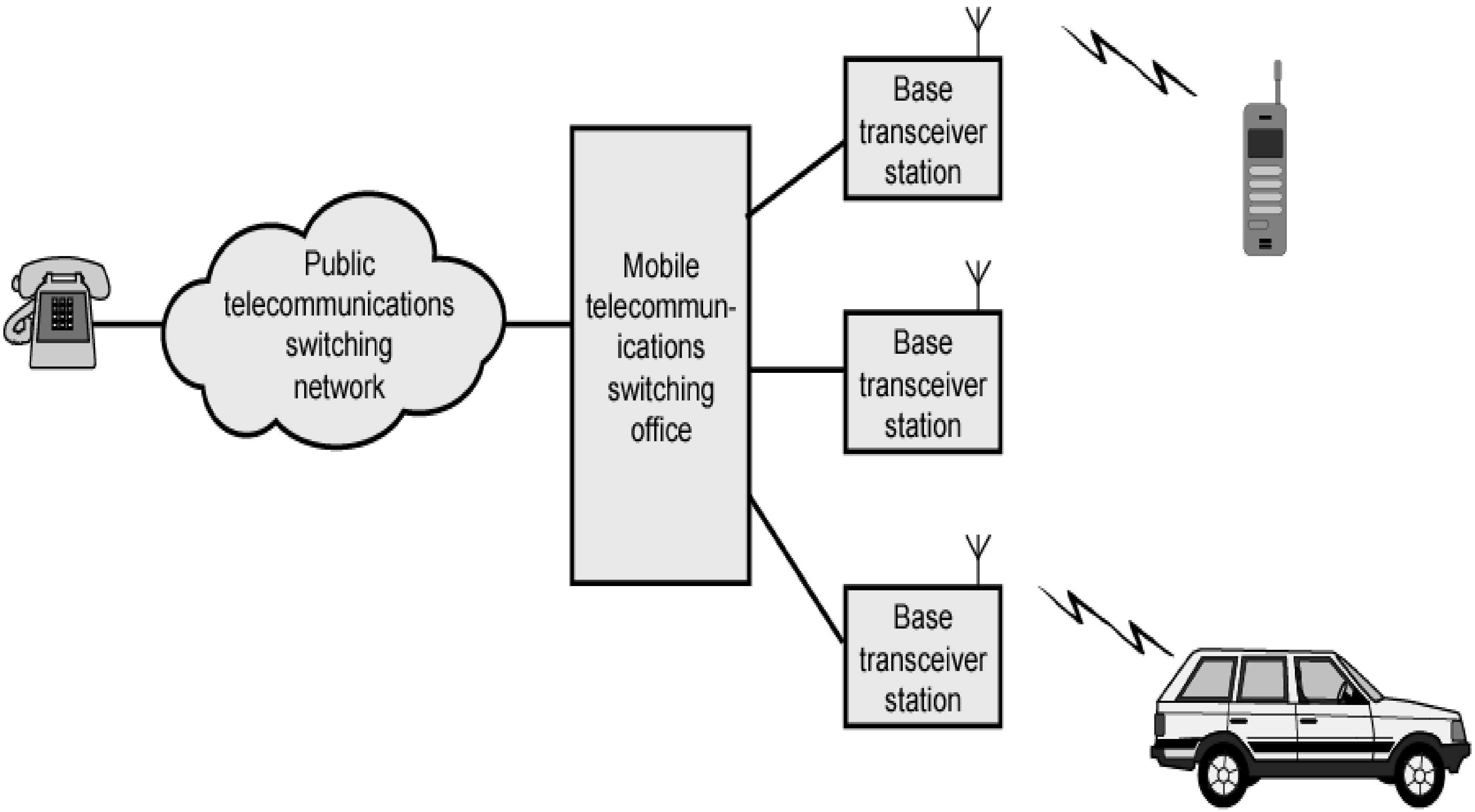
Hence $Q = \frac{D}{R} = \sqrt{3N}$

Smaller N (i.e. small value of Q) provides greater capacity, whereas larger value of Q improves transmission quality (due to smaller level of co-channel interference). TRADEOFF is required.

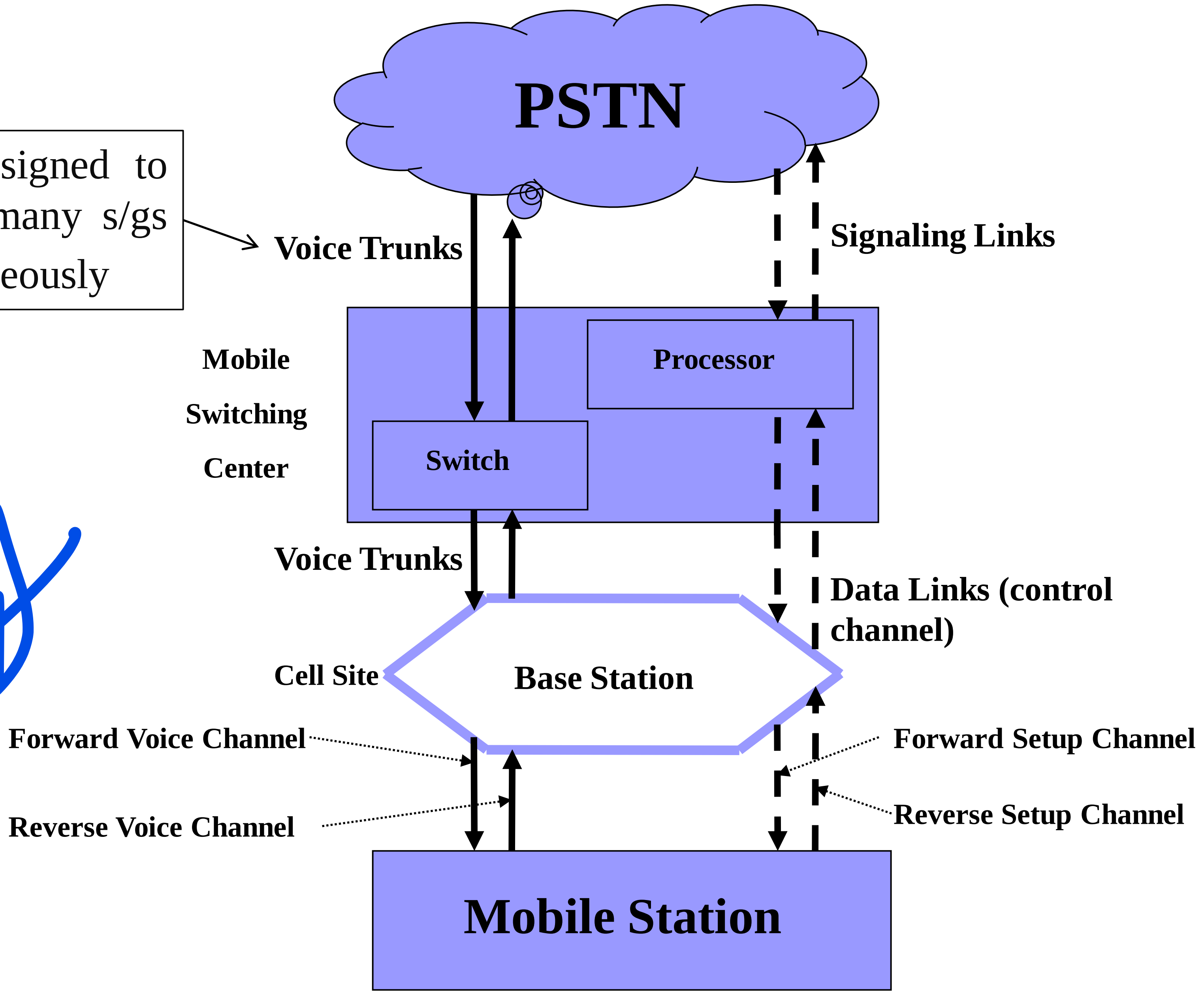
Co-channel Reuse Ratio for Some Values of N

	Cluster Size (N)	Co-channel Reuse Ratio (Q)
$i = 1, j = 1$	3	3
$i = 1, j = 2$	7	4.58
$i = 2, j = 2$	12	6
$i = 1, j = 3$	13	6.24

Overview of Mobile Cellular System



Link designed to handle many s/gs simultaneously



Mobile Cellular System Components

- Mobile Station (MS)

- Base Station (BS)

- Mobile Switching Center (MSC) or MTSO

Mobile telephone switching office

Mobile Station

Components:

- Transmitter
- Receiver
- Antenna
- CPU and Battery
- End User Interface

Base Station (BS)

- Each cell has a base station at its center.
- Interfaces with MSC using voice trunks.
- Communicates with MS using RF energy.

Functions:

- RF transmission of information to MS and RF reception from MS.
- Voice processing.
- Actual handoff.

Components:

- Voice radios
- Setup radios
- Locate radios
- Antennas
- Voice trunks to MSC
- Data link to MSC

Mobile Switching Center (MSC)

- Central point of control in the cellular system.
- Controls:
  + All or subset of BS.
  + Interfaces BS to PSTN

Functions:

- Allocation of radio channels and voice trunks to the cellular system.

- Coordination of paging and handoff.

- Communication with other cellular entities such as Databases (VLR, HLR, etc.)

- Performance monitoring, fault recognition.

- Switching of voice calls to and from PSTN.

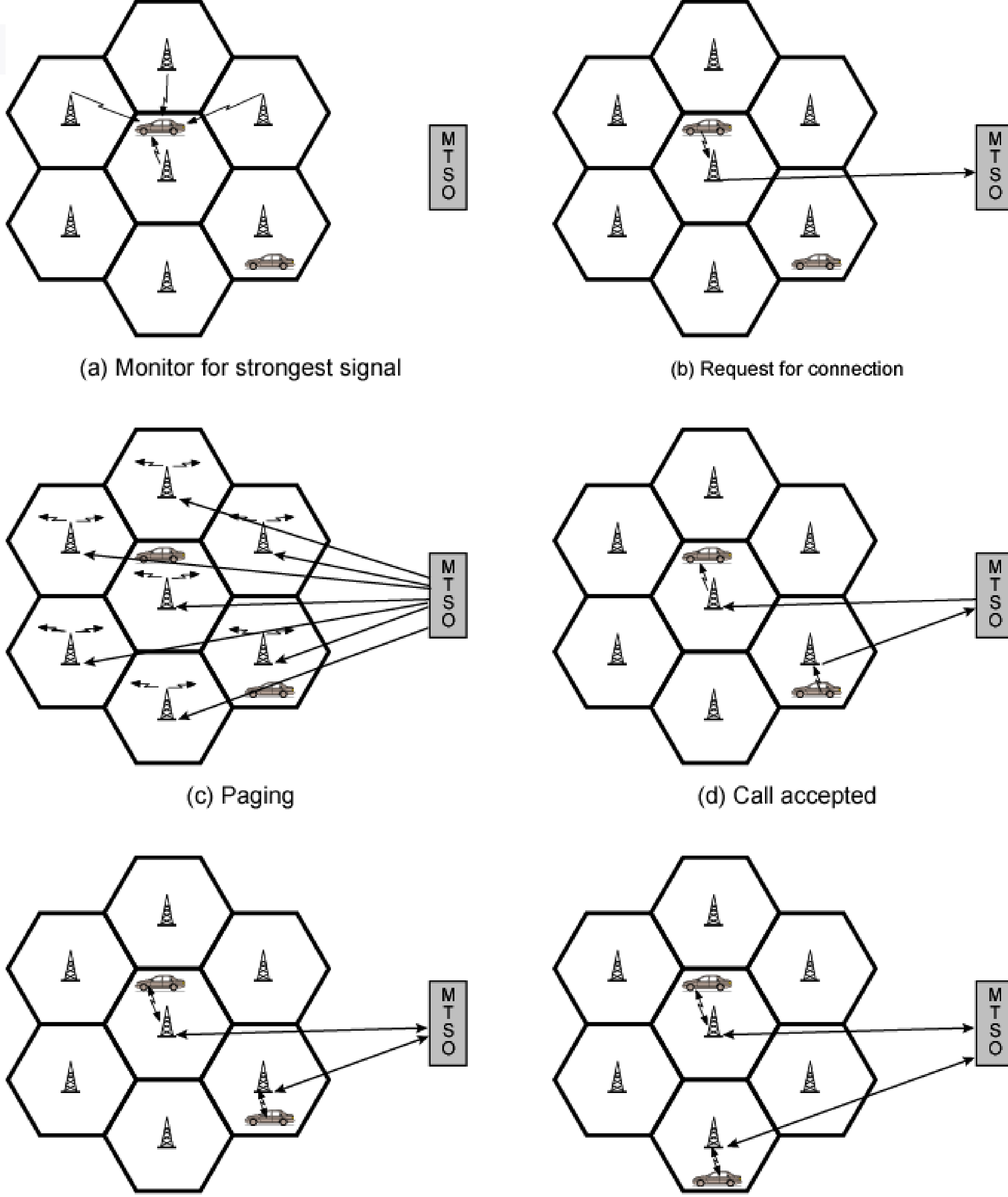
- Switching of voice calls to and from other cellular systems.

-Control of signaling functions for call establishment.

- Collection of billing data.

Channels

- Control channels
  - Setting up and maintaining calls
  - Establish relationship between mobile unit and nearest BS
- Traffic channels
  - Carry voice and data



(a) Monitor for strongest signal

(b) Request for connection

(c) Paging

(d) Call accepted

(e) Ongoing call

(f) Handoff

Wireless communication: some background

- Three general ranges of frequencies are of interest:
- 30 MHz – 1 GHz
- 1 GHz – 40 GHz
- $3*10^{11} – 2*10^{14}$ Hz

- Line of sight path (LoS) – Rician fading
- Non LoS path – Rayleigh fading

Free space propagation

- Free space path loss (LoS path loss): $\mathbf{P_L}$ is expressed in terms of ratio od radiated power (P_t) to the received power (P_r), i.e. P_t / P_r
- $EIRP = P_t.G_t$ (1)
- Power density at distance d (w/m^2)

$\rho = P_t.G_t /4\pi d^2$ (2)

- Power captured by Rx antenna at distance d

$P_r(d) = (P_t.G_t /4\pi d^2) * A_e$ (3)

- $A_e = Gr.\ \lambda^2 / 4\pi$ (4)
- Hence $P_r(d) = P_t.G_t.Gr.\lambda^2 / (4\pi)^2 d^2$ (5)
- $\mathbf{P_L\ (dB)} = 10\log (P_t / P_r) = 10\log [(4\pi)^2 d^2 / \lambda^2]$ (6)

Free space propagation

- $\mathbf{P_L\ (dB)} = 10\log (P_t / P_r) = 10\log [(4\pi)^2 d^2 / \lambda^2]$ (6)
- $P_L\ (dB) = 10\log [(4\pi d)^2 * f^2] / (3*10^8)^2$

  $= 20 \log 4\pi + 20 \log d + 20 \log f – 20 \log (3*10^8)$
- $P_L\ (dB) = 22 – 170 + 20 \log f\ (Hz) + 20 \log d\ (m)$ (7)
- $P_L\ (dB) = 32.4 + 20 \log f\ (MHz) + 20 \log d\ (km)$ (8)

- For other than isotropic antennas
- $P_L\ (dB) = 169.54 + 20\log d(km) - 20\log f(MHz) – 10\log A_T A_R$ (9)
  - $A_T A_R$ - effective area of Tx and Rx antenna

Free space propagation

- This model is only a valid predictor for values of d, which are in the far-field region of Tx antenna
- The far-field region (or Fraunhoffer region) is defined as the region beyond the far-field distance (d_f)
- $d_f = 2D^2 / \lambda$ 10(a)
- Additionally, to be in the far-field region, d_f must satisfy:
- $d_f >> D$ 10(b)
- & $d_f >> \lambda$ 10(c)

Free space propagation

- Large scale propagation models use a close-in distance d_0 (free space prop. distance), as a known received power reference point
- The received power $P_r(d)$ at any distance $d > d_0$, may be related to P_r at d_0 *[$P_r(d_0)$ may be calculated using eq. 5]*
- $\mathbf{d_0}$ is chosen such that $\mathbf{d \geq d_0 \geq d_f}$

1. It lies in the far-field region
2. Smaller than any practical distance used in mobile communication

- Using eq. 5, the received power in free space at any distance d
- $\mathbf{P_r(d) = P_r(d_0)*(d_0/d)^n}$ (11) [n = 2, path loss exponent for free space]
- $P_r(d)_{\mathbf{dbw}} = 10 \log [P_r(d_0)/1w] + 20 \log (d_0/d)$, (12) where $P_r(d_0)$ is in unit of watts
- $P_r(d)_{\mathbf{dbm}} = 10 \log [P_r(d_0)/0.001w] + 20 \log (d_0/d)$, (13) where $P_r(d_0)$ is in unit of milli watts

- **Signal to interference ratio (S/I or SIR) for a mobile receiver**

$$\frac{S}{I} = \frac{S}{\sum_{i=1}^{i_0} I_i}$$, i_0=Co channel interfering cells

S – desired signal power from BS

I_i – interference power caused by the i^{th} interfering co-channel cell BS

- From the power law of distance,

Avg. received power P_r at distance d from Tx antenna

$$P_r = P_0 (d/d_0)^{-n}$$

or $$P_r (dBm) = P_0 (dBm) - 10n \log (d/d_o)$$

Where P_0 = Power received at a close-in reference point in the far field region of the antenna at a small distance d_o from the transmitting antenna.

n = Path loss exponent

-For equal power transmission with same value of n

$$\frac{S}{I} = \frac{R^{-n}}{\sum_{i=1}^{i_0}(D_i)^{-n}}$$, i_0=Co channel interfering cells

- For first layer:
  - + All interfering base stations are equidistant = D
    - so, $S/I = (D/R)^n / i_0 = (\sqrt{3N})^n / i_0$

- This equation relates S/I to N, which in turn determines the overall system capacity, C = MKN

- This equation is based on hexagonal cell geometry where all the interfering cells are equidistant from the BS receiver, and hence provides an optimistic result.

Cell geometry layout for N = 7

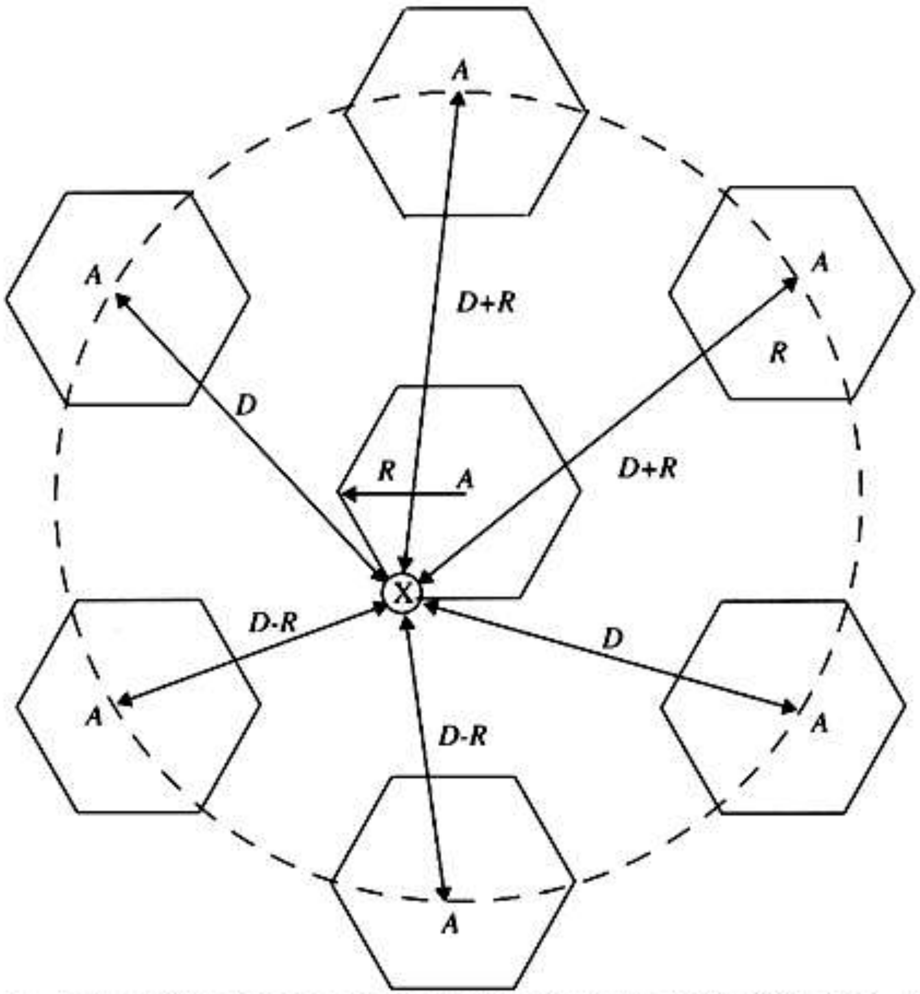


Illustration of the first tier of co-channel cells for a cluster size of $N = 7$. An approximation of the exact geometry is shown here, whereas the exact geometry is given in [Lee86]. When the mobile is at the cell boundary (point X), it experiences worst case co-channel interference on the forward channel.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

- Using the approximate geometry and n =4, SIR for the worst case:
- $S/I = R^{-4} / 2(D-R)^{-4} + 2(D+R)^{-4} + 2D^{-4}$
- $S/I = 1 / 2(Q-1)^{-4} + 2(Q+1)^{-4} + 2Q^{-4}$

- For N = 7, Q = 4.6   S/I ≈ 17.8dB, for n = 4

- For proper system design N should be increased

e.g. N = 9   i = 0   j = 3

- Co channel interference determines link performance

⇨ Dictates frequency reuse plan

→ (Over all system capacity.)

Improving Coverage & Capacity

- 3 techniques are used: Cell splitting, Sectoring, and Coverage zone concept
  - ✓ Cell splitting
    - allows orderly growth of cellular system
    - increases the number of BSs to increase capacity
    - do not suffer the trunking inefficiencies
    - reduces the computational load at MSC
  - ✓ Sectoring
    - uses directional antennas to further control the interference and frequency reuse
    - rely on BS antenna placements to improve capacity by reducing co-channel interference
    - suffer the trunking inefficiencies
  - ✓ Microcell zone
    - distributes the coverage of a cell and extends the cell boundary to hard-to-reach places
    - rely on BS antenna placements
    - do not suffer the trunking efficiencies

Trunking Interference

When multiple users use same frequency in a trunked radio system

Cell splitting

- Non-uniform distribution of topography and traffic
- Congested cells are subdivided into smaller cells
- Each cell has its own BS and a corresponding reduction in antenna height and Tx power (increases the capacity, since it increases the number of times channels can be reused.)
- Maintains Q (not upsetting channel allocation scheme)
- If cell radius is cut in half, approx. 4 times as many cells are required to cover the same area (area $\approx \pi R^2$)

- The cell which is saturated with traffic is splitted into smaller cells without changing the geometry of cluster.

- Example: BSs are placed at corners, BS-A is assumed to be saturated with traffic, so A is splitted.

- The original BS-A will be surrounded by 6 new microcells without changing the geometry of cluster.

- Smaller cells in high use areas
  - Original cells 6.5 – 13 km
  - 1.5 km limit in general

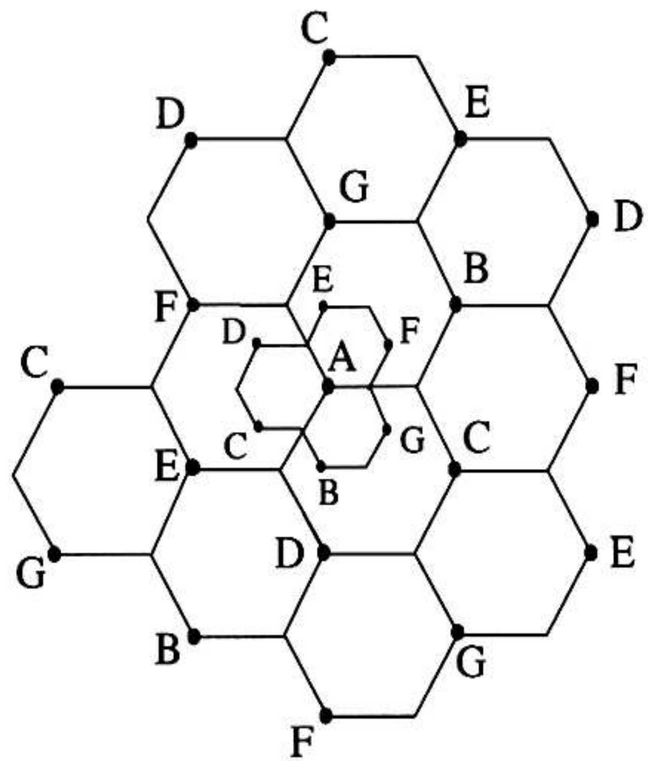


Illustration of cell splitting.

- Tx power must be reduced to ensure that freq. reuse plan behaves exactly same.

- If the radius of new cell is half that of original cell:

P_r[at old cell boundary] $\approx P_{t1}R^{-n}$

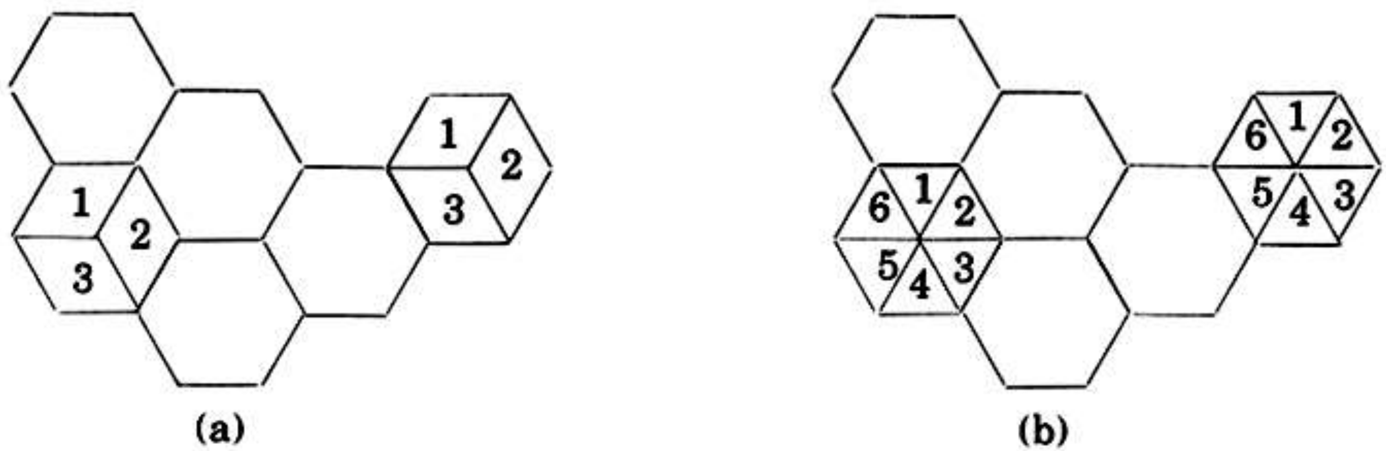
P_r[at new cell boundary] $\approx P_{t2}(R/2)^{-n}$

$$P_{t2} = P_{t1}/16, \text{ for } n = 4$$

- Tx power of smaller cell BS must be 16 times smaller than that of larger cell BS.

Sectoring

- Method of reducing co channel interference using directional antennas (instead of N ↑)
- Cell partitioned into sectors
  - 3 - 6 sectors per cell, i.e. 3-6 directional antennas/cell
  - No. of channels in each sector = no. of channels in a cell / no. of sectors in a cell



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

Sectoring involves:

1. First improving S/I using directional antennas
2. Then improving capacity by reducing N, i.e. more frequency reuse

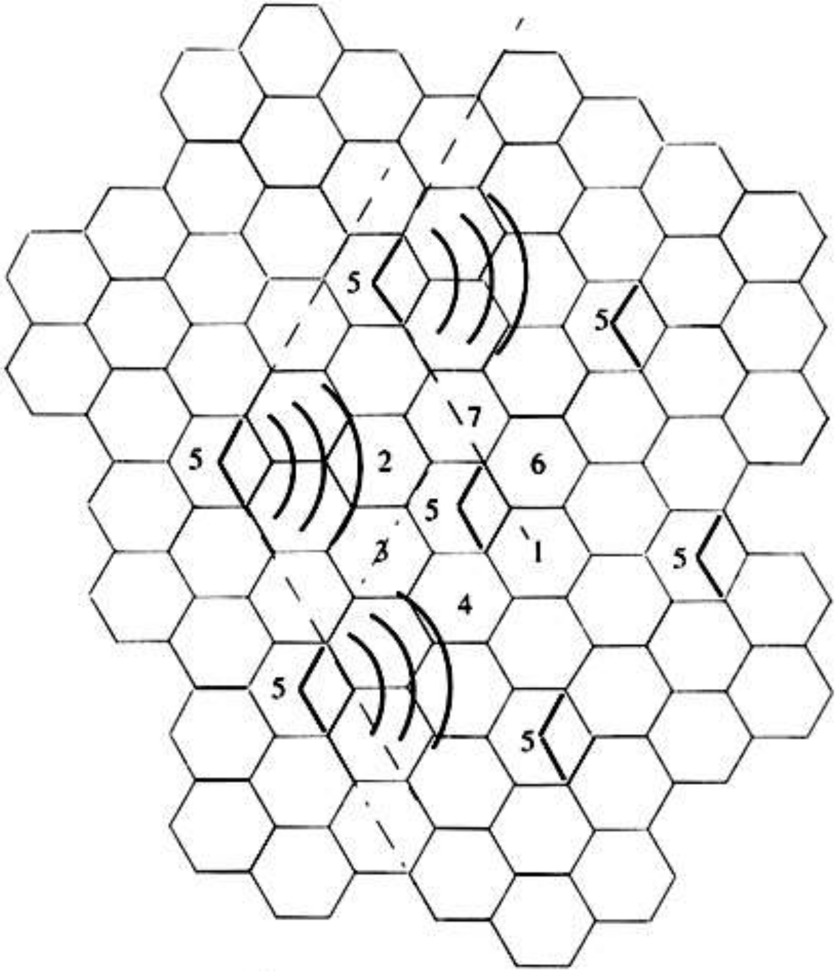


Illustration of how 120° sectoring reduces interference from co-channel cells. Out of the 6 co-channel cells in the first tier, only two of them interfere with the center cell. If omnidirectional antennas were used at each base station, all six co-channel cells would interfere with the center cell.

Co channel interference with 120^0 sectorized cells:

- Using approximate geometry,

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

$\approx$ 27 dB

- with omnidirectional antenna

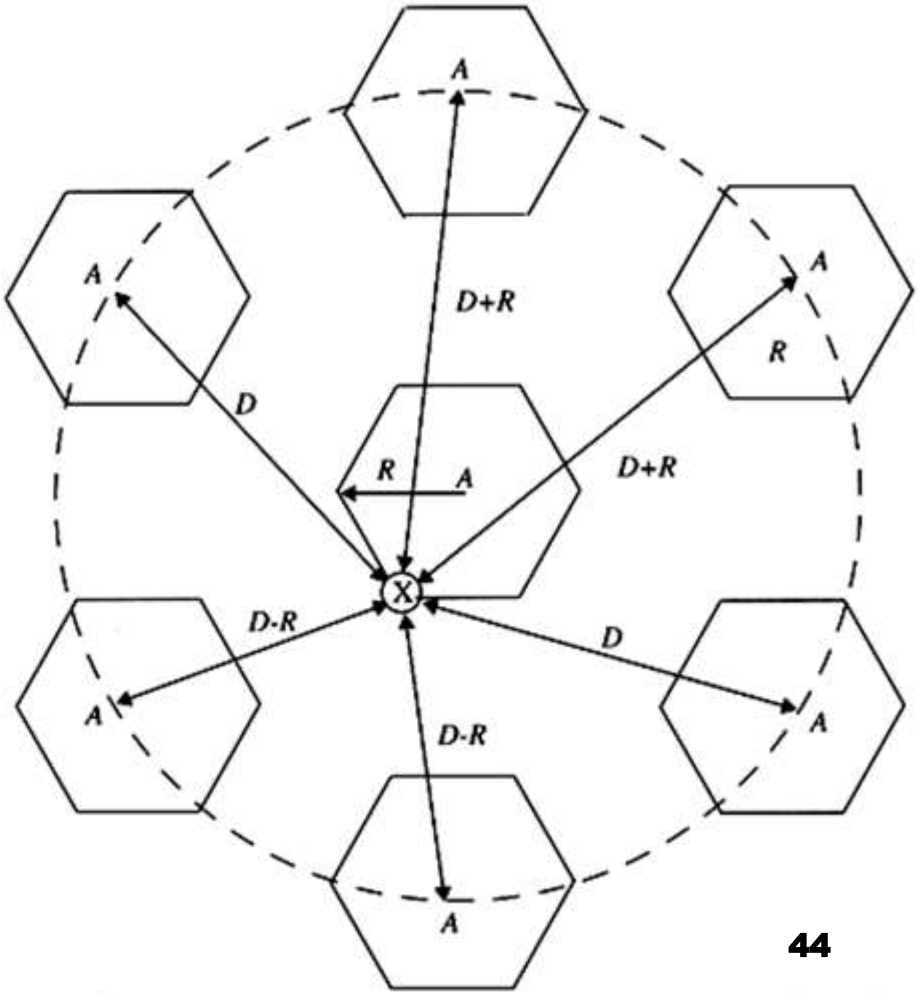
  S/I = 18 dB (N = 7)

- an increase of 9 dB can

  achieve N = 4

- 60^0 sectoring achieves

  N = 3



Handoff

- Identifying a new base station.
- Allocation of voice & control signals to channels associated with the new base station.

- Handoff depends on signal strength.

Margin $\Delta = P_{r\ handoff} - P_{r\ min\ usable}$

Large $\Delta \longrightarrow$ MSC overloading

Smaller $\Delta \longrightarrow$ Call loss $\longrightarrow$ may also happen when excessive delay by the MSC in assigning handoff (computational loading or channel unavailability)

Handoff

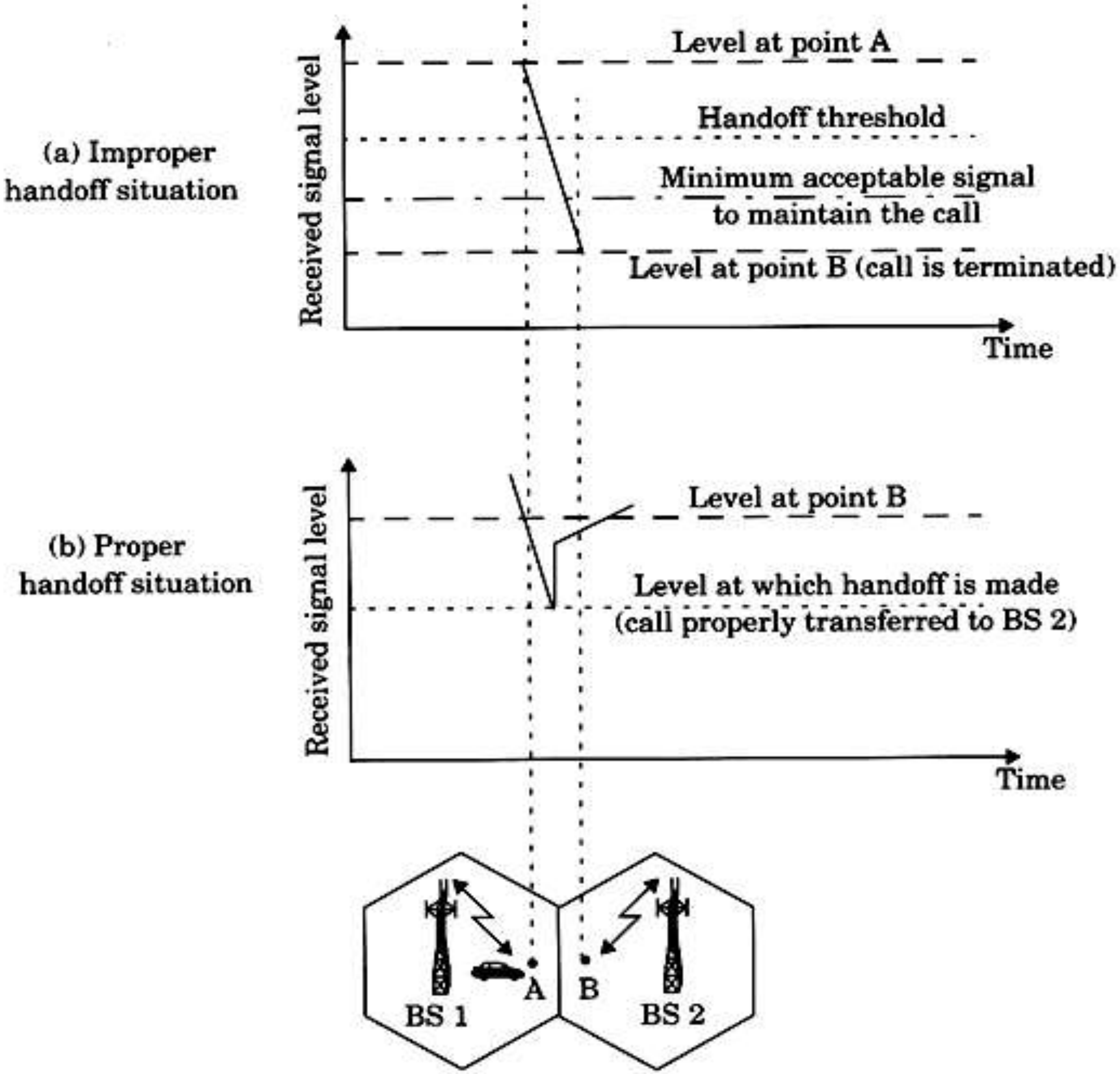
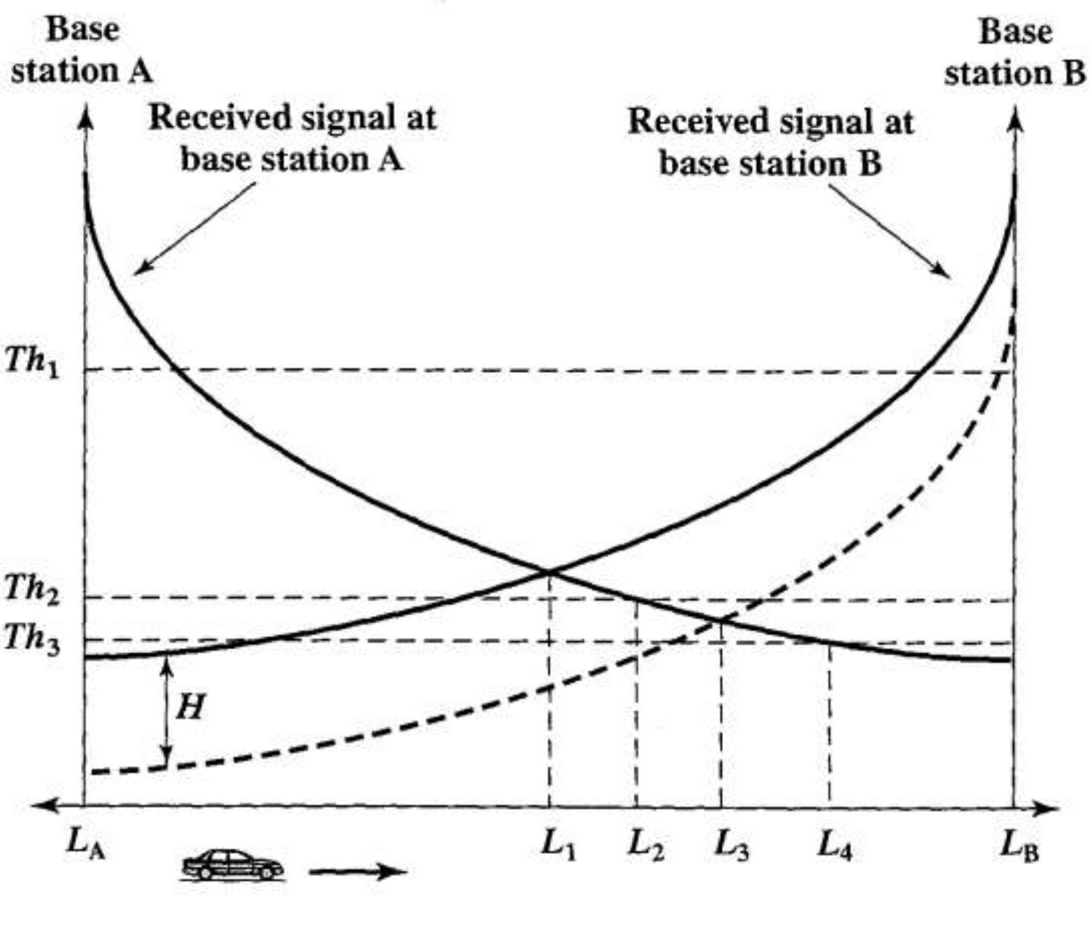


Illustration of a handoff scenario at cell boundary.

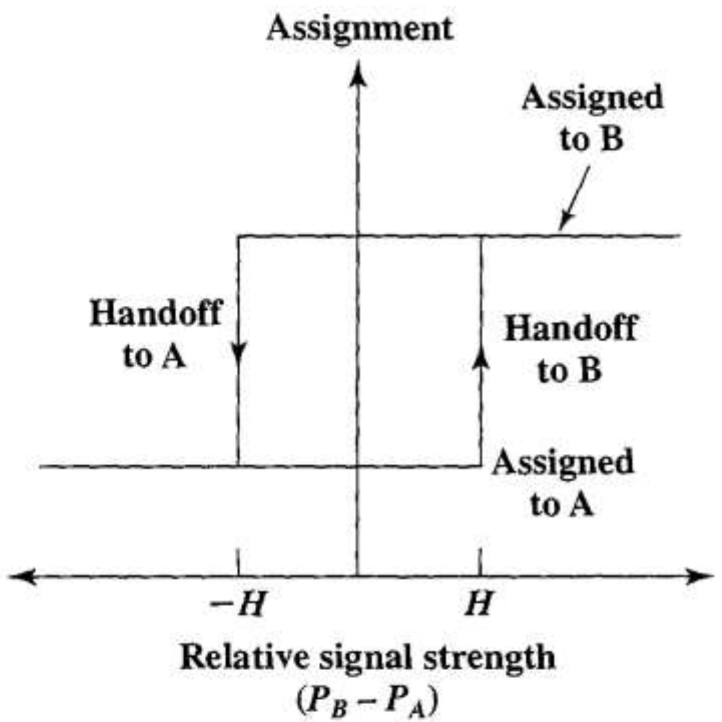
Handoff Strategies used to determine instant of Handoff

- Handoff decision (momentary fading)
- Relative signal strength
- Relative signal strength with threshold
- Relative signal strength with hysteresis
- Relative signal strength with hysteresis and threshold

Handoff between two cells



(a) Handoff decision as a function of handoff scheme



(b) Hysteresis mechanism

Styles of Handoff

- Network Controlled Handoff (NCHO)
  - in first generation cellular system, each base station constantly monitors signal strength from mobiles in its cell
  - based on the measures, MSC decides if handoff necessary
  - mobile plays passive role in process
  - burden on MSC

1. Network Controlled Handoff
2. Mobile assistend hand off

Styles of Handoff

- Mobile Assisted Handoff (MAHO)
  - present in second generation systems
  - mobile measures received power from surrounding base stations and report to serving base station
  - handoff initiated when power received from a neighboring cell exceeds current value by a certain level or for a certain period of time
  - faster since measurements made by mobiles, MSC don't need monitor signal strength

Types of Handoff

- Hard handoff - (break before make)
  - FDMA, TDMA
  - mobile has radio link with only one BS at anytime
  - old BS connection is terminated before new BS connection is made.

Types of Handoff

- Soft handoff (make before break)
  - CDMA systems
  - mobile has simultaneous radio link with more than one BS at any time
  - new BS connection is made before old BS connection is broken
  - mobile unit remains in this state until one base station clearly predominates

Intersystem handoff

- MSC can't find a cell within its system to which it can transfer the call in progress

- MU moves from one cellular system to a different system controlled by different MSC

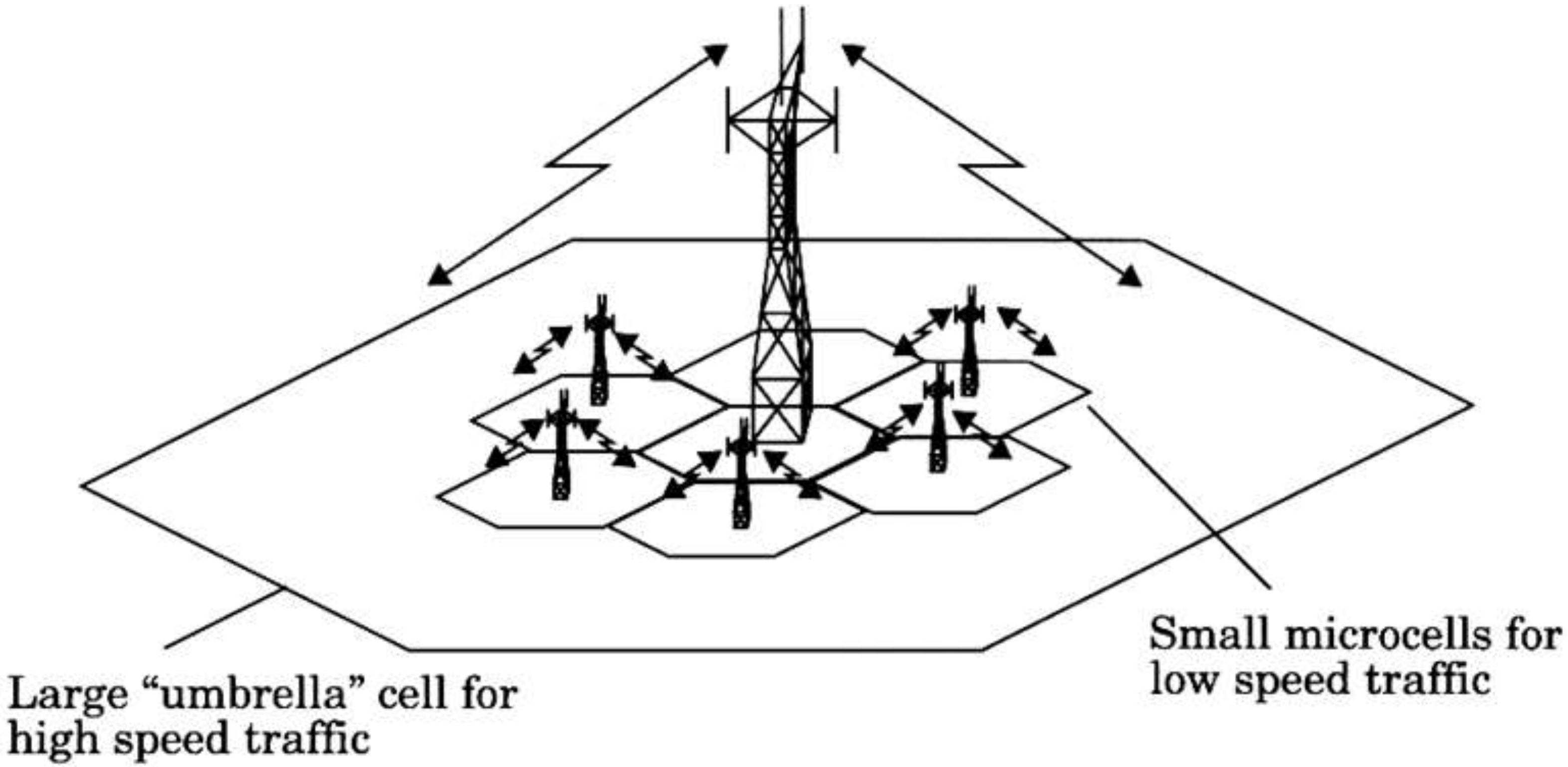
- MU becomes a roamer in a different system

Prioritizing handoff

- Prioritize handoff over call initiation request

- Guard channel concept
- Queuing of handoff requests

Practical Handoffs: Umbrella cell



The umbrella cell approach.