Wireless Communications

Cellular Concept

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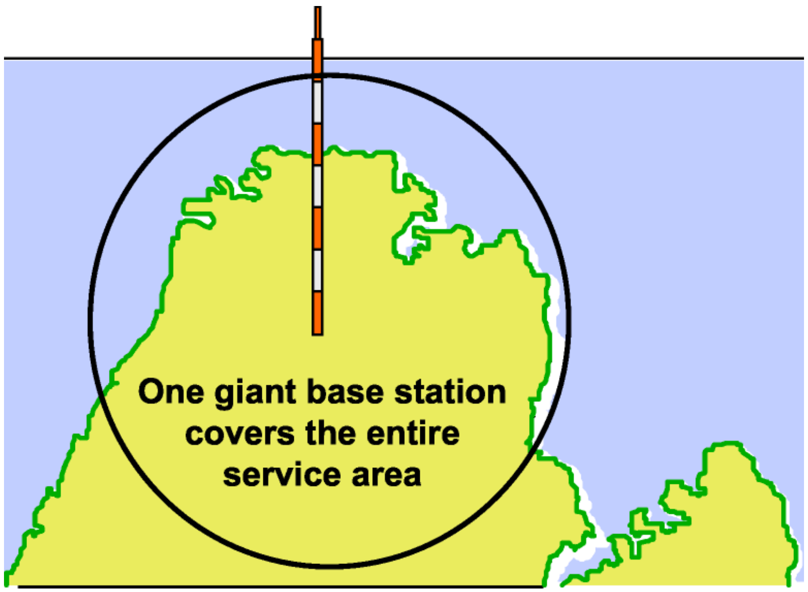
Reference: Rappaport Chap3

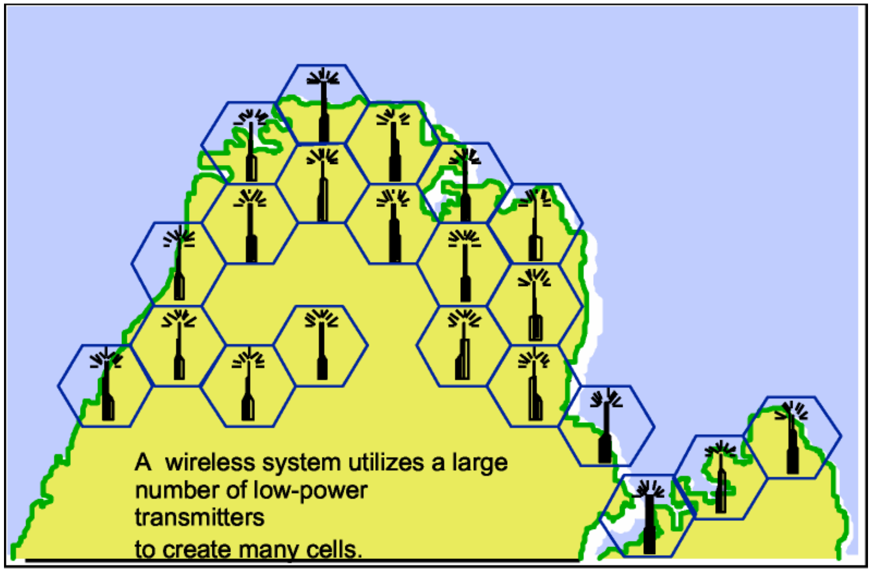
Electrical & Computer Engineering

Statements of Problems

- Solving the problem of
  - Spectral congestion
  - System Capacity
- A system-level design considers using cells
  - Low power transmitter
  - Small service areas
  - More base stations
  - Reduced interference between base stations

Design Difference

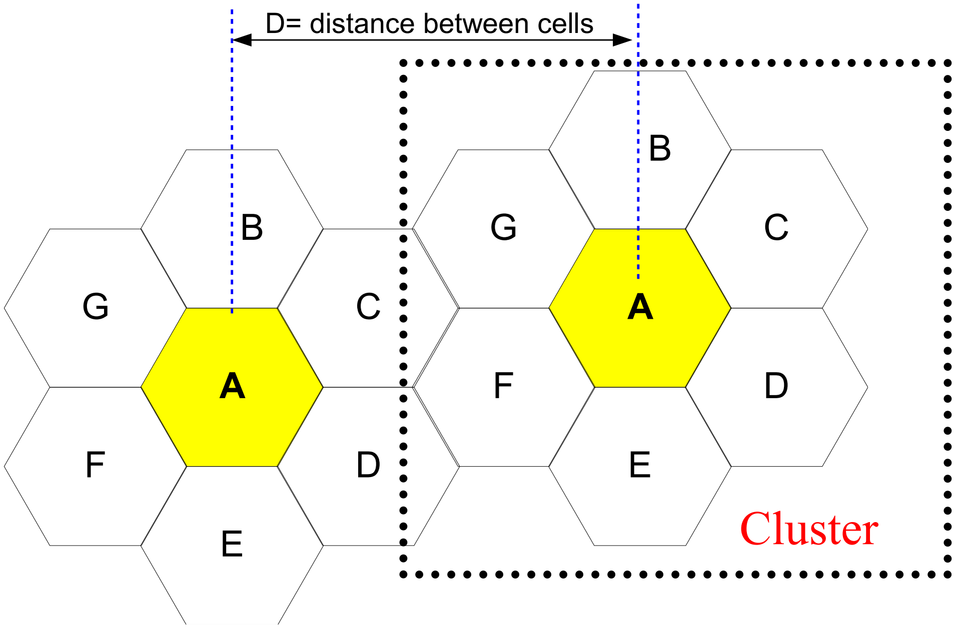




Frequency Reuse – Introduction

- Frequency reuse: a technique relying on allocation and reuse of channels throughout a coverage region
  - Increase the channel capacity
  - Minimize the interference
  - Low power transmission
  - Effective coverage area
- Approach…
  - Cell: a small geographic area, in which each cellular base station is allocated with a set of radio channels
  - Complete different channels among neighboring cells
  - Limiting the coverage area within a cell

Frequency Reuse – Concept

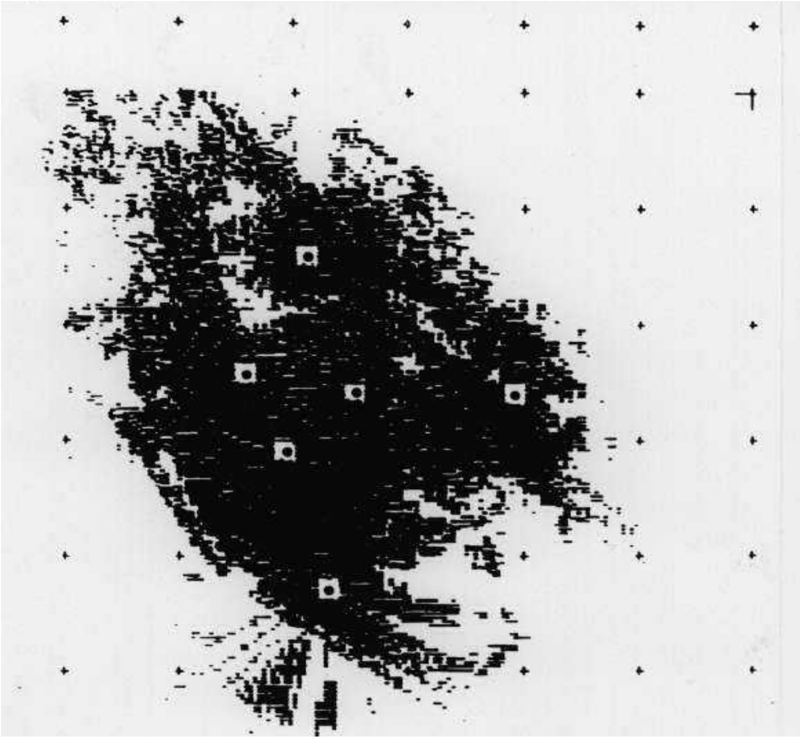


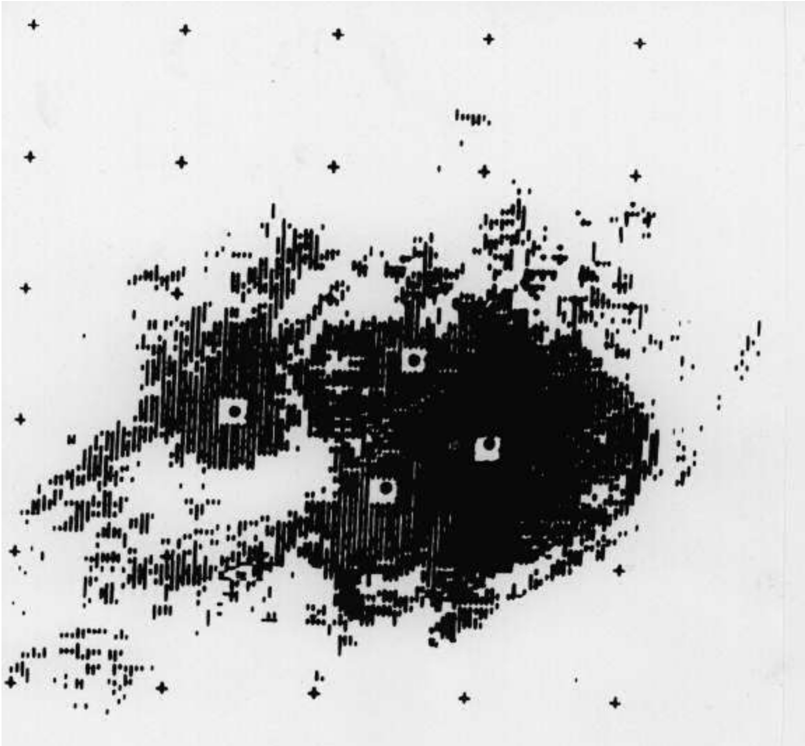
Cells labeled with the same letter use the same group of channels.

The hexagonal cell shape is conceptual and universally adopted.

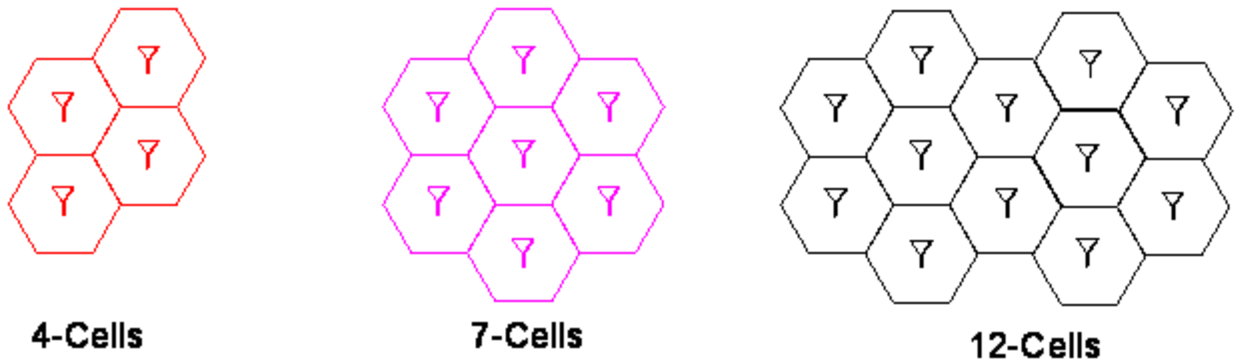
Base station transmitters could be in the center of the cell or on cell vertices.

Real-Life Coverage





Frequency Reuse – Cluster Size



- A larger cluster size causes the ratio between the cell radius and the distance between co-channel cells to decrease, leading to weaker co-channel interference
- A small cluster size indicates that co-channel cells are located much closer together

Frequency Reuse – Definitions

- Capacity, frequency reuse factor, cluster…
  - *S*: the number of duplex channels available for use per cluster in a cellular system
  - *k*: the number of channels in each cell $k<S$
  - *N*: the number of cells per cluster
  - *1/N*: frequency reuse factor
  - *C*: the total number of duplex channels (capacity) in a cellular system
  - *M*: the number of clusters

$$\boxed{S = kN \qquad C = MkN = MS}$$

Example: Rappaport page 97, problem 3.4

- If 20 MHz of total spectrum is allocated for a duplex wireless cellular system and each simplex channel has 25 kHz RF bandwidth. Find
  - The number of duplex channels
  - The total number of channels per cell size if N=4 reuse is used.

$$\frac{20M}{25K \times 2} = 400 \text{ channels}$$

$$400/4 = 100 \text{ channels per cell}$$

Example: Garg, page 130

We consider a cellular system in which total available voice channels to handle the traffic are 960. The area of each cell is 6km^2 and the total coverage is 2000km^2

- The system capacity if the cluster size is N=4.
- The system capacity if the cluster size is N=7.

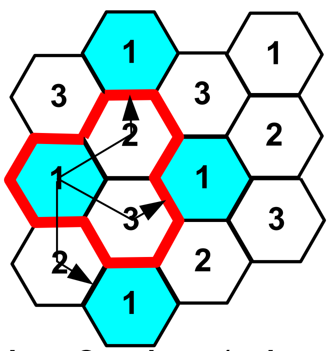
	Area of a cluster	# of clusters	# of channels /cell	System capacity
N=4	4*6=24 km^2	2000/24≅84	960/4=240	84*960=80640
N=7	7*6=42 km^2	2000/42≅48	960/7=137	48*960=46080

Comments:

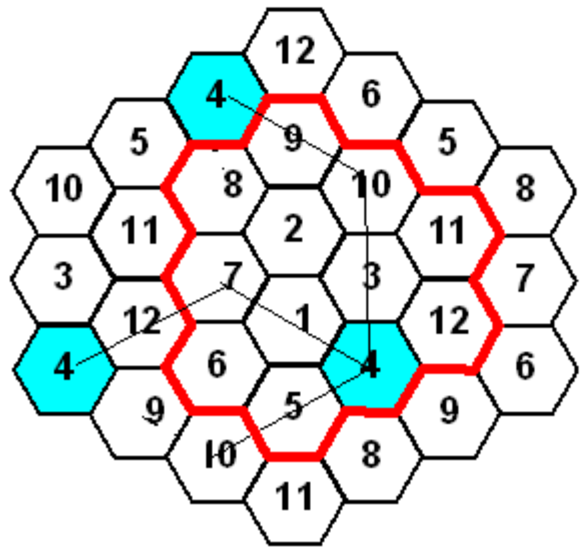
N from 7 to 4, the capacity ↑ [from 46080 to 80640]

No free lunch… what would be the cost?

Frequency Reuse
– Locating Co-channel Cells



N = 3: $i = 1, j = 1$



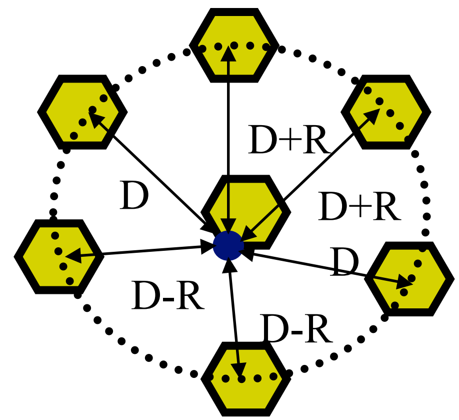
N= 12: $i = 2, j = 2$

1) Move i cells along any chain
2) Turn 60 degrees <u>counter-clock</u> wise and move j cells

$$\boxed{N = i^2 + ij + j^2}$$

Co-channel Interference

- Interference between signals from co-channels
  - *Increasing the signal-to-noise ratio (SNR) to overcome thermal noise does not work*
  - Physically separate co-channel cells
- Co-channel reuse ratio



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

Condition: same cell size, same transmitter power

R: radius of the cell

D: distance between centers of the nearest co-channel cells

Co-channel Interference

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

	Cluster size N	Co-channel reuse ratio Q
i=1, j=1	3	3
i=1, j=2	7	4.58
i=0, j=3	9	5.20
i=2, j=2	12	6

Tradeoff!!!

Large value of Q → smaller level of interference → improve the transmitter quality

Small value of Q → smaller N → improve the capacity

Co-channel Interference – SIR

- Signal-to-interference ratio (SIR) for a forward channel

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

S: the desired signal power from the desire BS
I_i: the interference power cause by the i^{th} interfering co-channel cell BS

$$P_r = P_0 \left(\frac{d}{d_o} \right)^{-n} \longleftrightarrow P_r(dBm) = P_0(dBm) - 10n \log\left(\frac{d}{d_o} \right)$$

The average receiver power at a distance d with the path loss exponent n

Co-channel Interference – SIR

- When the transmit power of each base station is equal
- The path loss exponent is the same throughout the coverage

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

  - Consider the first layer of interfering cells
  - All the interference BSs are equidistant from the desire BS
  - The distance is equal to D

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

Example: find the cluster size N

- Example: assuming that 6 cells are close enough to create significant interference and they are approximately equidistant from the desired BS. For the US AMPS system that uses FM and 30 kHz channels, it indicates that sufficient voice quality is provided when S/I is greater than or equal to 18 dB. What would be the cluster size? (n=4)

$$\boxed{\frac{S}{I} = \frac{\sqrt{3N}^{\,n}}{i_0}}$$

$$10\log_{10}\frac{S}{I} = 18dB \Rightarrow \frac{S}{I} = \frac{\sqrt{3N}^{\,n}}{i_0} = 63.09$$

$$N = \sqrt{63.09 \times 6}\Big/3 = 6.49$$

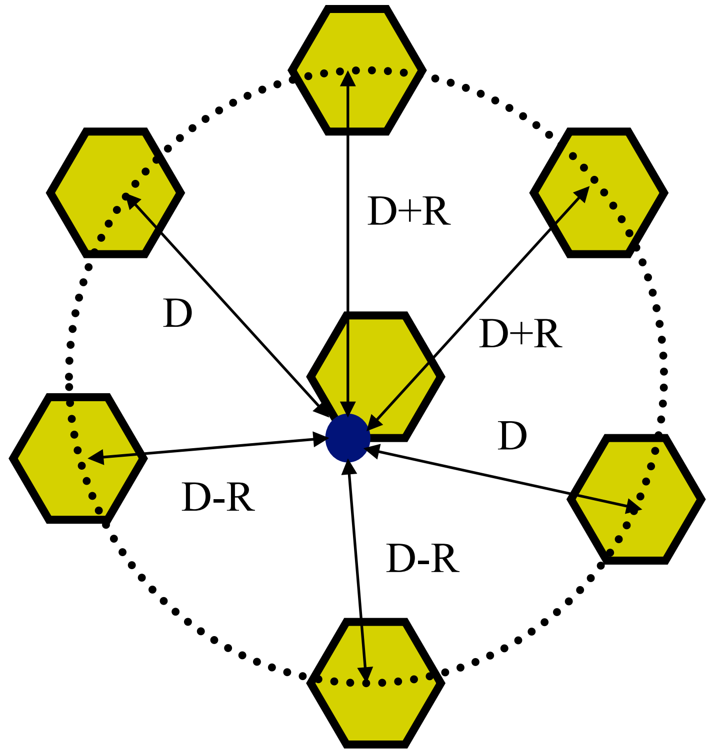
Example: Worst Case

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

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

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

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



For N=7, Q=4.6,
The worst case S/I for n=4 is about 17 dB (53.37)

Example:

- If a S/I ratio is 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 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.

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

$$\boxed{\frac{S}{I} = \frac{\sqrt{3N}^{\,n}}{i_0}}$$

Adjacent Channel Interference

- Interference resulting from signals which are adjacent in frequency to the desired signal
  - Imperfect receiver filters
  - Near-far effect
    - When a mobile user close to a BS transmits on a channel close to one being used by a weak mobile
  - Minimized by careful filtering; proper channel assignment; and power control

Power Control

- The power levels transmitted by every subscriber unit are under constant control by the serving BS
- Smallest power to maintain a good quality link on the reverse channel
- Advantage
  - Battery life
  - Reduce the reverse channel S/I

Channel Assignment and Planning

- Air Interface Standard
- Assigning the radio channels to each BS
  - Control channels 5% + voice channels 95%
- The available mobile radio spectrum is divided into channels
- Assigning control channels is done more conservatively (smaller frequency reuse)
- Challenge in practice
  - Appropriate frequency reuse ratio
  - Radio propagation
  - Imperfect coverage

Channel Assignment

- Plan
  - Keeping the frequency separation between channels in a given cell as large as possible
  - Sequentially assigning successive channels in the frequency band to different cells
- Objectives
  - Increasing capacity
  - Minimizing adjacent channel interference

Channel Assignment Strategies

- Fixed channel assignment strategy
  - Each cell is allocated a predetermined set of voice channels
  - Only the unused channels in the cell could be served
  - If all channels are occupied, the cell is <u>blocked</u> (no service)
    - Borrowing strategy: a cell is allowed to borrow channels from a neighboring cell, controlled by the Mobile Switching Center (MSC)

Channel Assignment Strategies

- Dynamic channel assignment strategy
  - The serving base station requests a channel from the MSC when a call is required
  - The MSC allocates a channel by taking into account
    - The likelihood of future blocking within the cell [to increase the <u>trunking</u> capacity]
    - The frequency of use of the candidate channel
    - The reuse distance of the channel [to avoid the co-channel interference]
    - Other cost
  - Requirement: real-time management

Handoff Strategies

- *Handoff*: when a mobile moves into a different cell while a conversation is in process, the MSC automatically transfers the call to a <u>new channel</u> belonging to the <u>new base station</u>
- Requirements
  - Successfully, Infrequently and Imperceptible to the users
  - Specify an optimum signal level at which to initiate a handoff - Received Signal Strength (RSS)

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

Handoff Strategies

- Ensure…
  - The drop in the measured signal level is not due to momentary fading
  - The mobile is moving away from the serving BS
  - Monitor: the <u>signal level</u> for a certain period of <u>time</u>
    - Dwell time: the time over which a call may be maintained within a cell without handoff
- Each wireless technology uses its own methods to implement the handoffs

Handoff Strategies

- 1G handoff strategy
  - Signal strength measurements are made by the BS and supervised by the MSC
    - Each BS monitors the signal strengths of all of its voice channels
    - The locator receiver in each BS scans and determines signal strengths of mobiles users in neighboring cells
    - The MSC decides if a handoff is necessary
- 2G Mobile Assisted Handoff (MAHO)
  - Every mobile station measures the received power and reports to the serving BS
  - Handoff – when the power received form the BS of a neighboring cell begins to exceed the power received from the current BS by the certain level or for a certain time

Handoff Strategies

- Prioritizing handoffs
  - Guard channel concept
    - A fraction of the total available channels in a cell is reserved exclusively for handoff
    - Reducing the total carried traffic, but offering efficient spectrum utilization
  - Queuing of handoff
    - Decreasing the probability of forced termination of a call
    - The delay time and size of the queue is determined from the traffic pattern of the particular service area

Handoff Strategies – Practical

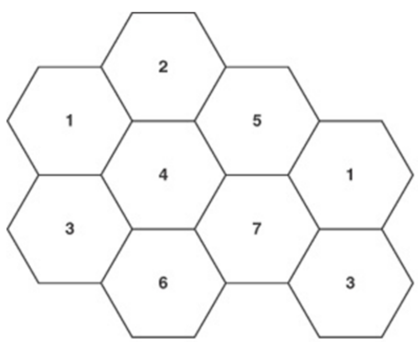
- Issue 1: high speed vehicles pass through the coverage region of a cell within a matter of seconds
- Solution: Umbrella cell
- Issue 2 (cell dragging): pedestrian users might provide a very strong signal to the BS. Even though the user has traveled well beyond the designed range of the cell, the received signal at the BS may be above the handoff threshold. Thus, no handoff occurs.
- Solution: more intelligent handoff strategies to decide on handoff thresholds and radio coverage parameters (e.g. dwell time), Ability to make handoff decision based on wide range of metrics other than signal strength
- Issue 3: hard handoff vs. soft handoff

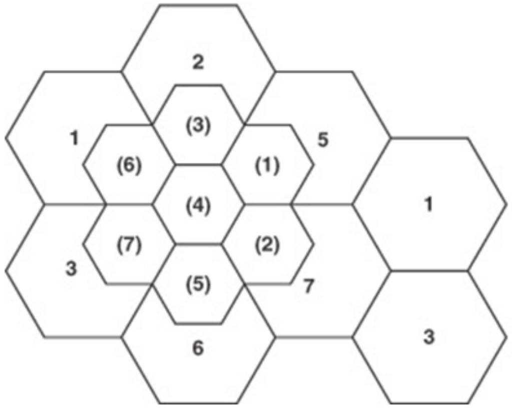
Improving Coverage and Capacity

- Statement of the problem
  - The need of increasing number of users
  - The number of channels assigned is insufficient
- Techniques
  - *Frequency reuse*
  - Cell splitting
  - Sectoring
  - Coverage zone

Cell Splitting

- The process of subdividing a congested cell into smaller cells, when the traffic load carried by the original cell exceeds its capacity
  - Each smaller cell has its own BS
  - Reduction in antenna height
  - Reduction in transmitter power





Cell Splitting

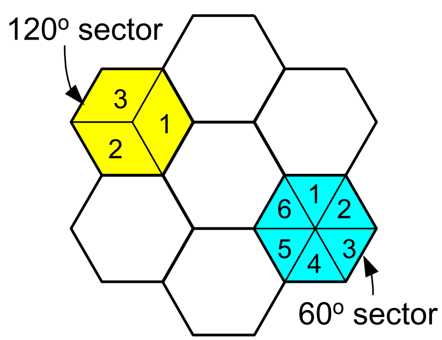
- Prove that splitting cells with radius R/2 could make the smaller transmitted power possible.

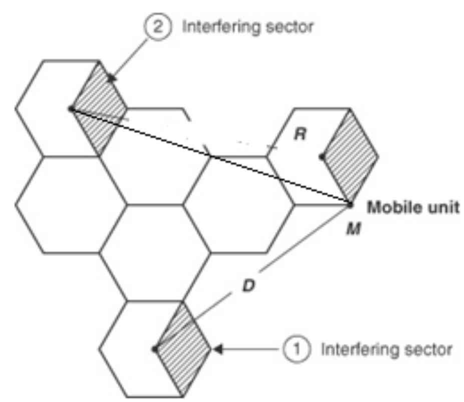
Cell Splitting

- To increase the capacity [logic?]
  - Increase the number of times that channels are reused
  - Increase the number of channels per unit area [smaller radius cells/microcells]
- More cells implies more cell boundaries will be crossed more often, hence increasing trunking and handoff
- It is not necessary to split all the existing cells at same time. Only those cells which have traffic overloads are candidates for splitting

Sectoring

- A process of replacing a single omni-directional antenna (ideal) with directional antennas (practical)
  - The total channels per sector = total channels/cell ÷ the number of sectors/cell
  - SIR could be increased, How about capacity?





Sectoring

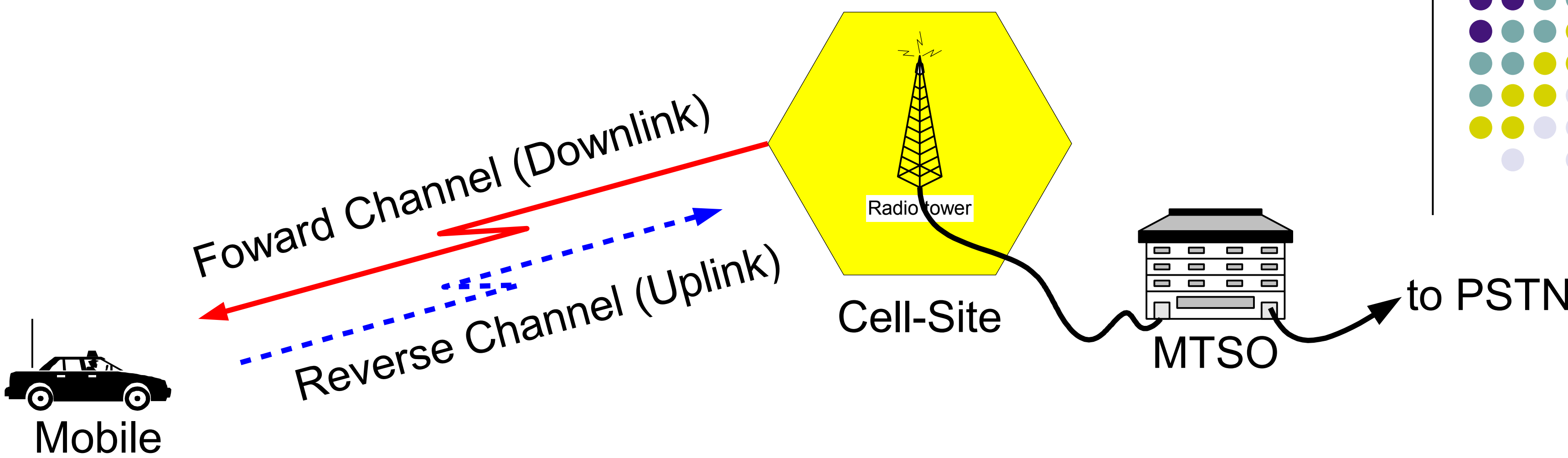
- Sectoring reduces CELL capacity because the channel resource is distributed more thinly among sectors…
- However, less co-channel interference → it is possible to reduce the cluster size → potentially increase the system capacity
- More cells partitions implies more cell boundaries will be crossed more often, hence increasing trunking and handoff

A Microcell Zone Concept

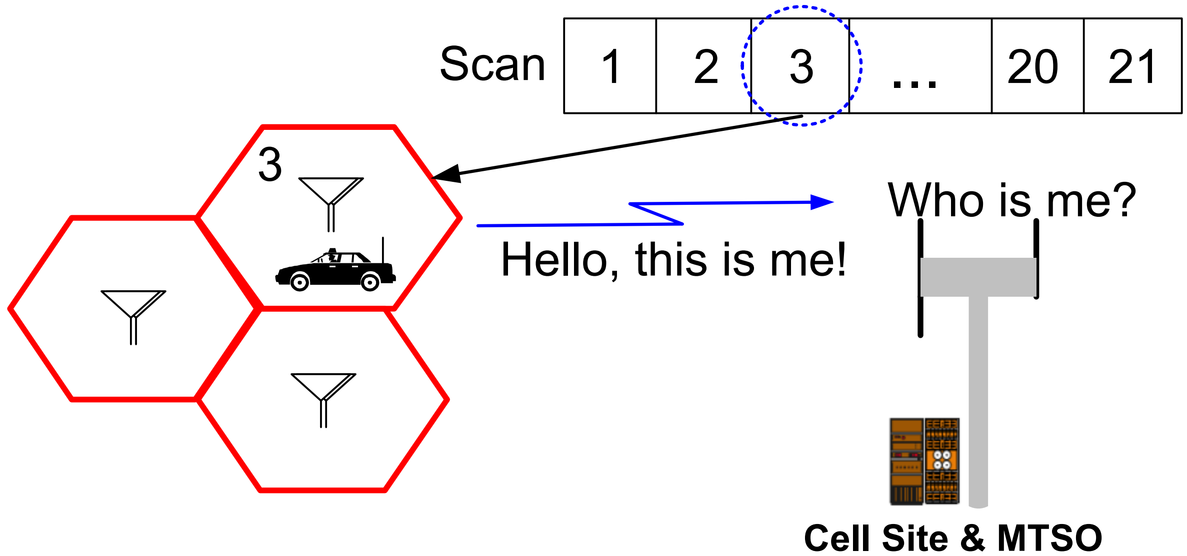
- Statement of the problem
  - The increased number of handoffs when sectoring is employed
- Concept
  - For seven cell reuse
  - Each of the three zone sites are connected to a single BS and share the same radio equipment
  - No handoff necessary inside three zones
  - Improve the capacity by decreasing interference

Repeaters

- Range extension
  - Cover the service gap
  - Hard-to reach
  - Within buildings, in valleys, in tunnels
- Radio retransmissions
  - Bidirectional in nature
  - Simultaneously send signals to and receive signals from a serving BS

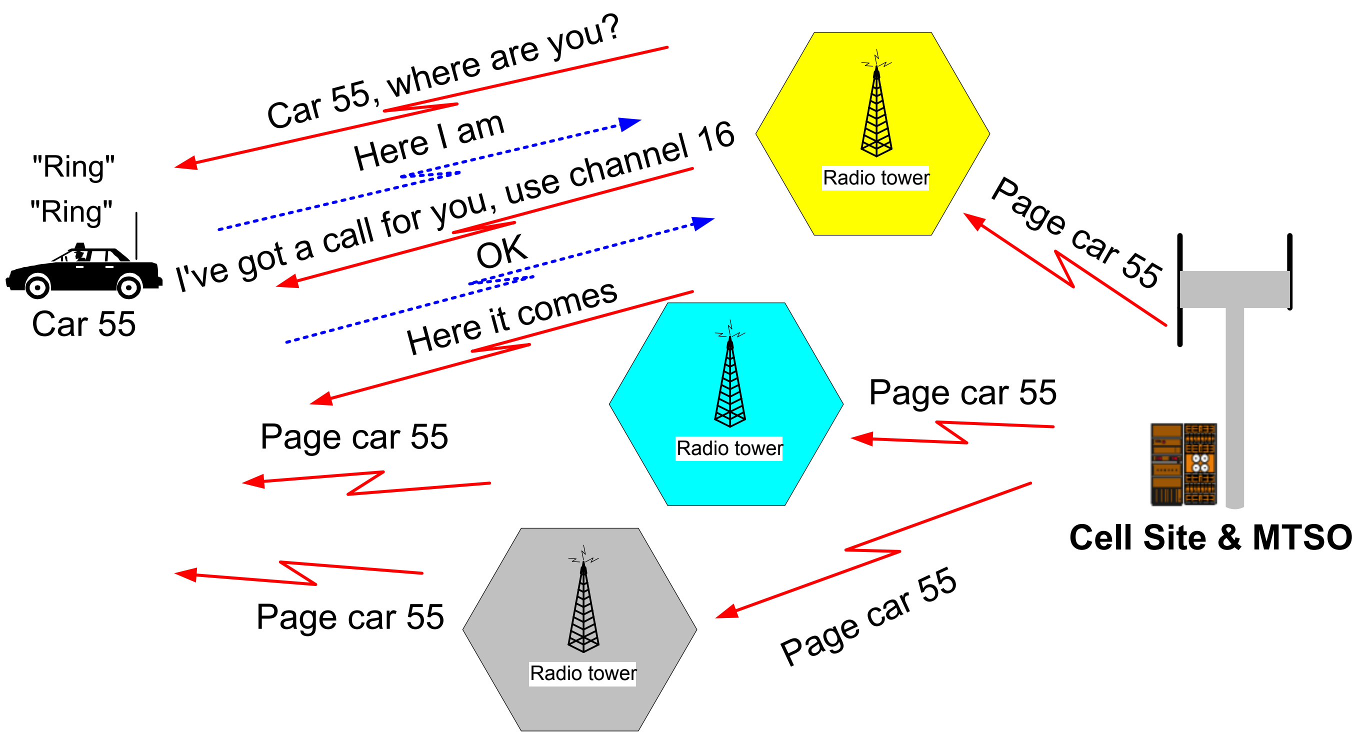


- **Power On/Log-On**
  - Handset reads a certain information from its memory
  - This info is usually programmed by the service provider to give the user a unique mobile assignment number (MAN)
  - Handset scans the Forward Control Channels for the strongest signals
  - It monitors the detected control channels for the level of signal

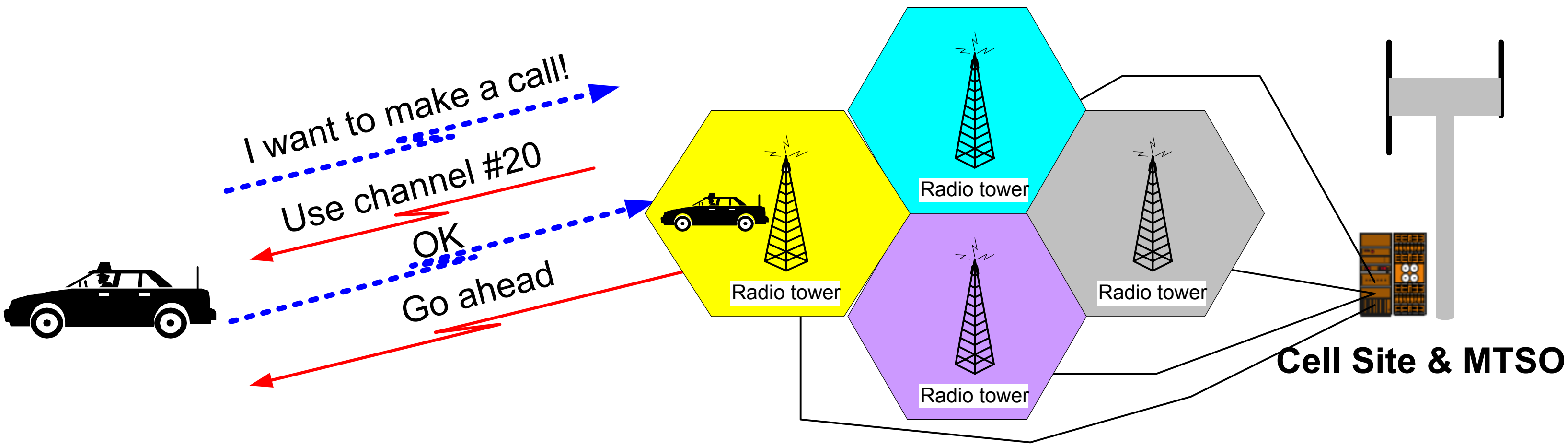


- It tunes itself to a suitable channel and goes into idle state
- In idle state, it constantly monitors the data/signal strength
- If the signal is below a threshold, the unit goes into scanning mode until it finds another channel
  - **Searching …..**
- A check is sent across the control channels to verify the area code or the ID number (registration)
- The MTSO continually monitors the mobile unit

- **Incoming Calls**
  - System finds the mobile unit through a paging channel
  - A page is sent by the MTSO to all base stations
  - The Mobile Identification Number (MIN) or MAN is broadcast to the paging message\Mobile handset receives the message and identifies itself
  - Each MU uses microprocessor to receive incoming calls and to shift to appropriate frequency
  - As a call comes in, the BS controllers assigns a channel and then directs a frequency synthesizer in the handset to shift to the appropriate frequency



- **Outgoing Calls**
  - Call initiation request is made by the Mobile Unit
  - MTSO validates request and makes connection. Validation comes back in the form of instruction to use a specific channel

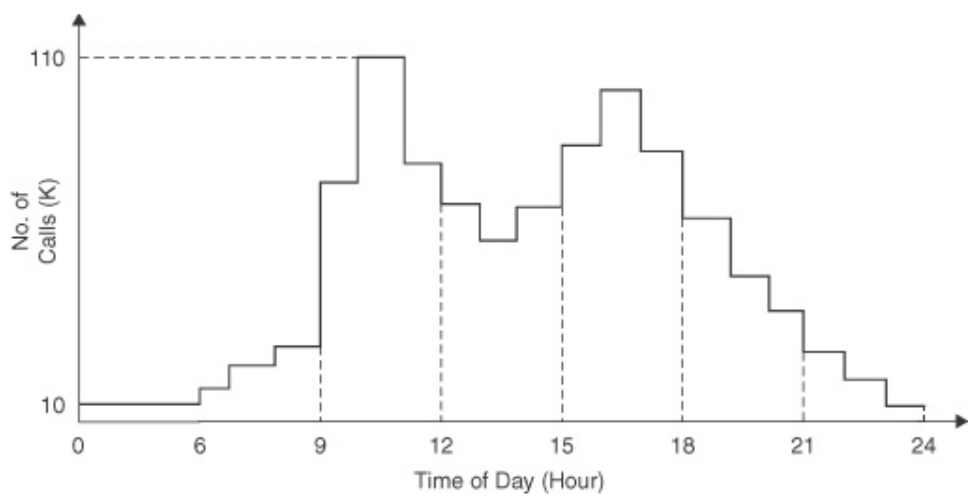


Traffic Management

- Statement of Problems
  - Dial-Tone delay
    - A large number of users compete for a small number of servers
    - An assumption that the user will wait until a server is available
  - Service denial
    - A large number of users compete for a small number of servers
    - An assumption that no delay will be encountered. The user is either give access to trunk or is advised by a busy signal or a recording that none are available
    - The user may frequently reinstate the call attempt
- Def: to determine the usage of a transmission route

Traffic Usage

- Calling Rate or Call Intensity: the number of times a route or traffic path is used per unit time (calls per hour) per traffic path during the busy hour
- Call holding time: the average duration of occupancy of a traffic path by a call



Traffic Intensity

- Def: the average number of calls simultaneously in progress during a particular period of time
- Unit: Erlangs
  - 1 Erlang = one call in process during an hour
  - Example: a radio channel that is occupied for 30 minutes during an hour carries 0.5 Erlangs of traffic

$$\boxed{\text{Traffice intensity} = \frac{\text{the sum of circuit holding time}}{\text{the duration of monitoring period}}}$$

Example: Check your understanding about the definition

- In a switching office, an equipment component has an average holding time of 5 seconds; about 450 attempts to use this equipment for a one-hour period. Assuming there is no overflow – the system can handle all calls. How much usage in Erlangs has accumulated on this piece of the equipment?

Answer:
The duration of monitoring period is one hour
The sum of holding time: 450 * (5/3600)
Traffic intensity: 450*5/3600/1=0.625 Erlangs

Example: Check your understanding about the definition

- In a wireless network, each subscriber generates two calls per hour on the average call holding time of 120 seconds. What is the traffic intensity?

Answer:
The duration of monitoring period is one hour
The sum of holding time: 2 * (120/3600)
Traffic intensity: 2*120/3600/1=0.0667 Erlangs

Example: working like a traffic manager

- In order to determine voice traffic on a line, we collected the following data during a period of 90 minutes. Calculate the traffic density.

Call no	Duration of calls (seconds)
1	60
2	74
3	80
4	90
5	92
6	70
7	96
8	48
9	64
10	126

Answer:
The duration of monitoring period: 1.5 hours
The sum of holding time:60+74+80+…+126=800 seconds =0.22 hour
Traffic intensity 0.22/1.5=0.148 Erlangs

Example: working like an engineer, not a mathematician

- The average mobile user has 500 minutes of use per month; 90% of traffic occurs during work days. There are 20 week days per month. Assuming that in a given day, 10% of traffic occurs during the busy hour (BH), determine the traffic per subscriber per BH.

Answer:
The total hours during work days: (500/60)*0.9=7.5 hours /
The average hours per work day: 7.5/20=0.375 hours
The average hours during the BH per day: 0.375*0.1=0.0375 hours
Traffic per subscriber per BH is about 0.0375 Erlangs

Trunking and Grade of Service

- Trunking: Accommodate a large number of users in a limited radio spectrum
  - A large number of users to share the relatively small number of channels in a cell
  - Providing access to each user from a pool of available channels
  - Erlang: the measure of traffic intensity

    A radio channel that is occupied for thirty minutes during an hour carries 0.5 Erlangs of traffic

Trunking and Grade of Service

- Grade Of Service (GOS): the ability of a user to access a trunked system during the <u>busiest hour</u>
  - A benchmark to define the desired performance of a particular trunked system
  - Specifying a desired likelihood of a user obtaining channel access given a specific number of channels available in the system

Trunking and Grade of Service

- *Set up time*: the time required to allocate a trunked radio channel to a requesting user
- *Blocked call (Lost call):* call which cannot be completed at time of request due to congestion
- *Holding time H*: average duration of a typical call
- *Traffic intensity A*: measure of channel time utilization, which is the average channel occupancy, in Erlangs
- *Load*: traffic intensity across the entire trunked radio system
- *Grade of service*: a measure of congestion, the probability of a call being blocked (B); the probability of a call being delayed for a certain time duration (C)
- *Request rate* λ: the average number of call requests per unit time

Trunking and Grade of Service

- Two types of trunked systems
  - 1st type: no queuing for call requests

$$\Pr[\text{blocking}] = \frac{A^C / C!}{\sum_{k=1}^{C} A^k / k!} = GOS$$

C: the number of trunked channels
A: the total offered traffic

  - 2nd type: a queue is provided to hold blocked calls

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