Cellular Networks: Concepts and Theory

Overview of Telecommunication Systems

- 1G: Basic mobile telephony service
  - Based on analog cellular technology
  - e.g., American Mobile Phone (AMPS) and NMT in Europe

- 2G: Mobile telephony services for mass users with improved ciphering and efficient utilization of the radio spectrum
  - Digital cellular technology
  - e.g., GSM (Global System for Mobile communications) and CDMA

- 2.5G: Mobile Internet/data services together with voice services
  - Packet switching technology adding into 2G
  - Providing mobile data services over 2G networks
  - e.g., GPRS (General Packet Radio Service) and EDGE

- 3G: enhanced 2.5G services with improved mobile internet services and emerging new applications
  - e.g., CDMA2000 and UMTS (Universal Mobile Telecom System)

Overview of Telecommunication Systems

- 4G (LTE/WiMAX): IP-based voice, data, and multimedia phones
  - faster than 3G
- 5G : New Radio (NR) and LTE
  - millimeter wave bands (e.g., 26, 28, 38, 60 GHz)
  - OFDM, SCMA (Sparse Code MA), and NOMA (Non-Orthogonal MA) are candidates of standards
  - massive MIMO antennas (64 ~ 256 antennas) & beamforming
  - offering as high as 20 Gbps

Telecommunication Services

- TRADITIONALLY, a mobile phone is used for talking with another person: point-to-point voice service
- NOW, mobile phones are more than phones. They are computing devices with networking capabilities
- What can be done with them?

Telecommunication Services

- Emails
  - Emails may be sent to other mobile phone users
  - Instant messages (SMS), WeChat…
  - What are differences in communication technology between emails and voice?
- Web browsing
  - 2G provides limited text-based web browsing services with low-resolution graphics. 3G is better but has still many limitations
  - Trans-coding and adaptation of web contents to fit into handheld devices
- Location-dependent services
  - Identify subscriber locations based on the connection points (base stations) and GPS network
  - Location-specific web contents/services

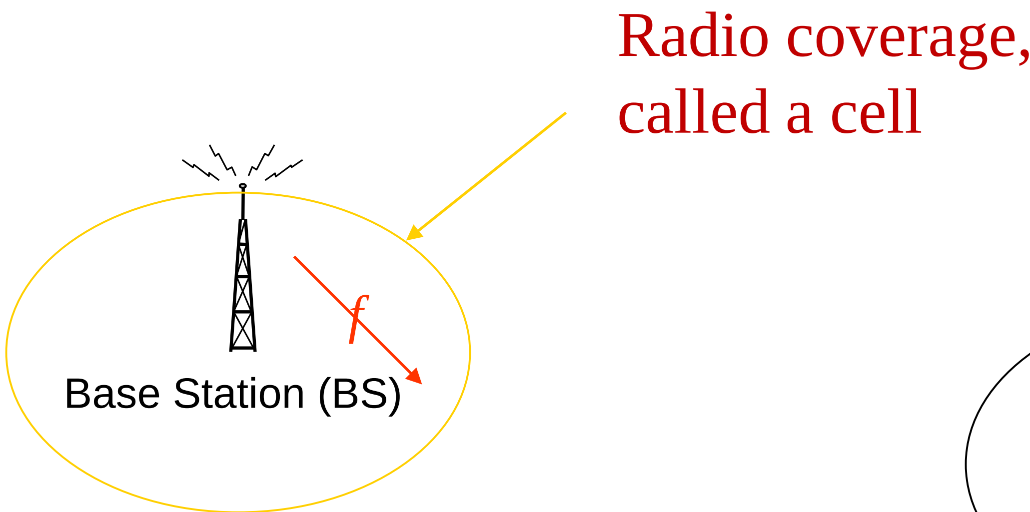
Telecommunication Services

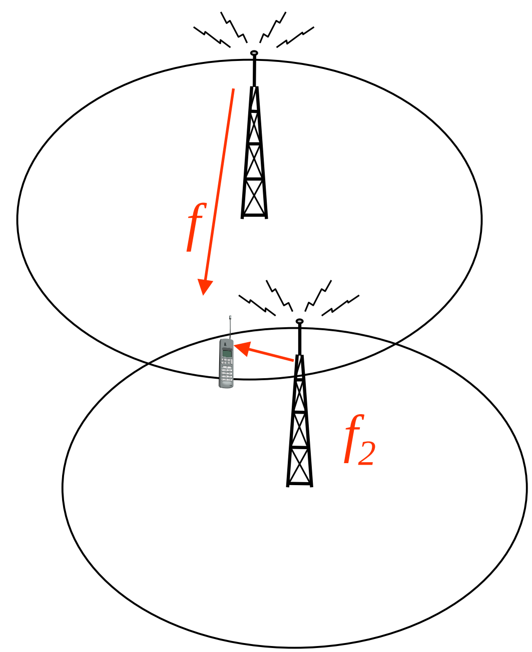
- Mobile game applications
  - Download and store a variety of dynamic applications and execute the applications in the mobile devices
  - Require a better operating environment and higher CPU power
- Video applications
  - 3G enables mobile users to obtain video contents
  - Real-time playback of videos (video stream data transmission)
- Other services
  - Tracking of mobile objects, vehicular networks, self-driving cars
  - Remote control and surveillance, e.g., home and field management
  - Shopping, marketing, logistic services, inventory control, IoT (Internet of Things)
  - ……..

Cellular Networks

- In a cellular network, service area is divided into a number of cells
  - Each cell has a BS that connects all MSs in the cell to the system
  - BS does channel allocation and management of MSs
  - One cell => one BS => multiple channels => many MSs
- Do you see the cell boundaries?
  - How to define the boundary of a cell?
  - No physical boundary, but there is a service boundary (no service signal)
- One particular location normally belongs to only one cell
  - Can it belong to more than one cell? Yes
  - Does it allow overlapping in cell area? Yes

Signal Coverage in Cellular Networks





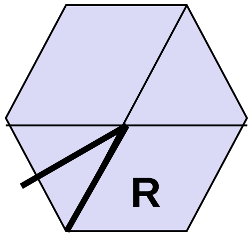
- If a MS is far away from any BS, it cannot receive any signal from BSs, it is out of service area
- A MS may receive signals from more than one BS

Why Cellular?

- Why cellular?
  - A cell is allocated with a number of channels (each channel has a fixed bandwidth and frequency band).
  - A frequency band can be reused after a separation of distance
    - but "Near-by" cells should not use the same frequency band due to interference
  - For a given service area, smaller size cells => more channel reuse. Why?

Modeling of a Cell

- Cells are modeled as polygons conceptually.

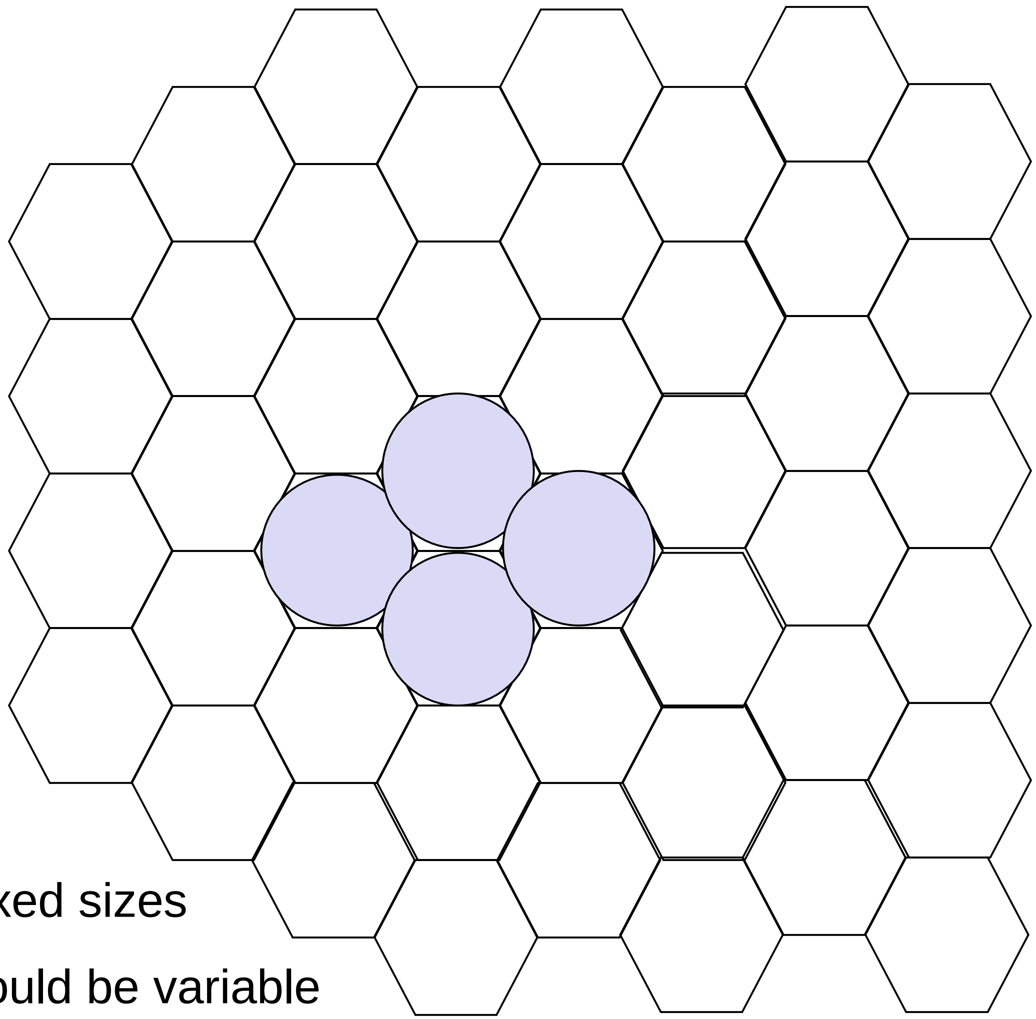


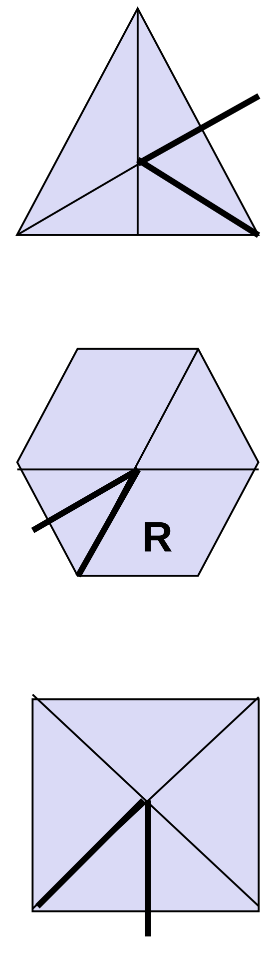
- Can it be circular?
  - Yes, the transmission range is more like a circle in open space, rather than a polygon.
- What is the distance from the center of the cell (location of the BS) to the edge (furthest MS in the cell)?
  - Transmission radius

Hexagonal cells cover all areas

Circular cells have some gaps (uncovered areas)

Why triangles or squares are no good?





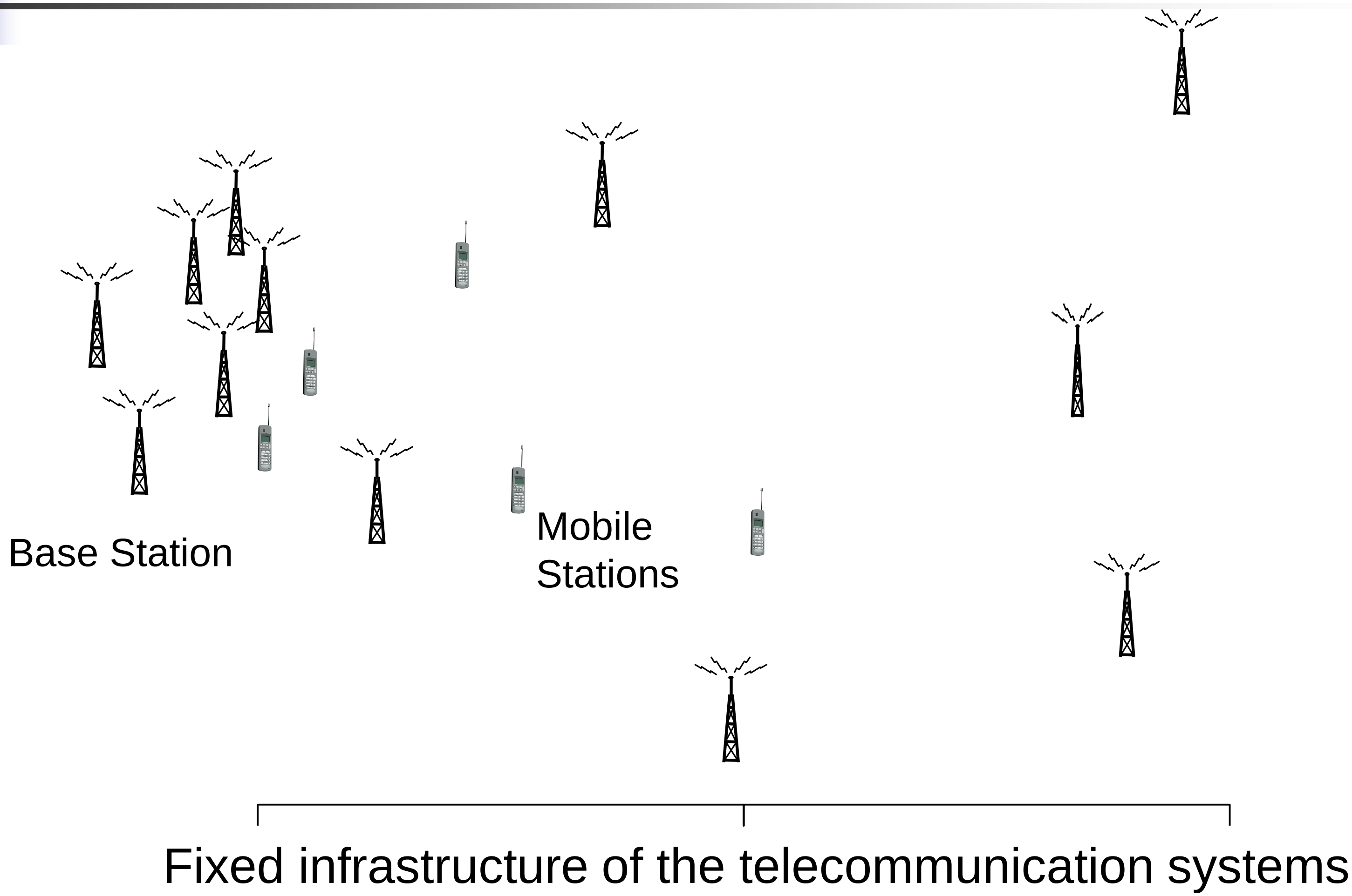
Fixed sizes

Could be variable

Handoff/Handover in Cellular Networks

- Handoff/handover
  - When a MS moves from one cell into another, handoff occurs where the MS is connected to a new BS
  - The new BS allocates a new channel to the MS and the connection is smoothly handed over to the new cell

Distribution of BSs in Cellular Networks



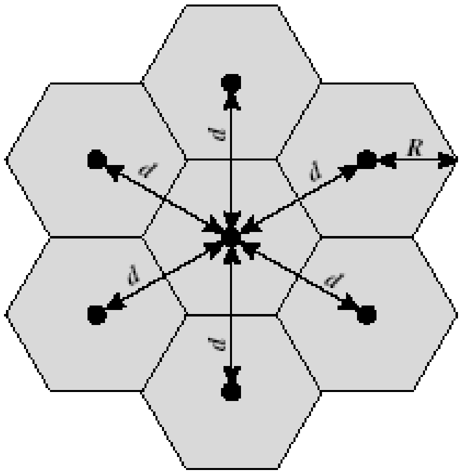
Uneven distribution of BSs → Why?

Cell Sizes

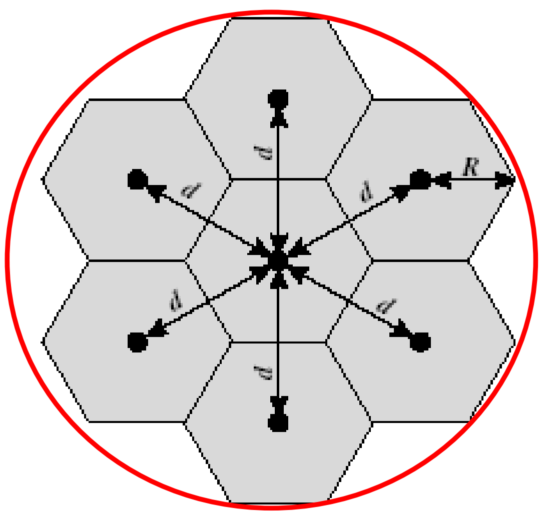
- Cell size: 0.1 – 30 Km (radius). Not a constant. How to determine?
  - Determined according to connection load (density of users)
- Macro cell
  - Large cell for sparsely populated area (lesser users)
- Micro cell
  - Small cell for densely populated area (more users)
  - Smaller cells => lower transmission power => more channel reuse
  - What happens if macro cells are used for highly populated area?
- Umbrella cell (hierarchical cell)
  - Two (or more) levels: macro cell over multiple micro-cells
    - Macro cell for fast moving users, micro-cells for slow users
  - Reduce number of handoffs for fast moving users (in vehicles)
  - A tradeoff solution for channel reuse and frequent handoffs

Umbrella Cell

- Purpose of umbrella cells: support both users with high mobility and users with high density
- An Umbrella cell: A macro cell on top of 7 micro cells.
- The macro cell need to use different set of channels from micro cells, i.e., macro cell channels + micro cell channels
- When a new call arrives, should it be assigned to the micro cell channel or macro cell channel?



7 cells with similar size



a macro cell on top of 7 micro cells

Pros and Cons of Cellular Networks

- Advantages of cellular networks
  - Higher capacity: space division multiplexing to allow frequency reuses to support more users and higher bandwidth
  - Less transmission power: MSs are not far away from BSs. The power consumption of mobile device is minimized
  - Local interference: shorter distance between MS and BS leads to low transmission power => less interference
  - Robustness: Decentralized system with multiple BSs for connection with MSs => more fault tolerant
- Disadvantages of cellular networks
  - Infrastructure: require a complex infrastructure to have full coverage of the whole service area and connect all base stations
  - Handoff: moving from one cell into another

Area Planning & Frequency Assignment

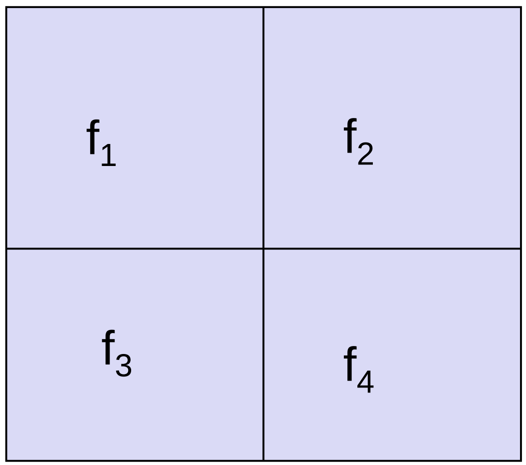
- Goal: Min the number of call blocking, Max channel utilizations, Min handoffs (reduce ping-pong effect)
  - Call blocking: a call-request from a MS is rejected due to no free channel available

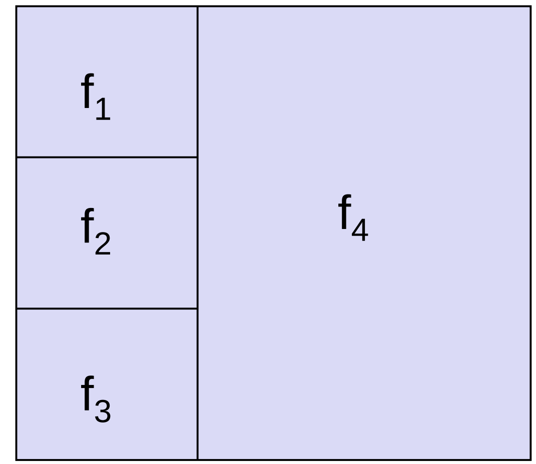
- Two directions to maximize system throughput at low cost:
  1) Divide the area into cells according to the distribution of users and traffic load
  2) Find the minimal channel-reuse distance, subject to the satisfactory signal quality (i.e., good SIR)

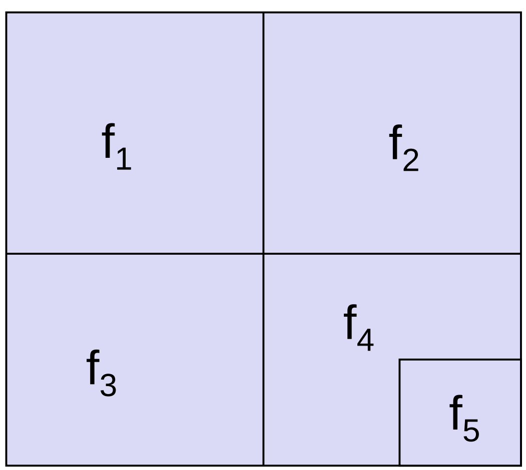
How to divide an area to cells?

- What is the right size of a cell?
  - Smaller cells => more cells => more BSs
    - More operational and management cost, but
    - More channel reuse and more users can be supported
  - Large cells => less BSs
    - Less operational cost of BSs, but
    - Poor channel utilization

Which cell division is better?







Suppose frequency bands can be reused in non-neighboring cells:

- Which cell division has better usage of frequencies?
- Suppose there are 12 channels in total and all cells have the same number of users. How many users a cell division can support?

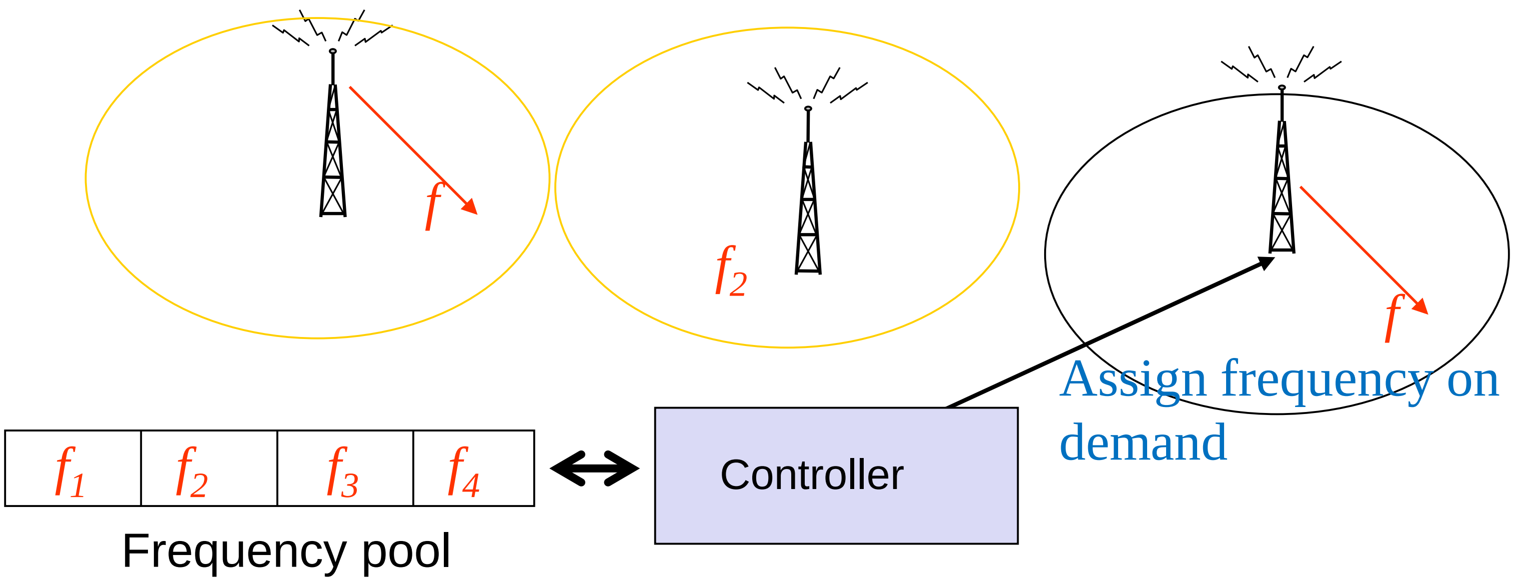
Frequency Assignment and Reuses

How to allocate frequency bands to a BS? Two basic ways to allocate frequencies to a BS, given the frequency bands of the system:

- Fixed frequency assignment:
  - Certain frequencies are assigned to a certain cell
  - Problem: Cells have different traffic load and this load changes from time to time
- Dynamic frequency assignment:
  - Any BS can assign the entire bands of frequencies that are currently free for use. (it needs to consider interference, i.e., frequencies currently used in neighbor cells.)
  - The cells with more traffic can use more frequencies
- How can a BS know the current free channels for assignment?
  - Coordination among BSs for assignment, or
  - A Central controller maintains a pool of free-channels

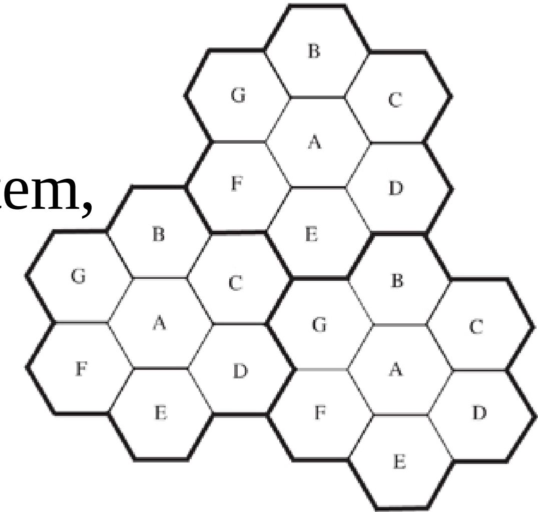
Dynamic Frequency Assignment

- A central controller maintains the pool of free frequencies
- Each BS needs to request the controller for assignment of a frequency for a newly arrived user
  - BS needs to interact with the controller for every new user, leading to longer time for handoff



Analysis of Channel Reuse in Cellular Networks

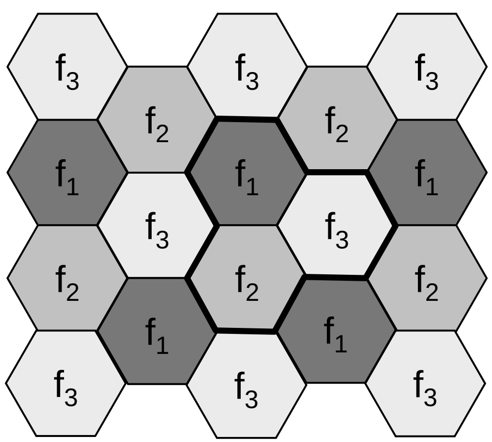
- Divide cells into clusters
  - Cells within a cluster all use different set of channels
  - The same set of channels are reused in cells in different clusters
- The size of the cluster (number of cells in a cluster), *K*, is called reuse factor
- The entire system only uses *K* sets of different channels
  - Given C, total number of channels in the system, the number of channels per cell is: C/K



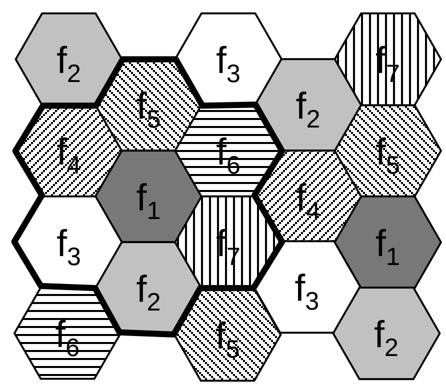
Frequency Planning

Which one is better, K = 3 or 7?

- When K = 3, only neighboring cells use different frequency sets (separated by one cell distance), but in practical, it requires larger separation distance
- With a strong transmission power, the separation distance should be larger (e.g., K = 7)



3 cell cluster



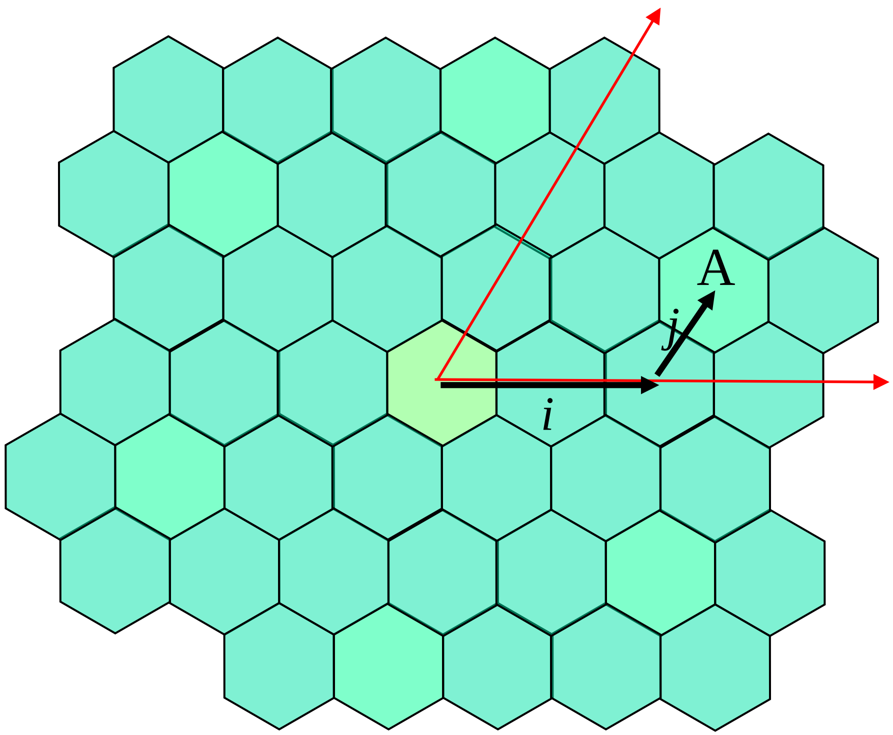
7 cell cluster

Reuse Factor K

- Consider a cluster with C duplex channels for K cells
  - $C = c \times K$, where c is the number channels for each cell
  - C is the total frequency bands used by the whole system (including guard space)
- The cluster is replicated across the space to cover the whole area
- K, the reuse factor, is the size (no. of cells) of each cluster
  - With a smaller K is (e.g., from 7 reduced to 3), more channels can be allocated to each cell
  - But, a smaller K leads to higher interference. Why?
  - $C = 105$: $K = 7 \Rightarrow c = 15$; $K = 3 \Rightarrow c = 35$

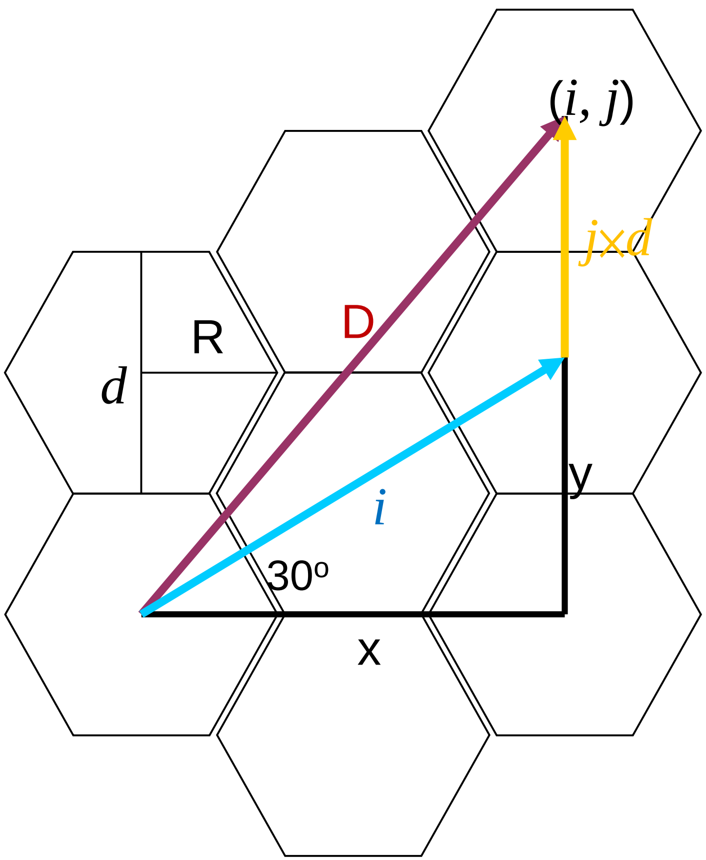
What is the right number of K?

Hexagon Cell Coordinate System



- A cell is denoted by coordinate (*i*, *j*). The center cell is (0,0)
- *i* and *j* are integers, called shift parameters, i.e., the number of cells being shifted from the center to the current cell
- *i*: number of cells moved horizontally
- *j*: number of cells moved vertically from the center cell
- Coordinate of cell A is (2,1), relative to the center cell

Distance between Cells in Hexagons



$$d = \sqrt{3}R$$

$$x = i \times d \cos 30^{\circ}$$

$$= i\sqrt{3}\ R \cos 30^{\circ} = 3/2\, i\, R$$

$$y = i\sqrt{3}\ R \sin 30^{\circ} = \sqrt{3}/2\, i\, R$$

$$D^2 = x^2 + (y + j)^2 \quad \boxed{j \times d}$$

$$= (3/2\, i\, R)^2 + (\sqrt{3}/2\, i\, R + j\sqrt{3}\, R)^2$$

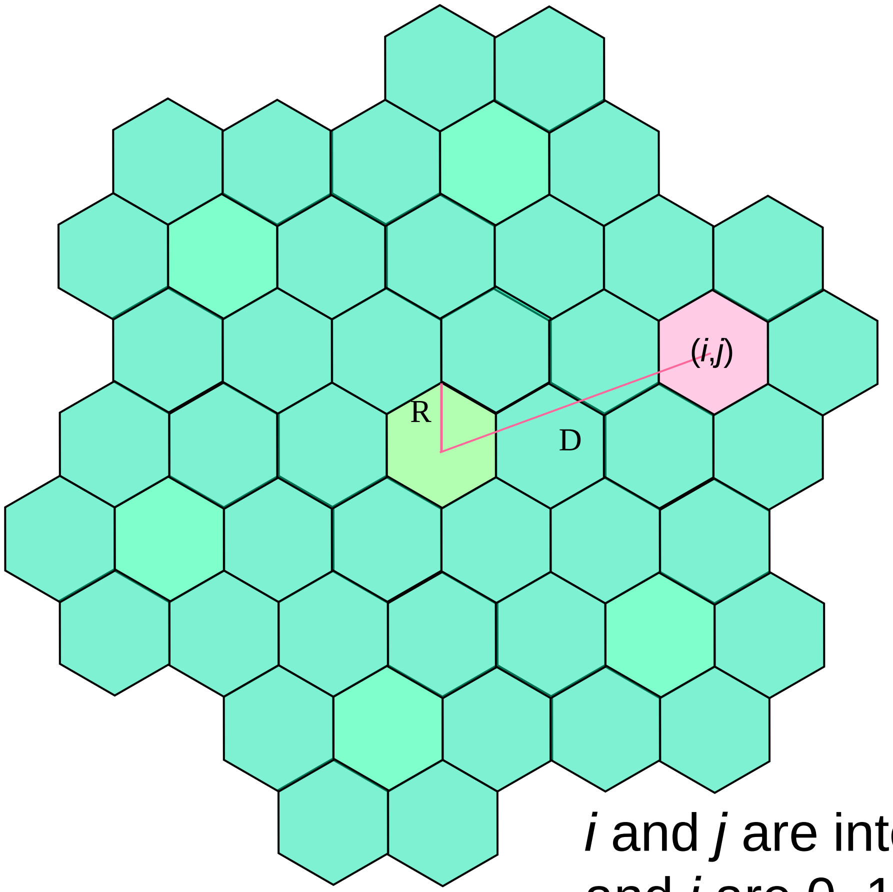
$$= 9/4\, i^2R^2 + 3R^2\, (i^2/4 + i\, j + j^2)$$

$$= 3R^2\, (i^2 + j^2 + i\, j)$$

$$D = \sqrt{3R^2\, (i^2 + j^2 + i\, j)}$$

$$= R\sqrt{3(i^2 + j^2 + i\, j)}$$

Distance & Reuse Factor



$$D = \sqrt{3(i^2 + ij + j^2)}R$$
$$= \sqrt{3K}R$$

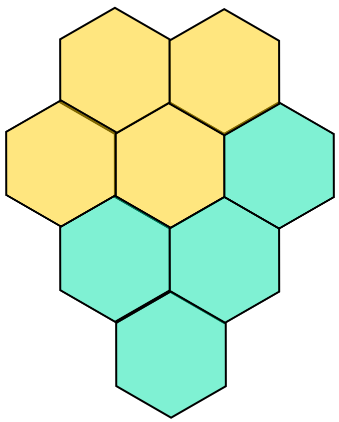
where

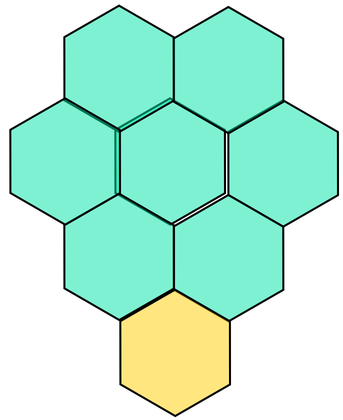
$$K = i^2 + ij + j^2$$

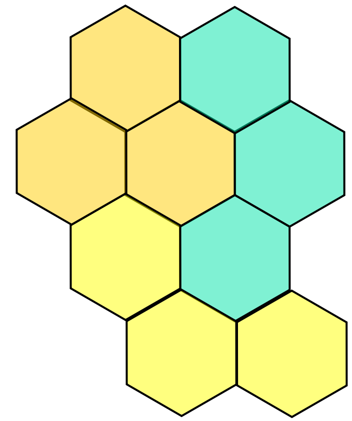
Reuse factor: number of cells in the cluster within distance from (0,0) to (i,j)

i and *j* are integers. The possible values for *i* and *j* are 0, 1, 2, 3, … Then, K = 1, 3, 4, 7, 9,…

K and No. of Channels per Cell







Each cell = C / K

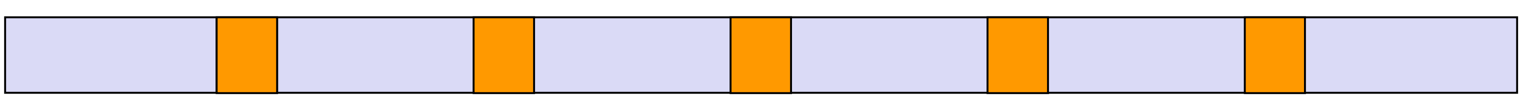
K = 7

Each cell = C / 7

K = 3

Each cell = C / 3

C is a constant for the entire system. It is divided into K groups of channels separated by guard frequencies



Signal Quality

- The signal quality depends on the ratio between signal power and interference (noise) power

$$\frac{S}{I} = \frac{S}{\sum_i I_i}$$

Interference from the i^{th} BS

- This is called signal-to-interference ratio (SIR) or Signal-to-noise ratio (SNR)

Signal-to-Interference Ratio (SIR)

- Signal-to-noise ratio (SNR, or SIR)

$$(SNR)_{\mathrm{dB}} = 10\log_{10}\frac{\text{signal power}}{\text{noise power}}$$

- SNR is typically measured at a receiver
- SNR sets the upper bound on achievable data rate
  - High SNR => high-quality signal, high data rate
  - Low SNR => low data rate (802.11 Auto Rate Fallback)

Calculation of SIR/SNR

- SIR is measured in dB (decibel) .
- SIR in dB = $10*\log_{10}(P_{Signal}/P_{Noise})$.
- Example: Given SIR = 20dB, what is ratio of P_{Signal}/P_{noise}?

  $P_{Signal}/P_{Noise} = 10^2 = 100$

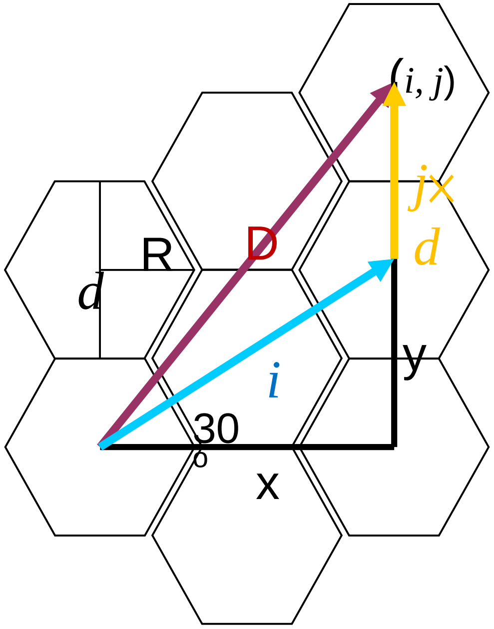
SIR = 20 ~ 25 dB	**Strong Signal**
SIR = 15 ~ 20 dB	Good Signal
SIR < 12 dB	Poor Signal

Signal Propagation Model

- The received signal power depends on the distance between the transmitter and the receiver.

$$P_r = P_0 d^{-\alpha}$$

- α is called the path loss exponent.
  - Typically, $2 \leq \alpha \leq 5$.



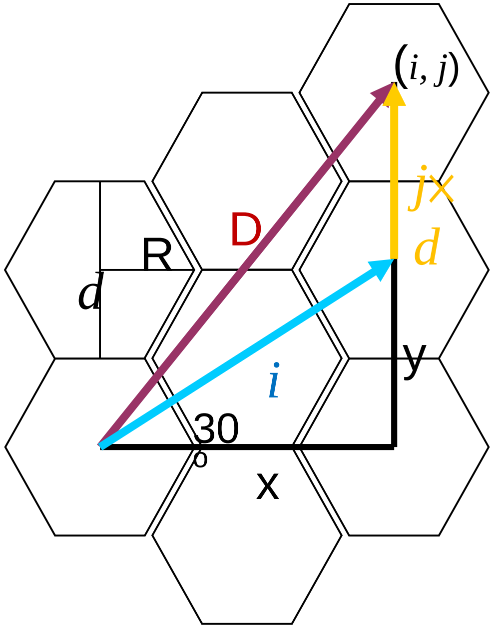
SIR Analysis in Cellular Networks

- Assumption:
  - The user is located at the corner of a cell, i.e., d = R
  - Interference from all other BSs using the same channel
  - All BSs use the same power

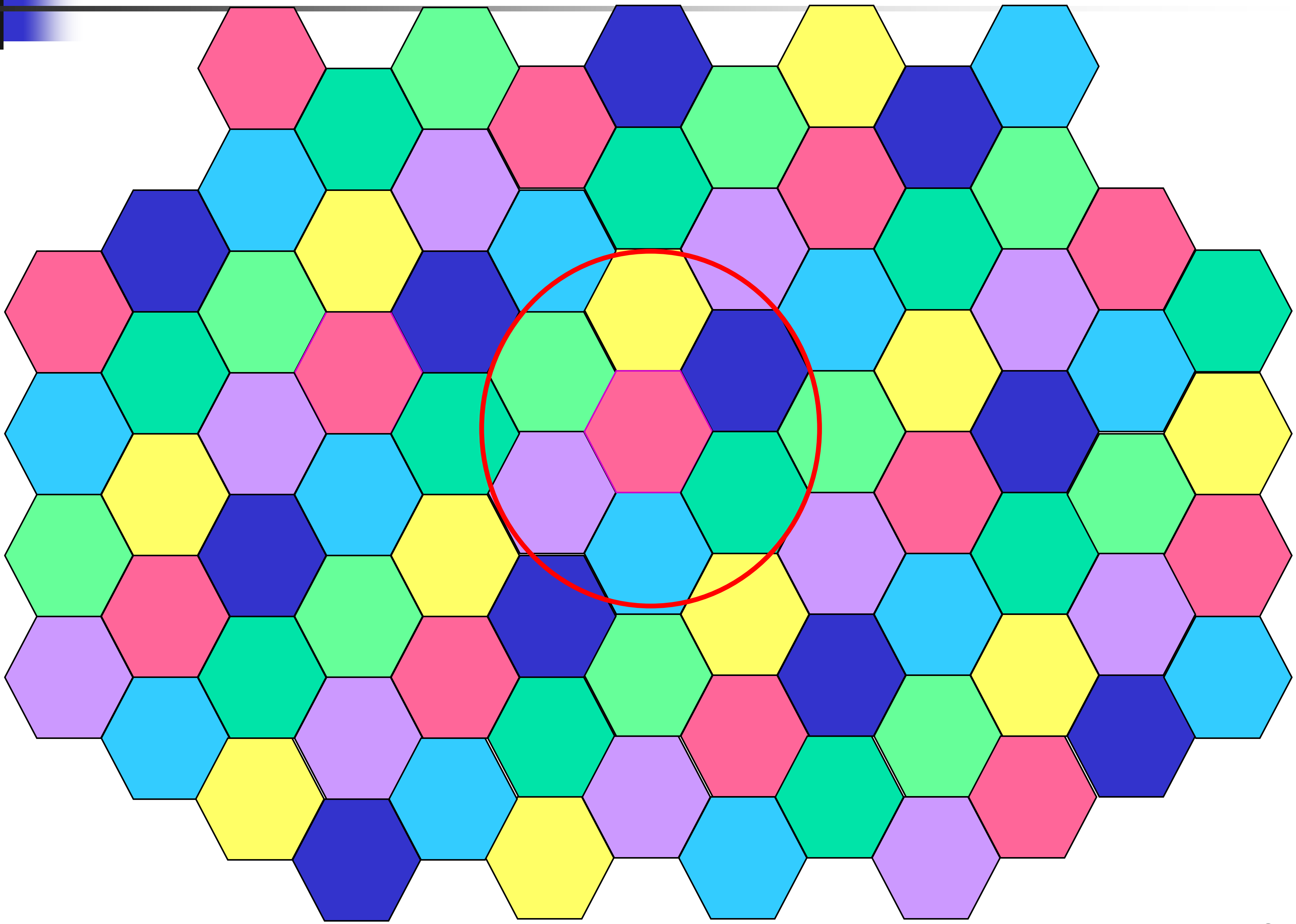
$$S = P_0 R^{-a}$$

$$\frac{S}{I} = \frac{P_0 R^{-\alpha}}{\sum_i P_0 D_i^{-\alpha}} = \frac{R^{-\alpha}}{\sum_i D_i^{-\alpha}}$$

D_i is the distance between the centers of the reference cell and the i-th interfering cell



Reuse Factor K = 7

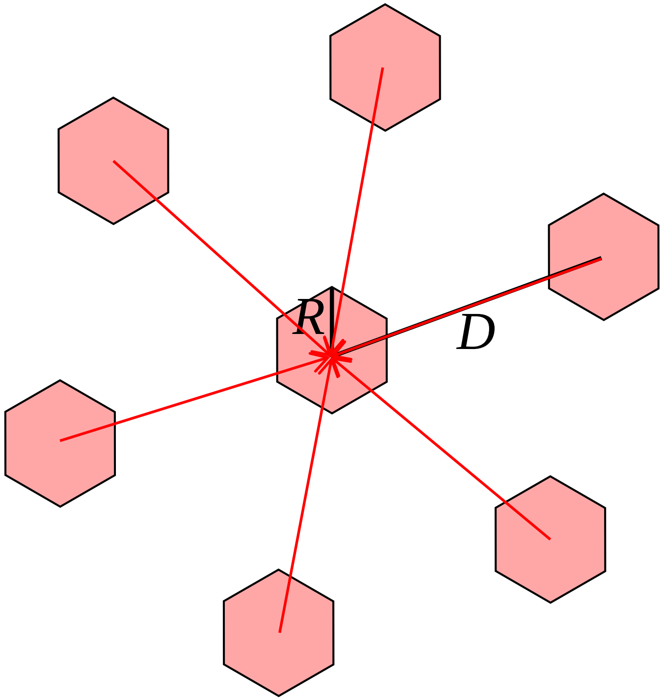


SIR Calculation for K = 7

- Consider only the 1st tier of interfering cells
- Note: in real cases, more factors need to be considered. What are these factors?

$$S/I = R^{-\alpha} / 6D^{-\alpha}$$

$$\frac{S}{I} = \frac{1}{6}\left(\frac{D}{R}\right)^{\alpha}$$



Calculate K for a Required SIR Value

- Suppose at least SIR = 18 dB.
- What is the minimum reuse factor? (assume $\alpha = 4$)
- We need to find the minimum distance D from the 1st tier of interfering BSs…

What is the right K?

$$10 log_{10} S/I \geq 18\text{dB}$$

$$\frac{S}{I} = \frac{1}{6}\left(\frac{D}{R}\right)^{\alpha} \geq 10^{18\text{dB}/10} = 10^{1.8} \approx 63$$

$$\boxed{D = \sqrt{3K}R}$$

$$D \geq 4.4R$$

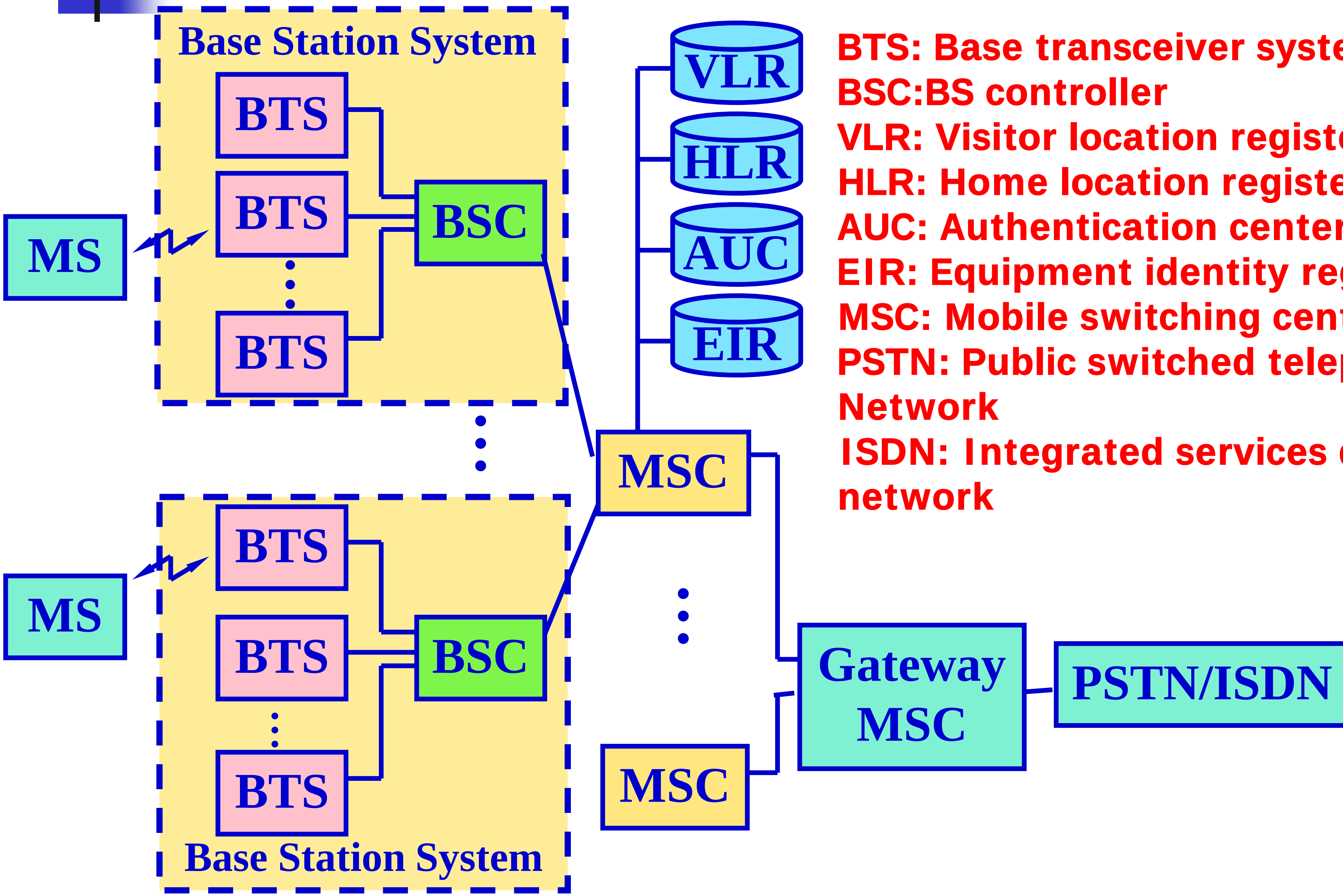
$$\sqrt{3K} \geq 4.4$$

$$K \geq 6.5$$

Choose $i = 2, j = 1$ or $i = 1, j = 2$

$\boxed{\text{Ans: } K = 7}$

Cellular System Infrastructure

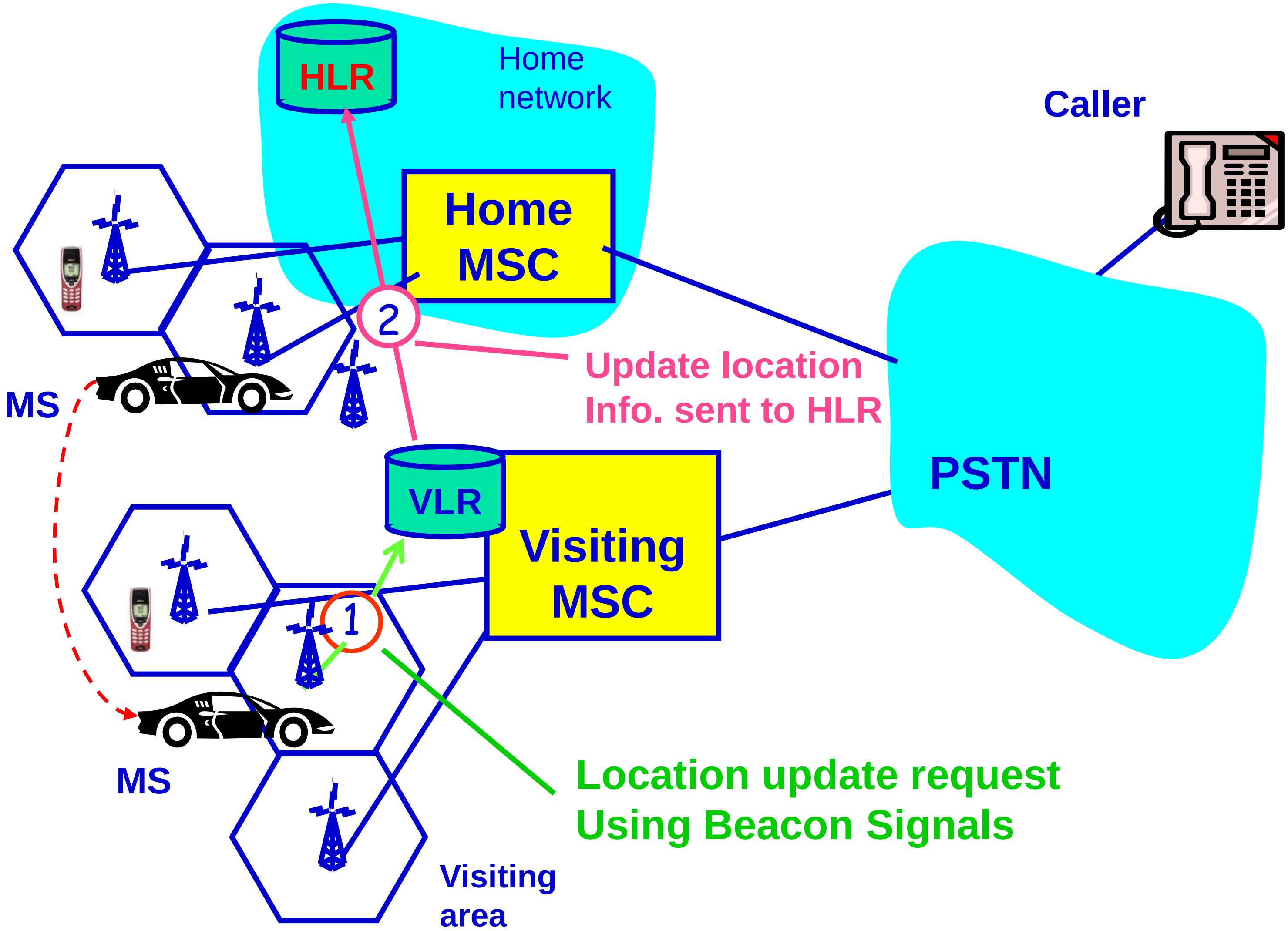


- BTS: Base transceiver system
- BSC:BS controller
- VLR: Visitor location register
- HLR: Home location register
- AUC: Authentication center
- EIR: Equipment identity register
- MSC: Mobile switching center
- PSTN: Public switched telephone Network
- ISDN: Integrated services digital network

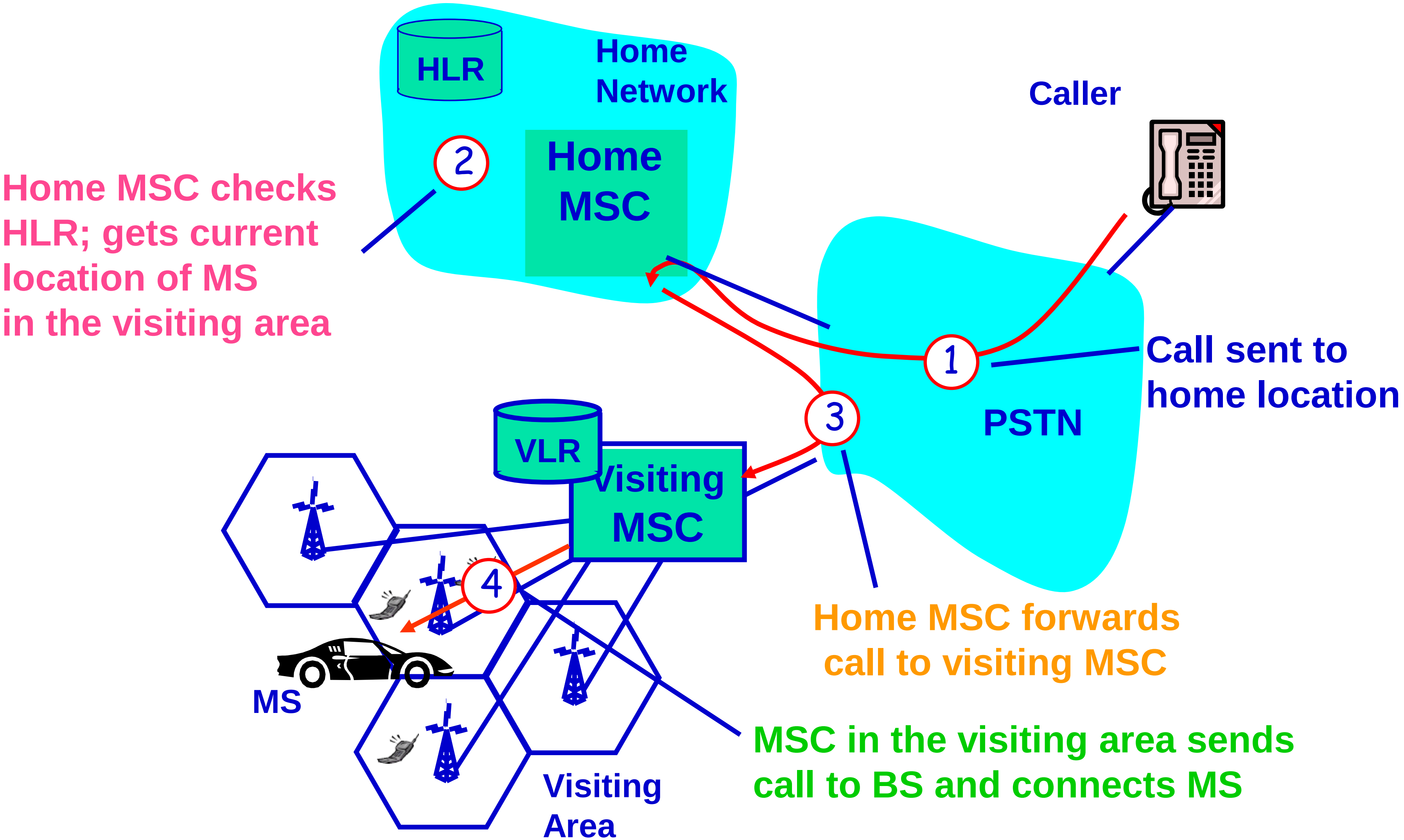
VLR/HLR/AUC/EIR

- VLR contains information about all visiting MSs in the particular area of MSC
  - VLR has pointers to the HLR's of visiting MS
  - VLR helps in billing and access permission to the visiting MS
- AUC provides authentication and encryption parameters
- EIR contains identity of equipment that prevents service to unauthorized MSs

Automatic Location Update



Automatic Call Forwarding using HLR-VLR



Tracking MS Location & Handoff

- Wireless system needs to know whether MS is currently located in its home area or some other area (for routing incoming calls)
  - This is done by periodically exchanging signals between BS and MS known as beacons
- BS periodically broadcasts beacon signal (e.g., 1 per second) to detect the MS around
- Each MS listens to beacons, when it hears signal from a new BS, it adds it to the active beacon kernel table
  - This information is used by the MS to locate the nearest BS
- Information carried by beacon signal: cell ID, gateway ID of the paging area, timestamp, etc.

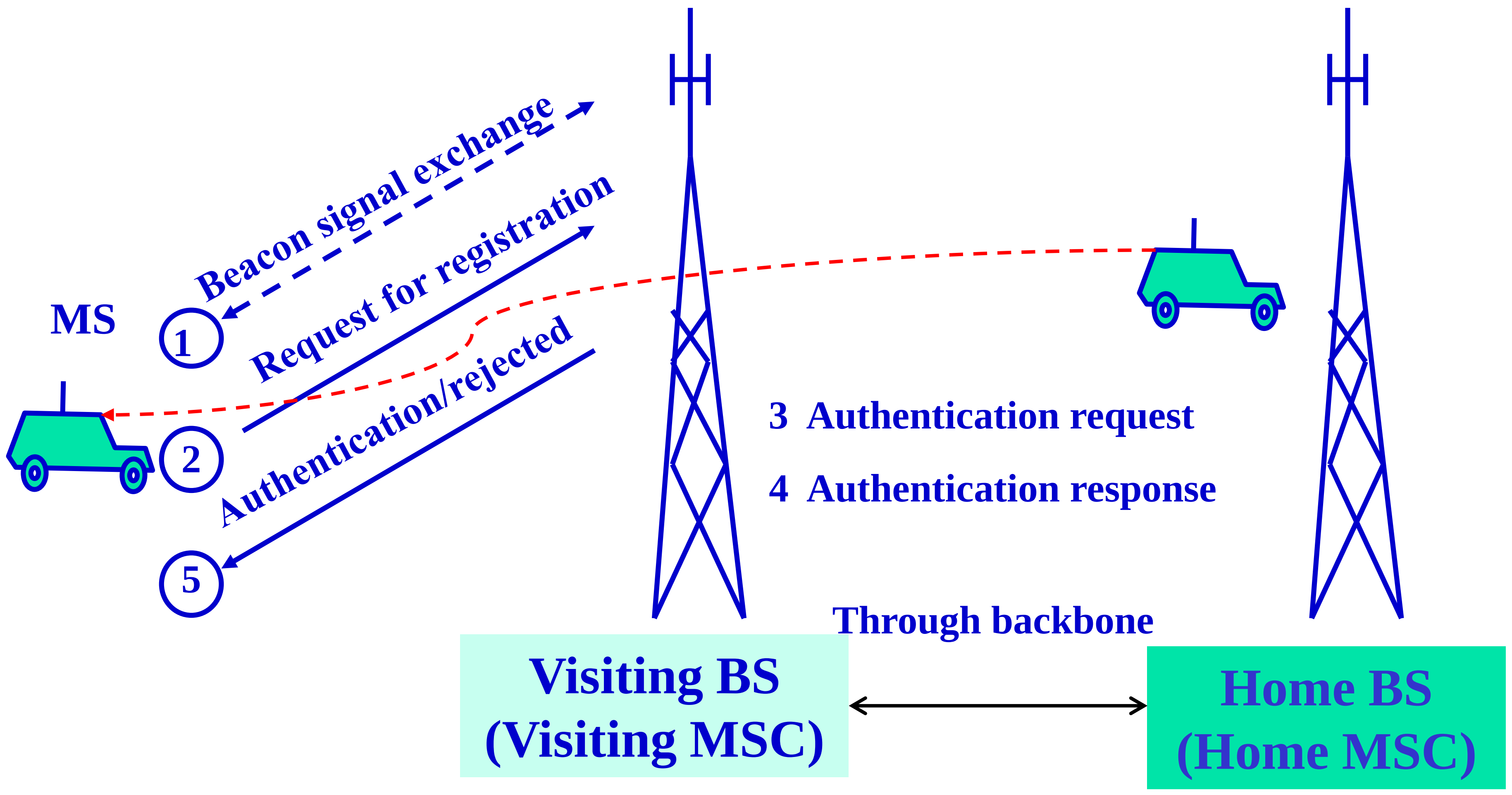
Steps for MS moving to a new MSC

- When MS decides that it needs to connect to a new BS (a new subscription area), it initiates the handoff process
- The new BS performs the user level processing by contacting the home MSC of the MS to find:
  - Who is the user?
  - What are its access permissions?
  - Keeping track of billing

(no need of this operation if the MS is within the same MSC)

- The home MSC sends appropriate authentication response to the current serving BS (visiting MSC)
- The visiting MSC (via the visiting BS) approves/ disapproves the user access

a MS moving outside its subscription area



Summary

- Cells are modelled as Hexagons
  - Channel reuse
  - Umbrella cells
- Cell size and density of users
  - Frequency assignment
- Channel reuse factor
  - Calculating interference distance in hexagon model
  - SIR in hexagon model
  - Calculating reuse factor K to meet required SIR
- Cellular system infrastructure
  - Keeping track of users and handoff

Exercise

- Suppose the system requires SIR $\geq$ 20 dB. What is the minimum reuse factor? Assume $\alpha = 3$.